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The embodied CO_2 of a wind farm

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Signed: Rebecca Couttie Date: 01/ 09/ 2014

Abstract

Scotland has an abundance of wind resource which has led to an increase in the number of wind turbines. Government incentives have also been introduced with the aim of reducing the carbon footprint of the country. The preconceived method of achieving lower carbon is to introduce more renewable energy systems because they provide 'clean energy'.

With this increase in the number of wind turbines being installed, it is important to fully understand the impact. When the feasibility of turbines is being investigated, or the carbon dioxide (CO_2) content is being discussed, it is the operation and maintenance CO_2 that is discussed. However there are other aspects that increase the CO_2. The hypothesis of this thesis is that the embodied CO_2 represents a significant part of the total CO_2 production.

To test this hypothesis each stage in the life cycle of a wind farm was evaluated. This was done by creating calculations at each stage, which calculated the CO_2 produced. It was found that the embodied CO_2 was a significant part of the total wind farm emission. This implies that that the embodied CO_2 should be included within any turbine feasibility analysis. This leads to the question that if all other renewable energy systems are the same then a significant part of their CO_2 production might be embodied.

An Excel tool was constructed that contains the calculations used to evaluate the total CO_2 production. This tool was used when testing the hypothesis of the thesis. To be employed as a decision support tool for wind farm feasibility assessment, several refinements will be required to the interface to render the tool more user friendly.

The tool was used to evaluate a case study on Whitelee Wind farm. The tool enables selections to be made with regard to the site location, land type, length of road, type of turbines and the number of each. The tool contains a more in depth level sheet which enables more in depth selections on the wind farm to be constructed.

Acknowledgements

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1. Project background

The world is full of ideas of about 'clean energy', sustainability and climate change. These are the trending topics of what is happening now in our society. Sustainability is described as the "question of our generation" along with the end of the use of oil (TED, n.d.).

'Clean energy' is a misleading term as it implies that the energy does not produce any harmful substances. A 'clean energy source' would be a more appropriate terminology. Renewable energy technologies such as wind, solar and wave have a reputation for being 'clean' because the source is renewable and hence sustainable but that does not take into consideration any other stage of the system life cycle:-

"Renewable technologies are considered as clean sources of energy and optimal use of these resources can minimize environmental impacts, produce minimum secondary wastes and are sustainable based on current and future economic and social societal needs." (N.L. Panwar, 2011, p. 1513)

There are still harmful substances that these technologies produce however, particularly during the materials and manufacturing phase:-

"Commentators often forget that some kind of machine is needed to covert this energy into usable power" (Ward, 2006)

Questions are being asked about how clean 'clean' energy actually is. Referring to the quote from Panwar above, it appears that if renewable technologies can be used effectively then it will further reduce the harmful waste products. It is not going to disputed that renewable technologies are the path of the future however it is important that their repercussions are understood in the fullest so that well informed decisions can be made about the current and future feasibility. It is a concern that perhaps renewable energy systems could produce more CO_2 than they save. Questions which are of a similar tone are not well documented:-

"To date it has been assumed as self-evident that wind generated electricity will save carbon." (Myhill, 2009)

These harmful byproducts are generally measured in CO_2 as this greenhouse gas is believed to be a main contributor to climate change. Figure 1 illustrates the combination of the greenhouse gas emissions in 2012 (EPA, 2012). It confirms that CO_2 is the largest contributor and explains why the other byproducts are not discussed as extensively.

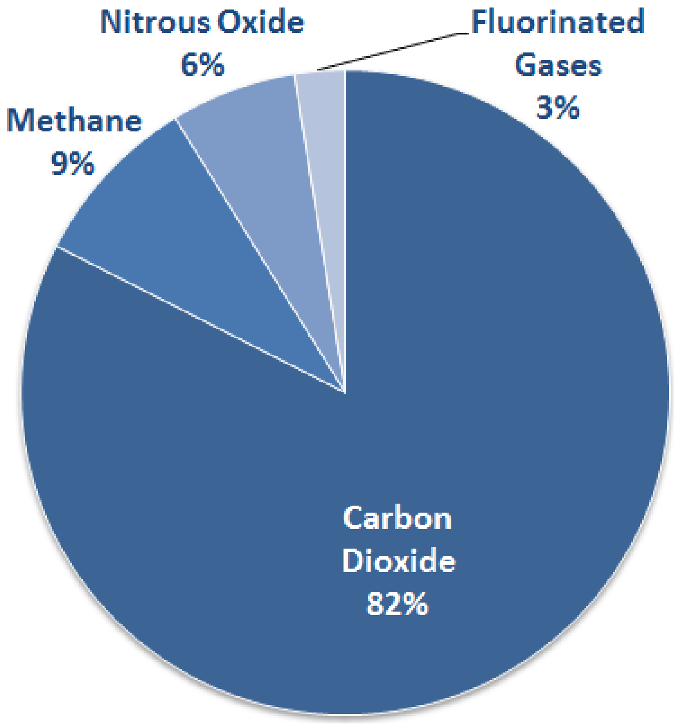

Figure 1- Greenhouse gas emissions 2012

Aside from the concern that renewable energy systems produce more harmful gases than previously thought, they still have other problematic characteristics. In particular, renewable energy systems produce varying amounts of energy. This is because the wind does not always blow and the sun does not always shine. This type of energy can be described as being stochastic produced with random peaks and troughs.

There are two main problems with this. First, the power does not always match demand. So, for example, it could be particularly windy one night but with low power demand. This situation would result in an excess of energy and illustrates the peak and trough tendency of renewable energy systems.

The second problem is that in the future when they are more renewable technologies installed, conventional systems such as thermal power stations will be used to meet the demand and fill the troughs. When conventional systems run in this way, they become less efficient and as a consequence more CO_2 is produced for the same amount of energy.

Unfortunately, those two issues will continue to plague renewable energy systems. This means that right now, fossil- derived power could not be replaced totally by those systems (Steadman, 2013). However, that does not mean to say that it will never be possible. If energy can be stored effectively then that would solve many of the problems. Solutions like batteries and pumped hydro could be implemented in the future alongside increased renewable energy derived energy supply.

Government incentives have been introduced to increase the number of renewables in use. There are many incentives all with the overall aim to reduce CO_2 emissions to limit the damage that they cause:-

"The Scottish Government's ambition is that by 2020, renewable sources generate the equivalent of 100% of Scotland's electricity consumption." (Government, 2011)

The incentives are generally relative to values of CO_2 production and therefore the thesis will measure CO_2 levels produced.

1. 1. Aims & methods

The hypothesis of the thesis is that in certain cases embodied CO_2 represents a significant CO_2 emission of a wind farm. The thesis will therefore address the ability to investigate the embodied CO_2 of a wind farm.

Initial research indicated that there was no tool available that will allow a user to estimate the embodied CO_2 of a wind farm as required to test the hypothesis. Therefore the methods involved are as follows:-

1. Investigate existing literature.
2. Collate and revise existing techniques for estimating the embodied CO_2 and produce new techniques where applicable.

3. Develop a 'Wind farm embodied CO_2 estimator' encapsulated in an Excel tool that can be used by others and downloadable from the ESRU website.
4. Apply it to a local wind farm.

1. 2. Embodied carbon dioxide

This following section focuses on embodied CO_2 defined as:-

"The embodied CO_2 of a material is a calculated value of the quantity of carbon derived due to the extraction, processing and transportation of the material to the product. This value is typically expressed as the mass in kg of embodied CO_2 from producing 1 kg of material, shown as kg CO_2/kg." (Wrap, n.d.)

The life cycle analysis of the CO_2 of a system includes a cradle- to- grave investigation or a as described by the source as life cycle analysis (LCA) as shown in figure 1 (Harrison, 2008). The figure illustrates the four stages in the system life which will be analysed in this thesis by looking at each stage individually. The materials and manufacture stage includes the embodied CO_2 for each material that it used for the turbine. The assembly and installation includes the transport of the turbine from manufacturing plant. These first two stages tend to have the highest level of associated CO_2. The operations and maintenance has the lowest level of CO_2 especially if the power required for the turbine is assumed to be from a renewable source. The decommissioning and disposal is the final stage of the turbine life, in which this thesis analyses several disposal options. Each stage with the corresponding assumptions is described in section 2.

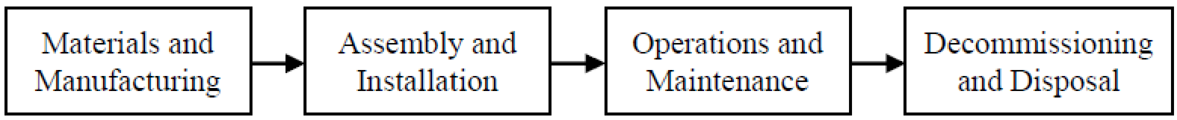

Figure 2- LCA

As the thesis is considering the embodied CO_2 of an entire system and not only of the materials then the stages shown in figure 2 are relevant. The embodied value excludes the operations and maintenance stage. In general it is the emission for the operations and maintenance aspects that is used to describe and compare with a conventional power station.

It is a value that can be manipulated to be relatively small in the renewable systems because it is at this stage that the renewable source is used to generate power. Wind turbines require a power source to allow them to begin to generate power and often it is advertised that this power is from another renewable source. Therefore the life cycle or cradle- to- grave CO_2 (figure 2) should be compared with the embodied CO_2 to test the hypothesis.

1. 3. Wind turbines

Wind turbines were chosen to be investigated in the project as Scotland has made increasing investments in this technology. For example, Whitelee Wind farm in Eaglesham has 215 turbines and claims to power 300,000 homes (Whitelee, n.d.). David MacKay, author of Sustainability without the hot air, supplied a realistic view on these claims:-

"I'm simply trying to convey a helpful fact, namely that if we want wind power to truly make a difference, the wind farms must cover a very large area." (MacKay, 2008, p. 33)

Figures show that Scotland has a high potential for further development of wind power due to the deep red that indicates high wind speed from the legend in the figure. Figure 3 below is an image that demonstrates the abundance of wind potential in the world (Co, 2010). Scotland's location has been highlighted on the map which shows that its abundance of wind is competitive with the rest of the world.

"The widespread availability of wind power has fuelled substantial interest in this renewable energy source as one of the needed technologies." (C. Wang, 2009, p. 2053)

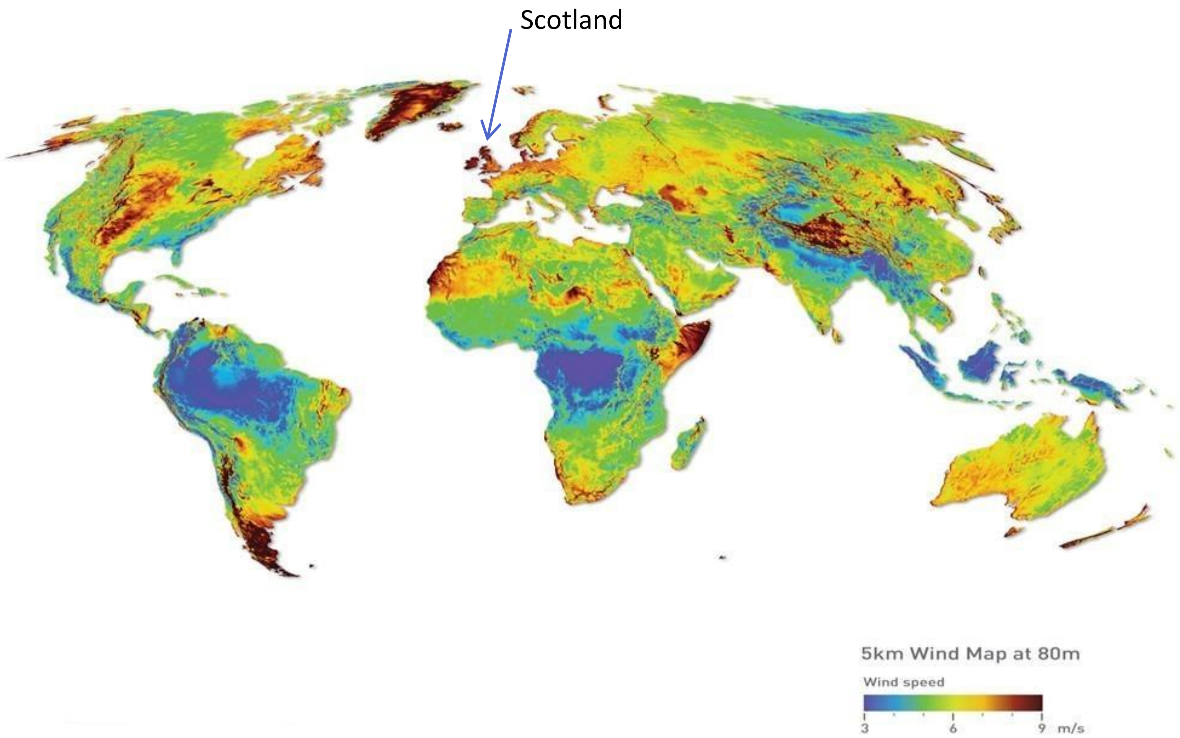

Figure 3- Wind energy world distribution

With these numbers and figures being published, the number of turbines in Scotland has been on the rise as it is often advertised that wind turbines have "environmental benefits in generating electricity without emission of 'greenhouse' gases" (Alan H. Fielding, 2006, p. 359) If Scotland is to expand the number of wind farms, then the consequences of these actions should be considered and this aspiration coincides with the purpose of the thesis.

Research has shown that wind turbines still have lower life cycle emissions than conventional systems:-

"The life cycle emissions are comparatively very high in conventional sources as compared to renewable sources. In conventional sources only nuclear-based power electricity generation has fewer emissions to the environment but the dumping of the radioactive material causes higher damage to the surroundings." (Varun, 2009)

This quote insinuates that wind turbines could be viable for the future based on the fact that they have lower emissions than conventional systems.

2. Calculations required for estimating CO_2

When calculating the embodied CO_2 of a wind farm, the life cycle was broken down into the stages as illustrated in figure 1. Data was collated from existing tools and information found from the literature review and then further supplemented with new calculations that were required to complete the analysis. Due to the different data received, the results will contain errors. This was explained by the following:-

"The variation in published data stems from differences in boundary definitions (including geographic origin), age of the data sources and rigour of the original life-cycle assessments." (Jones, 2008, p. 87)

There was also data that was not possible to acquire and therefore the results contain assumptions. The combination of varying data and assumptions meant that the results were better described as estimations or indications of the embodied CO_2 as opposed to fully reliable answers. Furthermore, the results have not been fully validated, which if the tool was to be used accurately would have been essential. However due to time constraints this was not possible.

There are many things that have an effect on the results of the embodied CO_2 of a turbine-

"The CO_2 analyses of wind turbines is presented considering the influence of different parameters like life time, load factor, power rating, country of manufacture, etc." (Varun, 2008, p. 1069)

All the parameters that were included in the analysis are detailed where relevant.

There are two main parts to a wind farm, the turbines and the site. To estimate the total embodied CO_2 for a wind farm both must be considered and therefore the following life cycle stages contain the calculations for both a wind turbine and the site.

The following stages vary in size according to the relevance of each section. For example, the materials and manufacture section of the wind turbine is one of the largest as it has a large impact on the result of the overall embodied CO_2 estimation.

2. 1. Materials & Manufacture

The materials and manufacture section of the life cycle of the wind farms can contain the largest mass of CO_2 relative to any of the other life cycle stages. This is due to the large volume of manufacturing required for each turbine.

2. 1. 1. Wind turbine

To calculate the embodied CO_2 the turbine needs to be broken down into its main component parts. One of the very first stages of the life cycle of a turbine is the transport of the raw materials to the manufacturer. This was not considered within the thesis due to its complexity and the time that would have been required to assign to the task.

Ideally if the analysis was to be finished with complete accuracy then each component to the smallest part would need to be considered. However only the main components were considered because of time constraints and that the smaller components were seen as insignificant when compared to the larger components.

Another major assumption that followed this was that a particular component was made of the same material and its entire weight associated with a facticular emission factor. While this was not an ideal method, it is considered to be a reasonable assumption to make in the face of uncertainty.

The mass and specified material of each component is essential for calculating the embodied CO_2. Once these details were known a data base called the Inventory of Carbon and Energy (ICE) which was produced by the University of Bath was used to find the corresponding embodied CO_2 per kg for each material ($kgCO_2/kg$).

From this point the calculation is:-

$$\text{(1)}\quad CO2 \text{ per component } (kgCO_2e) = Mass\ (kg) * kgCO2/kg$$

Table 1 is based on a Gaia Wind 133 turbine and shows the weight and of each main component, the corresponding embodied CO_2 per kg for each material and the resulting mass of CO_2. (GaiaWind, 2014) The unit for the resulting mass of CO_2 is $kgCO_2e$. This means the equivalent $kgCO_2$ and it is used here because CO_2 is not the only "greenhouse" gas which is released during manufacture and the ICE database equates the other relevant gasses into CO_2.

Table 1- Gaia Wind 133 Materials & Manufacture

Component	Material	Weight (kg)	$kgCO_2e/kg$	$kgCO_2e$
Gearbox	Steel	75	0.47	35
Chassis	Steel	590	0.47	277
Generator	Copper	150	2.71	407
Cover	Fibreglass	10	1.54	15
Blade	Fibreglass	200	1.54	308
Tower	Steel	2300	0.47	1081
		Foundation		
Base	Concrete	49500	0.47	23265
Rebar	Steel	810	0.47	381
Cable	Copper	572	2.71	1550

Table 1 highlights that the highest level of CO_2 corresponds to the concrete base. The Gaia Wind 133 turbine is a small turbine and as size increased so emissions rise.

2. 2. Assembly & Installation

The assembly and installation mass of CO_2 with regards to the turbine is minimal compared to the materials and manufacturing stage. However the site preparation was assumed to take place during this stage meaning that roads with the associated concrete are within this stage.

2. 2. 1. Wind turbine

During this stage the CO_2 mass related to the wind turbine is due particularly to transport and then the CO_2 which corresponds to the machinery used to assemble and install the turbine.

Firstly the transport of the turbine was required to be broken down into component parts because each part can come from a different location. The distance and type of transport is crucial for this part of the calculation.

An assumption used within the thesis was that the turbine could be transported by, lorry, plane or ship. More realistically, a combination would be most appropriate however due to the other assumptions the difference it would make was regarded to be insignificant. Table 2 illustrates a summary of the CO_2 values relevant to each method of transport (change, 2011).The freight mass is the additional load on the lorry.

Table 2- Modes of transport

Mode of Transport	**kgCO_2e/ton of freight/km**
Lorry	0.15
Plane	0.5
Ship	0.04

To complete the calculation for total mass of CO_2 with respect to travel of the turbine, the distance to be travelled and the mass to be transported must be known. The equation can be applied to multiple modes of transport if deemed necessary. The calculation becomes:-

(2) Component Transport (kgCO_2e) = Mode of transport value (kgCO_2/ton of freight/km) * Mass to be transported (kg) /1000 * Distance (km)

The next step is to calculate the CO_2 with regard to the assembly of the turbine which is turbine specific. In this thesis, an assumption was made that a crane was used for the length of the construction time. Therefore the CO_2 from the crane was assumed to be the CO_2 required for assembly.

Selecting an appropriate crane for a job can be a complicated project. Figure 4 below illustrates the considerations that are involved in the process (Shafiul Hassan, 2013). There are various inputs that could be a consideration for example the load capacity. These details were not considered within this thesis as it was too complex and the additional detail required would make an insignificant change to the result. Interestingly, the process includes a section on the analysis of CO_2 emissions. Crane hire companies are using this is a selling factor, rather like the car industry.

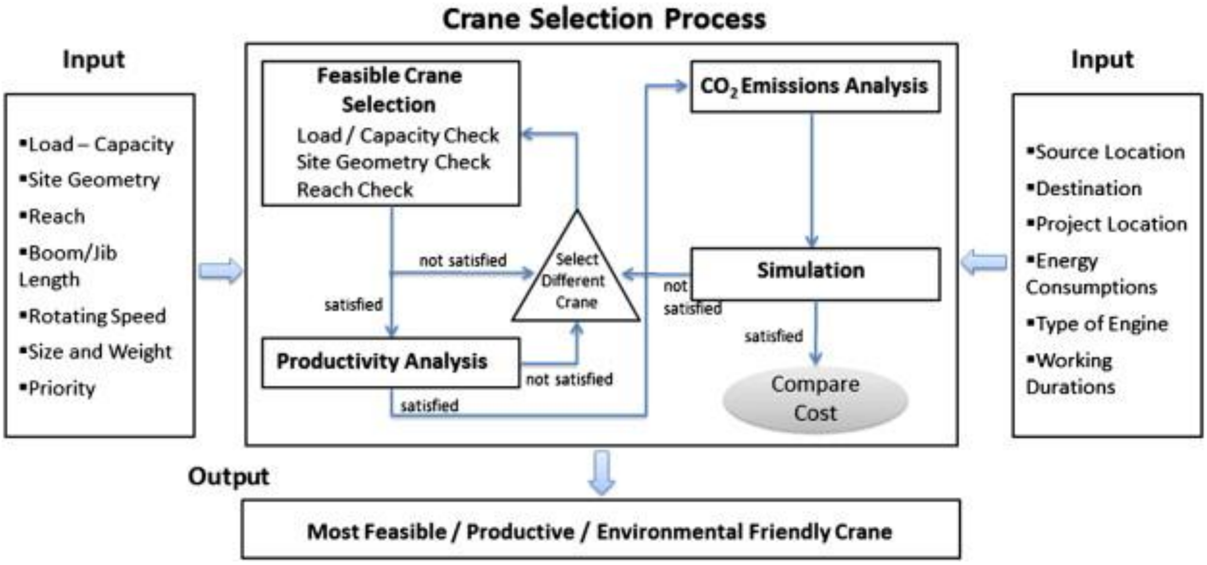

Figure 4- Crane selection process

Therefore due to these complications within the crane selection process, values were taken for a general crane.

Table 3 below, shows the CO_2 produced from a crane when in use. The figure for the volume of diesel a crane uses in an hour comes from Hiab, a company which works to "improve the efficiency of cargo flows" (Hiab, n.d.). Once this information was known, the mass of CO_2 within diesel was used to convert into the mass of CO_2 per hour (U.S.EnergyInformationAdministration, 2014).

Table 3- CO_2e associated with crane

Plant equipment details	
kgCO_2e per hour for plant equipment	5

The calculation for the assembly of the turbine is then:-

$$(3)\quad \text{Assembly } (kgCO_2e) = \text{Mass of } CO_2 \text{ per hour for crane } (kgCO_2e/hr) * \text{Time for assembly } (hr)$$

Additionally, the transport of the crane to the site must also be taken into consideration. An assumption made here was that the diesel required to transport the crane to site would be similar to that of a fully loaded lorry and therefore figures were used from the data in table 2.

The lorry was assumed to be 6 axle with a weight limit not exceeding 8500kg per axle. (Buthcher, 2009, p. 1) Therefore: –

Freight weight= 6 * 8500

= 51000kg

It was deemed unlikely that the crane would have to be transported by sea or air because it would be logical if a plant hire was chosen that was close to the site. The distance here is multiplied by 2 as the crane will need to travel back to base. Therefore the calculation for the transport of the crane becomes:-

(4) Crane Transport (kgCO_2e) = Lorry mode of transport value (kgCO_2/tonnes of freight/km)*Freight weight (tonnes) *(Distance * 2) (km)

This concludes the calculations required for the assembly and installation of a turbine.

2. 2. 2. Site

The CO_2 associated with site assembly and installation can vary. This is because it is largely dependent on the type of land that the farm will be built on. For example if there is no road access then that already means a large mass of CO_2 will released when roads are implemented before even the site preparation is under way for the turbines. Currently, the concrete production accounts for about 6% of the total CO_2 emissions (Vanderley, 2003).

Three land types were considered in the thesis which were, industrial, agricultural and moorland. These were chosen because they would give a spectrum of varying degrees of CO_2 production.

The definition of industrial land in the thesis is that it is concrete land and is assumed that because of this no new roads would be required for construction. Therefore as an assumption it does not have additional CO_2 production. The concrete base for the turbine was taken into consideration in the wind turbine sections. Having wind turbines on industrial sites is becoming more popular as companies like GSK strive to show that they employ renewable energy systems.

Agricultural land is also becoming a more popular option to install turbines, particularly with farmers. There is a high likely hood that turbines on this land will require road access and therefore a calculation will be required which can be applied if road access if roads are required. The roads are assumed to be made of concrete with a set width and depth. Therefore the data that is required from a user is a value for the length of the road. The width chosen is to allow for the width of machinery and turbine to reach the final site. The embodied $kgCO_2e/kg$ for concrete is the same value as used in table 1 from the ICE database. The density of the concrete is also required to complete the calculation and is shown in table 4 below (Clarke, 1993).

Table 4- Road and concrete details

Road & Concrete details	
Width (m)	12.192
Depth (m)	0.25
Density of concrete (kg/km^3)	2400
kgCO2e/kg	0.47

Using these details, the CO_2 associated with the road can be calculated using the following equation:-

$$(5)\quad Road\ (kgCO_2e) = Width\ (km) * Depth\ (km) * Length\ (km) * Density\ (kg/km^3) * kgCO_2e$$

This calculation will give the estimate of the mass of CO_2 production for a road.

There will be CO_2 emissions associated with the building of the road and which would include the digging up of the soil as a base for the road. These were not considered in the thesis due to time constraints and also because they were seen to be minor in relation to the total CO_2 of the other processes.

The issue with the varying land types becomes problematic when the turbines are built on moorland. It is assumed that this land type is mostly peat land and bogs. There are many arguments existing which argue that building wind farms on peat outweigh the CO_2 saved from building wind farms in the first place. A blog on the Carbon Brief quotes the Sunday Telegraph saying that building on peat bogs "threatens the entire rationale of the onshore wind farm industry" (Staff, 2013). However an article from the East Renfrewshire says that it is possible for a CO_2 payback if the roads and turbines have been built properly:-

"A wind farm constructed sympathetically on peat can produce a positive CO2 return within 3 years of operation. If however the wind farm is poorly built, the CO2 payback can take 30 years - longer than the lifespan of the wind farm" (Council, 2013)

More information on peat bogs can be found in Appendix, section 8.1 of the thesis.

The information and figures is limited on peat lands. A value of "0.92 t CO_2/ ha /yr is assumed to be an acceptable approximation" (Government, 2008). Therefore as a low level calculation to provide a ball park figure was established:-

$$\text{(6) Peat Road } (tCO_2) = 0.92 * (\text{Length of road (m)} * \text{Width of road (m)} * 0.0001)\ (ha) * 20$$

This concludes the calculations that are associated with the assembly and installation.

2. 3. Operations & Maintenance

The operations and maintenance stage of the wind farm life cycle is relatively small compared to the other stages. This is because all the main tasks assigned with the implementing of wind farm have already been completed. There is assumed to be no operations and maintenance required for the site. It was also assumed that no repairs were required during the life span of the farm.

2. 3. 1. Wind turbine

The CO_2 which is relative to the turbines at the stage is only relevant to the maintenance. This is because the operations required for the turbines are generally derived from a renewable system.

The maintenance CO_2 relative to this stage repeats equations that have already been applied. It is assumed that a crane will be in use for the period of time that the turbine is under maintenance for.

In general wind turbines have a maintenance scheduled to approximately 3 months after installation and then again once yearly until the end of the life cycle. Therefore equations (3) and (4) should be multiplied by the number of years that the turbine is in service for. Equations (3) and (4) are the base for the new equations (7) and (8) respectively because of the mentioned minor changes that need to be made.

(7) Maintenance ($kgCO_2e$) = Mass of CO_2 per hour for crane ($kgCO_2e/hr$) * Time for maintenance (hr)* Years of service (yr)

And

(8) Crane Transport ($kgCO_2e$) = Lorry mode of transport value ($kgCO_2$/tonnes of freight/km)*Freight weight (tonnes)*(Distance * 2) (km) * Years of service (yr)

Calculations (7) and (8) conclude those required for this stage in the life cycle process.

2. 4. Decommissioning & Disposal

The decommissioning and disposal stage of the wind farm life cycle is rarely documented. However, studies are beginning to look to future of what is going to happen to the farms. Scotland is not the first country to introduce wind turbines so in theory lessons can be learned from other countries whose turbines have come to the end of their life cycle. There are several ends of life cases that face turbines. Mostly documented are the cases of landfill, recycling and incineration:-

"The goal is to model two end-of-life scenarios for a wind turbine upon decommissioning. The first model is for burial at a landfill and the second is for waste recycling." (Z.W. Zhong, 2011, p. 2230)

Table 5 below shows certain materials and their recycle and disposal options (Z.W. Zhong, 2011, p. 2230). All the materials illustrated in the table require at least 10% of the material to go to landfill. In relation to the thesis, looking at concrete, it is not disposable and therefore all the concrete that is used for the roads and the turbine bases will be used as land fill. In some cases however developers are expected to leave the concrete foundations and not dispose of them at all (Myhill, 2009). In keeping with this the thesis will not consider the CO_2 emissions that relate to the site being returned to its original state. This assumption was made with time constraints as a main consideration.

More information on the fate of the turbines can be found in the Appendix section 8. 2.

Table 5- Turbine disposal

Materials	**Recycle (%)**	**Disposal**
Steel and cast iron	90	10% landfill
Copper	90	10% inert landfill
Glass fiber and plastics	0	100% incinerate
Concrete	0	100% inert landfill
Rubber	0	100% incinerate
Aluminum	90	10% assumed disposal to landfill
Lead	90	10% loss during recycling

2. 4. 1. Wind turbine

Similarly to the materials and manufacture stage, to calculate the CO_2 each component should be broken down into the main material and then the decision made on how that should be disposed of. Some of the components will also require dismantling time before being transported. Transport is also a consideration at this stage.

The transport of the crane must also be taken into consideration and is the same as the equations (3) and (8). The following is specific to decommissioning and becomes equation (9).

*(9) Crane Transport ($kgCO_2e$) = Lorry mode of transport value ($kgCO_2$/tonnes of freight/km)*Freight weight (tonnes)*(Distance * 2) (km) * Years of service (yr)*

In the thesis the dismantling of the wind turbine was assumed to be similar to that of the installation values of CO_2 production in equation (3). The following is equation (10) which relates to decommissioning of the turbine.

*(10) Decommission ($kgCO_2e$) = Mass of CO_2 per hour for crane ($kgCO_2e$/hr) * Time for decommission (hr)*

The next step is to calculate the transport of each component to its relative destination which will vary depending on the disposal type. Equation (11) below is the same as equation (2) however the distance travelled will most likely be different.

*(11) Component Transport ($kgCO_2e$) = Mode of transport value ($kgCO_2$/ton of freight/km) * Mass to be transported (kg) /1000 * Distance (km)*

The final step in the life cycle of the turbine is the disposal process. It was assumed in this thesis that after transportation to the relative disposal sites, recycled components and components sent to land fill carried no further CO_2 emissions. This is not necessarily correct as some of the components will be required to be broken down before transport or for its disposal process but it was not considered in the thesis.

The fiberglass was the only material from the turbine that had to be incinerated and therefore the following equation (12) is specific only to fiberglass materials.

The coefficient for the fiberglass in terms of $kgCO_2$/kg that was used was 0.1574 (Larsen, 2009).

*(12) Fiberglass Incineration ($kgCO_2$) = Fiberglass coefficient * Mass of fiberglass*

2. 5. Energy Calculation

For calculations of the total energy produced by the turbines, there needed to be an equation that would represent the wind in the site area called the velocity exceedance curve. The exceedance curve used in this thesis is shown below:-

$$V_{\infty}T^{0.5} = 60 \quad (13)$$

Where V∞ is the wind speed (m/s) and T the number of days in a typical year when the mean wind speed exceeds V∞. This equation can be altered within the tool if the user would prefer different wind characteristics.

Once this equation is established it must be applied to each turbine individual turbine with reference to the rated wind speeds.

The total energy of that the turbine produced was calculated using the following equation:-

$$TE = Cp.\ 0.5.\ \rho.\ A.\left[\int_{T_1}^{T_2} V_{\infty}^{3}.\, dT + V_R^3[T_2 - T_3]\right] \quad (14)$$

Where Cp stands for the power coefficient, ρ is the density, A is the swept area of the blades, V is the velocity and T the number of days. These parameters need to be known before the total energy can be calculated.

"The Cp value is unique to each turbine type and is a function of wind speed that the turbine is operating in. Once we incorporate various engineering requirements of a wind turbine – strength and durability in particular – the real world limit is well below the Betz Limit with values of 0.35 - 0.45 common even in the best designed wind turbines." (NPower, n.d.)

2. 6. Summary of Calculations

The following is a summary of the calculations required to estimate the cradle- to- grave CO_2 of a wind farm.

(1) CO2 per component ($kgCO_2e$) = Mass (kg) * kgCO2/kg

*(2) Component Transport ($kgCO_2e$) = Mode of transport value ($kgCO_2$/ton of freight/km) * Mass to be transported (kg) /1000 * Distance (km)*

*(3) Assembly ($kgCO_2e$) = Mass of CO_2 per hour for crane ($kgCO_2e$/hr) * Time for assembly (hr)*

*(4) Crane Transport ($kgCO_2e$) = Lorry mode of transport value ($kgCO_2$/tonnes of freight/km)*Freight weight (tonnes) *(Distance * 2) (km)*

*(5) Road ($kgCO_2e$) = Width (km) * Depth (km) * Length (km)* Density (kg/km^3) * $kgCO_2e$*

*(6) Peat Road (tCO_2) = 0.92 * (Length of road (m) * Width of road (m) * 0.0001) (ha) * 20*

*(7) Maintenance ($kgCO_2e$) = Mass of CO_2 per hour for crane ($kgCO_2e$/hr) * Time for maintenance (hr)* Years of service (yr)*

*(8) Crane Transport ($kgCO_2e$) = Lorry mode of transport value ($kgCO_2$/tonnes of freight/km)*Freight weight (tonnes)*(Distance * 2) (km) * Years of service (yr)*

*(9) Crane Transport ($kgCO_2e$) = Lorry mode of transport value ($kgCO_2$/tonnes of freight/km)*Freight weight (tonnes)*(Distance * 2) (km) * Years of service (yr)*

*(10) Decommission ($kgCO_2e$) = Mass of CO_2 per hour for crane ($kgCO_2e$/hr) * Time for decommission (hr)*

*(11) Component Transport ($kgCO_2e$) = Mode of transport value ($kgCO_2$/ton of freight/km) * Mass to be transported (kg) /1000 * Distance (km)*

(12) ***Fiberglass Incineration ($kgCO_2$) = Fiberglass coefficient * Mass of fiberglass***

(13) $$V_{\infty}T^{0.5} = 60$$

(14) $$TE = Cp.\,0.5.\,\rho.\,A.\left[\int_{T_1}^{T_2} V_{\infty}^{3}.\,dT + V_{R}^{3}[T_2 - T_3]\right]$$

3. Software tool

The 'Wind farm embodied CO_2 estimator' was developed based on the above calculations to allow the hypothesis of the thesis to be evaluated. The aim of the tool was to be able to evaluate the total cradle- to- grave CO_2 of different wind farms. The output of the results contains figures relating to the CO_2 and power produced. In addition to this a comparison was also included the embodied CO_2 a coal power station. The purpose behind this was to help to quantify the figures that were produced from the turbine calculations. As an addition to this it will also be available for download on the ESRU website.

Embedded within the tool database were three wind turbines. The turbines were chosen because they covered a range of powers. This enabled the tool to apply to as many wind farms as possible. The turbines chosen were: Gaia Wind 133, Siemens G2 and the E- 126 with powers 0.011, 2.3 and 7.58 MW respectively.

The Gaia Wind turbine is one that is most commonly used for farmers. In contrast the Siemens G2 is responsible for the majority of the turbines that are installed in Whitelee wind farm. The E-126 is the largest onshore turbine to date. More information can be found on each turbine in the Appendix section 8. 3. However if these turbines are not suitable for the user, they will need to change one of the existing turbines. In the initial plans the user was to be able to add any number of new turbines in addition to the three already in the database. Unfortunately, due to time constraints and the complexity of the task this was not accomplished.

The tool is structured similarly to that of the section 2. All the calculations described in that chapter are embedded within it. It follows the sub headings of the chapter also, calculating each stage in the life cycle individually. The tool was designed to be user friendly and therefore easy to follow through each of these stages. Each of the stages were broken down into the calculations so that every step could be viewed. It was also set up so that each of the calculations and values could be easily changed if the user wished to make alterations. All cells within the tool that are green are cells which require a user input or if changed will alter the results.

The tool consists of a Welcome, Wind farm Definition, Worksheet, Carbon Appraisal sheets in addition to individual sheets for each turbine within the database. The Welcome sheet has no particular use other than to introduce users to the tool. The Wind farm Definition sheet is vital for any user as it the main input page where aspects of the site and the wind turbines within the farm can be selected. This page is a high level approximation of the wind farm and contains the following selections and other required user inputs- site selection, land type, length of new road required, type of turbines in site and how many. The Worksheet contains the majority of the calculations within the tool and all additional information and assumptions that were made when carrying out the calculations. These are set out clearly for each stage in the life cycle of the wind farm. In this sheet, more in depth selections can be made. For example what type of transport was used for each component to reach the site. As that is a site dependent variable it cannot be pre assumed by the tool. The Carbon Appraisal sheet presents the results of the embodied CO_2 of the described wind farm in both graphical and tabular form. The individual sheets for each turbine in the database can be altered to the user's preference. Table 6 represents the results that the tool calculates for each wind farm.

Table 6- Results displayed from carbon appraisal

Carbon appraisal breakdown
Total CO_2 produced (kgCO2e)
CO_2 running per year (kgCO_2e)
Total energy produced in a year (MWh)
CO_2 running per MWh (kgCO2/MWh)

CO_2 Cradle- to- Grave (kgCO2e/MWh)

The results of the tool were partially validated against data from a journal. The journal stated figures for a life cycle analysis (LCA) for wind turbines. The figures produced were for individual turbines but measured the results were measured in gCO_2/kWh which is directly comparable to the measurement used in the tool of $kgCO_2$/MWh. The figures from the report range from about 9 to 124 gCO_2/kWh (Varun, 2009, p. 6069). This value was compared to the cradle- to- grave value that was produced from the tool.

As a comparison to the result established from the Varun journal, scenarios were run in the tool with individual turbines to evaluate if the results lay within the figures outlined. The details of the site and the wind turbine can be seen in table 7 below.

Table 7- Validation inputs

Validation site and turbine	
Site location	UK- Glasgow
Land type	Agricultural land
Length of new road required (km)	0.1
Turbine	Siemens G2
Transport from manufacture to site	Ship

With these selected inputs the cradle to grave result was 16$kgCO_2e$/MWh which is within the assumed range. Although the result appears to be within the range, the tool cannot be assumed to be fully validated as it has only been compared to one source. To fully validate the tool, many more scenarios would need to be tested and compared to a variety of sources.

3. 1. Applying the tool

The tool was applied to Whitelee Wind farm to illustrate the how a user would use the tool and to analyse the total embodied CO_2 result of the farm. The following will describe the user interface and as a user would encounter and will display the results as found in the tool.

Whitelee wind farm has 215 turbines and 130km of roads (Whitelee, n.d.). 140 of those turbines are Siemens G2 turbines which are included in the tool database. For the purpose of demonstrating how the tool can work, it will assume that all the turbines are the Siemens G2 turbine. The farm was built on moorland which will be relevant when selecting the land type.

Initially the user will be introduced to the tool on the Welcome page before moving on to the Wind farm Definition sheet. As explained in the previous section this is where the user can make initial high level inputs to the tool. Also all cells which are green require a user input or if changed will alter the results. A screenshot of this page can be seen in figure 5 below.

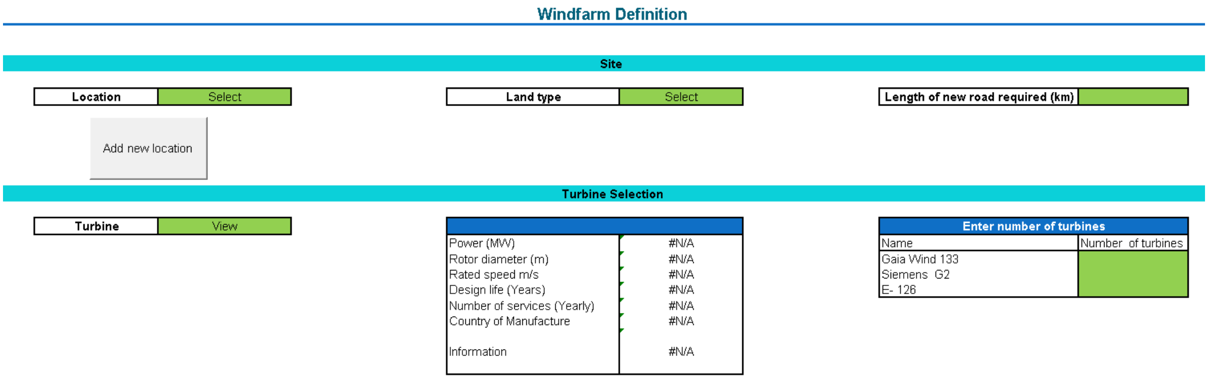

Figure 5- Wind farm Definition Sheet

The sheet is split into two parts. The first refers only to the site where location, land type and length of road can be selected. The location and land type can be selected by pressing on the green cells as a drop down list will show all the possible selections. For the length of new road required to be built for the new farm, a number measured in kilometers (km) should be entered.

The turbine selection is made by entering the number of turbines required in the green cells by the according turbine. Turbines can be selected to be viewed in by choosing a turbine from the ‘Turbine’ drop- down menu. The table with the blue title will then fill with that particular turbine details. The aim behind this feature was so that the user would be able to efficiently and easily review the details of each turbine within the database.

Once these initial inputs have been made, the user can move to view the details within the Worksheet. As explained this sheet contains the majority of calculations and assumptions made within the tool. Therefore it would be worthwhile for any user to examine this sheet before continuing to the results. However there is one part that requires a user input as it cannot be pre assumed in the tool. This is the type of transport that each component uses to reach the site. This can be selected from a drop menu for each distance travelled.

There is in built calculation within the tool which estimates the distance between the origin and destination which will not always be entirely accurate and therefore the user can change the distance if necessary. This is because the automatic distance is the one of the most direct route with a disregard for any roads or other obstacles. Figure 6 below illustrates the part of the sheet that requires a user input.

Assembly & Installation									kgCO2e
Crane CO2 per turbine									
Gaia Wind 133									0
Siemens G2									0
E- 126									0
Transport									
Site	Latitude	Longitude							
0	0	0							
	Gaia Wind 133			Siemens G2			E- 126		
Turbine part	Distance (km)	Transport	kgCO2e	Distance (km)	Transport	kgCO2e	Distance (km)	Transport	kgCO2e
Gearbox	6343.205534	Select	0	15937.24368	Select	0	15937.24368	Select	0
Chassis	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Generator	6343.205534	Select	0	15937.24368	Select	0	15937.24368	Select	0
Cover	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Blade	6343.205534	Select	0	8355.519153	Select	0	15937.24368	Select	0
Tower	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Base	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Rebar	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Cable	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Total Transport									0
Road									
Details									
Width (m)	12.192	Density of concrete kg/m^3		2400					
Depth (m)	0.25	Concrete kgCO2e/kg		0.47					
Volume (m^3)	0	Road kgCO2e		0					
Mass (kg)	0	Land type kgCO2e		0					0
Total									0

Figure 6- Section of Worksheet

The turbine parts will have a distance to travel which is relevant to the type of turbine which is the reason why it is set out as such. A large assumption in this section is that only one mode of transport is used for the whole distance required to be travelled. This is most probably unlikely but for the purpose of maintaining simplicity this was assumed. For Whitelee wind farm it was assumed that the turbine parts were shipped as all parts were manufactured overseas.

Before examining the results the user may wish to view full details of the turbine or make their own changes. The turbine sheets contain information on the turbine part for example, what material and where it was manufactured. Figure 7 below is a screen shot from the Siemens G2 turbine page.

Embodied CO2 of Materials Manufacture				
Turbine part	**Typical Material**	**Typical Weight (kg)**	**kgCO2e/kg**	**kgCO2e**
Gearbox	Steel	112.5	0.47	53
Chassis	Steel	4583.846154	0.47	2154
Generator	Copper	1165.384615	2.71	3158
Cover	Fibreglass	15	1.54	23
Blade	Fibreglass	1553.846154	1.54	2393
Tower	Steel	162000	0.47	76140
Foundation				
Base	Concrete	384576.9231	0.47	180751
Rebar	Steel	6293.076923	0.47	2958
Cable	Copper	4444	2.71	12043

Manufacturer			
Turbine part	**Manufacturer**	**Latitude**	**Longitude**
Gearbox	Kansas- Hutchinson	38.0608	-97.9297
Chassis	Denmark- Brande	55.95	9.1167
Generator	Kansas- Hutchinson	38.0608	-97.9297
Cover	Kansas - Hutchinson	55.95	9.1167
Blade	Canada- Tillsonburg	42.8667	-80.7333
Tower	Denmark- Brande	55.95	9.1167
Base	Denmark- Brande	55.95	9.1167
Rebar	Denmark- Brande	55.95	9.1167
Cable	Denmark- Brande	55.95	9.1167

Figure 7- Section of Siemens G2 sheet

Finally once all inputs are complete, the Carbon Appraisal Results sheet can be viewed. Figure 8 illustrates the resultant graph and tables 8 and 9, the tabular output.

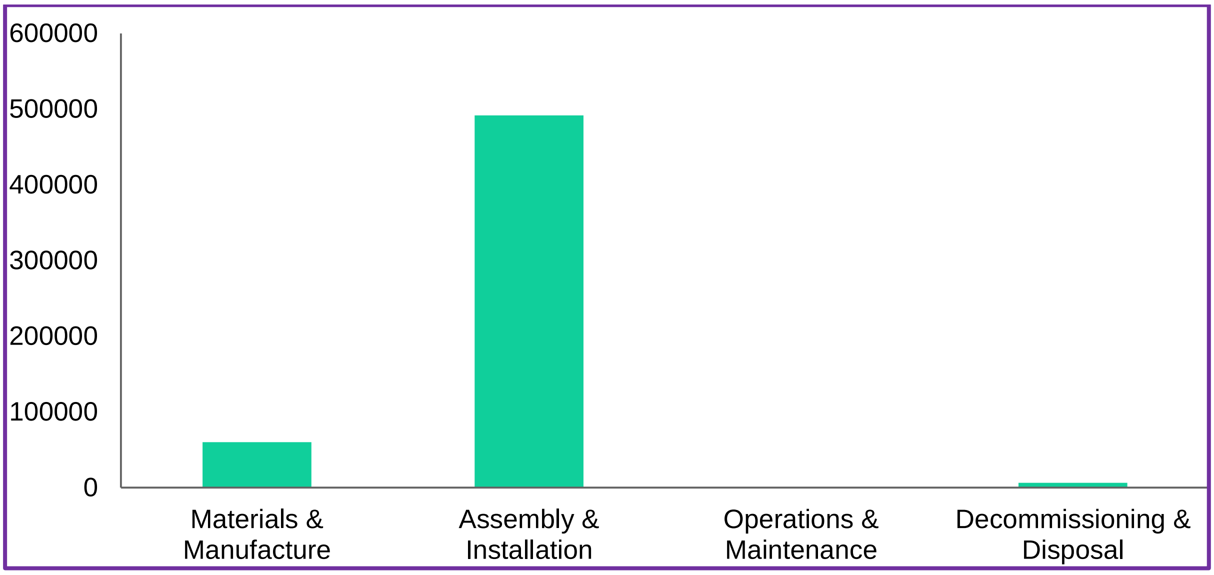

Figure 8- Whitelee Wind farm graph result

The vertical axis of the graph is measured in tonnes of CO_2e. The horizontal axis refers to each of life stages of the wind farm. The operations and maintenance section refers to the running CO_2 required.

Table 8- Scenario 2 life cycle

Whitelee Wind farm (kgCO_2e)			
Materials & Manufacture	Assembly & Installation	Operations & Maintenance	Decommissioning & Disposal
60129832	491706384	14100	6117606

Table 9- Scenario 2 carbon appraisal

Whitelee Wind farm Carbon appraisal breakdown	
Total CO2 produced (kgCO2e)	551936958
CO_2 running per year (kgCO_2e)	14100
Total energy produced in a year (MWh)	739087
CO2 running per MWh (kgCO2/MWh)	0.02
CO2 Cradle to Grave (kgCO2e/MWh)	37

It is apparent from the results that the assembly and installation of the farm dominates with regards to the scale of CO_2 produced. This is caused by several reasons. Mainly that this stage includes the construction of the roads on the site. The roads themselves because of the large volume of concrete required but also due to the farm being built on moorland.

The carbon appraisal results have not been fully validated but can be compared to the CO_2 produced from a coal power station. This will not validate the answer but will make the result quantifiable. The value for of CO_2 produced varies greatly depending on the type and quality of the coal (eia, 2014). For this purpose the value does need to be exact as it is being used purely to quantify the results. However there is no data available on the embodied CO_2 of coal. This was out with the scope the thesis to calculate the value for that also. Therefore the value for the coal signifies the CO_2 produced when it is burned. This value is 97975kgCO_2/MWh. Perhaps this cannot be compared directly to the wind turbine result but it helps to quantify the answer, showing that the cradle- to- grave value of the turbine is relatively small to the coal power station.

3. 2. Use ability

The instructions used in section 3.1 on how to use the tool go alongside the tool so that it can be used with ease. The aim of the tool, aside from aiding in calculating results for the hypothesis was to aid in decision making for the feasibility of wind farms. However due to time constraints of the thesis, the tool was not complete in terms of use ability. Therefore it was deemed necessary to establish a use ability test of the tool to be carried out by several people to analyse the status.

To test this tool, several tasks were constructed that participants were to complete and comment on how easy the tool was to use. Their feedback was then taken into consideration and the results which were seen to be valid were included in the future work section 6. For the task results to be of use the participants ideally would have some technical background or work in renewable energy sector. The participants who carried out the tasks fulfilled the requirements and therefore the results were of use to the project.

There were two tasks, the first that consisted of the participants using the tool to replicate the Whitelee wind farm inputs described in section 3. 1. The aim of this test was to establish if the tool could be used correctly. The results that the participants achieved would then be compared to the results achieved in the previous section. The guidance that the participants had on how to use the tool were similar to section 3. 1. This can be seen in the Appendix section 8.4 along with the details of the tasks. They would not be provided with the results of the section to ensure that that they would not alter the original answer. The results would then be collected (in the form of return of the excel sheet) and analysed to find any variation in the answers. If there was a particular point that kept occurring then it would need to be addressed.

The second task was for participants to evaluate their own chosen wind farm and comment on the ease of use. The aim of this part of the test was to gain some general feedback on the tool use ability.

4. Hypothesis findings

The hypothesis stated that embodied CO_2 would have a significant impact on the overall CO_2 produced. To test this, a scenario was established that would evaluate a wind farm, which is summarised in table 10 and named scenario 1, to determine if the embodied CO_2 was a significant part of the total CO_2 production.

Table 10- Hypothesis test

Details	
Site Location	UK-Glasgow
Land Type	Industrial
Transport	Ship
Turbine Model	Siemens G2
Number of turbines	30
Length of road (km)	15

It was assumed that each of the Siemens components were shipped to the Glasgow site as each of them was manufactured in a country other than Glasgow. The distance travelled was taken to be as the crow flies for a reasonable estimation. This also entailed that one method of transport was used for the entire journey. This method varied in accuracy but was seen as an appropriate estimation. In depth detail was not required to prove or disprove the hypothesis as it was thought that there was likely to be a significant difference between the different CO_2 measurements.

The result for scenario 1 is shown in the table 11 illustrating a summary of the CO_2 that is particular to each stage in the life cycle.

Table 11- Scenario 1 life cycle

Scenario 1 ($kgCO_2e$)			
Materials & Manufacture	Assembly & Installation	Operations & Maintenance	Decommissioning & Disposal
8390209	2807821	8550	860202

From the results of the calculations carried out it can be seen that this is correct. The operations and maintenance of the turbine can be regarded as the running CO_2. Therefore if it stands that this is the running then the remainder is of the CO_2 represents the embodied CO_2. From this deduction of the total, 99.9% is the embodied CO_2 of the wind farm.

The operations and maintenance calculations did not include any major repairs that would significantly increase the CO_2 content. Although theoretically this could have reduced the embodied carbon ratio it would have increased the overall CO_2.

The embodied CO_2 of renewable energy systems is not well documented and reports generally refer to the CO_2 which relates to the running of the systems only. However as the hypothesis of the thesis has been proven to be correct it shows that this measurement is something that must be considered at the planning stage of a wind farm. It is also a measurement that should be carefully considered when discussing the feasibility of a wind farm and the future of wind energy. As the embodied CO_2 is such a large proportion of the total demonstrates how important it is to understand all the aspects and potential impacts of building wind farms. It would not be an unrealistic to suspect that if the embodied CO_2 was considered before implementation of a wind farm it would be found that some would be unfeasible.

This hypothesis result as positive also puts to question the term of ‘clean energy’. Wind energy has shown to be far from ‘clean’ when all of the CO_2 aspects are considered. This does not mean however that wind energy is bad, just that it is not as it is advertised.

There is little doubt that wind will be prominent in Scotland’s energy future but it is a technology that must be fully understood before it is embraced to readily without a full consideration of the potential impacts. This statement can be supported from the values used from a coal power plant in section 3.2, as it produces significantly more CO_2 from the burning process alone, assuming of course that the figures are a good estimate of the real values. As described in the Project background, Scotland has a particularly good wind energy resource and it should be used effectively.

5. Conclusion

The hypothesis of the thesis was that the embodied CO_2 was a significant part of the total CO_2 produced which has been proven. According to the results from the calculations, the embodied CO_2 represents the majority of the total CO_2. If the calculations are correct then 99.9% of the total CO_2 can be termed as embodied. This is relevant as it is a measurement that it is not usually included when feasibility analyses are being carried out. Another important outcome of the project was that when compared to the CO_2 produced during the burning of coal was significantly more than the cradle- to- grave values of the turbine.

As previously explained Scotland is increasing the number of wind farms both onshore and offshore. Although some of the equations are not applicable to offshore, the implications are the same. This means that the result is highly relevant to the future of wind energy. It was an initial aim that the tool could be used in a decision support to aid in this matter. However due to the lack of time to fully establish the tool with a high use ability, it cannot be implemented as such.

This result questions the term ‘clean energy’ which is commonly used to describe these systems. It was found that although the figures for the turbine was less than that of the coal, it aides in the conclusion that turbines cannot be described as ‘clean’. The analysis only took into consideration wind turbines it would be a valuable exercise to apply it to other renewable systems. The policies introduced by Government are not particular for any one type of system however for Scotland wind energy is most abundant. That does not mean to say that these other systems are not used. Photovoltaics in particular are also a common site. This therefore enforces the theory that this analysis should be applied to other systems. The potential impacts need to be understood before the implementation to meet the policies continue.

Rare earth materials must also be a consideration when investigating the feasibility of the turbines and also any other renewable energy system. Unfortunately it was out with the scope of the project to include the analysis but it is a vital aspect of the turbines. They cannot be advertised as sustainable energy sources whilst they use materials in an unsustainable way. More research should be carried out to investigate this subject because it is integral to the success of renewable energy systems.

6. Future work

The future work of the thesis incorporates both the calculations used in the tool and also the tool itself. The calculations used within the thesis were simplistic with the aim to achieve an estimation of what the embodied CO_2 could be. However there are many places where the depth of the calculations could be increased to give a more accurate result. This was a main area within the thesis where improvements could have been made. As there are so many areas in the calculations where the depth could have been increased, only the main gaps in them will be mentioned. Although not to disregard the previous statement, a line has to be drawn somewhere as it could go on infinitely, increasing in accuracy at each stage but reducing in overall difference. The assumptions made in the calculations were thought to have covered the major aspects of the CO_2 emissions to give a reasonable estimate of an answer.

Firstly, with regards to the materials and manufacture stage of the turbine there were several steps that could have been included. For example the transport of the raw materials to the manufacturing plants was not considered. However even this is not the beginning of the turbine life cycle. The life begins with the excavating of the raw materials from source. Including the transport of the raw materials to the manufacture site would be a reasonable addition to the calculation however.

On a slightly different direction with regards to the materials used in the turbines, there are many rare materials that are required, in particular materials used to make magnets, dysprosium (Dy) and neodymium (Nd) (Elisa Alonso, 2012, p. 3406). Using these materials although may not have a large consequence on the total CO_2 they can have serious economic and social impacts on the surrounding areas where these materials are sourced. Also these rare materials do not come from an infinite source and therefore if the number of wind farms rise as expected in Scotland then these material reserves will begin to dwindle. This really calls into question how sustainable these systems are. Therefore this would be an important aspect of the future work to investigate the impacts that are related to the use of the rare materials.

The assembly and installation stage included the transport of the materials from the manufacturers. However as mentioned previously the calculations assume one mode of transport for the whole distance which would be improbable. Also with regard to the tool in particular, the distance is of the most direct route with no consideration of roads. For an increase in accuracy these parts could be considered. Also the CO_2 which is representative of the preparation of the roads and any machinery required to transport and install the concrete was not considered in the calculations. These aspects of the stage could add a noticeable number onto the total CO_2 and should be a consideration for further work on the tool.

There is little documentation on the decommissioning and disposal of the wind turbines. A more in depth analysis would benefit the accuracy and understanding of the calculations. In particular for Scotland with a large number of onshore and offshore projects being introduced, the disposal process is a concern. With a greater knowledge of this stage in the life cycle more informed decisions can be made with regard to the feasibility of wind turbines.

With respect to the tool, there are upgrades which could potentially increase the use ability. The feedback from the use ability test was encouraging in that participants could understand the process and method of using the tool. However there was consistent feedback which stated that it could be improved if all the user inputs that were required were all on the one sheet as this caused some confusion. Additionally, the tool lacks the ability for the user to 'add own turbine' which is a major issue that would need to be overcome before it could be used as a tool. The complexity of the macro required was not completed within the thesis time frame.

This is relevant feedback and for the tool to be able to be used as a decision support then this would need to change. However once the participants had understood the lay out of the tool, they found it more easy to use.

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8. Appendix

8. 1. Peat bogs

The reason why peat causes such controversy is described by the Scottish Government:-

"Overall, peats represent a large reservoir of CO2 captured by plants and held in soils." (Government, 2008)

When peat is dug up, in this case for road access and for turbine bases, the CO_2 is released to atmosphere. There is information surrounding these arguments which say that the type of bog can make a difference in the CO_2 production. They can be separated into pristine and degraded peat land. The difference is that pristine bog is land that has not yet been touched and therefore contains more CO_2 than degraded as that has already lost CO_2 to atmosphere. (Staff, 2013) Therefore it would be more desirable to build on degraded peat land. It is a valid argument that building on peat contradicts everything that wind farms stand for. For example saving CO_2 and limiting its release to atmosphere. Dr. Jo Smith, leader of the research on this topic summarises:-

"If wind farms are constructed on non-degraded peatlands, the drainage of the peats causes them to start emitting carbon. If this is left unchecked, then eventually the construction of the wind farm will result in all of the carbon held in the peat being lost." (Staff, 2013)

However Whitelee wind farm was built on mainly peat bog land and "approximately 850000m^3 of peat was excavated and spread." (Council, 2013) There is a section on the Whitelee website which describes they have built on peat land and how they plan to restore the land. (Whitelee, n.d.) There is limited information to be found on the CO_2 problems associated with building on these types of land.

A more accurate value for the mass CO_2 lost can be calculated from an Excel tool called "Calculating carbon savings from wind farms on Scottish peat lands". The following link from the Scottish Government will present the download page-http://www.scotland.gov.uk/Topics/Business-Industry/Energy/Energy-sources/19185/17852-1/CSavings/CC-2-9-1

The excel tool from above will also calculate the peat associated CO_2 from the wind turbine foundations and base which the thesis has not considered purely due to time constraints as this number is likely to be significant and for a more accurate embodied CO_2 of a wind farm should be considered.

8. 2. Recycling of turbines

Turbine blades are usually made of glass reinforced plastics which need to be incinerated which produces harmful greenhouse gases. An extravagant way to recycle the blades was introduced in Holland and they use the blades for part of a children's' play park. (BBC, 2013)

These are not the only options that face turbines at the end of their life. For example in California they are selling their old turbines with refurbished parts to countries with limited electricity. (Gallucci, 2014)

The final option, if it can be considered an option, would be to leave the turbines where they were. This paints a depressing picture as although no CO_2 would be lost in the decommissioning, the habitat would not be able to recover from the impact of the turbines. Figure 5 depicts abandoned turbines from Hawaii. (Leonard, 2012)

Figure 9- Rusted turbines

8. 3. Turbines in the tool database

Table below summarises all three wind turbines within the tool.

Table 12- Wind turbine summary

	Gaia Wind 133	Siemens G2	E- 126
Power (MW)	0.011	2.3	7.58
Rotor diameter (m)	13	101	127
Rated speed (m/s)	10	12.5	10
Power coefficient	0.42	0.3	0.199
Yearly energy production (MWh)	0	0	0
Design life (Years)	20	20	20
Number of services (Yearly)	1	1	1
Country of Manufacture	UK	Denmark	Portugal

Information	http://www.gaia-wind.com/our-people/generating-better-value/	http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/platforms/g2-platform/	http://www.enercon.de/en-en/66.htm
IEC Class	III (means suitable for sites with an annual average wind speed up to 7.5m/s)	IIB (means suitable for sites with an annual average wind speed up to 8.5m/s)	IA (means suitable for sites with an annual average wind speed up to 10m/s)
Cut in wind speed (m/s)	3.5	3.5	3
Cut out wind speed (m/s)	25	25	34
Blade length	0	49	
Swept area (m^2)	0	0	12, 661
Tower height (m)	18.3	80 or site specific	135
Hours equipment in use for turbine construction	12	24	30
Hours equipment in use for turbine maintenance	6	6	6
Hours equipment in use for turbine decommission	12	24	30

8. 4. Use ability test

The information and guidelines below was what was supplied to the participants in the tasks. The aim of the first test was to establish if tool could be used correctly and the second for participants to give an opinion on the overall use of the tool. The participants had previously been explained briefly the purpose of the tool and the project background.

Task 1

The first task is for you to use to use the tool to calculate the cradle to grave CO_2 of Whitelee Wind farm.

The details of Whitelee Wind farm are as follows in table 13:-

Table 13- Task 1, Whitelee

Whitelee	
Site Location	UK-Glasgow
Land Type	Moorland
Transport	Ship
Turbine Model	Siemens G2
Number of turbines	215
Length of road (km)	130

The first page on the tool is the Welcome page which is then followed by the Wind farm Definition which is shown in figure 10 below. This sheet is where you will make the selections shown in table 13 aside from the transport selection as that must be selected in the Workbook sheet.

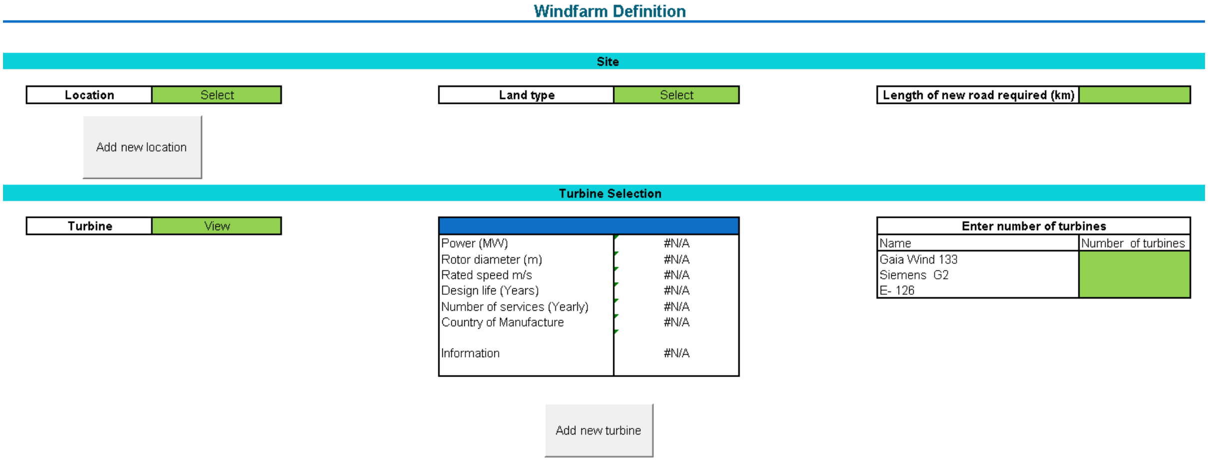

Figure 10- Wind farm Definition Sheet

Figure 11 below is a cut out from the Worksheet to illustrate where the transport selection should be made. It can be selected from a drop down menu highlighted in green. Each turbine type within the tool has a transport selection per part each. As they are only Siemens turbines being used in the task only transport method from that column need be selected.

Assembly & Installation									kgCO2e
Crane CO2 per turbine									
Gaia Wind 133									0
Siemens G2									0
E- 126									0
Transport									
Site	Latitude	Longitude							
0	0	0							
	Gaia Wind 133			Siemens G2			E- 126		
Turbine part	Distance (km)	Transport	kgCO2e	Distance (km)	Transport	kgCO2e	Distance (km)	Transport	kgCO2e
Gearbox	6343.205534	Select	0	15937.24368	Select	0	15937.24368	Select	0
Chassis	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Generator	6343.205534	Select	0	15937.24368	Select	0	15937.24368	Select	0
Cover	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Blade	6343.205534	Select	0	8355.519153	Select	0	15937.24368	Select	0
Tower	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Base	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Rebar	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Cable	6343.205534	Select	0	15781.22865	Select	0	15937.24368	Select	0
Total Transport									0
Road									
Details									
Width (m)	12.192	Density of concrete kg/m^3	2400						
Depth (m)	0.25	Concrete kgCO2e/kg	0.47						
Volume (m^3)	0	Road kgCO2e	0						
Mass (kg)	0	Land type kgCO2e	0						0
Total									0

Figure 11- Section of Worksheet

Your results can then be viewed in the Carbon Appraisal Result sheet. Once you have completed the task you should save the result and return the excel sheet for evaluation.

Task 2

The second task is for you to build your own wind farm and to comment on the use ability. For example if you found it easy to change selections or if you felt that the tool was missing a function.

That concludes the usability test the results of which can be seen in the future work section 6.