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USING LIFE CYCLE ASSESSMENT TO COMPARE WIND ENERGY INFRASTRUCTURE

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Abstract

Given the need to significantly reduce greenhouse gas (GHG) emissions due to the production of electricity, countries worldwide are trying to develop and implement different energy saving strategies and technologies to mitigate global warming. A core part of achieving this is the development and implementation of renewable energy technologies such as wind.

This has resulted in the development and innovation of wind turbines with output ranges of 10-15MW likely to be deployed by 2020. This increased output has a knock on effect on the growth of rotor diameters and tower heights requiring the wind turbine system to be assessed from an economic, environmental and structural performance viewpoint. This has led to the proposal of using concrete as an alternative to the current preference of steel for wind turbine towers due to a number of limiting issues.

Thus, the main focus of this paper is to investigate and compare the life cycle emissions (LCE) of GHG of concrete relative to steel as a tower solution in order to identify a solution for both onshore and offshore facilities. The main findings indicated that the LCE for a wind turbine with a concrete tower range between 4-9% lower than its equivalent steel solution over a 40 year life cycle.

1 INTRODUCTION

International consensus that fossil fuels have a major impact on global warming resulting in international agreements such as the European Commission's Renewables Directive 2009/28/EC which has been implemented in national legislation and support the deployment of renewable energy sources [1][2]. At the forefront is wind energy which is one of the world's fastest growing renewable energy sources with an average annual growth rate of more than 26% since 1990 [3]. Moreover, some forecasters have predicted wind energy will contribute to 12% of the global demand of electricity by 2020 [1].

The global wind energy sector must generate electricity more economically and in a more environmentally friendly way in order to fight the effects of global warming. This has resulted in the development and innovation of wind turbines (WTs) over the last two decades with various manufacturers releasing turbines in output ranges of 7-10MW with both Clipper and Sway developing 10MW prototypes for offshore deployment [4], [5]. This increased output has a knock on effect on the growth of tower heights and rotor diameters requiring wind turbine towers (WTTs) to become taller, stronger and stiffer to carry the increased weight and associated structural loading [6]. Consequently, the dimensions of the tower cross-sections must be increased which results in greater manufacturing and transportation costs aswell as the associated greenhouse gas (GHG) emissions. This has led to an exploration of alternative tower solutions such as the use of precast or in-situ prestressed and reinforced concrete and/or hybrid materials [7–9].

Additionally, to date a significant amount of life cycle assessments (LCAs) have been conducted by various authors [1], [10–14] based on the whole life cycle of a wind turbine (WT) from extracting raw materials, turbine component manufacture through to decommissioning of the windfarm (WF). However, there has been while little emphasis on the life cycle emissions (LCE) associated with the tower component whereby the WT component has taken precedence.

Thus, the purpose of this paper is to investigate and compare both onshore and offshore concrete and steel WTTs using an appropriate LCA approach in order to quantify the LCE of GHG from raw material extraction, manufacturing through to decommissioning of the WF while also taking into account the reference WTs chosen. The main objective of this paper is to identify a tower solution for both onshore and offshore facilities in order to encourage manufacturers to produce environmentally more "greener" WTTs.

2 GOAL AND SCOPE

2.1 Goal

The goal of the LCA is to create life cycle inventories based on the reference data shown in Table 1 of two different WTs and WTTs (steel and concrete) located in two specific locations in Ireland for which accurate and reliable data was available. The inventories are compiled from cradle to grave and their results expressed in tCO_2-e are analysed.

Table 1 : Onshore and offshore reference data

Property	Onshore		Offshore	
Height (m)	96.55	96.55	126.5	126.5
Top diameter (m)	3.5	3	3.4	3
Top thickness (m)	0.01	0.4	0.02	0.4
Base diameter (m)	4.5	8.2	5.1	8
Base thickness (m)	0.02	0.6	0.06	0.6
Tower material	steel	concrete	steel	concrete
Density (kg/m3)	7,850	2,400	7,850	2,400
Tower mass (kg)	142,000	1,856,000	625,000	2,146,000
Wind turbine rating (MW)	2	2	3.6	3.6
Wind turbine mass (kg)	80,000	80,000	1,364,000	1,364,000
Location	Castledockrell, Co.Wexford, Ireland	Castledockrell, Co.Wexford, Ireland	Arklow Bank, Co.Wicklow, Ireland	Arklow Bank, Co.Wicklow, Ireland

2.2 Scope

The LCA has been prepared on the basis of the reference data presented above and includes all the life cycle (LC) GHG emissions from the individual WT components, the onshore and offshore construction activities as well as the associated transport. This paper refers to LC GHG emissions which are expressed in tCO_2 equivalents (tCO_{2}-e) where the CO_2 equivalents are the result of the aggregation of GHG which takes into account their respective global warming potential [12] . The expected lifetime of the WTs have been set to 20 years (the period usually guaranteed by the manufacturers) while certain components of the WF have estimated lifetimes of up to 40 years as illustrated by Figure 1 [13].

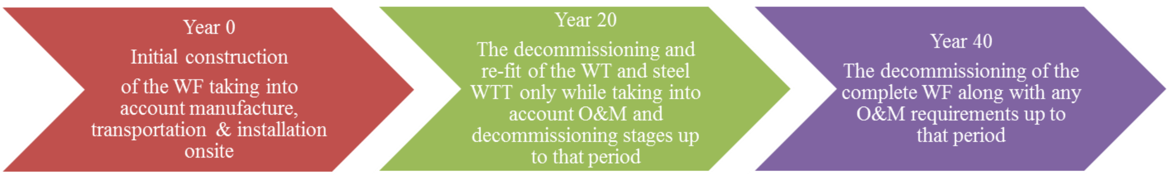

Figure 1 : LC timeline

To achieve the goal setout and to determine a viable tower solution, a system boundary based on a LC from cradle to grave taking into account the extraction, manufacturing, transport, installation, O&M, decommissioning, disposal and recycling are implemented. This is illustrated by the Figure 2 along with the attendant explanation of the specific LC stages. In all cases both direct and indirect emissions are accounted for. For example, nacelle manufacture considers GHG emissions from the manufacturing plant as well as 'upstream' activities such as metal ore extraction and refinement; 'horizontal' activities such as factory insurance and maintenance are also included.

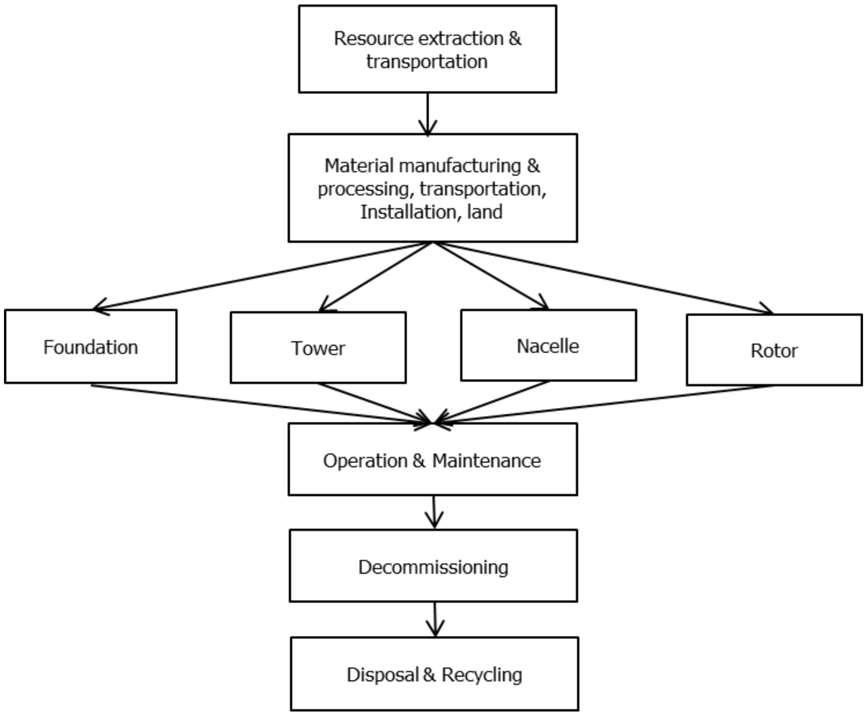

Figure 2 : LCA Model

- **Manufacturing**
  Manufacturing includes the manufacturing of foundation, tower, nacelle and rotor. Also the manufacture of the parts of the transmission grid including transformer station and main cable are included. All steel components are assumed to be manufactured in the east of the United Kingdom (UK) and transported by road and sea. The nacelle including all internal components and the rotor consisting of three blades and the hub are also manufactured in the east of the UK and transported by road and sea. This manufacturing location has been chosen due to the rapid development of wind energy in the UK and the commitment by WT manufacturers to investment in production facilities [15]. Since there are no such facilities or plans for these facilities in Ireland to date this is the closest manufacturing location and the process data used in the LCIs reflect this.
- **Transport and Installation**
  Transport from factory gate to site. This includes transport by lorry and cargo ship at road and sea for onshore and offshore facilities respectively. Installation includes crane work, installation vessels and other construction work at site.
- **O&M**
  Changing of oil, lubrication and transport to and from the WF are included in this stage. Furthermore, renovation of gear and generator, service and spare parts are included.
- **Decommissioning**
  The offshore WF includes craneage for dismantling, transport from the WT to the onshore location via vessel. The onshore WF includes for craneage and excavator only.

- **Disposal and Recycling**
  This includes plant for crushing and transport from onsite to the final disposal location via lorry.

3 LIFE CYCLE INVENTORY

A hybrid analysis incorporating both process and I-O (Input-Output) analyses were used to compile the LCIs in Microsoft Excel spread sheets; this is the preferred method for the assessment of renewable energy systems as used by Crawford et al. [10] and Lenzen et al. [16]. First the different WT LC stages were identified and the WT system was broken down into individual components; these were further broken down into sub components for which material types and quantities were determined. The quantities were then multiplied by an embodied GHG intensity factors (kgCO_2-e/kg). For the remaining LC stages with monetary values, they were multiplied by sector emission intensities (kg/€).
The GHG intensity factors for the process inventory analysis were obtained from the Inventory of Carbon and Energy (ICE) tables [17]. The I-O inventory analysis uses three main sources of data [18–20] and from these the sector emission intensities were derived as shown in Table 3 in appendix A. The construction and services (excl. transport) economic sectors were the only sectors used for the I-O analysis. The LC GHG emissions were the same for the common components in each inventory but differ for the components such as the WT, WTT and foundation.
On completion of the inventories, the sub-total values for the embodied GHG emissions for each of the LC stages were compiled and expressed in tCO_2-e. Based on the summarised results, the values for each LC stage are inputted into equation 1 below in order to form a comparison of the onshore and offshore reference data in Table 1.
The LCE are the GHG emissions of each LC stage of the onshore and offshore WFs given by:

$$\mathrm{LCE} = \mathrm{CE} + \sum_{i=1}^{n}\left[\left(\mathrm{ME} + \mathrm{OE}\right)\right] + DE \qquad (1)$$

Where:
CE are the capital related emissions in year 0 (tCO_2-e)
ME are the maintenance emissions in year *i* (tCO_2-e)
OE are the operational emissions in year *i* (tCO_2-e)
DE are the decommissioning emissions in year *n* (tCO_2-e)

4 RESULTS AND DISCUSSION

Although the WTT only makes up one component of each of the LC stages the results are presented based on WTT type (either steel or concrete) in order to highlight a comparison. The LCE for the on- and offshore WTTs are indicated by Figure 3 . It indicates that at year 20 the LCE are 35% greater for the concrete than the steel offshore WTT due to weight of the concrete relative to steel, 1,600t versus 400t respectively. The foundation for the offshore concrete WTT consists of a concrete gravity base foundation which requires sufficient weight to counter act the over turning moment of the tower and thus contributes significantly to the LCE.

Similarly, at year 20 the LCE for onshore WTTs are greater (circa 12%) for concrete relative to steel. Also a cross-over point at circa year 35 occurs for both facilities. However, over 40 years, the LCE for a WT with a concrete WTT are 4% and 9% lower than its equivalent steel solution for both on- and offshore locations respectively. This due to the fact that concrete WTTs have a practical service life of between 40-60 years [7] whereas the steel WTTs need to be removed and replaced after 20 years.

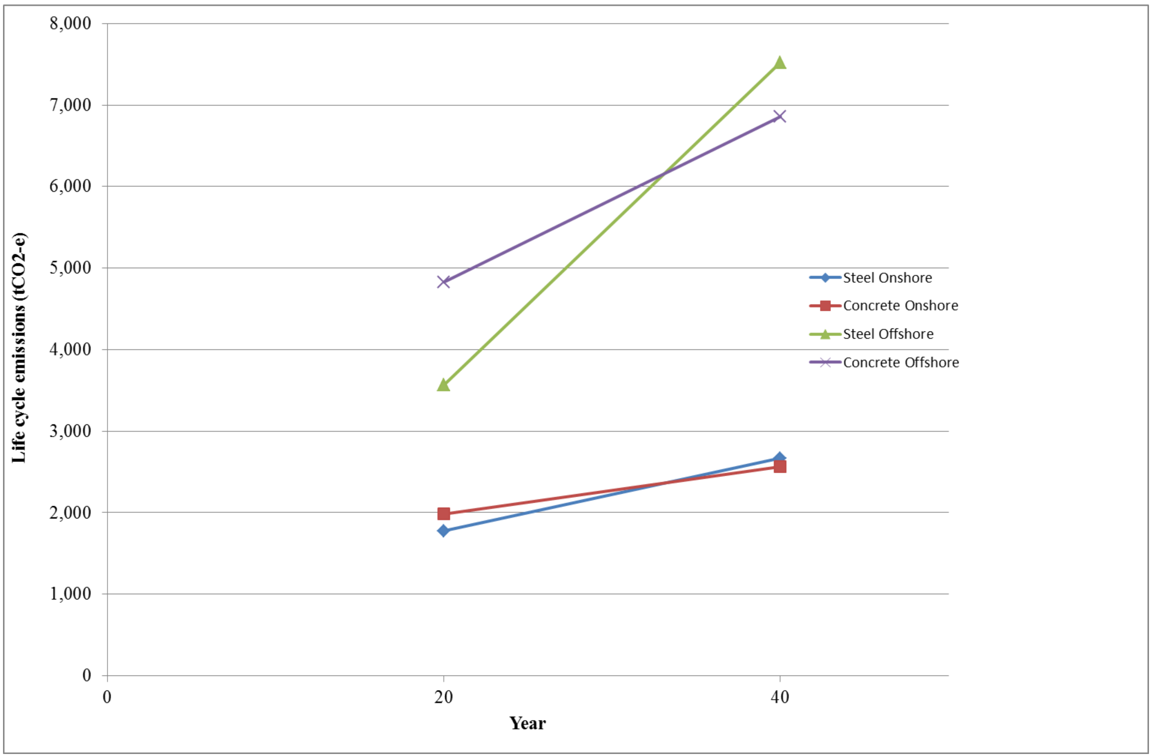

Figure 3: LCE for onshore and offshore WTTs

Figure 4 and Figure 5 present the proportion of LCE of GHG in tCO_2-e arising from each LC stage for both onshore and offshore facilities. It can be seen that the manufacturing stage dominates approximately 75% and 60% of the LCE for the on- and offshore facilities respectively. Production of the concrete mixes for the tower and foundations are the main contributors to these manufacturing emissions. The tower component contributes 77% and 33% of the emissions to the manufacturing stage for on- and offshore facilities respectively due to the large amount of steel and concrete required for its production.
One solution to reducing the GHG emissions associated with the manufacturing stage is to introduce low cost and low GHG emission mineral admixture replacements such as ground granulated blast furnace slag (GGBS). GGBS replaces a portion of the cement within the concrete mix, thus reducing the quantity of CO_2.e emitted while improving the concrete strength and durability performance [21]. Based on this, Table 2 indicates the possible reduction in LCE that can be achieved based on the percentage of GGBS added to the concrete mixes during the manufacturing stage of the concrete for the tower and foundations. By adding 70% GGBS the onshore concrete WTT LCE will reduce by 14%

resulting in a drop in LCE relative to onshore steel WTT at year 20 with further disparity expected by year 40.

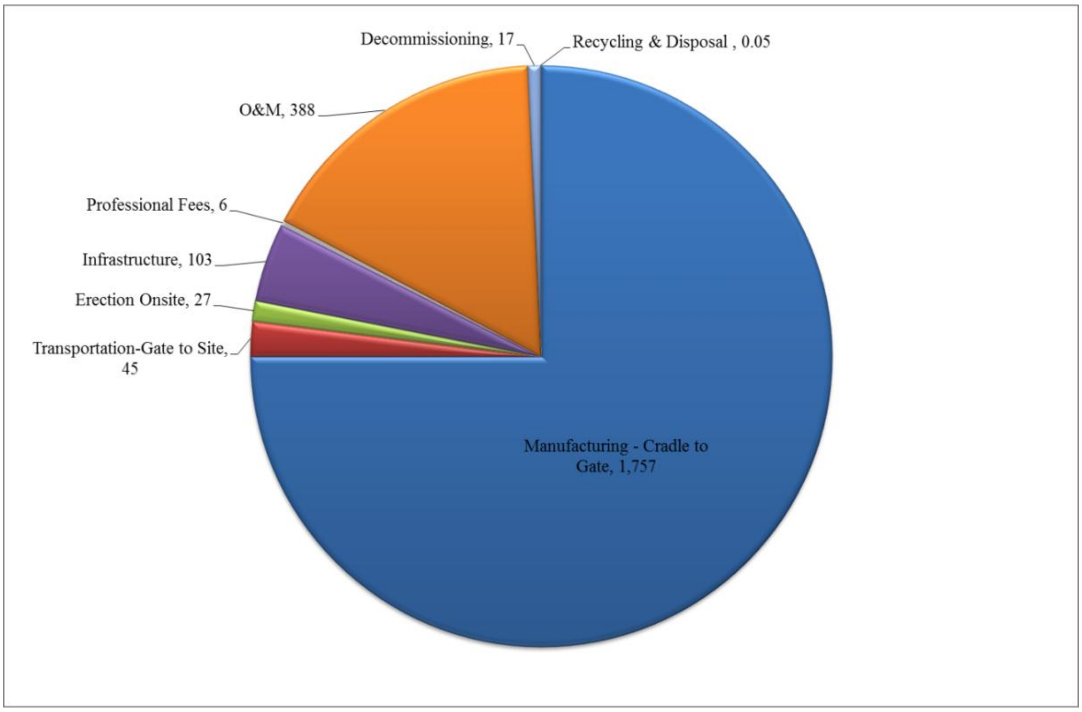

Figure 4: Cumulative LCE of GHG share for onshore concrete WTT

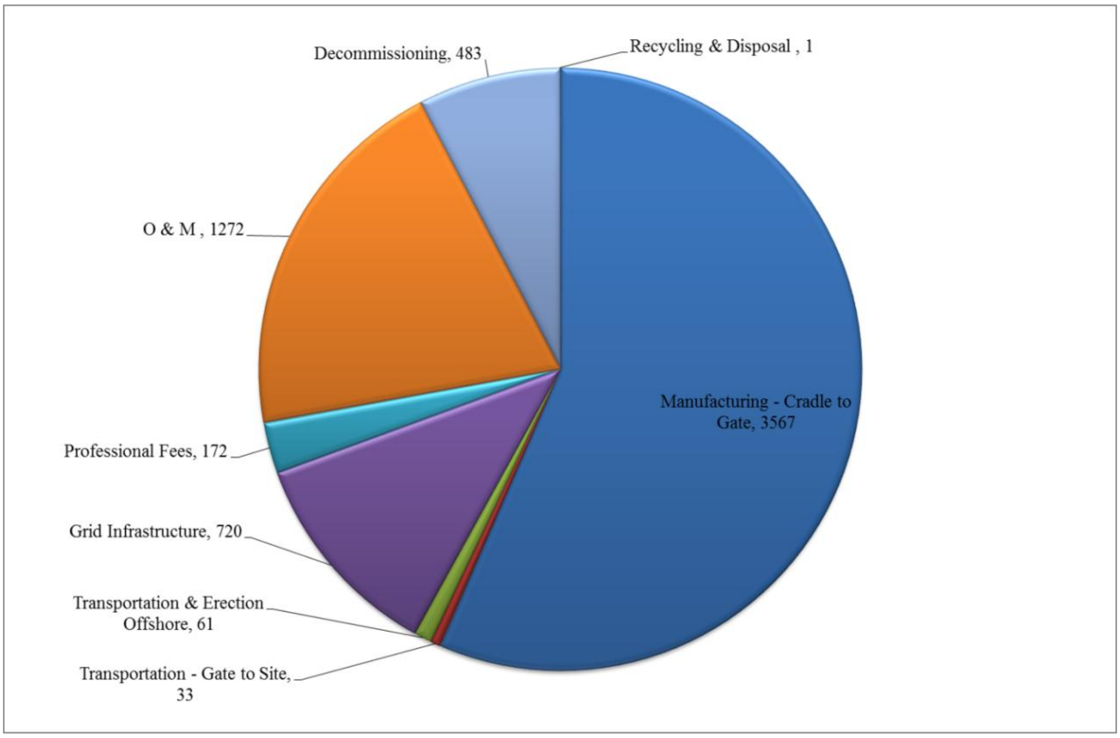

Figure 5: Cumulative LCE of GHG share for offshore concrete WTT

Table 2: Effect of % of GGBS addition on concrete LCE

WTT type	WTT height (m)	GGBS (%)	LCE (tCO_{2}-e)	LCE % decrease
Onshore	96.55	0 (using CEM 1)	1,984	0%
Onshore	96.55	50	1,805	9%
Onshore	96.55	70	1,706	14%
Offshore	126.5	0 (using CEM 1)	4,829	0%
Offshore	126.5	50	4,394	9%
Offshore	126.5	70	4,249	12%

5 CONCLUSIONS

Based on the LCA conducted, it was observed from the results that due to the potential longer service life, concrete WTTs have a significant long term advantage by the adoption of a WT re-fit programme at year 20. It was highlighted that the LCE are lower than the steel WTT due to the fact that the concrete WTT can remain in place for another 20 years where as the steel WTT is removed and replaced. Also it was observed that manufacturing has the greatest impact on the LCE for both on- and offshore facilities with the towers and foundations contributing the largest impact.

The LCE of GHG for the concrete WTTs can be reduced further by introducing mineral admixture replacements such as GGBS which results in a more durable, sustainable and environmentally friendly solution. The resulting WTT possess a much longer service life with a practical design life in excess of 40-60 years [7], [21]; the LCE are negatively impacted by the relatively low life expectancy of steel WTTs in an aggressive marine environment. It was indicated that between 12-14% reduction in LCE is achievable with the addition of 70% GGBS.

The results from this paper indicate that concrete WTTs perform better than steel WTTs from a LC GHG emissions perspective. This has obvious implications for a technology which is being promoted to mitigate GHG emissions. It remains for continuing research to study the effects of several WTT designs and to develop a multi-objective optimisation model which minimises the LC cost and associated LC GHG emissions of these designs.

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APPENDIX A

Table 3: Derived sector emission intensities for Ireland

Economic sector	Sector emissions ($tC0_{2-e}$)	Sector expenditure (€)	Sector emission coefficients (t/€)	Sector emission coefficients (kg/€)	Sector emissions intensities (kg/€)
Agriculture, fishing, forestry	19,581,197	7,199,953,861	0.0027	2.7196	3.6822
Coal, peat, petroleum, metal ores, quarrying	117,040	1,332,454,398	0.0001	0.0878	0.5869
Food, beverage, tobacco	1,130,134	3,070,489,505	0.0004	0.3681	1.4372
Textiles Clothing Leather & Footwear	113,832	13,724,033,055	0.0000	0.0083	0.1447
Wood & wood products	60,533	958,497,292	0.0001	0.0632	0.7067
Pulp, paper & print production	87,164	1,949,197,990	0.0000	0.0447	0.0800
Chemical production	704,723	890,978,058	0.0008	0.7910	0.8480
Rubber & plastic production	53,612	787,808,094	0.0001	0.0681	0.3423
Non-metallic mineral production	4,499,022	2,339,857,621	0.0019	1.9228	2.4973
Metal prod. excl. machinery & transport equip.	1,683,633	1,790,570,359	0.0009	0.9403	1.1876
Agriculture & industrial machinery	85,703	11,847,475,104	0.0000	0.0072	0.1700
Office and data process machines	217,613	2,037,107,643	0.0001	0.1068	0.1323
Electrical goods	708,424	32,085,694,900	0.0000	0.0221	0.1113
Transport equipment	35,962	861,237,406	0.0000	0.0418	0.1951
Other manufacturing	532,304	1,510,404,137	0.0004	0.3524	0.5291
Fuel, power, water	15,687,598	3,661,065,817	0.0043	4.2850	5.5803
Construction	706,642	12,382,236,633	0.0001	0.0571	0.3361
Services (excl. transport)	3,919,151	55,995,901,537	0.0001	0.0700	0.1874
Transport	13,036,898	18,444,732,042	0.0007	0.7068	0.8833