The role of infrastructure in meeting UK climate change targets: A case study of wind energy

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Abstract

Whichever scenario of the future energy system in the UK materialises there will be a need for large-scale infrastructure development to build-up such a system. At present, none of the scenario modelling used in the UK Government's Low Carbon Transition Plan takes into consideration the carbon implications of building a new energy system, albeit nuclear, wind or carbon capture and storage. However, building a new energy system is an energy-intensive process, which reduces the overall energy and carbon efficiency of the power generation. Although a new energy system can reduce direct emissions from the energy generation itself, the indirect emissions related to capital investment are very significant and have to be taken into account.

In addition to the need to account for the embodied carbon in energy systems, there is also a limitation with current approaches associated with these calculations. Process Life Cycle Analysis (PLCA) has often been employed to establish the indirect emissions associated with energy systems and this can lead to significant truncation errors in the calculations. Input-output based Life Cycle Analysis (IO-LCA) on the other hand suffers from other shortcomings such as aggregation and allocation errors. Hybrid analysis methods combining the strengths of PLCA and IO-LCA have therefore been developed to reduce the limitations of both approaches and have been successfully applied in many studies.

In this study we develop an integrated hybrid life cycle assessment model with a multi-regional input-output component to establish comprehensive life cycle greenhouse gas inventories of key energy technologies. We provide an example application of this model to off-shore wind energy in the United Kingdom. The results shows that the total CO_2 emissions increase by 19 percent by applying integrated hybrid LCA compared to a process-based LCA, which is 16.3 g CO_2/kWh. The largest part of emissions is from metal extraction accounting for about 40 percent of total emissions. Wind power is a favourite energy for electricity generation comparing to other fossil electricity generation technology in terms of mitigation of CO_2 emissions.

Key words: *Life-cycle assessment, Input-output analysis, Embodied carbon, Climate change, Energy systems, wind power*

1. Introduction

With the increasing recognition of the impacts of anthropogenic climate change, both global and regional climate change mitigation strategies have been discussed in the last few years. There is growing scientific consensus that global temperature rise must not succeed two degrees to avoid some of the most extreme consequences of climate change (Pachauri and Reisinger, 2007). Over 100 countries have adopted this target as a guiding principle for mitigation (Meinshausen et al., 2009). This target can be linked to a total global budget for Greenhouse Gas Emissions of 750 Gt CO_2-e between 2010 and 2050 and would lead to a 75%

probability of achieving 2 degrees. When allocating these emissions to countries based on population, it is already infeasible for the UK to meet this target based on current climate change targets: if it follows the Low Carbon Transition Plan (HM Government, 2009) the UK will exceed its budget by 2022. However, there is still a possibility that a global budget of 1,200 Gt could be achieved with a 50% probability of achieving a 2 degree future. For the UK, this would mean an annual reduction of 14% from a territorial perspective after the current carbon budgets already in place are achieved by 2022. This would allow the UK to emit a total of 2.5 Gt CO_2-e of GHG emissions between 2023 and 2050.

The UK has set up a legally binding target to reduce greenhouse gas emissions to at least 80 percent below 1990 levels by 2050 through action at home and abroad (Defra, 2009). One area where most radical change is required is in the electricity sector. Many of the scenarios that demonstrate an 80% reduction in UK GHG emissions by 2050 highlight the growing role of the electricity sector in achieving this target (UKERC, 2009). Not only will the current demand for electricity need to be met but transport services could also be provided through using electricity. This could more than double the demand for electricity in the UK by 2050 from 2000 levels (UKERC, 2009). This will require an almost complete transformation of the electricity sector. Many of the scenarios undertaken as part of the UKERC 2050 project suggest that nuclear power, fossil fuel power plant with carbon capture and storage (CCS) and wind power will form a major part of the electricity system in the future (UKERC, 2009). However, in all the scenarios attempting to define a low carbon pathway for the UK, the indirect GHG emissions of nuclear, CCS or wind are not taken into account, and the upstream impacts of all technologies are ignored. In reality, building a new energy system is an energy-intensive process, which reduces the overall energy and carbon efficiency of the power generation (Odeh and Cockerill, 2008b). This emphasises the need for a shift in the assessment of a low carbon energy system from direct greenhouse gas emissions to embodied greenhouse gas emissions – particularly when large scale infrastructure developments are concerned. Also, it is very important to know how much of the remaining 2.5 Gt CO_2-e of GHG emissions that the UK has left will be used up by providing the new low carbon electricity infrastructure.

The embodied carbon emissions of energy systems can be calculated using life cycle assessment methods. Life Cycle Assessment (LCA) is one of the most widely used methodologies for quantifying the environmental impact of a given product or process throughout its entire life (Crawford, 2008; Suh and Huppes, 2005). There are three methodological variants: process analysis, Input-Output (IO) analysis and hybrid analysis. Process Life Cycle Analysis, as a bottom-up approach, has often been employed to establish the indirect emissions associated with energy systems, but can lead to significant truncation errors in the calculations (Lenzen, 2002; Menzies et al., 2007). The limitation of process analysis has led the use of IO analysis as a top-down approach which represents monetary flows between sectors, and which can capture environmental fluxes between economic sectors by transforming monetary flows to physical flows (Menzies et al., 2007; Suh and Huppes, 2005). The advantage of IO analysis is data completeness and clear system boundaries since the entire economic activities of a nation are represented, however, it suffers from some shortcomings such as aggregation and allocation errors (Crawford, 2008; Lenzen and Munksgaard, 2002; Menzies et al., 2007; Suh and Huppes, 2005). Hybrid analysis has been suggested to combine the strengths of PLCA and IO-LCA. Originally introduced by Bullard et al. (1978) and developed by Treloar (1997), Lenzen and Munksgaard (2002), Suh (2004) and Suh and Huppes (2005) hybrid life cycle assessment methods have been increasingly applied and refined in recent years.

This paper develops an integrated hybrid life cycle assessment model with a multi-regional input-output model component to assess the direct and indirect GHG emissions of key energy technologies in the UK using offshore wind energy as a case study. In section 2 we develop an hybrid LCA model for assessing CO_2 emissions from wind power plant based on Suh (2004) by integrated process-based life cycle inventory (LCI) with a multi-regional input-output based LCI. Section 3 describe and discuss the results and associated policy implications. Section 4 is the conclusion including limitations and next steps.

2. Methodology

2.1 Embodied CO_2 emissions of different energy technologies: a review

Over the last three decades, many studies have been undertaken on life cycle emissions from fossil fuel generation technologies (Bates, 1995; Kannan, 2007; Odeh and Cockerill, 2008a; Proops et al., 1996; Scheafer and Hagedorn, 1992), nuclear power (Dones et al., 2005; Fthenakis and Kim, 2007; Lenzen, 2008; Tokimatsu et al., 2006; Yasukawa et al., 1992), wind power (Celik et al., 2007; Hondo, 2005; Khan et al., 2005; Lenzen and Munksgaard, 2002; Martínez et al., 2009; Proops et al., 1996; Weinzettel et al., 2009), solar PV (Alsema, 2003; Fthenakis and Kim, 2007; Muneer et al., 2005; Scheafer and Hagedorn, 1992; Stoppato, 2008), hydro power (Gagnon and van de Vate, 1997; Varun and Prakash, 2008), biomass (Cherubini et al., 2009; Gnansounou et al., 2009; Ishikawa et al., 2006; Kaltschmitt et al., 1997; Spath and Mann, 2004) and carbon capture and storage (CCS) (Koornneef et al., 2008; Korre et al., 2010; Livengood et al., 1993; Odeh and Cockerill, 2008b; Pehnt and Henkel, 2009; Singh et al., In press; Tzimas et al., 2007; Waku, 1996) using a LCA approach. A summary of CO_2 emissions from different fossil and non-fossil generation technologies as well as CCS is given in Table 1. From Table 1 we can see that the emissions intensity of fossil generation technologies without CCS is more than five times higher than the renewable and nuclear generation technologies. In general, for the fossil generation technologies with CCS, CO_2 emissions can be reduced by up to 80 percent. The data in Table 1 indicates that wind, nuclear and CCS can serve as the key potential generation technologies for the UK in terms of climate change mitigation. In this study we use wind generation technology as a case study to assess the embodied CO_2 emissions to build a new wind power system.

Table 1: Summary of studies on life cycle analysis of electricity generation technologies

Electricity generation technologies	**g-CO2/kWh**
Coal fired	975.3 - 990
Pulverized coal (PC)	847 - 879
PC with CCS	247 - 274
Natural gas combined cycle (NGCC)	488 - 499
NGCC with CCS	200 - 245
Integrated gasification combined cycle (IGCC)	861 - 872
IGCC with CCS	167 - 240
Combined cycle gas turbine (CCGT)	409
Nuclear	10 - 130
Wind	7.9 - 123.7
Solar PV	53.4 - 250
Biomass	35 - 178
Solar thermal	13.6 - 202
Hydro	3.7 - 237

Note: Data are collected from various studies: Varun (Varun et al., 2009), Lenzen (Lenzen, 2008), Odeh and Cockerill (Odeh and Cockerill, 2008b), Proops et al. (Proops et al., 1996). CCS is Carbon Capture and Storage.

In the LCA literature three main methods have emerged to calculate the greenhouse gas emissions of products or technologies: PLCA, IO-LCA and Hybrid LCA, have all been applied to different energy technologies including wind, solar, nuclear, NGCC, IGCC and CCS (Crawford, 2009; Gnansounou et al., 2009; Lenzen, 2008; Lenzen and Munksgaard, 2002; Odeh and Cockerill, 2008b; Varun et al., 2009). The process analysis method is the oldest and still most commonly used method, and involves evaluation of direct and indirect energy inputs to each product process, such as extraction, transportation, manufacturing, use, recycling and disposal (Menzies et al., 2007). IO-LCA is based on national input-output tables and uses national average data for each economic sector to assess the environmental impacts along the whole supply chain, which is considered to be more complete, in terms of system boundary, by many researchers (Crawford, 2008; Lenzen and Munksgaard, 2002; Suh and Huppes, 2005; Treloar et al., 2001). Hybrid LCA is a relatively new approach but has become very popular in recent energy studies (Crawford, 2009; Heijungs et al., 2006; Lenzen, 2008, 2009; Lenzen and Munksgaard, 2002; Suh and Huppes, 2005; Treloar, 1997; Treloar et al., 2001).

2.2 Hybrid LCA for wind power

Many studies have been carried out on wind energy, in terms of the energy requirement, energy output and CO_2 emissions, in order to determine the overall environmental benefit (Crawford, 2009; Lenzen and Munksgaard, 2002). The results from these studies vary considerably between 9.7 g-CO_2/kWh and 123.7 g-CO_2/kWh depending on the method of assessment chosen, the system boundary, and the life cycle stages considered (Varun et al., 2009). Figure 1 shows that the life cycle of a wind power plant includes production of the turbine and components, transport, erection, operation and dismantling and disposal.

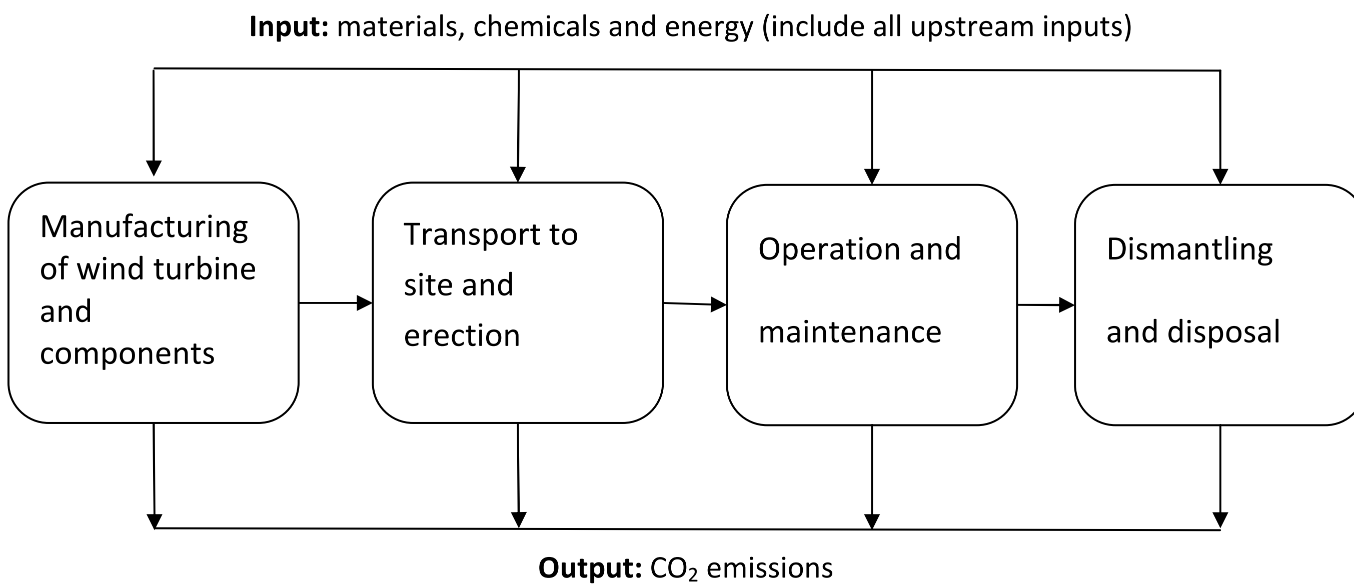

Figure 1: stages in the life cycle of wind power plant

2.2.1 System boundary

In the process-based approach a boundary is drawn around the main process inputs. Integrating this into a top-down economic model incorporates the process into the wider economy, accounting for interactions between the energy sector(s) and the rest of the economy. The embodied CO_2 emissions of a wind power plant include the CO_2 emissions emitted from the manufacturing, construction, installation and ongoing maintenances stages. When considering these wind turbines as part of a wind farm, with a multiple number of turbines, the embodied emissions may also include the emissions required for other materials and components, including wiring, grid connection, transformers and access roads. For this study, we use Ecoinvent database[1] which includes the processing, transport needs, energy requirements, the area necessary for the installation itself and the connection to the grid on the land, as well as waste disposal (incineration).

2.2.2 Process-based LCA

Life Cycle Inventory (LCI) is a phase of LCA involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle (ISO 14040, 1998). Heijungs (1994) first introduced the matrix inversion method to LCI computation (Suh and Huppes, 2005). In Heijungs' study, an inventory problem is solved by a system of linear equations, which can be shown in a *mxm* matrix notation of commodity by process. We define $A_{cp} = a_{ij}$ as LCA technology matrix, which shows inflows (negative value) or outflows (positive value) of commodity i of process j for a certain duration of process operation (Heijungs and Suh, 2002). The assumption is that processes at stake are being operated under a steady-state condition, which means selection of a specific temporal window for each process does not change the ratio between elements in a column (Suh and Huppes, 2005). For convenience, here we use a column vector S as scaling factor (Heijungs and Suh, 2002), which indicates the required factor of scaling each process to produce the required net output of the system. Therefore, commodity net output of the systems f_p is given by

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[1] Ecoinvent database: http://www.ecoinvent.org/

$$A_{cp} * S = f_p \quad (1)$$

Which shows that the amount of a commodity delivered to outside of the system is equal to the amount produced minus the amount used within the system. Therefore, the equation can be rearranged to calculate the scaling factor (Eq.2)

$$S = A_{cp}^{-1} * f_p \quad (2)$$

To calculate the emissions we define a matrix E = e_{kj} of which an element e_{kj} shows the amount of emissions emitted or consumed by process j during the operation that $a_{.j}$ is specified. The total direct and indirect emissions by the system to deliver a certain amount of commodity output to the outside of the system is calculated by

$$G_p = E_p * A_{cp}^{-1} * f_p \quad (3)$$

Where G_p is the total direct and indirect emission matrix, and f_p is a vector that is defined as the functional unit of the system.

2.2.3 IO-based LCA

All the processes in an economy are directly or indirectly linked with each other. However, process-based LCA is always truncated to a certain degree as the system boundary is not complete where the upstream emissions are not captured. Thus, to deal with this system boundary problem authors have used input-output methods (IOA) to conduct LCAs, as they have the advantage of depicting the entire (global) economy including all processes (at an aggregate level) and therefore avoiding truncation.

Input-output analysis originally developed by Leontief describes how sectors are inter-related through producing and consuming intermediate economic outputs that are represented by monetary transaction flows between economic sectors, which can be transformed to physical flows such as carbon under the assumption that all outputs of a sector are produced with the physical flow intensity (Miller and Blair, 2009). The input-output model assumes that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output (Miller and Blair, 2009; Suh and Huppes, 2005).

Based on this assumption, we define an *nxn* matrix A_{ss} that each column of A_{ss} shows domestic and import intermediate economic outputs in monetary values required to produce one unit of monetary output of another. Now, we define x as the total economic output, where x is equal to the summation of the economic output consumed by intermediate economic sectors and by final consumers (e.g. household, government, capital investment and export). For the economy as whole, the input-output model can be shown by

$$\boldsymbol{x} = \boldsymbol{A_{ss}} * \boldsymbol{x} + \boldsymbol{f_{IO}} \qquad (4)$$

where f_{IO} denotes final demand. Then, the total economic output x required to supply the final demand is calculated by

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A_{ss}})^{-1}\boldsymbol{f_{IO}} \qquad (5)$$

Where *I* denotes the *nxn* identity matrix. Note that we are using an multi-regional input-output model in a supply and use formulation here. The supply and use framework has particular importance for LCA applications of IOA, since LCA is an analytical tool based on the functionality of goods and services, and a supply and use framework makes it possible to distinguish different functions from an industry output (Suh and Huppes, 2005). The total direct and indirect emissions by domestic and import sectors to deliver a certain amount of economic output can be calculated by the environmental extended multi-regional input-output model (MRIO) which assumes that the amount of emissions generated by a sector is proportional to the amount of output of the sector and the identity of the emissions and the ratio between them are fixed. We define a *kxn* matrix E_{IO}, which shows the amount of emissions incurred to produce one monetary unit output of each economic sector. Therefore, the total direct and indirect emissions are calculated by

$$\boldsymbol{G_{IO}} = \boldsymbol{E_{IO}} * (\boldsymbol{I} - \boldsymbol{A_{ss}})^{-1} * \boldsymbol{f_{IO}} \qquad (6)$$

Where G_{IO} is the total domestic direct and indirect emission matrix, and f_{IO} is a vector that shows net economic output of the system. Despite the comprehensive framework and complete system boundaries, IO-LCA is subject to many uncertainties due to the high level of aggregation of products; many dissimilar commodities or sectors containing many variations are aggregate into the same category and assumed identical, and assumptions are based on proportionality between monetary and physical flows.

2.2.4 Hybrid analysis

Four hybrid LCA methods so far have been introduced in the literature including Process-based hybrid analysis, Input-output based hybrid analysis, Tiered hybrid method and integrated hybrid analysis. Many studies have discussed the differences among those methods (Heijungs et al., 2006; Menzies et al., 2007; Suh and Huppes, 2005). In this study, we mainly focus on the integrated hybrid LCA which offers the possibility of combining IOA's strength of being complete with LCA's strength of being detailed (Heijungs et al., 2006; Udo de Haes et al., 2004). The general integrated hybrid LCA framework is shown in Table 2.

	Processes	**Economic sectors**	**Final Demand**
Commodities	A_{cp}	$-C_d$	F_p
Economic sectors	$-C_u$	$I - A^*$	F_{IO}
CO2 emissions	E_p	E_{IO}	

Table 2: General Framework of Integrated Hybrid Life Cycle Assessment

In this study, we construct an integrated hybrid analysis framework with MRIO to calculate the direct and indirect emissions from wind energy technology based on the hybrid LCA developed by Suh (2004). In this framework, the IO table is interconnected with the matrix representation of the physical production system only at upstream and downstream cut-offs where process data are not available. The general formula of the integrated hybrid model is

$$G_{HL} = E_{HL}A_{HL}^{-1}f_{HL} = \begin{bmatrix} E_p & 0 \\ 0 & E_{IO} \end{bmatrix} \begin{bmatrix} A_{cp} & -C_d \\ -C_u & I - A^* \end{bmatrix}^{-1} \begin{bmatrix} f_p \\ 0 \end{bmatrix} \qquad (7)$$

Where A* is technical coefficients of MRIO in the supply and use formulation (see Wiedmann et al., 2010). Matrix C_u denotes upstream cut-off flows to the LCA system, linked with the relevant economic sector in IO table, and matrix C_d represents downstream cut-off flows to the IO system from the LCA system. Each element of C_u has a unit of monetary value per functional unit while each element of C_d is in a unit of physical unit per monetary value. Under certain assumptions, C_d can be set to zero (cf. Peters and Hertwich (2004)). The integrated hybrid LCA can model the full interactions between individual processes and industries in a consistent framework.

2.2.5 Data

The basis for our two-region MRIO modelling framework are supply, use and imports tables of the UK economy in 2004 with a sector resolution of 123, extended with sectoral greenhouse gas emissions derived from national environmental accounts. The tables were generated in a previous project; details are provided in (Wiedmann et al., 2008), see also (Wiedmann et al., 2010). For the rest-of-world region (ROW) we use data from the GTAP 7 database.[2] The materials and energy input in physical unit of wind power plant and associated CO_2 emissions are collected from Ecoinvent database. The detail description of the method which was used for calculating the matrix C_u can also be found in Wiedmann et al. (2010).

3. Results and discussion

3.1 CO_2 emissions based on Process LCA and Hybrid LCA

The hybrid LCA is more complete in terms of system boundary and captures the upstream emissions and the emissions embodied in services such as retail and insurance, which are

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2 https://www.gtap.agecon.purdue.edu.

usually ignored by the process-based LCA. Table 3 shows the CO_2 emissions from a 2-MW offshore wind farm by process-based LCA and integrated hybrid LCA. From Table 3 we can observe that the total CO_2 emissions increase by 19 percent by applying integrated hybrid LCA compared to a process-based LCA. The CO_2 emissions from wind farm operation is more than doubled when shifting from process-based LCA to integrated hybrid model as there is a significant input from service sectors such as computer services, technical consultancy, and other business services which were not captured by the process-based LCA. Emissions from metal processing also grew by 65.5% when applying hybrid LCA. A detailed comparison of IO-LCA, IO-based hybrid LCA, and integrated hybrid LCA can be found in Wiedmann et al. (2010).

Table 3: Whole lifecycle CO_2 emissions from 2-MW offshore wind farm by Process LCA and Integrated Hybrid LCA (ton)

Processes	Process-based LCA	Integrated hybrid LCA	Percentage change
Metal extraction	647.7	695.8	7.4%
Metal process	100.3	166.0	65.5%
Plastics	321.8	334.9	4.1%
Construction	251.7	288.5	14.6%
Operation	112.4	235.3	109.3%
Transport	26.9	26.9	0.0%
Waste disposal	38.3	38.3	0.0%
Others	35.0	40.3	14.9%
Total	1534.2	1825.9	19%

3.2 Life cycle CO_2 emissions of wind energy

The total embodied CO_2 emissions calculated by the integrated hybrid LCA model is 16.3 g CO_2-e/kWh, which is within the range found in the literature (9.7 g CO_2-e/kWh to 123.7 g CO_2-e/kWh). From Figure 2 we can see that metal extraction is the largest contributor to CO_2 emissions accounting for about 40 percent of the total CO_2 emissions. Plastics, construction and operation also have large shares of total CO_2 emissions responsible for 18 percent, 16 percent and 13 percent, respectively. However, transport and disposal together only share 4 percent of the total emissions.

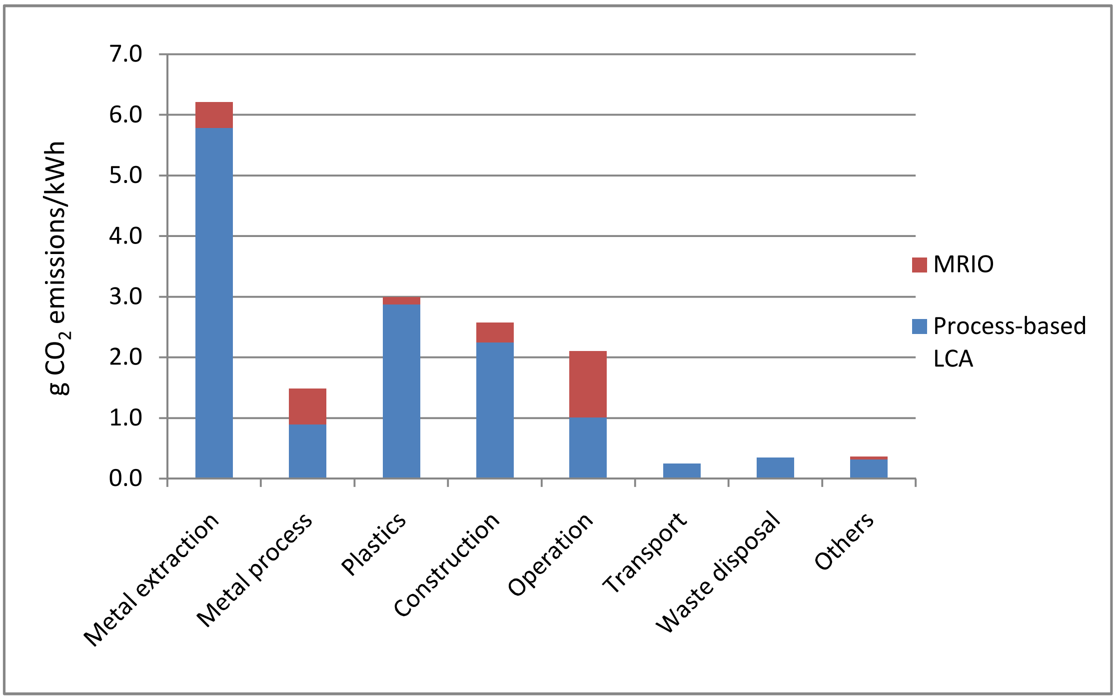

Figure 2: CO_2 emissions from wind electricity generation (g CO_2 emissions/KWh)

4. Conclusion

In this paper, we calculate the full impacts of CO_2 emissions for consideration of wind energy for the UK's transition to a low carbon economy, and this is the first time to apply a hybrid LCA model to assessing CO_2 emissions from wind power in the UK. Also, the results will help to improve IO model in UK (Wiedmann, T., Scott, K., Lenzen, M., Feng, K. and Barrett, J., 2010).

4.1Limitations

There are two major limitations in this study. One is the uncertainties in the data sources e.g. unknown system boundary cut-off in the process data, estimation of upstream inputs without access to an actual wind farm expenditure accounts. Another is use of Ecoinvent data for process part does not reflect UK production technology (e.g. steel / cement production). However, this limitation is somehow alleviated by the fact that there was not wind turbine manufacturer in the UK in 2004 and all parts were imported, mostly from mainland Europe.

4.2 Next steps

The next step of this research will be applying the developed hybrid framework to other energy technologies, such as nuclear power and carbon capture and storage.

Reference

Alsema, E., 2003. Energy Pay-Back Time and CO2 Emissions of PV Systems, in: Tom, M., Luis, C. (Eds.), Practical Handbook of Photovoltaics. Elsevier Science, Amsterdam, pp. 869-886.

Bates, J., 1995. Full life cycle atmospheric emissions and global warming impacts from UK electricity generation, Technical Report ETSU-R-88. Harwell, HMSO, London.

Celik, A.N., Muneer, T., Clarke, P., 2007. An investigation into micro wind energy systems for their utilization in urban areas and their life cycle assessment Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 221, 1107 - 1117.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources, Conservation and Recycling 53, 434-447.

Crawford, R.H., 2008. Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management 88, 496-506.

Crawford, R.H., 2009. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. Renewable and Sustainable Energy Reviews 13, 2653-2660.

Defra, 2009. e-Digest of Environmental Statistics. Department for Environment, Food and Rural Affairs.

Dones, R., Heck, T., Emmenegger, M.F., Jungbluth, N., 2005. Life cycle inventories for the nuclear and natural gas energy systems, and examples of uncertainty analysis: ecoinvent: energy supply. International journal of Life Cycle Assessment 10, 10 - 23.

Fthenakis, V.M., Kim, H.C., 2007. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. Energy Policy 35, 2549-2557.

Gagnon, L., van de Vate, J.F., 1997. Greenhouse gas emissions from hydropower : The state of research in 1996. Energy Policy 25, 7-13.

Gnansounou, E., Dauriat, A., Villegas, J., Panichelli, L., 2009. Life cycle assessment of biofuels: Energy and greenhouse gas balances. Bioresource Technology 100, 4919-4930.

Heijungs, R., 1994. A generic method for the identification of options for cleaner products. Ecological Economics 10, 69 - 81.

Heijungs, R., de Koning, A., Suh, S., 2006. Toward an information tool for integrated product policy. Journal of Industrial Ecology 10, 147 - 158.

Heijungs, R., Suh, S., 2002. The computational structure of Life Cycle Assessment. Kluwer Academic Publisher, Dordrecht, The Netherlands.

HM Government, 2009. The UK Low Carbon Transition Plan: National strategy for climate and energy the Climate Change Act 2008.

Hondo, H., 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 30, 2042-2056.

Ishikawa, S., Hoshiba, S., Hinata, T., Hishinuma, T., Morita, S., 2006. Evaluation of a biogas plant from life cycle assessment (LCA). International Congress Series 1293, 230-233.

ISO 14040, 1998. Environmental management - Life cycle assessment - Principles and framework: International Organisation for Standardisation, Geneva, Switzerland.

Kaltschmitt, M., Reinhardt, G.A., Stelzer, T., 1997. Life cycle analysis of biofuels under different environmental aspects. Biomass and Bioenergy 12, 121-134.

Kannan, R., 2007. Life cycle energy, emissions and cost inventory of power generation technologies in Singapore. Renewable and Sustainable Energy Reviews 11, 702 - 715.
Khan, F.I., Hawboldt, K., Iqbal, M.T., 2005. Life Cycle Analysis of wind-fuel cell integrated system. Renewable Energy 30, 157-177.
Koornneef, J., van Keulen, T., Faaij, A., Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. International Journal of Greenhouse Gas Control 2, 448-467.
Korre, A., Nie, Z., Durucan, S., 2010. Life cycle modelling of fossil fuel power generation with post-combustion CO2 capture. International Journal of Greenhouse Gas Control 4, 289-300.
Lenzen, M., 2002. Differential Convergence of Life-Cycle Inventories toward Upstream Production Layers. Journal of Industrial Ecology 6, 137-160.
Lenzen, M., 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. Energy Conversion and Management 49, 2178-2199.
Lenzen, M., 2009. Dealing with double-counting in tiered hybrid life-cycle inventories: a few comments. Journal of Cleaner Production 17, 1382-1384.
Lenzen, M., Munksgaard, J., 2002. Energy and CO2 life-cycle analyses of wind turbines--review and applications. Renewable Energy 26, 339-362.
Livengood, D., Doctor, R.D., Molburg, J., Thimmapuram, P., Berry, G.F., 1993. Recovery, transport, and disposal of CO2 from an integrated gasification combined-cycle power plant, POWER-GEN Americas Conference, Dallas, TX.
Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., Blanco, J., 2009. Life cycle assessment of a multi-megawatt wind turbine. Renewable Energy 34, 667-673.
Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2[thinsp][deg]C. Nature 458, 1158-1162.
Menzies, G.F., Turan, S., Banfill, P.F.G., 2007. Life-cycle assessment and embodied energy:a review. Construction Materials 160, 135-143.
Miller, R.E., Blair, P.D., 2009. Input- Output Analysis: Foundations and Extensions, 2nd ed. Cambridge University Press, New York.
Muneer, T., Asif, M., Munawwar, S., 2005. Sustainable production of solar electricity with particular reference to the Indian economy. Renewable and Sustainable Energy Reviews 9, 444-473.
Odeh, N.A., Cockerill, T.T., 2008a. Life cycle analysis of UK coal fired power plants. Energy Conversion and Management 49, 212-220.
Odeh, N.A., Cockerill, T.T., 2008b. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. Energy Policy 36, 367-380.
Pachauri, R.K., Reisinger, A., 2007. Climate Change 2007: Synthesis Report. Intergovernmental Panel on Climate Change (IPCC), Cambridge, UK.
Pehnt, M., Henkel, J., 2009. Life cycle assessment of carbon dioxide capture and storage from lignite power plants. International Journal of Greenhouse Gas Control 3, 49-66.
Peters, G., Hertwich, E., 2004. A comment on "Fuctions, commodities and environmental impacts in an eclogical-economic model", Program for inudstriell okologi.
Proops, J.L.R., Gay, P.W., Speck, S., Schroder, T., 1996. The lifetime pollution implications of various types of electricity generation: An input-output analysis. Energy Policy 24, 229 - 237.

Scheafer, H., Hagedorn, G., 1992. Hidden energy and correlated environmental characteristics of PV power generation. Renewable Energy 2, 159-166.
Singh, B., Strømman, A.H., Hertwich, E., In press. Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. International Journal of Greenhouse Gas Control In Press, Corrected Proof.
Spath, P.L., Mann, M., 2004. Biomass power and conventional fossil systems with and without CO2 sequestration—comparing the energy balance, greenhouse gas emissions and economics. US National Renewable Energy Laboratory, Golden, CO.
Stoppato, A., 2008. Life cycle assessment of photovoltaic electricity generation. Energy 33, 224-232.
Suh, S., 2004. Functions, commoditites and environmental impacts in an ecological-economic model. Ecological Economics 48, 451 - 467.
Suh, S., Huppes, G., 2005. Methods for Life Cycle Inventory of a product. Journal of Cleaner Production 13, 687-697.
Tokimatsu, K., Kosugi, T., Asami, T., Williams, E., Kaya, Y., 2006. Evaluation of lifecycle CO2 emissions from the Japanese electric power sector in the 21st century under various nuclear scenarios. Energy Policy 34, 833-852.
Treloar, G., 1997. Extracting embodied energy paths from input-output tables: towards an input-output based hybrid energy analysis method. Economic Systems Research 9, 375-391.
Treloar, G., Love, P.E.D., Holt, G.G., 2001 Using national input-output data for embodied energy analysis of individual residential buildings. Construction Management and Economics 19, 49-61.
Tzimas, E., Mercier, A., Cormos, C.-C., Peteves, S.D., 2007. Trade-off in emissions of acid gas pollutants and of carbon dioxide in fossil fuel power plants with carbon capture. Energy Policy 35, 3991-3998.
Udo de Haes, H.A., Heijungs, R., Huppes, G., Suh, S., 2004. Three strategies to overcome the limitations of life-cycle assessment. Journal of Industrial Ecology 8, 19 - 32.
UKERC, 2009. Energy 2050 - Making the transition to a secure and low-carbon energy system: synthesis report. UK Energy Research Centre
Varun, Bhat, I.K., Prakash, R., 2009. LCA of renewable energy for electricity generation systems--A review. Renewable and Sustainable Energy Reviews 13, 1067-1073.
Varun, B., Prakash, R., 2008. Life cycle analysis of run-of river small hydro power plants in India. Open Renewable Energy 1, 11 - 16.
Waku, H., 1996. Life cycle analysis of fossil power plant with CO2 recovery and sequestering system. Fuel and Energy Abstracts 37, 210-210.
Weinzettel, J., Reenaas, M., Solli, C., Hertwich, E.G., 2009. Life cycle assessment of a floating offshore wind turbine. Renewable Energy 34, 742-747.
Yasukawa, S., Tadokoro, Y., Kajiyama, T., 1992. Life cycle CO2 emission from nuclear power reactor and fuel cycle system Expert workshop on life-cycle analysis of energy systems methods and experience. International Energy Agency, Paris, France: Organisation for Economic Co-operation and Development.