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Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield

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ABSTRACT

Wind turbines, used to generate renewable energy, are typically considered to take only a number of months to produce as much energy as is required in their manufacture and operation. With a life expectancy of upwards of 20 years, the energy produced by wind turbines over their life can be many times greater than that embodied in their production. Many previous life cycle energy studies of wind turbines are based on methods of assessment now known to be incomplete. These studies may underestimate the energy embodied in wind turbines by more than 50%, potentially overestimating the energy yield of those systems and possibly affecting the comparison of energy generation options. With the increasing trend towards larger scale wind turbines, comes a respective increase in the energy required for their manufacture. It is important to consider whether or not these increases in wind turbine size, and thus embodied energy, can be adequately justified by equivalent increases in the energy yield of such systems. This paper presents the results of a life cycle energy and greenhouse emissions analysis of two wind turbines and considers the effect of wind turbine size on energy yield. The issue of incompleteness associated with many past life cycle energy studies is also addressed. Energy yield ratios of 21 and 23 were found for a small and large scale wind turbine, respectively. The embodied energy component was found to be more significant than in previous studies, emphasised here due to the innovative use of a hybrid embodied energy analysis approach. The life cycle energy requirements were shown to be offset by the energy produced within the first 12 months of operation. The size of wind turbines appears to not be an important factor in optimising their life cycle energy performance.

Contents

1. Introduction . . . 2654
2. Life cycle energy analysis of wind turbines . . . 2654
    2.1. Trends in wind turbine size . . . 2654
    2.2. Capacity factors . . . 2654
    2.3. Wind levels and availability . . . 2655
    2.4. Service life . . . 2655
    2.5. Embodied energy . . . 2655
    2.6. Process analysis . . . 2655
    2.7. Hybrid analysis . . . 2655
    2.8. Energy yield . . . 2656
3. Methodology . . . 2656
    3.1. System details . . . 2656
    3.2. Life cycle energy . . . 2656
    3.3. Embodied energy . . . 2657
    3.4. Energy output . . . 2658
    3.5. Energy yield . . . 2658
    3.6. Greenhouse gas emissions . . . 2658

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4. Results and discussion 2658
4.1. Embodied energy 2658
4.2. Annual energy output 2659
4.3. Life cycle energy analysis and energy yield ratio 2659
4.4. Life cycle greenhouse emissions 2659
5. Conclusions 2660
Acknowledgements 2660
References 2660

1. Introduction

The wind industry has been growing at an ever-increasing rate since the early 1990s, with a total capacity of 121,188 MW installed at the end of 2008. With the increasing focus on sustainable development, renewable energy generation and its popularity as a clean energy source, it is predicted that the worldwide installed wind capacity will more than double by 2012 [1].

Rapid advances in wind turbine technology and materials are leading to an increase in the size and output of wind turbines, maximising the efficiencies of scale and potential energy output. With this trend towards larger scale turbines comes a respective increase in the energy required for their manufacture, assuming similarly energy intensive materials.

It is important to consider the environmental benefits of renewable energy systems, such as wind turbines, to ensure that they provide a net environmental benefit. A life cycle analysis is just one tool for assessing the most significant environmental impacts and benefits of such systems. Previous life cycle energy studies of wind turbines have typically assumed that these systems pay back the energy invested in them within several months. Whilst these embodied energy requirements have been shown to be relatively insignificant in comparison to the energy generated, there is significant variability in the values presented. This variation may be due to problems with the embodied energy assessment methods used.

Traditional methods of quantifying embodied energy, namely process analysis and input–output (I–O) analysis, have been shown to have significant limitations, despite the different benefits each method offers. The most important stage of an embodied energy analysis is the quantification of the inputs to the product or system. Traditionally, a boundary has been drawn around the quantification of inputs to the product being assessed, mainly due to difficulties in obtaining necessary data and the understanding of this data. Many inputs are therefore neglected in the quantification of inputs to a product, and thus the system is incomplete.

Due to the inherent problems with process analysis and I–O analysis, hybrid methods of embodied energy analysis have been developed in an attempt to minimise the limitations and errors of these traditional methods. Hybrid methods combine both process data and I–O data in a variety of formats. This study uses an I–O-based hybrid analysis approach to determine the life cycle energy requirements and energy yield of two on-shore wind turbines. Energy yield is an indication of the amount of energy generated by the turbines over their lifetime in relation to the energy required for their manufacture and on-going operation. The aim of this study was to determine whether the trend towards larger scale wind turbines is having a significant impact on their energy yield, through the improved economies of scale and higher rated outputs, despite potential increases in embodied energy.

2. Life cycle energy analysis of wind turbines

A life cycle energy analysis of a wind turbine involves a study of the energy flows over its entire life. This includes the embodied energy associated with the manufacturing process and subsequent replacement and repair of components; the energy required for operation, maintenance and disposal; and the energy generated by the turbine over its life. Traditionally, the energy output has been the focus of studies dealing with the life cycle energy of wind turbines. This may be partly due to conceptual failure in quantifying the life cycle energy requirements of these systems through underestimating the possible importance of embodied energy. Embodied energy is particularly important due to the complexity of the supply chain. This complexity means that the supply chain has to be modelled for each product and process upstream to the raw materials.

There have been numerous studies that have considered the energy requirements and energy output associated with wind turbines in order to determine the overall environmental benefit from these systems. The findings from these studies tend to vary considerably depending on a number of key factors, including: the method of embodied energy assessment chosen; the system boundary; and the life cycle stages considered.

There are numerous factors affecting the energy production and yield of wind turbines. The generation of energy is highly dependant on the conversion efficiency of the actual turbines and the availability and levels of wind in the specific location. The energy yield is dependant on the service life of the turbine, the life cycle energy requirements of manufacture and installation, operation, maintenance and disposal and the energy produced over the life of the system.

2.1. Trends in wind turbine size

There is an increasing trend towards larger scale wind turbines (1 MW and above) with the aim of providing efficiencies of scale and greater energy output per turbine. With the increased size of these systems comes an inherent increase in the quantity of materials and energy required for their manufacture, assuming similarly energy intensive materials. It is important to consider whether or not these increases in wind turbine size, and thus embodied energy, can be adequately justified by equivalent increases in the energy output and lifetime energy yield of such systems.

Careful consideration must be given to whether or not the additional energy requirements of manufacture provide a net energy saving through an increase in the quantity of energy generated by these turbines. This assessment may then help to determine the optimal size of wind turbines for maximising net energy production.

2.2. Capacity factors

The capacity factor of a wind turbine represents the actual energy output for the given system and conditions as a proportion of the rated power output over an entire year. Capacity factors can range from around 10 to 50% [2], with 20–35% considered typical for modern wind turbines. These efficiencies will vary depending on the size of the system, wind availability and reliability, and will have a significant impact on the total energy output and energy yield of a wind turbine. A low capacity factor is usually an indicator of a poor choice of location, whilst a capacity factor at the higher end of the scale is usually representative of extreme off-shore locations.

2.3. Wind levels and availability

The location of a wind turbine is a crucial factor in maximising their energy output. Whilst wind turbines are usually installed in high wind areas, seasonal variability in wind availability and strength will impact on the energy output of a turbine.

Cold wintry and hot summer periods reflect times of high demand for electricity. These periods are characterised by stable high-pressure weather systems with low wind levels. This means that during times of peak electricity demand, wind energy is usually only capable of making a minor contribution towards this demand.

2.4. Service life

The service life of a wind turbine refers to their expected lifetime, or the acceptable period of use in service. The longer the service life, the greater the opportunity there is to generate energy to offset the life cycle energy requirements and potentially improve the energy yield.

Typically the anticipated service life of a wind turbine ranges from 20 years [3–5] to 30 years [6,7]. The main structural components of a turbine (such as the tower and base) are capable of lasting many years beyond this, however more regular replacement of the moving parts, such as the generator, gearbox and blades is generally required [8].

2.5. Embodied energy

Whilst larger scale turbines are capable of producing greater quantities of energy, the energy produced by these turbines should not be considered in isolation. It is important also to consider the energy requirements over the entire life cycle of a wind turbine, from raw material extraction to final disposal at the end of their service life.

An important component of the energy requirements of a wind turbine is the energy embodied in their manufacture, construction, installation, maintenance, and parts replacement. Embodied energy has been shown to account for a significant proportion of the life cycle energy requirements for particular products [see 9 and 10].

There is a considerable amount of variability in the figures provided in the past for the embodied energy of wind turbines, typically considered to be the most significant area where variation between life cycle energy studies occurs [2]. Past studies have shown embodied energy values ranging from 3948 GJ for a 500 kW system [11] to 70,152 GJ for a 4.5 MW system [12].

Whilst turbine size, materials used, energy intensities and location will have an impact, the major reason for the variability in embodied energy figures is due to the method of assessment chosen. This can have a significant impact on the validity of the life cycle energy results. When calculating the embodied energy of wind turbines, previous studies have traditionally used process-based methods of assessment, commonly known as process analysis.

2.6. Process analysis

Crawford [9] has shown that when assessing embodied energy using traditional assessment techniques (such as process analysis based on ISO 14040), the product system boundary can be up to 87% incomplete. A process analysis approach is generally seen to be more accurate and relevant to the product being analysed, but on the other hand, its collection can be labour- and time-intensive. It considers the energy requirements for only a limited number of inputs, usually the main materials, and typically excludes the energy requirements associated with supporting goods and services (e.g. advertising, insurance and financial services), capital equipment (e.g. machinery used to make wind turbines), converting basic materials into more complex products (e.g. rolled steel into metal products) and minor materials, by truncating the system boundary, as demonstrated in Fig. 1 for a wind turbine. With this incomplete system boundary, the errors typically associated with assessing these energy requirements may be exacerbated even further. This may then lead to incorrect findings, in particular, greater energy yields, shorter energy payback periods and greater environmental benefits than are actually possible.

This issue of system boundary incompleteness in process analyses is not a problem that brute force can solve, even with practically unlimited resources. As a result, life cycle studies based on process analysis do not usually cover the input system of the functional unit to a sufficient degree.

Although many previous studies have indicated that the energy embodied in a wind turbine may equate to less than 5% of the energy generated during their service life, these findings need to be reassessed in light of the potential errors associated with the process-based assessment methods used in these studies.

2.7. Hybrid analysis

Hybrid methods have been developed in an attempt to minimise the limitations and errors of traditional embodied energy assessment methods. National average statistics that model

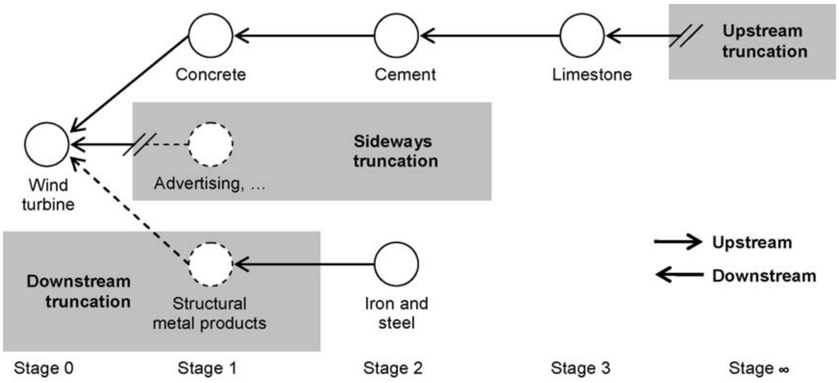

Fig. 1. Upstream, downstream and sideways truncation errors in the wind turbine system boundary.

the financial flows between sectors of the economy, referred to as input–output (I–O) data, can be used to fill the gaps that are caused by system boundary incompleteness [13].

Input–output data can be combined with national energy use data in the form of an I–O model in order to trace energy requirements between industry sectors. Generally, an I–O model covers completely the economic system defined by the national or regional statistics. The whole economy is treated as a system and any number of inputs from other sectors are included, an almost limitless number of potential transactions upstream through the supply chain. The system boundary is economic, such that if a sector pays for any product, the inputs to that product are counted.

Hybrid analysis combines process data and I–O data in a variety of formats [13,14]. The I–O-based hybrid technique developed by Treloar [15] starts with a disaggregated I–O model to which available process data is integrated. Using this approach, the systemic completeness of the I–O model is not compromised in any way and the more reliable process data is able to be integrated where it is available. This avoids the possibility for sideways and downstream truncation errors discussed above, in addition to upstream truncation.

Lenzen and Munksgaard [2] and Crawford et al. [16] have demonstrated that the use of an I–O-based hybrid technique is the preferred method for the assessment of the energy content of renewable energy systems, such as wind turbines, in order to achieve system completeness, thus minimising the limitations of previous studies.

2.8. *Energy yield*

Many previous studies that have considered the net energy production associated with wind turbines have based these assessments on the time required for the life cycle energy requirements to be paid back by the energy produced (known as the energy payback period). Richards and Watt [17] have highlighted the deficiencies in this type of approach to assessing the benefits of energy generation technologies. One of the main problems with this method is that it does not reflect the life of a product. For example, a product with a longer energy payback and a longer expected life than a similar alternative may in fact generate more energy over its entire life. Richards and Watt [17] and Pick and Wagner [11] suggest that the energy yield ratio (EYR) provides a more informative indication of the potential energy savings possible. The EYR shows how many times the energy invested in the wind turbine is returned or paid back by the system in its entire life [11].

Varying results have been presented in the past for the EYR of wind turbines. This variation can be attributed to a number of key variables, including: the materials used and their embodied energy; assessment methods used; geographic location; turbine service life; capacity factor; and power rating [18]. The EYRs that have been presented in the past vary from 10 [4] to 70 [11]. In the past, the variation in yield ratio between different sized turbines has been shown to vary by as little as 10% [11] and thus the scale of a turbine may have little impact on its energy yield.

There is a lack of studies analysing the energy requirements and potential energy yield of large scale wind turbines, particularly using a systemically complete approach for assessing the embodied energy component. This paper presents the results of a life cycle energy and greenhouse gas emissions analysis of two wind turbines and an analysis of the effect of wind turbine size on life cycle energy yield, addressing the issue of incompleteness associated with many similar previous studies of wind turbines.

3. Methodology

This section describes the wind turbines chosen for the study and outlines the methods used to calculate the life cycle energy requirements, greenhouse emissions and energy yield of these wind turbines. Two wind turbines were analysed (850 kW and 3.0 MW) to demonstrate the potential impact of turbine size on energy yield.

3.1. *System details*

The main components of the wind turbines include the rotor (hub and blades), nacelle (generator, gearbox, brakes, electronic controller, transformer, and control system), tower and base. The two wind turbines chosen for this study were horizontal axis, 3 blade systems with an anticipated service life of 20 years. The main features of these turbines are shown in Table 1.

Table 1
Wind turbine characteristics.

	Wind turbine 1 (850 kW)	Wind turbine 2 (3.0 MW)
Total rated power output (kW)	850	3000
Capacity factor	34%	33%
Cut-in wind speed	4 m/s	4 m/s
Cut-out wind speed	25 m/s	25 m/s
Hub height	60 m	80 m
Blade length/rotor diameter (m)	25/52	44/90

A number of important assumptions were also made in the analysis:

- wind velocity distribution is based on Weibull's distribution;
- roads, working and turning areas have not been included as they are expected to be insignificant [8];
- component replacement scenario based on [8] – equivalent to the replacement of half of the gearbox over the service life;
- materials required for maintenance have been included, i.e. change of oils and lubricants every 5 years;
- energy requirements and savings associated with decommissioning or use of recycled materials have not been included; and
- energy saved through the recovery of materials at the end of the turbine's life has not been included as Krohn [3] has shown that the potential net energy recovered is likely to be less than 5% of initial embodied energy. Also material recovery at the end of the turbine service life cannot be guaranteed and as such any environmental credit for this re-use of materials should be given to the particular product in which those materials are re-used.

3.2. *Life cycle energy*

For the purpose of this study and the comparison between systems, the period of the life cycle energy analysis chosen was 20 years. This period corresponds with the stated design life of the turbines studied. The main structural components of a turbine (such as the tower and base) are capable of lasting many years beyond this, however, more regular replacement of the moving parts, such as the generator, gearbox and blades is generally required [8]. The net energy produced over the life cycle of each wind turbine is equal to the gross energy output of the turbine, minus the initial embodied energy, the energy associated with the necessary replacement of components during the 20-year period and the energy required for operation, maintenance and repair.

3.3. Embodied energy

The embodied energy of a wind turbine includes the energy required in the manufacturing, construction, installation and on-going maintenance stages. When considering these wind turbines as part of a wind farm, with a multiple number of turbines, this embodied energy may also include the energy required for other materials and components, including wiring, grid connection, transformers and access roads. For this study, these components have not been included as they are considered to be insignificant or equivalent for each scenario and thus have little impact on the comparison of net energy production and yield [8].

Hybrid embodied energy intensities of materials were calculated using the I–O-based hybrid analysis method, combining available process data for specific materials, with I–O data. The process data was obtained from the latest available SimaPro Australian database [19]. No other source of substantially better, more up-to-date public domain process data covering such a broad range of materials is known to be available in Australia. The I–O data was obtained from an I–O model of Australian energy use for more than 100 sectors of the Australian economy, developed by Professor Manfred Lenzen, Department of Physics, The University of Sydney. The base I–O data was taken from the Australian National Accounts [20] and combined with national energy data. The combination of these two sources comprises the I–O model. The model includes the value of capital purchased in previous-years, and capital imported from other countries, amortised over the capital item's life [as described and analysed in 21]. Capital refers to the equipment and machinery used to make products such as wind turbines. The inputs for which process data was collected were subtracted from the energy-based I–O model, leaving a 'remainder' that was used to fill the 'upstream' gaps in the process data. This value was then added to the process data to give the total energy intensity of the specific materials (Table 2).

Table 2
Hybrid material energy intensities (GJ/unit).

Material	Unit	Energy intensity
Concrete 20MPa	m^3	4.08
Steel	t	85.3
Aluminium	t	252
Copper	t	379
Glass fibre	t	168
Epoxy	t	163
Paint	m^2	0.096

The quantities of materials used in the manufacture of each of the turbines were determined (Table 3). Information regarding components, materials, masses, areas and volumes was obtained from the manufacturers of the various components. All information was in the public domain. The embodied energy values of the wind turbines were derived using the I–O-based hybrid analysis method, as described by Treloar [15], using I–O data for Australia for the financial year 1996–1997 and available process data. The hybrid material embodied energy intensities (Table 2) were multiplied by the quantities of basic materials contained in the wind turbines. These individual material embodied energy figures were then summed to obtain an initial estimation of the embodied energy value for the wind turbines.

The disaggregated energy-based I–O model, was then used to complete the system boundary by correcting potential 'sideways' and 'downstream' gaps (see Fig. 1). The total energy intensity values of the individual inputs, for which physical quantity data was obtained, were deducted from the total energy intensity of the appropriate economic sector to give the 'remainder' (which in this

Table 3
Material breakdown of wind turbines.

Component	Item	Wind turbine 1 (850 kW)		Wind turbine 2 (3.0 MW)	
		Weight	Materials	Weight	Materials
Foundation	Reinforced concrete	495 t	480 t concrete 15 t steel	1176 t	1140 t concrete 36 t steel
Tower	Painted steel	70 t	69.07 t steel 0.93 t paint	160 t	158.76 t steel 1.24 t paint
Nacelle	Bedplate/frame	3.35 t	3.35 t steel	13 t	13 t steel
	Cover	2.41 t	2.41 t steel	9.33 t	9.33 t steel
	Generator	1.84 t	1.47 t steel 0.37 t copper	7.14 t	5.71 t steel 1.43 t copper
	Main shaft	4.21 t	4.21 t steel		
	Brake system	0.26 t	0.26 t steel	1.02 t	1.02 t steel
	Hydraulics	0.26 t	0.26 t steel		
	Gearbox	6.2 t	6.08 t steel 0.062 t copper 0.062 t aluminium	24.06 t	23.58 t steel 0.241 t copper 0.241 t aluminium
	Cables	0.42 t	0.18 t aluminium 0.24 t copper	1.63 t	0.69 t aluminium 0.94 t copper
	Revolving system	1 t	1 t steel	3.87 t	3.87 t steel
	Crane	0.26 t	0.26 t steel	1.02 t	1.02 t steel
	Transformer/sensors	1.79 t	0.894 t steel 0.357 t copper 0.357 t aluminium 0.18 t plastic	6.93 t	3.47 t steel 1.38 t copper 1.38 t aluminium 0.7 t plastic
Rotor	Hub	4.8 t	4.8 t steel	19.2 t	19.2 t steel
	Blades	5.02 t	3.01 t fibre glass 2.01 t epoxy	20.07 t	12.04 t fibre glass 8.03 t epoxy
	Bolts	0.18 t	0.18 t steel	0.73 t	0.73 t steel

Table 4
Calculation of initial embodied energy of 3.0 MW wind turbine.

	Embodied energy (GJ/turbine)
Process data for quantified wind turbine materials	18,716[a]
Input–output data used to fill 'upstream' gaps	14,914[b]
Initial embodied energy[(a+b)]	33,630[c]
Input–output data for wind turbine	
Total energy intensity	87,300[d]
Inputs covering process data	36,693[e]
Remainder (to fill 'sideways' and 'downstream' gaps)[(d−e)]	50,607[f]
Total[(c+f)]	84,237
Proportion of process data	22%

case comprised only part of the I–O component of the hybrid result). The 'remainder' thus corrects 'sideways' and 'downstream' truncation error (Fig. 1), at least in terms of the Australian economic system as defined by the Australian Bureau of Statistics [20]. The initial embodied energy value, as calculated above, was then added to this figure to give the total embodied energy using I–O-based hybrid analysis (as demonstrated in Table 4).

The energy associated with component replacement and repair during the life of the wind turbines has been calculated based on the assumption that 50% of wind turbines will require a gearbox replacement during their life. All other components are assumed to last for the life of the turbine (i.e. 20 years). Therefore, to represent the recurring embodied energy requirement, half of the embodied energy of the gearbox for each turbine has been calculated and added to the initial embodied energy.

3.4. Energy output

The quantity of energy generated by a wind turbine is dependent on a number of factors, including: geographic location; system type; tower height; rated energy output; and system efficiency.

The climate of the chosen location for the wind turbines has a significant impact on their energy output. Whilst wind turbines are usually installed in high wind areas, seasonal variability in wind availability and strength will influence the energy output of a turbine. An on-shore site was selected for the location of the wind turbines in this study, on the south-west coast of Victoria, Australia (latitude 37.3°S). This site was chosen to reflect the typical conditions within which most Australian wind farm developments would occur. The average annual wind speed for this site was 7.75 m/s. The annual gross energy output of the wind turbines was calculated using the hourly wind data of the chosen location and characteristic power curve of the two wind turbines. Capacity factors of 34% and 33% for the 850 kW and 3.0 MW systems, respectively, were also used. Reduced operational efficiencies over time, due to system wear, have not been factored in, assuming uniform performance of the systems over their entire life.

The gross annual energy output was then converted to net annual output by subtracting the energy required for internal controls and day-to-day maintenance and system losses, assumed to be approximately 10% of gross generated energy. As these initial output figures were in delivered energy terms, they were then converted to primary energy terms, using a factor of 3.4 to represent the substituted primary energy supplied by the brown coal fired electricity network in Victoria, Australia.

3.5. Energy yield

The initial and recurring embodied energy and total net output were combined to determine the energy yield. The energy yield ratio was calculated using the following equation:

$$\mathrm{EYR} = \frac{E_{out} \times L}{EE_{in+rec}} \tag{1}$$

where E_{out} = net annual energy output; L = wind turbine service life; and, EE_{in+rec} = sum of initial and recurring embodied energy requirements.

The respective energy yield ratios of the two wind turbines were then able to be compared and evaluated to determine the impact of a wind turbine's rated output on its energy yield.

3.6. Greenhouse gas emissions

The greenhouse gas emissions associated with the energy required in the manufacturing, construction, installation and on-going maintenance stages of the wind turbines have been estimated by multiplying the embodied energy values by a single greenhouse emissions rate of 60 kg/GJ [22]. This figure includes the emissions associated with the primary energy used in the production of "bought" energy.

4. Results and discussion

This section describes the results of the evaluation of the effect of wind turbine size on their potential energy yield. The embodied energy values, annual energy output, life cycle energy and greenhouse emissions analysis findings of the two wind turbines, as well as their anticipated energy yield are presented.

4.1. Embodied energy

The embodied energy of the two wind turbines, calculated using the I–O-based hybrid analysis method is shown in Table 5. The embodied energy represented by I–O data is shown to account for at least 74% of the total for both wind turbines. This represents the gap, or incompleteness associated with a traditional process analysis, on which many previous studies are based.

These embodied energy figures are at least six times more than the figures presented in the past, for equivalent sized turbines [8]. Previous studies have indicated that the embodied energy of a wind turbine may equate to less than 5% of the energy generated during their service life. This study shows that whilst the embodied energy figures have increased significantly over those presented in the past, this is still the case, with the embodied energy representing less than 5% of the total generated energy for both turbines, assuming a minimum 20-year service life.

Fig. 2 shows a component level breakdown of the embodied energy of the 850 kW turbine. The 'other items' represents a number of the inputs that are typically excluded in process-based studies, in this case representing over half of the total embodied energy. These items would include energy required to supply such things as financial and insurance services, telecommunication services and capital equipment required to manufacture turbine components. The tower makes up the next largest proportion of the embodied energy of this turbine (25%).

Table 5
Embodied energy of wind turbines (GJ).

	Wind turbine 1 (850 kW)	Wind turbine 2 (3.0 MW)
Initial embodied energy	27,158	84,237
Recurring embodied energy	2,230	7,939
Embodied energy/MW rated output	34,574	30,725

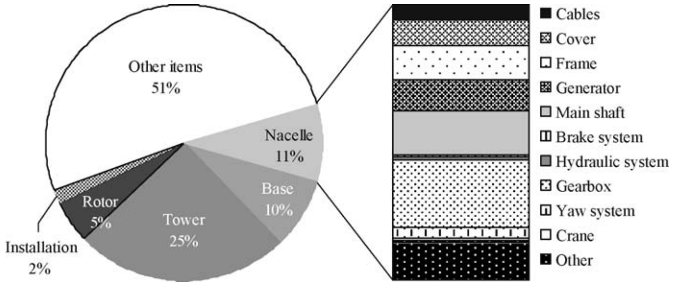

Fig. 2. Embodied energy of 850 kW wind turbine, by component.

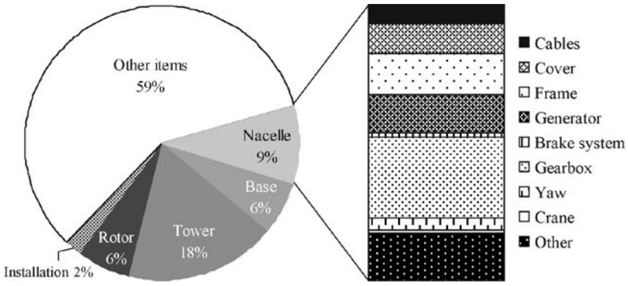

Fig. 3. Embodied energy of 3.0 MW wind turbine, by component.

The breakdown of the embodied energy of the 3.0 MW turbine (Fig. 3) shows that the 'other items' represent a slightly larger proportion of the total embodied energy (59%). As for the smaller turbine, the tower makes up the second largest proportion of the embodied energy of this turbine, at 18%. Installation represents only 2%, whilst the gearbox represents almost one third of the embodied energy associated with the nacelle.

4.2. Annual energy output

The annual gross energy output of the two wind turbines was calculated, based on the characteristic power curve and hourly wind data for the chosen location. The net energy output was determined by subtracting the energy required for internal controls and day-to-day maintenance from the gross output. The annual gross and net energy output, in primary energy terms, of each wind turbine are shown in Table 6.

4.3. Life cycle energy analysis and energy yield ratio

Considering a total service life of 20 years for the two systems studied, the total net life cycle energy produced (net life cycle output minus the embodied energy and energy required for maintenance and operation) and the energy yield, were determined. The net life cycle energy produced over a 20-year period was 588 TJ and 2049 TJ for the 850 kW and 3.0 MW wind turbines, respectively.

Table 6
Annual energy output of wind turbines, in primary energy terms.

	Wind turbine 1 (850 kW)	Wind turbine 2 (3.0 MW)
Gross annual output (MWh)	9486	32,915
Net annual output (MWh)	8571	29,743
Specific yield (kWh/m^2)	4036	4,675

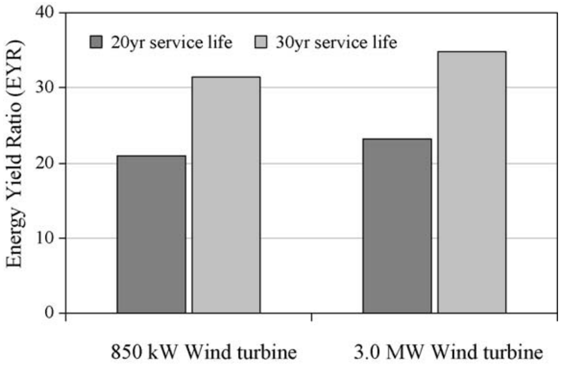

Fig. 4. Energy yield ratio of 850 kW and 3.0 MW wind turbines.

The EYR ranges from 21 for the 850 kW turbine to 23 for the 3.0 MW turbine (Fig. 4). This shows that both turbines produce a significantly larger amount of energy than is required for their manufacture, operation and maintenance during their effective life. These EYRs are expected to increase to 32 and 35 for a service life of 30 years, as seen in Fig. 4, demonstrating the potential benefits of maximising wind turbine service life.

Whilst the larger 3.0 MW system has been shown to provide a higher EYR, the 11% increase is not considered to be significant. The size of a wind turbine therefore may have little influence on its potential energy yield.

The energy yield of these turbines may vary with the recovery of energy from the reuse or recycling of components and materials. However, it is not considered that this would significantly influence the energy yield, considering the small proportion of the life cycle energy that the embodied energy represents.

As stated previously, wind turbines have been shown to payback the energy invested in them in a number of months (for example, Schleisner [5] states a figure of 3 months and Martinez et al. [23] state a figure of just under 5 months). This study has shown that the time required for the embodied energy to be paid back by the energy generated by the turbines is closer to 12 months – still considered a reasonable period of time.

This study highlights, despite significant improvements in the method of embodied energy assessment used for this study over those in previous methods, the relative insignificance of the embodied energy of wind turbines over their service life. Further energy savings are possible if the life of the system is prolonged beyond the 20 years assumed in this study.

4.4. Life cycle greenhouse emissions

Table 7 shows the initial and recurring embodied greenhouse emissions associated with the two wind turbines, based on an emissions coefficient of 60 kg CO_2-e/GJ of embodied energy.

The total net (avoided) greenhouse emissions of the wind turbines are calculated by subtracting the initial and recurring embodied emissions from the net emissions that would have been released from traditional fossil-fuel-based energy production for the equivalent quantity of energy produced by the wind turbines. These emissions have also been calculated based on the above

Table 7
Embodied greenhouse emissions of wind turbines (t CO_2-e).

	Wind turbine 1 (850 kW)	Wind turbine 2 (3.0 MW)
Initial embodied emissions	1629	5054
Recurring embodied emissions	134	476
Embodied emissions/MW rated output	2074	1844

Table 8
Net avoided greenhouse gas emissions of wind turbines (t CO_2-e).

	Wind turbine 1 (850 kW)	Wind turbine 2 (3.0 MW)
Total life cycle embodied emissions^a	1,763	5,530
Gross avoided emissions from energy output^b	37,028	128,491
Net avoided emissions (after 20 years)$^{(b-a)}$	35,265	122,961

emissions coefficient rate for average energy generation in Victoria, Australia. The net avoided emissions of each wind turbine over their 20-year life are shown in Table 8.

The total net avoided greenhouse gas emissions equate to 35,265 t and 122,961 t of greenhouse gases for the 850 kW and 3.0 MW turbines over a 20-year service life, respectively. The net annual avoided emissions associated with the 850 kW turbine, of 1763 t CO_2-e, are equivalent to the annual emissions from 147 typical Victorian households. The net annual avoided emissions associated with the 3 MW turbine, of 6148 t CO_2-e, are equivalent to the annual emissions from 512 typical Victorian households.

Whilst energy and greenhouse emissions are a useful indicator of the environmental impacts of wind turbines, other factors should also be considered. These are typically the focus of a much broader life cycle assessment study.

5. Conclusions

The aim of this study was to assess the life cycle energy and greenhouse gas emissions of two wind turbines and determine the impact of wind turbine size on energy yield. It was thought that the increase in embodied energy for larger scale turbines may have adversely affected their potential energy yield, despite increased energy output. This study has shown, by analysing the energy requirements and production of two varying sized wind turbines, that there is no significant difference in the energy yield between small and large scale turbines, particularly considering the errors associated with this type of assessment. However, other benefits exist for the use of larger scale wind turbines, such as the ability to reduce the required footprint area per unit of rated output.

The use of a systemically complete hybrid embodied energy analysis method has shown that previous embodied energy assessments of wind turbines may be up to 78% incomplete. Despite these significant improvements in embodied energy assessment, the relative insignificance of the embodied energy component of wind turbines over their service life has been highlighted.

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