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Life Cycle Assessment of a Wind based Electric Power Generation System: An Indian Perspective

N. Leela Prasad
Associate Professor
Department of Mechanical Engineering
Vignan Institute of Technology and Science
Deshmukhi (T.S.) [INDIA]
Email: nlp123@rediffmail.com

P. Usha Sri
Professor & H.O.D
Department of Mechanical Engineering
University College of Engineering (A),
Osmania University
Hyderabad (T.S.) [INDIA]
Email:emailushasri@yahoo.com

K. Vizayakumar
Academic Advisor
Bapatla Engineering College
Guntur (A.P.) [INDIA]
Email: vizaya@gmail.com

ABSTRACT

To make electricity price affordable in developing countries like India, some alternative power generation options were identified for exploitation. These are mainly recommended due to fast depletion of fossil fuels and scarcity of hydrocarbon & uranium resources. The development and promotion of cleaner & renewable sources of energy is a high priority for security and diversification of energy supply to meet the ever-growing demand for electric power and also the environmental protection demands of Paris Climate agreement. One such option appears to be Wind even though it is site specific in nature. Many Life Cycle Assessment (LCA) studies have been carried out worldwide on energy & environmental performance of Wind based electric power generation systems, but this study emphasizes on one such Wind Energy Conversion System (WECS) of 3MW capacity located in India with various post-life disposal scenarios added to it. In the present study, the system is modelled and run on SimaPro 8.3.0.0 LCA software with ECOINVENT 3 as database. The investigation results are expressed in the form of pre-defined metrics such as Energy Return on Investment (EROI), Energy Pay Back Time (EPBT) in years and Global Warming Potential (GWP) in g CO_2-equivalent per kWh produced, to indicate the energy and environmental burdens associated with the system. These *investigations help policy makers and energy planners to compare various power generating options to justify the investments in power sector.*

Keywords:—*Life Cycle Assessment; Wind Energy Conversion System; Energy Return on Investment; Energy Pay Back Time and Global Warming Potential.*

I. INTRODUCTION

The exploitation of wind energy for electricity generation has several advantages like low gestation period, no fuel cost, non-polluting and renewable in nature. World Wind Energy Association (WWEA) predicts and sees a global capacity of 1,900 GW as possible by the year 2020 (World Wind Energy Association report, 2009). The IPCC even estimates that wind energy could potentially provide over 20% of the global electricity demand by 2050 (IPCC 2011), while other more moderate estimations foresee a smaller contribution [1]. This makes wind energy an important renewable energy option for the future. The development in this sector in India is controlled by Minis try of New and Renewable Energy (MNRE), Govt. of India., which offers policy and financial incentive schemes to projects in the country. The wind-power potential in India is 48.5 GW for grid interaction. The p resent installed capacity is 26.87 GW as on March, 2016. Wind electric generators of unit sizes between 225 kW and 2.1 MW have been deployed across the country. India now ranks 4th in the world after China, USA and Germany in grid connected wind power installations. Southern and western states have maximum wind capacity installed due to highest wind density and velocity. Tamil Nadu is leading state in terms of wind installations with 33% share in overall wind capacity installed in the country. Energy systems based on wind, as well as other renewable energy sources, are often automatically assumed to be sustainable and environmental-friendly sources of energy in much of the mainstream debate. However, all systems for converting energy into us able forms have various environmental impacts, not to mention a requirement of natural resources. It is essential to have cons is tent evaluation methods for analyzing all aspects of a given energy source. Without such methods, it is difficult to compare them and make the right decisions when planning and investing in energy systems for the future. A popular way of measuring the environmental impact and energy performance of wind energy is life cycle assessment (LCA).

II. LITERATURE REVIEW

A study [2] carried out on comparative Life Cycle Assessment for a high power wind turbine (4.5 MW), which is part of a wind farm, and a s mall one (250 W), which is integrated in a building or to be used on an isolated site, tevaluate their environmental impacts. Results are expressed in terms of PEPBT (primary energy payback time) and CO_2 emissions for a functional unit for comparison. As this study is focused on France, French mix electricity production based on nuclear and hydroelectricity is utilized here. The SimaPro software is used herein to perform the life cycle analysis of the two turbines. It is also suggested that recycling during decommissioning is an important step, not to be underestimated, to get good environmental impact figures.

The real impact of wind energy technology is analyzed in [3] by s electing current wind turbines with high rated power. The LCA model seeks to identify the main types of impact on the environment throughout the life cycle of a wind turbine with doubly fed inductor generator (DFIG). The study has specifically focused on the Gamesaonshore wind turbine model G8X with 2MW rated power installed in the Munilla wind farm in

Spain. Where ever the data is not available or reliable, the study used quasi-process information from commercial SimaPro software. The LCA model developed includes both the turbine and the foundations which support it, leaving aside the system for connection to the grid (medium voltage lines and transformer substation). The calculations of this study show that, during its lifetime, the wind turbine allows us to recover nearly 31 times the environmental contamination caused by its manufacture, start-up, operation and decommissioning.

The work presented in [4] examines the life cycle environmental impacts of two 2.0 MW wind turbines of different make/design. Manufacturing, transport, installation, maintenance, end of life have been considered for both models and are compared using the ReCiPe 2008 impact assessment method. In addition, energy payback analysis was conducted based on the cumulative energy demand and the energy produced by the wind turbines over 20 years. Life cycle assessment revealed that environmental impacts are concentrated in the manufacturing stage, which accounts for 78% of impacts. The energy payback period for the two turbine models are found to be 5.2 and 6.4 months, respectively. The study was facilitated using a commercially available software tool, SimaPro 7.3. The tower is the key contributor to the environmental impact, followed by the rotor, nacelle, and foundation respectively.

All four LCA reports by leading wind turbine manufacturers, 3rd by Vestas and 1st by Gamesa for different rating models, pointed out the same fact that this technology is superior in energy and environmental performance to the conventional sources of energy. These studies are carried out internally or by a client, basically for product promotion in mind. From the above literature survey, it is also identified that only few review papers are available on LCA of renewable sources of energy with Indian context [5]. Apart from those works, there are no Indian specific LCA studies on wind energy in the literature probably due to non-availability of LCI data (as suppliers are mostly foreign based).

III. Wind Energy Conversion Systems (WECS)

It is an apparatus for converting the kinetic energy available in the wind to mechanical energy which in turn can be used to power the machinery (grain mills, water pumps, *etc*.) and/or to operate an electrical generator.

3.1. Main Components of WECS

The main components of the system are: Tower, Nacelle, Rotor with Three blades, Gearbox, Generator, Braking System, Yaw System, Controllers and Sensors. The tower of the wind turbine shown in Figure 1, carries the nacelle and the rotor. The towers for large wind turbines may be either tubular steel towers, lattice towers, or concrete towers. The higher the wind tower, the better the wind. Winds closer to the ground are not only slower, they are also more turbulent. Higher winds are not corrupted by obstructions on the ground and they are also steadier.

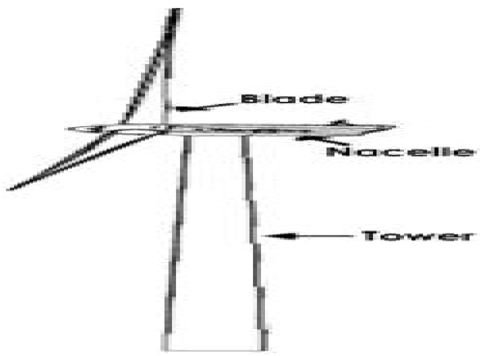

Figure 1: Wind Energy Conversion System (WECS)

3.2. WECS: Supplier Rating, Installation and Operation

An industrial wind turbine is constructed to supply power to the nearby electric grid. These systems typically feature three-bladed glass fiber rotors mounted on steel tube or concrete tower bolted into a platform, transmitting power via gearbox to an induction generator, which again is attached to the standard utility grid lines via an electronic control box. Rotor gearbox and induction generator together are called Nacelle and it is located at the top of the tower. The power is generated from the energy in the wind, so a turbine's power is determined by its ability to capture that energy and convert it to rotational torque that can turn the generator and push electrons into the grid.

Vestas, a Danish supplier of wind turbines makes a widely used V90-3.0 MW model. If the wind is in the ideal range, i.e., between 15 and 25 m/s, this 3 MW wind turbine will produce power at the rate of 3 MW, which is it s rated, or maximum capacity. Production of power at the rate of 3 MW for 1 hour equals 3 MWh of energy. But at s lower wind speeds, however, the production falls off dramatically. If the wind speed decreases by half, power production decreases by a factor of eight. On average, therefore, wind turbines do not generate near their capacity. Indus try estimates project an annual output of 30-40%, but real-world experience shows that annual outputs of 15-30% of capacity are more practical. With a 25% capacity factor, a 3.0-MW turbine would produce 3.0 MW × 365 days × 24 hours × 25% = 6,570 MWh in a year.

IV. LIFE CYCLE ASSESSMENT: A RESEARCH METHODOLOGY

It is crucial that policy makers are provided with accurate information describing the quality and quantity of benefits that are offered by the diversity of energy alternatives. In order to do so, many of the research groups involved in such practices are turning to the life-cycle assessment (LCA) methodologies. The Life-Cycle Analysis has now become a vital sustain able development tool. LCA is a practical approach for evaluating the environmental impacts of any product or service as it combines the systematic rigors of science with a holistic perspective on the contributing factors. LCA has many similarities to energy analysis, but is not restricted to just energy. An LCA can be defined as “the compilation and evaluation of the inputs, outputs and potential environmental impact of a product system throughout the life cycle” [6].

The LCA methodology considers all aspects of a product or service over its entire lifetime: from the acquisition of materials to produce it, to its final disposal or recycling. Furthermore, the information provided by an LCA is of high value and reliability because LCA methodology is strictly guided by international standards such as ISO 14040:2006 and ISO 14044:2006. While the LCA approach does have limitations in terms the accuracy of assumptions and upstream considerations, but having a standardized method ensures that all studies are at least conducted in the same manner and by using similar criteria.

4.1 Goal and Scope

The goal and scope phase determines the method, the functional unit, and system boundaries as well as studied environmental impacts and level of detail. Choices made here about methodology, system boundaries, cutoff limits, or functional units can have large impact on the final results [7]. The goal of this study seeks to identify the impact on the environment due to emission of greenhouse gases (GHG) including CO_2, CH_4 and N_2O throughout the life cycle and energy performance in terms of EROI and EPBT of a 3.0 MW onshore wind turbine. The scope of the study encompasses all the stages that include the manufacture of components, transportation of components to the construction site, the construction of the facility itself, operation and maintenance over the lifetime of the facility, overhead, possible grid connection costs, decommissioning, and recycling of component materials. As the functional unit for this system, we have selected the kWh produced by the wind turbine in such a way that it has been possible to obtain a relations hip between the environmental impact of the turbine and the electricity generated. In this way it is also possible to make a comparative study with regard to other kinds of energy producing systems.

4.2 Life Cycle Stages and Related Inventory

In the life cycle inventory (LCI), inputs and outputs throughout the entire life cycle are estimated, according to the chosen system boundaries and methods. There are two main approaches that can be used for the LCI: process chain analysis (PCA) and input –output (I/O) analysis. I/O analysis uses economic data to estimate the resource use in different parts of the economy, while PCA estimates the actual physical flows of mass and energy. In I/O-based LCA, inter-industrial relations hips are quantified in an I/O matrix, representing interactions between different sectors of the economy. But, it appears to be very common to us e PCA. The tendency to primarily rely on PCA might very well lead to underestimated figures for energy use, but it is also possible that I/O analysis exaggerates energy use. Further studies on this issue are required and should be encouraged.

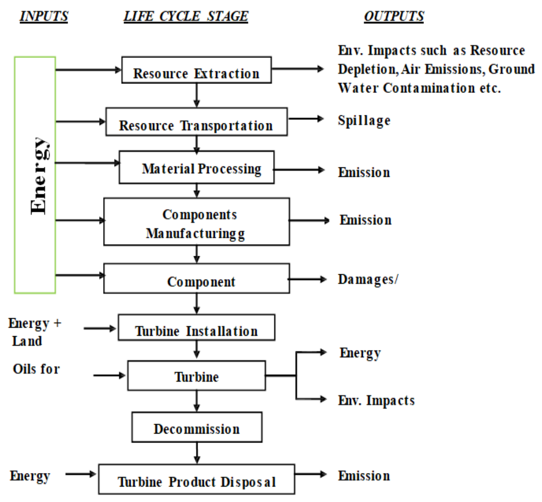

Figure 2: Life Cycle of a Wind Energy Conversion System

The prominent stages in the life cycle of a WECS as given in figure 2 include manufacturing, operation, maintenance, trans port, dismantling and disposal.

- Manufacturing comprises the raw material production (concrete, aluminum, steel, glass fiber and soon) needed to manufacture the tower, nacelle, hub, blades, foundations and grid connection cables.
- On-site erection and assembling includes the work of erecting the wind turbine. This stage used to be included in the construction or trans port phases.
- Trans port takes into account the transportation systems needed to provide the raw materials to produce the different components of the wind turbine, the trans port of turbine components to the wind farm site and trans port during operation.
- Operation and Maintenance is related to the maintenance of the turbines, including oil changes, lubrication and transport for maintenance, usually by truck in an onshore scheme.

- Dismantling and Disposal: once the wind turbine is out of service, the works of dismantling the turbines and the transportation (by truck) from the erection area to the final disposal site; the current scenario includes recycling some components, depositing inert components in landfills and recovering other material such as lubricant oil.

4.3 Environmental Impact Assessment

The next step is the life cycle impact assessment (LCIA), where results from the inventory are converted into environmentally relevant information [6]. Sometimes an attempt is made to express the impact on a common scale through weighting. The potential environmental impacts include Global Warming Potential (GWP) is the atmosphere's ability to reflect a part of the heat radiation to the earth. Global warming is increased by the atmosphere's content of carbon dioxide, CFC, laughing gas and methane, among others. Increased emission of these substances might impact the heat balance of the earth and over the next decades this may result in a warmer climate.

V. Case Study

The data from a supplier manual by Vestas for 3.0 MW V90 [8] onshore sited wind turbine is utilized for carrying out this LCA study.

Indirect Life-Cycle Energy Input is 4,304.221 MWh / Turbine (that includes Manufacturing, Foundation & Erection, Grid Connection for Transmission, O & M, Transport and dismantling/Disposal.)

With 30% capacity factor on an average over a 20 years lifetime, a 3.0-MW turbine would produce a *Lifetime Electric Output is 20×3×365×24×0.30 equal to 1, 57,800 MWh.*

Energy *Performance and Primary Energy: t*he energy performance is usually expressed as EROI, defined as cumulative electricity generated divided by cumulative primary energy required, or EPBT, defined as the amount of time it takes to "pay back" the energy used over the life cycle. EROI and EPBT can be good indicators on whether a wind turbine actually produces more energy than is consumed during its life cycle. However, some studies also include a conversion of the produced electrical energy to primary energy. Larger turbines require greater initial energy investments in materials, the increase in power output due to improvements more than compensates for this over the lifetime of the turbine.

EPBT [8] = Indirect Life-Cycle Energy Input / AEO (1)

= 4,304.221 × 20 / 1,57,800 = 0.55 Years (AEO = Average Annual AC Output)

*EROI [9] = Lifetime Electric Output / Indirect Life-*Cycle Energy *Input* (2)

= 36.66

Table 1: Emissions to Air per kWh Produced [8]

S. No	Emissions	Quantity in g/ kWh	g - CO_2 Equivalent / kWh
1. 2. 3. 4.	Carbon Dioxide (CO_2) Nitrous Oxide (N_2O) Methane (CH_4) SOx	4.640 0.0177 -- 0.0218	4.64 5.487 -- --

NOTE: *NO_X has 310 times more Global Warming Potential than CO_2, CH_4 has 25 times more Global Warming Potential than CO_2 [10]*

GWP (Global Warming Potential) is 10.127 g - CO_2 Equivalent/kWh from Table 1.

If coal is the source of energy input to WECS then, it has huge implications for carbon dioxide emissions, and in any scenario wind power has negligible emissions.

Gross CO_2 Emissions if LEO (in kWh) of this system is produced by current Danish Electricity Mix

= LEO (in kWh) × CO_2 Emission Factor [13]

= 157800000 × 0.511 / 1000 = 80, 635.8 Tons of CO_2e

TLE is the Total Lifetime Emissions in Tons of CO_2e.

Net CO_2 Mitigations

= Gross CO_2 Emissions if LEO (in kWh) of this system is produced by Danish Electricity Mix – TLE

= 80, 635.8 – 157800000×10.127 / 1000 × 1000 = 79,037.76 Tons of CO_2e

Net CO_2 Mitigations per annum = 79,037.76 / 20 = 3952 Tons of CO_2e

VI. Modeling and Simulation

Life Cycle Assessment of 3.0 MW onshore wind turbine is modelled & run on SimaPro 8.3.0.0 LCA software [11]with ECOINVENT 3 as database [13].

6.1 Geographical Boundaries

India is the geographical limit in this LCA. A location suitable for wind farm, which means relatively with high wind speed, is chosen. It is also assumed that all the manufacturing operations are carried out within the chosen geographical boundaries by using Indian electricity mix.

6.2 Time Horizon

The time horizon considered in this study is the life time of the wind turbine which is 20 years.

6.3 Cut-Off Criteria

One of the cut-offs performed in the study is the omission of the "transmission" stage of the energy produced by the wind turbine, since it is considered that the transmission of electricity from any energy source would be the same.

6.4 Allocation Procedure

Allocation is necessary when a process yields more than one product, i.e. a multifunctional process. There is no allocation problem in the manufacture and operation of the wind turbine because only one product is produced.

6.5 Assumptions and Limitations

Capacity factor, which is the ratio between the actual energy produced and the possible energy to be produced if running at rated power all the time is assumed as 30% in this study as it is typically lies between 0.20 and 0.35. Due to the limitation of data availability specific to India, Global/ ROW/ CH specific data is utilized in this study from ECOINVENT 3 database, with an exception for Electricity consumption.

6.6 Impact Categories and Impact Assessment Methods Covered

The developed nations that signed Kyoto Protocol, 1997 has to progressively reduce carbon emissions, meaning CO_2. At the national level the focus is more on reducing energy consumption, but since this and CO_2 production are closely related and are nearly equivalent, two single issue methods are considered in this study. One is Cumulative Energy Demand (CED), based on the method published by Ecoinvent version 2.0 and another one is IPCC 20 13 GWP (100a) method in SimaPro.

6.7 Disposal Scenario

The below mentioned scenarios in Table 2 are derived from secondary data available in the literature.

Table 2: Material wise Disposal Scenarios

Material	Scenario
Steel & Iron	90% Recycling
Aluminum	90% Recycling
Concrete	100% Land Fill at Foundation Site
Copper	95% Recycling
Plastics	100% Incineration

6.8 Results

First model is based on IPCC 2013, which is an update of the method IPCC 2001 developed by the International Panel on Climate Change. This method lists the climate change factors of IPCC with a timeframe of 20, 100 and 500 years [12]. Figure 3 is a network representation of 3 MW; On -Shore wind turbine based electric power generation system with disposal scenario, generated after simulating the model by using IPCC 2013 GWP (100a) method.

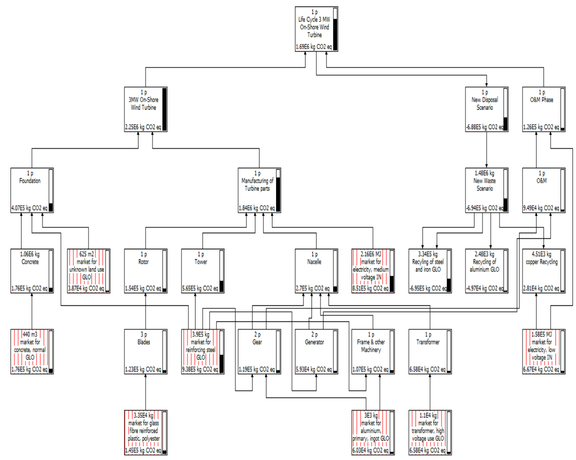

Figure 3: Model flow chart for 3.0 MW wind turbine in SimaPro with cut-off value of 1% / IPCC 2013 Method

Lifetime Electric Output (LEO) = 20×3×365×24×0.30 = 1,57,680 MWh

GWP (Global *Warming Potential) = TLE / AC output in kWh* (3)

= 1.69× 10^9 */ 157680×1000 = 10.718 g of* CO_2e */ kWh*

Gross *CO_2 Emissions if LEO (in kWh) of this system is produced by current Indian Electricity Mix*

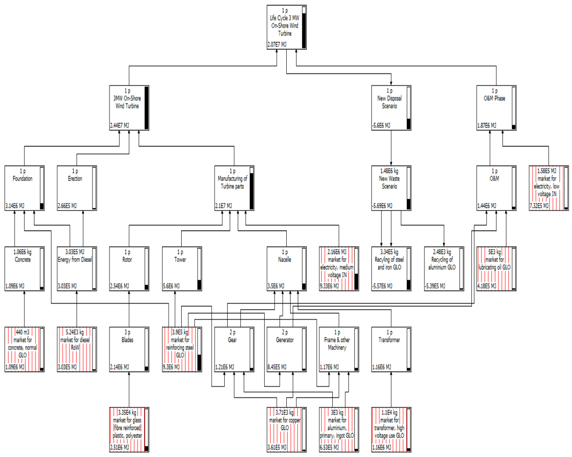

Figure 4: Model flow chart for 3.0 MW wind turbine in SimaPro with cut-off value of 1% / CED Method

= LEO (in kWh) × CO_2 Emission Factor [13] = 157680000 × 1.42/1000 = 2,23,905.6 Tons of CO_2e

Net CO_2 Mitigations = Gross CO_2 Emissions if LEO (in kWh) of this system is produced by current Indian Electricity Mix – TLE

= 2,23,905.6 – 10.718 × 1,57,680 × 1000 / 1000 × 1000 = 2,22,215.6 Tons of CO_2e

Second model is based on a method called Cumulative Energy Demand (CED), which is published by Ecoinvent version 1.01 and expanded by PRé for energy resources available in the SimaPro database manual [12]. Extra substances, according to the Ecoinvent database version 2.0, are implemented. Characterization factors are given for the energy resources divided in 5 impact categories :

- Non renewable, fossil
- Non renewable, nuclear
- Renewable, biomass
- Renewable, wind, solar, geothermal
- Renewable, water. Normalization is not a part of this method.

In order to get a total ("cumulative") energy demand, each impact category is given the weighting factor 1. Figure 4 is a network representation of 3 MW, On-Shore wind turbine based electric power generation system, generated after simulating the model by using Cumulative Energy Demand (CED) method.

EPBT = ILEI or CED / AEO = 5,750 / 7,884 = 0.73 Years (8.76 months)

EROI = Lifetime Electric Output / Indirect Life-Cycle Energy Input = 1,57,680 / 5,750 = 27.4

6.9 Comparative Results

Before comparing the results, let us calculate the energy & environmental performance of 3 MW, On-Shore wind turbine based electric power generation system, modelled and run without disposal scenario.

Lifetime Electric Output $= 20 \times 3 \times 365 \times 24 \times 0.30 \times 1000 = 1{,}57{,}680$ *MWh*

GWP (Global Warming Potential) = TLE / AC output in MWh $= 2.38 \times 10^9 / 157680000 = 15.1$ *g of* CO_2e */kWh*

Gross CO_2 *Emissions if LEO (in kWh) of this system is produced by current Indian Electricity Mix = LEO (in kWh)* $\times$ CO_2 *Emission Factor [13]* $= 157680000 \times 1.42/1000 = 2{,}23{,}905.6$ *Tons of* CO_2e

Net CO_2 *Mitigations = Gross* CO_2 *Emissions if LEO (in kWh) of this system is produced by current Indian Electricity Mix – TLE*

$= 2{,}23{,}905.6 - 15.1 \times 157680 \times 1000 / 1000 \times 1000 = 2{,}21{,}524.6$ *Tons of* CO_2e

Energy Payback Time = ILEI or CED / AEO = 7305.5 / 7884 = 0.926 Years (11.12 months)

EROI = 157680 / 7305.5 = 21.6

VII. Improvement Analysis Based on Results

The dominant phase that is consuming more energy and producing more CO_2 emissions is the material phase. More energy is consumed and high amount of CO_2 is released into the atmosphere during the raw material production of the wind turbine parts. The second dominant phase is the manufacturing process. This is particularly due to the type of electricity used. The more "green" the source of electricity used in the manufacturing phase of the wind turbine; the less the environmental impacts of the wind turbine. On analyzing the contribution of each raw material in the wind

Table 3: Comparative Results on Energy and Environmental Performance

Model	Capacity Factor	EROI	EPBT in Years	GWP in g CO_2e	Net CO_2 Mitigations in Ton CO_2e
Vestas V90-3.0 MW Turbine	0.30	36.6	0.546	10.127	79,037.76
3.0 MW WECS with DS	0.30	27.4	0.73	10.718	2,22,215.6
3.0MW WECS without DS	0.30	21.6	0.926	15.1	2, 21,524.6

turbine manufacturing processes as a whole, prepreg (the blade material) is the element which has the greatest impact in the GWP category, while steel and copper are those which most affect the reduction in mineral resources. Prepreg is also the main culprit in the consumption of fossil fuels. Transport distances are not considered much in this study except for O&M phase and in disposal scenario which have the potential to affect the energy and environmental performance of the system.

VIII. CONCLUSIONS

The comparative results clearly show that CO_2 mitigation potential is high for wind energy in India than in Denmark because our energy mix is more of coal base. Comparative results in table 3 confirm the fact that disposal scenario is a very important phase of the life cycle of the wind turbine. With recycling of the materials, we are able to reduce the negative environmental impacts greatly. In other words, without recycling wind turbines have greater negative environmental impacts. Most of the environmental impact caused by the foundation is centered on the IR category. This is basically due to the environmental impact of the processes involved in making cement. During this process the emission of particulate matter into the atmosphere is considerable. The location of WECS, its capacity & manufacturer, source of energy inputs may affect the results of Life Cycle Assessment. In spite of this, Wind power has huge advantage over conventional and renewable energy sources in terms of Energy Payback Ratio and GWP. Presently, wind energy, together with biomass, is one of the most promising renewable energy sources and for sure it is the first one, after hydroelectricity, for green electricity. There is also some concerns about the impacts of wind energy on birds and bats which requires to be probed a bit further.

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