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RESEARCH ARTICLE

LIFE CYCLE IMPACT ASSESSMENT OF RENEWABLE ENERGY SYSTEMS: WIND VS. PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Life Cycle Assessment (LCA) is a well-structured method usedto estimate the environmental impacts associated with the full life cycle of product, service, or system. To effectively analyze products, a cradle-to-grave approach is used, from the acquisition of the raw materials to final disposal. LCA studies offer an overview of the associated environmental impacts, which can be used for sustainable improvements, policy making and marketing purposes.This LCA study compares two renewable energy technologies, a 2.0-MWwind turbine and a 570 kWp photovoltaic system. For comparative purposes, the systems were analyzed based on an annual electricity consumption of 47,410 MWh for a periodof 60 years. The two systems were modeled in the LCA software, SimaPro 8.0.4.26, using the European impact assessment ReCiPe. The results are presented based on characterization, damage assessment, normalization, weighting and single score elements. The assessment resulted indemonstrable environmental impacts associated with the implementation of wind turbines compared tophotovoltaic plants. Wind turbine contributed to greater impact in 12 out of the 17 midpoint impact categories. The single score of total environmental damage were found to be 35.9 MPt for wind turbines and 23.8 MPt for photovoltaic systems.

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INTRODUCTION

The increase in energy demand has led to the evolution of renewable energy technologies such as wind power and solar energy. Although both technologies generate clean energy in comparison to fossil fuels, the full environmental impact from raw material extraction to final disposal is rarely taken into consideration. Photovoltaic (PV) solar systems and wind turbines do not produce direct pollution to the atmosphere during operation, however pollutants are released into the surrounding environment through manufacturing, installation and decommissioning. As climate change awareness increases, renewable energies are becoming increasingly competitive. Wind and PV technologies have the highest technical potential to produce the electricity required, but the electricity generation varies as these technologies are weather and climate dependant. Through wind power, Canada currently has the capacity to supply 6% of its total energy demand; this provides enough clean energy for 3 million homes (Canadian Wind Energy Association, 2017). In terms of cumulative wind power capacity, Canada was ranked eighth place internationally in 2016 (Global Wind Enery Council, 2017). In addition, Canada has experienced an increase in residential solar energy application due to the decrease in capital cost. Homeowners across Canada are installing solar panels, resulting in annual electricity savings of 20-50% and thus a reduction in their hydro bills (HES, 2017). Multiple case studies have agreed the two largest environmental contributions associated with wind turbines is the manufacturing stage, specifically the manufacturing of the steel tower and the transportation. Guezuraga *et al* (2011), conducted an LCA of two different wind turbines and their carbon dioxide (CO_2) emissions, and found the main impacts originated from the manufacturing (84%) and the transportation (7%) of the turbines. The steel tower accounted for 55% of the energy requirement of the total production. Oebels &Pacca (Oebels, 2012), conducted an LCA based on CO_2 emissions, where over 90% of the emissions were from the manufacturing stage and another 6% from transportation. The manufacturing of the steel tower was responsible for more than half of the emissions. The study was compared to three previous LCA reports carried out for Vestas wind turbine and found similar results, with the largest discrepancies in results was identified in the operation and transportation stages. The Vestas reports only assumed a small distance of 700 km covered by trucks and trains, whereas, Oebels & Pacca estimated a total travel distance of 125,000 km (Oebels, 2012). Vestas has conducted multiple LCAs for their different wind turbines that they manufacture. A study conducted on the Vesta V112 turbine wind plant in 2012

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demonstrated the manufacturing of the wind turbine accounted for 81% of the GWP with CO_2 being the main emitted pollutant (Razdan, 2015). Tremeacc & Meunier (Tremeac, 2009) found the manufacturing of a 4.5 MW wind turbine accounted for 75% of the life cycle energy consumption and that the type of transportation and distance were important factors for human health, resources and climate change. It was also found that transportation by train instead of transport truck could reduce up to 20% impact on ecosystems, 30% on resource depletion, 40% on climate change and 55% on human health. Similarly, Jungbluth *et al*. (Jungbluth, 2005), found that air emissions from the production of the different types of steel for the tower and the nacelle, concrete for the foundation and the glass fiber-reinforced plastics for the rotor blades were dominant in the cumulative results. Carbon dioxide contributed to more than 90% of the emitted greenhouse gases. Similar to wind turbines, the manufacturing of PV modules has considerable environmental impact. An LCA study conducted by Stoppato (Stoppato, 2008), accessed polycrystalline silicon PV panels and found that the most energy intensive processes were the transformation of metallic into solar silicon (1190.1 MJ/panel) and the panel assembling (272.7 MJ/panel). Pacca *et al*. (Pacca, 2007), performed an LCA on two state-of-the-art PV technologies and found the most effective method to improve the module's environmental performance is to reduce the energy input in the manufacturing phase. It was also found the net energy ratio (NER) from PV systems was 3.7 times greater than the NER from electricity supplied by the traditional grid mix in Michigan. Multiple PV LCAs focus on the GHG and CO_2 emissions generated and the associated payback period. Sherwani *et al*. (Sherwani, 2010), were reported that the energy payback time (EPBT) for photovoltaics (amorphous, monocrystalline and polycrystalline) can range from 1.7 years to 15.5, with an average of 2.65 years. The higher payback periods for the polycrystalline were typically associated with smaller power ratings. Overall, studies have shown both wind turbines and PV systems are more environmentally friendly than traditional fossil fuel electricity generating technologies (Guezuraga, 2011). Thislife cycle assessment (LCA) compares the potential environmental impactsof a2.0MW (megawatt) wind turbine and a 570 kWp(kilowatt peak) photovoltaic system. LCA is a broadcradle-to-grave approach that allows for a detailed study of the environmentalimplications of one or more products, services or systems (United States Environemental Protection Agency, 2017). For large, complicated systems such as wind turbines and photovoltaic modules, the required life cycle inventory (LCI) (i.e., the inputs and outputs) can be difficult to acquire, and calculating the environmental impacts, through an impact assessment, has proven to be challenging. Therefore, comprehensive LCA software, such as SimaPro provides an easier and more detailed approach to LCA. In this work, SimaPro was utilized to model the two renewable energies employing two built-in datasets.

MATERIALS AND METHODS

System Boundaries

This is a cradle-to-grave analysis includes the materials, processing and assembly, operation, maintenance and disposal. The system boundary only includes the disposal of the products under study, excluding the disposal of capital equipment involved in the manufacturing process. The manufacturing, connection to grid, transportation to construction site from manufacturing and the transport of personnel for maintenance over the lifetime of the turbines have been taken into consideration. The solar system analysis is based on the already existing photovoltaic plant on open ground. Additional transportation for maintenance has been included in this system without additional considerations for their use. This system is based on the pre-existing databases and therefore is limited to the compilation of additional data to attempt full life cycle. The underlying databases include end of life treatment for the most important materials for each system production.The lifespan of an onshore wind turbine has been defined as 20 years and the lifespan of a solar photovoltaic module is estimated to be 30 years according to the already existing models in SimaPro.

Functional unit

Comparative LCA studies require a functional unit, to which the inputs and outputs of the systems, products or services can be related. Since one wind turbine and one PV plant produce different rates of electricity, the functional unit of the study was based on the amount electricity needed for 10,000 residents in Toronto, Ontario. Canada has one of the highest residential electricity consumption per capita in the world, with an average of 4,741 kWh/year/capita (Shrink That Footprint, 2017), therefore 47,410 MWh/year is required for 10,000 residents. The wind turbine dataset used in this study was based on a popular windturbine, the Vesta V80-2.0 MW. The onshore wind turbine requires a cut-in wind speed of 4.0 m/s. Over a 25-year period, the average wind speed in Toronto is 4.3 m/s. Assuming no power losses as turbines, produce AC power, the annual energy output was calculated using the Equation 1 below (Windpower Engineering and Development, 2017).

$$AEO = 0.01328(D^2)(V^3) \qquad \ldots\ldots\ldots\ldots\ldots\ldots Eq. 1$$

where, AEO = Annual Energy Output (kWh/year)

D = Rotor diameter (ft) = 262.5 ft for the Vesta V80-2.0 MW turbine
V = Annual average wind speed (mph) = 9.6 mph

One turbine will theoretically produce 809.6 MWh/year. Therefore 59 wind turbines are required to produce enough electricity for 10,000 Toronto residents. Wind turbines have an average life span of 20 years, 10 years less than solar panels, therefore, a period of 60 years was used. Assuming no repairs and at the end of 20 years the wind turbine is completely replaced, 177 wind turbines will be required. Multiple factors influence energy production of photovoltaic systems including, solar radiation, climate, tilt angle of the solar panels. For example, a common misconception is solar panels produce more energy in the summer months, which is not always the case. An important manufactured specification is the temperature coefficient where the value of the coefficient, given in a percentage, means for each degree over standard testing conditions of 25°C, the energy output is reduced by the given coefficient (Energy Matters, 2017). Therefore, bright, cooler days are ideal for maximum energy output. Unfortunately, in Canada the sun is at a lower angle and with the shorter days and snow cover, the energy generation is about 10-20% of the summer months (Energy Matters, 2017; The Kingston Whig-Standard, 2017; The Greenage, 2017 and Current Results, 2017). The photovoltaic system dataset used in the model was based on a 570 kWp photovoltaic plant, consisting of multi-crystalline silicon solar panels, the most commonly manufactured solar panels. Most PV systems are assumed to have a lifespan of 30 years. The plant consists of the solar panels, the mounting systems for an open ground systems, and inverters, as photovoltaics produce DC power that must be converted into AC power.A total area of 4402 m^2 is covered by solar panels and around 3 inverters of 500 kW capacity are required for a single system. The database used corresponds to an open ground power plant in Spain where the solar panels are produced by Edisun Power Europe Ltd. Photovoltaic are specified in kWp, the maximum power the system can generate. Assuming a south tilt angle equal to the latitude of Toronto of 43°, and taking the average of three different methods as seen in Table 1, 72 solar plants, producing 667.2 MWh/year/plant are required for 10,000 Toronto residents. Over a 60-year period, 144 solar plants are required. The life cycle modelling and assessment is developed using SimaPro software to integrate existing data and information identified during research.

manufacture, Canadian Solar manufactures PV systems isin Guelph, Ontario, 100 km from Toronto. Canadian solar manufactures the wafers, solar cells, solar PV modules, solar power systems (Canadian Solar, 2017). Therefore, it was assumed all products for the PV plant is manufactured in Guelph. In SimaPro transportation by transport trucks is measured in ton-kilometers (tkm), which is the weight of the product multiplied by the distance. The wind turbine dataset specified the weight of the rotors, each blade, nacelle, tower and the reinforced steel concrete foundation. The weight of the PV system, was assessed using SimaPro's network tree (a process flow diagram). Corresponding weights were determined for the processes which overall contributed to 95% of the total environmental load. In terms of maintenance and operation, the turbines are assumed to use the energy contained in the wind to produce electricity without emitting any kind of pollutants. Some electricity is needed for the yaw system operation to turn the wind turbine rotor against the wind, this value is assumed to be included in the assembling and

Table 1. Toronto's Potential Energy Output

Method	Potential Energy Output (kWh/kWp/year)	Output power (MWh/year)	Number of Systems Required	Reference
1	1,231	701.9	67	[18]
2	1,161	661.8	72	[19]
3	1,119	637.8	75	[20]
Average	1170	667.2	72	

Table *2.* Databases used for the life cycle assessment of wind energy

Database Entry: Inputs from technosphere
Wind turbine manufacture, installation and decommission:
Wind turbine, 2 MW, onshore {GLO} │construction│Alloc Def, U
Wind turbine connection to electricity grid:
Wind turbine network connection, 2 MW, onshore {CA-QC} │wind network connection construction, 2 MW, onshore│Alloc Def, U
Transport of personnel for maintenance:
Transport, passenger car, large size, diesel, EURO 3 {GLO} │market for │ Alloc Def, U
Transportation of parts from the manufacturing sites in Windsor and Tillsonburg Ontario to Toronto:
Transport, freight, lorry 16-32 metric ton, EURO3{GLO}| market for | Alloc Def, U

Modeling Assumptions

To compare the two renewable technologies, the nominal power output of 47,410MWh/year of was calculated. Solar systems produce DC power and was assumed to the converted into AC power. No other power conversions or losses were taken into consideration. Transportation to the installation location and maintenance was not specified in either datasets and therefore had to be added in. It was assumed the blades were manufactured from Siemens, located in Tillsonburg Ontario, 175 km from Toronto. Siemen's manufactures the blades for the South Kent Wind Project located within the Municipality of Chatham-Kent, Ontario (Siemens, 2017). CS Wind located in Windsor (370 km from Toronto) manufactures the tower components, it was assumed the tower, the rotor and the nacelle was also manufactured in Windsor. Lastly, LaFarge cement which produces concrete foundations for wind turbines was assumed to be the supplier for the foundation. LaFarge has two cement manufacturing plants in Ontario, it was assumed the reinforced concrete was transported from the plantthat was farthest away from Toronto, in Bath, Ontario which is approximately 245 km away. It was assumed manufactured parts were transported by transport trucks, and maintenance personnel were transported in a pick-up truck. The solar panel transportation was simplerto the wind turbines, as a local

manufacturing electricity. Maintenance for the wind turbines was assumed to be based on periodic checkups done by personnel being transported to the site, assumed to be from Northwind Solution located in Oakville, 40 km away from Toronto. Therefore, the total transportation of a pickup truck was assumed to be 80 km (there and back) 3 times a year for 60 years.For the maintenance of the PV system, it was assumed that annual checkups are required two timesa year with experts coming from Markham, Ontario, 30 km (one way) from Toronto. The end of life of the system has been included in the underlying databases used, therefore it is assumed that the transportation and treatment of the waste was completed accordingly. The main wastes taken into consideration in the production and disposal of the panels are wastewater, mineral oil, plastic and municipal solid waste according to the database used for this analysis. The treatment is based in municipal solid and wastewater treatment and includes transportation.

Life Cycle Inventory

LCA studies are based on qualitative data collected for material, energy and other resources involve in the life cycle of the product known as Life Cycle Inventory (LCI). For wind turbine, Table 2summarizes the databases used for the analysis of a single wind turbine. A total of 177 turbines are required, each with a lifetime of 20 years to complete the energy requirement for the chosen timespan of 60 years. Similarly, Table 3 summarizes the input databases used for the analysis of a single photovoltaic system. Each system has a useful life of 30 years, for which a total of 144 systems are required to meet the nominal power for design and the lifetime of the study corresponding to 60 years.

figures only consider 92.5% of the total environmental impacts (7.5% cutoff rate). The single score impact and percent contribution are included in each of the processes. The largest environmental impact for the wind turbines is the market production of steel. The environmental impacts for the photovoltaic plants are spread over more processes, with most production of the multi-crystalline silicon panels and

Table 2: Databases used for the life cycle assessment of solar energy

Database Entry: Inputs from Technosphere
Manufacturing, installation, decommission and end of life treatment for a single system:
Photovoltaic plant, 570kWp, multi-Si, on open ground {GLO}| construction | Alloc Def, U
Transportation of solar panels and components of the system from Guelph to Toronto:
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U
Transport of personnel for maintenance:
Transport, passenger car, large size, diesel, EURO 3 {GLO} | market for | Alloc Def, U

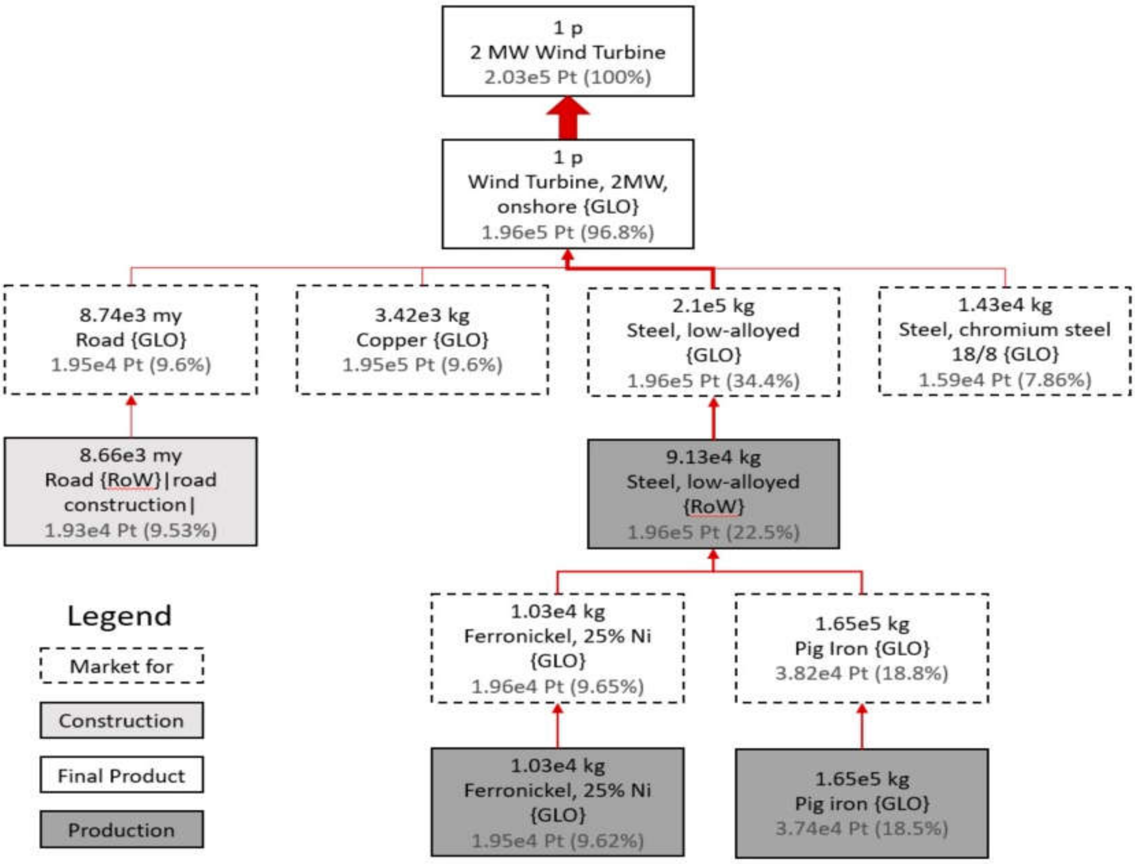

Figure 1. One 2.0 MW Wind Turbine Network Resul

RESULTS AND DISCUSSION

The results obtained from SimaPro using the impact assessmentReCiPe Endpoint (H) V1.11/ Europe ReCiPe H/A method, which uses European normalization and weighting factors. Under the assumptions and specifications of the project, the 177 wind turbines resulted in the renewable energy with a greater environmental impact compared to the 144 photovoltaic plants. The results are presented in characterization, damage assessment, normalization, weighing and single score impact assessment for the 144 PV plants and the 177 wind turbines.

Networks

Figures 1 and 2 represent the network/flow diagram of 1 wind turbine and 1 photovoltaic plant. The process boxes in both aluminum mounting system resulting in the largest environmental impacts. Both network diagrams demonstrate that 92.5% of the environmental impacts strictly result in the manufacturing of the systems and do not included transportation, maintenance, or disposal.

Characterization

This is a mandatory element of a life cycle assessment where the pollutant emissions are given a common frame of reference to account for the environmental impacts. Here, the substances or pollutants that contribute to an impact category are multiplied by the characterization factor corresponding to each category (*SimaPro Database Manual, 2016*). The percent contribution of characterization impact assessment of wind vs. solar is illustrated in Figure 3. It is clearly seen that the PV planthas lower impacts except for ozone depletion, ionizing radiation, terrestrial ecotoxicitiy, agricultural and urban land occupation. These five characterization impacts could be attributed to the toxic pollutants such as nitric oxides during the wafer process, the energy intensive silicon extraction and purificationprocesses and the large amount of land required for the 570 kWp plant.

Damage Assessment

The damage assessment aims to combine several similar impact categories into a damage categoryby adding impact categories with the same units. The three damage categories are human health, ecosystems, and resources.

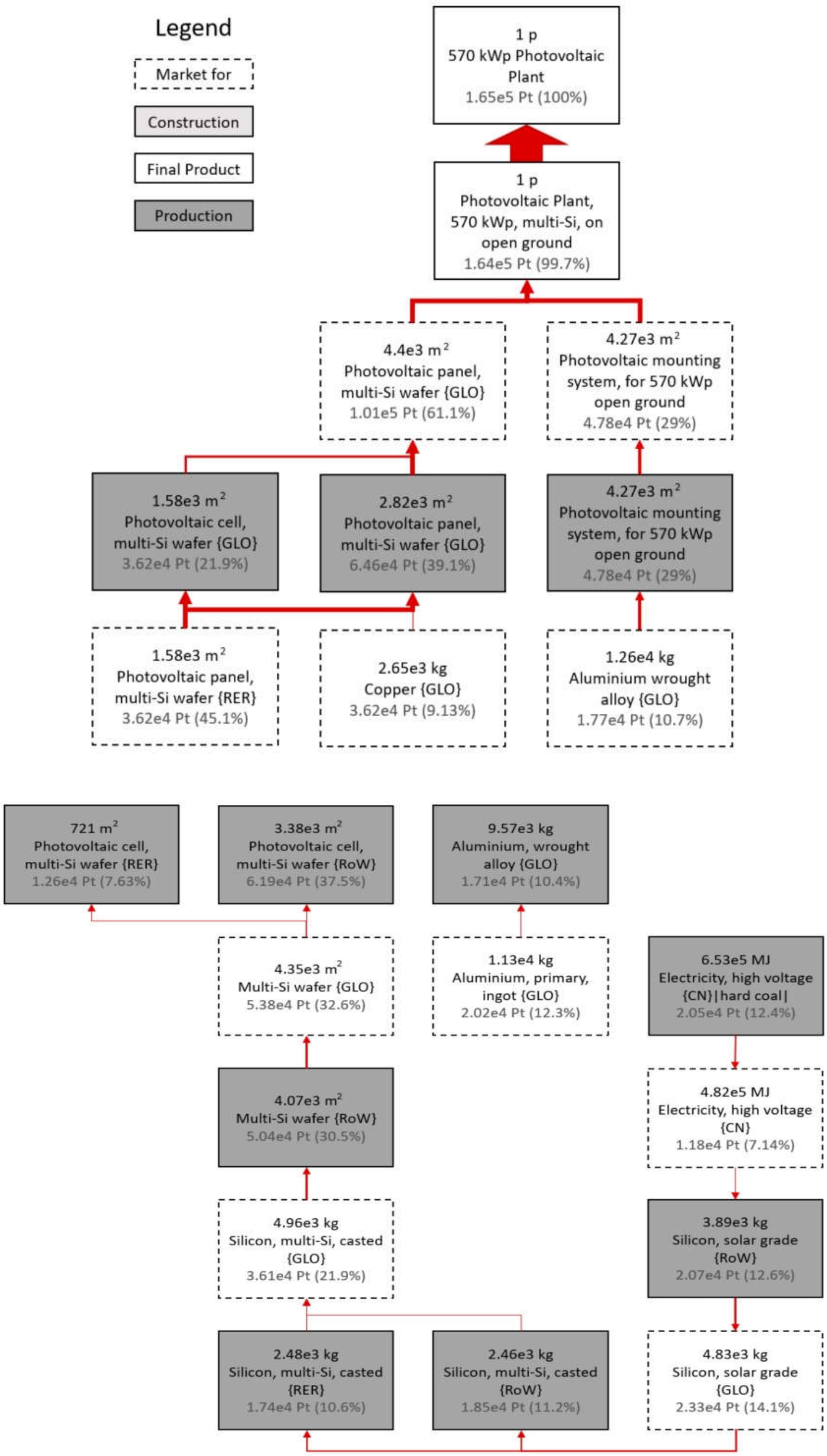

Figure 2. One 570 kWp Photovoltaic Plant Network Result

The damage category of human health combines the impact categories of climate changehuman health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, and Ionizing radiation.Ecosystems category includes climate change ecosystems, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation and natural land transformation.Finally, the resources damage category includes metal depletion and fossil depletion as the impact categories.The results for the three damage categories scores are tabulated in Table 5. The damage assessment results can also be shown in percentages as illustrated in Figure 4.

The impact assessment Europe ReCiPe H/A the normalization reference values correspond to the annual impact of a single European in each damage category. The normalization factors of endpoint impacts for human health, ecosystems and resources are 49.5 DALY, 5.72e3 species.yr and $3.27e-5, respectively [26]. Normalization allows for the impact category indicators to have the same units, making it easier for comparison.The results are shown in Table 6.

Weighting and Single Score

Weighting has been carried out using the Europe ReCiPe H/A weighing factors: 400 for Human Health, 400 for Ecosystem

Table 3. Characterization Assessment of Wind Energy and Solar Energy

Impact category	Unit	Wind	Solar
Climate change Human Health	DALY	254	323
Ozone depletion	DALY	0.0997	0.0509
Human toxicity	DALY	122	241
Photochemical oxidant formation	DALY	0.0298	0.0411
Particulate matter formation	DALY	117	191
Ionising radiation	DALY	0.4562	0.3391
Climate change Ecosystems	species.yr	1.44	1.83
Terrestrial acidification	species.yr	0.0068	0.0072
Freshwater eutrophication	species.yr	0.0045	0.0063
Terrestrial ecotoxicity	species.yr	0.0477	0.0050
Freshwater ecotoxicity	species.yr	0.0133	0.1048
Marine ecotoxicity	species.yr	0.0025	0.0187
Agricultural land occupation	species.yr	0.1410	0.1092
Urban land occupation	species.yr	1.30	0.3878
Natural land transformation	species.yr	0.0462	0.0515
Metal depletion	$	3,375,575	13,574,054
Fossil depletion	$	7,975,729	10,121,831

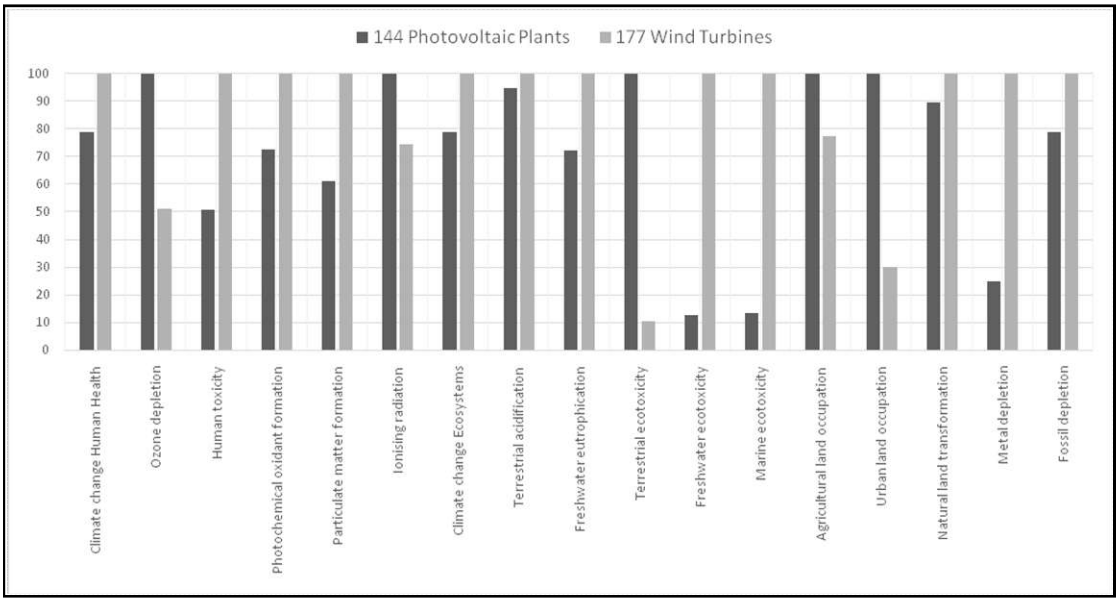

Figure 3. Percent Contribution of Characterization Impact Assessment of Wind vs. Solar

As in Figure 3, the percentage within the category is calculated based on difference in the inventory scores between wind and PV systems.The wind turbines have an overall higher damage to human health and depletion of resources, but the photovoltaic plants have a slightly higher impact to ecosystems.

Normalization

Normalization of categories is achieved by dividing the scores by a reference value to obtain a normalized data corresponding to the geographic location where the results are applicable.

and 200 for Resources (Benini, 2014). The last part of the assessment includes the compilation of the results to form a single score after the results have been normalized and weighted. The results are presented in Table 7. Thefirst raw in Table 7 corresponds to the total environmental impacts for the wind turbines and the photovoltaic system. The results show that the total score for photovoltaic systems is almost two thirds of the total score for wind turbines under the assumptions made and the weighing applied. The largest damage contributing to the elevated score of wind turbines is seen in the damage to human health and resource depletion categories. Figure 5 below shows the final score with the individual contributions of each technology to the impact categories studied in this assessment. Climate change human health, human toxicity, and fossil depletion are the midpoint impact categories that contribute the most to the damage caused by both technologies.

Table 4. Damage assessment for wind and solar energy systems

Damage category	Unit	Solar	Wind
Human Health	DALY	494	755
Ecosystems	species.yr	3.00	2.52
Resources	$	11,351,305	23,695,885

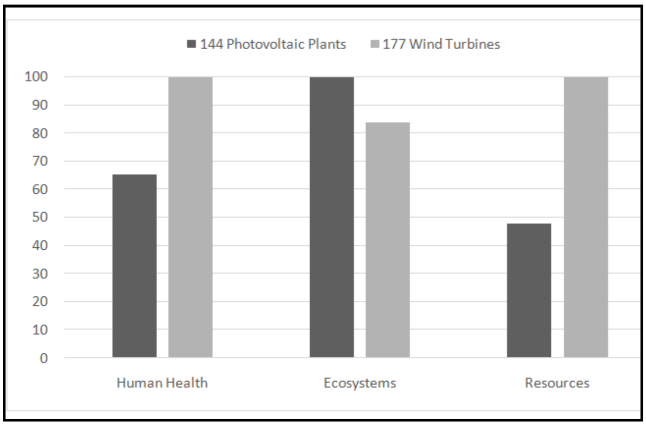

Figure *4.* Damage assessmentpercent contribution for wind and solar systems

Table 6. Normalization of Wind and Solar

Damage category	Unit	Solar	Wind
Human Health	-	24,437	37,380
Ecosystems	-	16,575	13,922
Resources	-	36,778	76,775

Table 5. Weighting and Single Score Impact Assessment of Wind and Solar

Damage category	Unit*	Solar	Wind
Total	MPt	23.8	35.9
Human Health	MPt	9.8	15.0
Ecosystems	MPt	6.6	5.6
Resources	MPt	7.4	15.3

*MPt = Million Point, where 1 Pt represents one thousandth of a yearly environmental load of one average European citizen.

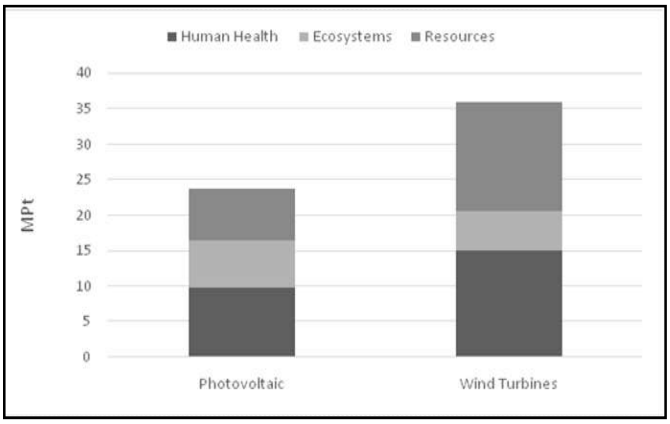

Figure 5. Total Environmental Impact of Wind and Solar presented as a Single Score

Interpretation

The assessment results under the assumption and data used demonstrated that higher environmental impacts are associated with the implementation of 177 wind turbines compared to 144 PV plants to produce the same amount of nominal power of 47,410MWh/year for 60 years. Photovoltaic systems contributed to greater impact in 12 out of the 17 impact categories as seen in Figure 3.The wind turbines have a higher environmental impact in 2 out of the 3 endpoint impacts, damage to human health and depletion of resources. The PV systems have a slightly higher impact to ecosystems which may be associated with the chemicals included as part of the manufacturing process of the solar cells. The total environmental impact of the PV plants was only 2/3 of the wind turbines. In order for wind to be more favorable from an environmental perspective, 118 wind turbines (2/3 of the original 177) would need to be manufactured. This can be achieved with an average wind speed of 4.9 m/s or greater (as opposed to Toronto's 4.3 m/s). The second, more viable option is the wind turbines last 30 years instead of 20 years. Multiple LCAs of wind turbines assume a standard design life of 20 years, however the wind turbine industry is still young, as Vestas was established in 1979 and only a few turbines have ever been disposed of, reaching operation lifespans of 30 or more years (Vestas, 2011). If the wind turbines lasted 30 years and if the average wind speed was greater than 4.3m/s, the wind turbines would have less environmental impacts than the PV plants. Wind speed and solar radiation are some important factors for LCAs and many production processes, especially for PV plants are still under development (Jungbluth, 2005). It is recommended to continue to conduct LCAs as new improvements and technologies are implemented.

Conclusion

A total of 177 wind turbines and 144photovoltaic systemswere compared using a SimaPro model developed for this study. The Life Cycle Impact Assessment was conducted using the ReCiPe Endpoint (H) V1.11/ Europe ReCiPe H/A method. A total of 17 midpoint impact categories were used to evaluate the environmental performance of the two technologies compiled into 3 endpoints to account for the damage to human health, ecosystems and the depletion of resources. The characterization, normalization, damage assessment and weighing were used as phases to understand the impact of each technology and create a common framework to develop the single score for wind turbines (35.9MPt) and photovoltaic (23.8 MPt) systems.

This comparative Life Cycle Assessment study concluded that wind turbines for energy generation imply more environmental damage than photovoltaic systems when compared under the premise of producing 47,410 MWh/year of nominal power during a period of 60 years. The study considers the materials, manufacturing, construction, transportation, and end of life cycle stages of both products. The results obtained through this work and similarstudies help interested parties to define area of improvement where more sustainable options can be applied. Companies focused on wind turbine and photovoltaic module manufacturing can create similar model for their products to decrease the impact of their activity on the environment.

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