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Comparative life-cycle assessment of a small wind turbine for residential off-grid use

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ABSTRACT

As the popularity of renewable energy systems grows, small wind turbines are becoming a common choice for off-grid household power. However, the true benefits of such systems over the traditional internal combustion systems are unclear. This study employs a life-cycle assessment methodology in order to directly compare the environmental impacts, net-energy inputs, and life-cycle cost of two systems: a stand-alone small wind turbine system and a single-home diesel generator system. The primary focus for the investigation is the emission of greenhouse gases (GHG) including CO_2, CH_4, and N_2O. These emissions are calculated over the life-cycle of the two systems which provide the same amount of energy to a small off-grid home over a twenty-year period. The results show a considerable environmental benefit for small-scale wind power. The wind generator system offered a 93% reduction of GHG emissions when compared to the diesel system. Furthermore, the diesel generator net-energy input was over 200 MW, while the wind system produced an electrical energy output greater than its net-energy input. Economically, the conclusions were less clear. The assumption was made that diesel fuel cost over the next twenty years was based on May 2008 prices, increasing only in proportion to inflation. As such, the net-present cost of the wind turbine system was 14% greater than the diesel system. However, a larger model wind turbine would likely benefit from the effects of the 'economy of scale,' producing superior results both economically and environmentally.

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1. Introduction

As the public understanding of climate change increases, it is expected that many people will reassess their energy use and lifestyle choices. Household electricity production could become one of the focal points of this environmental movement as it is accessible to the individual and possesses a strong potential for meaningful impact. For this reason, it is crucial that individuals 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 practises are turning to the life-cycle assessment (LCA) methodologies. LCA is a practical approach for evaluating the environmental impacts of any product or service as it combines the systematic rigours of science with a holistic perspective on the contributing factors. 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 [1]. 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 [1,2]. While the LCA approach does have limitations in terms the accuracy of assumptions and upstream considerations, having a standardized method ensures that all studies are at least conducted in the same manner, using similar criteria to base assumptions.

This comparison focuses on small off-grid home energy systems, contrasting a small wind turbine system with the conventional off-grid energy source. As a stand-alone diesel generator system is currently the typical method of producing off-grid electricity [3], it was used for the comparison. The LCA data from this study was organized into four sections as indicated by the ISO standards [1]: Goal Definition, Scope, Inventory Assessment, and Impact Analysis. In addition, an economic analysis and a discussion of possible improvements to reduce the energy inputs and emissions of the two systems are also included.

2. Goal definition

Small-scale wind power is becoming a popular alternative for providing household electricity produced by a renewable and clean source. In fact, one study [4] suggests that there are already an

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estimated 2500 small wind turbines in operation in Canada. This energy option is particularly relevant to the many off-grid homes across the country. Off-grid or remote locations are typically powered by fossil fuels such as diesel generators. However, renewable energy systems with battery banks can be used to replace such systems in many circumstances [3]. Therefore, as the title suggests, this study intends to provide accurate information to household owners and remote energy industry members comparing the environmental benefits and impacts of two off-grid systems: small-scale wind power and diesel generators. To do so, the study was primarily focused on determining the energy flows and greenhouse gas (GHG) emissions of the two systems over their entire life-cycle. These data were assessed independently for all stages of the system's production, use, and disposal. For the purpose of clarity, the different processes and stages of the systems life-cycle studied in this paper have been subdivided and labelled as *unit processes*. A *unit process* is defined as the smallest element considered in an LCA for which input and output data are quantified [1]. From this point on, processes which have been included in this study and have independently assessed energy flows and emissions will be referred to as *unit processes*.

A system boundary describing how far upstream and downstream the system is analyzed was established. Processes that are considered to have a negligible impact on the results fall outside the boundary. As a secondary objective, an economic analysis was also performed in order to determine the cost difference between the two systems.

While much information is available describing the benefits of large-scale wind power, little has been shown for small wind turbines which can differ significantly in cost and performance [4]. This study evaluated the performance of one small wind turbine both environmentally and economically in comparison with a diesel generator system. While this study was conducted for only one specific model of wind turbine, it should be noted that small wind turbines typically follow an economy of scale both in terms of life-cycle impact and cost such that large wind turbines perform better than small ones [5]. Therefore, as this study made use of a very small turbine (400 W), it will likely represent the lower limit scenario for the benefits of small wind turbines. It is expected that most other models will perform at least equally well, if not significantly better.

3. LCA scope

3.1. Functional unit

In order to properly compare the two systems, the energy flows and emissions of each system must be calculated based on a single reference value. This value is referred to as the *functional unit* (the quantified performance of a product system for use as a reference unit [1]) of the study and represents a product or service that is provided by both systems in an identical quantity and quality. The functional unit for this study is the delivery of 162.5 kWh of AC electrical energy each month to a small off-grid home over a twenty-year period. The 162.5 kWh is derived from one quarter of the monthly energy use of the average Alberta home [6]. This is based on the assumption that off-grid homes have lower energy demands than typical homes, either due to less use, fewer large appliances, smaller house size, or fewer residents. Given this assumption, the value of one quarter was selected arbitrarily. However, as the results in the form of a ratio (value per functional unit), they can be multiplied by an appropriate factor to represent different scales of energy demands. This will hold true so long as the system components themselves remain the same and are merely scaled to meet the energy demands. Therefore, the value of the 162.5 kWh will serve as the 'reference electricity consumption' by which both systems are compared.

The twenty-year period refers to the typical lifetime of the wind turbine that was studied [5,7]. In order to add a local context to the problem, the functional unit also included the criteria of locating the home within a distance of 100 km from Edmonton, Canada. It was assumed that weather patterns and wind speeds are similar for all locations within this region, excluding areas within Edmonton city limits. This region will represent a "typical" semi-rural or rural location within the 100 km range.

The two systems that were evaluated have been labelled as the *wind system* for the wind turbine and other required components, and the *diesel system* for the diesel generator and all other related processes. The systems are described in the following sections.

3.2. The wind system

The wind system was composed of a complete off-grid wind generation system including the wind turbine, the turbine tower, the battery bank, and an inverter. The study examined a specific wind turbine model: Southwest Wind power's Air X which has a rated power of 400 W, a 1.17 m diameter rotor, and charges batteries at either 12 or 24 V [7]. This turbine was selected for the study for two reasons. First, the small size of the turbine allows the possibility for experiments to be conducted within a wind tunnel. Second, the turbine was one of the few models commonly available to the public at local retailers. The other components of this system, such as the battery bank and inverter were based on the typical recommendations for similar off-grid applications. As the study was focused on the performance of the wind turbine, rather than on the performance of other system components, data for this equipment (battery bank, inverter, etc.) were based on general performance data or on an averaged data set from numerous products.

Preliminary calculations determined that the Air X wind turbine was not capable of producing sufficient power to meet the functional unit. Therefore, this study simply considered the use of multiple wind turbines and towers in the required quantity. Given that the results are provided as a ratio with respect to the functional unit (162.5 of electrical energy), values can be multiplied by an integer factor to represent an equivalently proportioned system with a different number of Air X wind turbines. However, it should be noted that results do not accurately represent wind turbine systems that produce the same quantity of monthly energy with fewer turbines. Given the economy of scale, a single large turbine would likely perform better than any results determined by this study.

3.3. The diesel system

The diesel system is a complete small diesel generator system. This system includes the generator, the diesel fuel, and the fuel storage tank. It was assumed that the generator operates such that it produces the required power at any given time, and, therefore, a battery storage system is not required. Furthermore, diesel generators typically produce A/C power and thus do not require an inverter. Generator sizing and performance properties were based on averaged data from various generators that are of appropriate capacity to produce the monthly energy requirement for the functional unit.

3.4. System boundaries

A process flow diagram can be seen for each system in the figures below: the wind system in Fig. 1 and the diesel system in Fig. 2. In

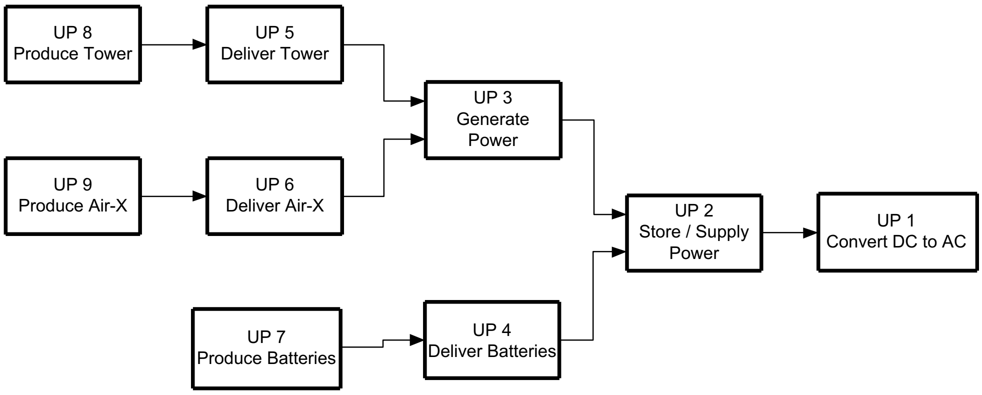

Fig. 1. Process flow diagram for all unit processes of the wind system that are within the boundary of the study.

reality, both the wind system and the diesel system have additional processes reaching further upstream and further downstream. While many of these processes lie outside of the scope of this project, none were excluded without motivation to do so.

Furthermore, many upstream processes are accounted for by the use of aggregated data (data which describes the total effects of all upstream processes beyond the boundary). In this case, the effects of the upstream processes are accounted for by including all of the aggregated data within one of the unit processes inside the system boundary. Aggregated data was primarily taken from other LCAs conducted on the specific processes.

The following list describes specific processes that were not included within the system boundaries.

- Battery production materials, processes, and infrastructure for the wind system was represented by one unit process which includes aggregated data for all upstream processes for battery production.
- Diesel extraction, refining, processing, and transportation to local service stations for the diesel system were accounted for by one unit process containing the aggregated information.
- Power transmission from the power source to the home has not been considered. It was assumed that this process was similar for both systems and therefore their effects will cancel out in the comparison. It was also assumed that wires are sized appropriately such that power losses are negligible.
- Installation and maintenance (excluding component replacement) processes are not considered in this study due to a lack of reliable data. It was assumed that these processes are small enough over the entire life cycle to be considered negligible.
- Heat loss due to inefficiencies will not be considered as a heat source. It was assumed that all components of each system are located outside of the home and therefore have no impact on heating or cooling requirements for the home.
- Raw material extraction, processing, and infrastructure are not included within the system boundary. These data were represented by aggregated data describing all upstream processes required to produce 1 kg of each type of material considered in this study.

3.5. *Environmental impacts*

This study is concerned with the environmental impacts of these two systems. In order to compare the wind system to the diesel system, it was first important to establish the criteria for comparison. This was accomplished by determining which specific types of environmental impacts are relevant to the two systems and by identifying the unit with which to quantify the impact. The following is a description of impacts that have been considered in this study.

1. Greenhouse Gas Emissions (GHGs): GHGs are global impacts in the sense that they impact the environment regardless of where

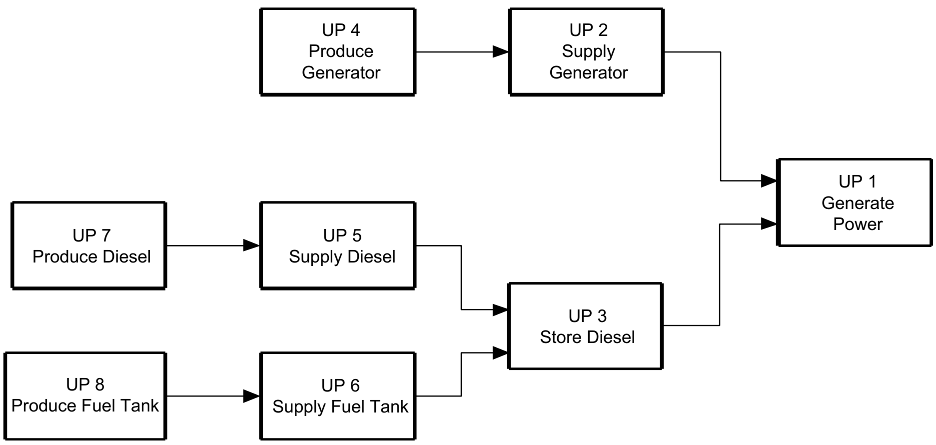

Fig. 2. Process flow diagram for all processes of the diesel system that are within the boundary of the study.

Table 1
Global warming potential for the greenhouse gases considered in this study.

Gas	Unit	Factor	Data Source
CO_2	Kg CO_2 Eq.	1	[20]
CH_4	Kg CO_2 Eq.	23	[20]
N_2O	Kg CO_2 Eq.	296	[20]

they are emitted [8]. Therefore, GHG emissions from all system processes were considered and weighted equally regardless of the location at which they were emitted. Several types of emissions can act as GHGs, however, their effects differ in magnitude (global warming potential) [2]. For this reason, their effects must be converted into a common form in order to be cumulated properly. The global warming potential of the various GHGs can be seen in Table 1. Values are expressed in kg of CO_2 equivalent.

- Acid rain precursors: these emissions typically include emissions of SO_2 and NO_x.
- Toxic emissions: this category would include ground level ozone production, a toxic gas resulting from NO_x emissions, and releases of lead into the ground and water.

For both acid rain precursors and toxic emissions, the environmental impacts are highly dependent on the geographical location and the local environment [9]. For the two systems being considered, many processes such as production, transportation, and operation of the generator may occur in several different locations and types of environments. As each type of environment may respond differently to the emissions, the specific impacts would be difficult to assess. Because of the relatively low and quickly diluted emissions associated with a single diesel generator in a rural setting, it was assumed that off-grid home energy systems will not experience the environmental impacts typically associated with large point source emitters, such as coal-fired power plants. Therefore, the environmental impact assessment of this study was focused solely on global climate change, evaluated by comparing all of the associated GHG emissions.

4. Inventory assessment

The inventory section of an LCA describes all of the data and assumptions involved to evaluate the systems. This includes reference data used for calculations, energy flows, and emissions for each unit process of the systems.

All data used for the inventory assessment have been assigned a value of uncertainty. The magnitude of uncertainty was based on data variability, the degree of assumption involved, and the number of sources or source reliability. Using these values, overall uncertainty (representing a 95% confidence range) was calculated for the key results using a Monte Carlo Simulation. This technique performs several simulations (10,000) with random values assigned to the given variables in order to determine the expected range of results.

Table 2
Energy flows and GHG emissions associated with the production of materials.

Material	Energy Input (kWh/kg)	GHG Emission (kg $CO2_{eq}$/kg)	Sources
Stainless steel	17.92	6.45	[21,22]
Aluminium	34.75	13.06	[21–23]
Copper	14.85	4.56	[21–23]
Steel	5.98	1.98	[21–23]
Galvanized steel	11.11	3.9	[a]
Plastic	12.69	4.29	[23]

[a] Based on data presented by source [24].

Table 3
Production and combustion data for 1 L of diesel fuel.

	Unit	Value	Sources
Diesel production			
Energy input	kWh/L	1.01	[25,26]
GHG emission	kg CO_{2eq}/L	0.29	[25,26]
Diesel combustion			
Chemical energy content	kWh/L	10.72	[26]
GHG emission	kg CO_{2eq}/L	2.86	[25,26]
Total GHG emissions	kg CO_{2eq}/L	3.15	[25,27,28]

4.1. Materials information and properties

Many of the unit processes in this LCA involve the calculation of energy flows and emissions associated with producing materials. Aggregated data for material production and manufacturing processes were collected for the various materials considered in this study. These values and the data sources can be found in Table 2.

Diesel fuel was another material used extensively in this study. Properties, such as emissions and energy input are provided in Table 3 for both the production of diesel and its combustion in an international combustion engine.

4.2. Transportation data and assumptions

Many of the unit processes in this study include the transportation of materials from their manufacturer to the site. An assumption has been made that all transportation was within North America; such that materials are brought by freight trucks (large truck) to Edmonton and then brought from Edmonton to the site by a pickup truck (small truck). Transportation data have been collected and and are described in Table 4 in terms of large and small trucks. These data, with estimated distances for both types of transportation, were used for all processes involving transportation.

4.3. Overview of both systems

The calculations for each system involve many assumptions, considerations, and data values. Summaries of all unit processes for the wind system and the diesel system can be seen in Tables 5 and 6 respectively.

4.4. The wind system: wind power estimate

No data are available to predict the performance of the Air X turbine at the location specified by the functional unit. It was thus necessary to calculate the number of required turbines based on estimated energy production. To do so, the power curve method of calculating the monthly energy output of one turbine was used, as outlined in Ref. [10].

The power curve method uses the manufacturer provided power curve subdivided into bins of wind speed intervals. These

Table 4
Energy flows and GHG emissions associated with the production of materials.

	Unit	Value	Sources
Large truck			
Energy input	kJ/kg km	1.79	[29,30]
GHG emission	g CO_{2eq}/kg km	0.09	[27,30,31]
Small truck			
Energy input	kJ/kg km	2.77	[29]
GHG emission	g CO_{2eq}/kg km	0.2	[27]

Table 5
Unit process considerations for the wind system – wind generator.

Unit process	Assumptions and considerations
UP1 convert DC to AC	Average home inverter efficiency is 92% [13,32]. No emissions are associated with this loss as the increased power production requirement was accounted for by number of wind turbines required.
UP2 store/supply power	The overall battery efficiency is 75% (includes: input loses, storage loses, and output loses combined) [13,32]. As with UP2, no emissions are associated with this energy loss.
UP3 generate power	An appropriate number of wind turbines (5) produce the quantity of power described by the functional unit. See Section 4.4 on wind power estimation. No emissions are associated with this process.
UP4 transport batteries	It is unknown where in North America the batteries are produced. An assumption that the manufacturer was located 3000 km from Edmonton accounts for most locations on the continent. Assumption: batteries are transported 3000 km to Edmonton by large truck and 100 km to the site by small truck. Transport also includes 100 km from site to Edmonton for recycling after use. See the Section 4.5 for battery bank and mass calculated based on charge density of 32.5 Wh/kg [30,32]. Battery lifetime of 10 years [13,14].
UP5 transport tower	Tower mass is 36 kg [33] for 10 m height. The tower used in this study is 30 m in height. Assume doubling the mass to 72 kg was an overestimating correction. One tower is used per turbine and it is assumed that towers will not be replaced over 20 years. The towers are produced by the wind turbine manufacturer in Arizona, and are transported 2500 km to Edmonton by large truck [7].
UP6 transport Air X	Each turbine has a mass of 6 kg. The required number of turbines are transported 2500 km from the manufacturer in Arizona, to Edmonton by large truck. Turbine lifetime is 20 years [5,7].
UP7 produce batteries	Based on battery bank storage size. Aggregated data for battery production (including 50% recycling after use) of 620 kWh per $kWh/kWh_{storage}$ and 40 kg of $CO_2/kWh_{storage}$ is used to calculate emissions and energy flows [14,34].
UP8 produce tower	The tower is a guyed mast composed of galvanized steel pipes and steel cables [33]. Assume entire mass to be of galvanized steel (overestimate).
UP9 produce Air X	See Table 8 for measured mass of turbine components. Assume: magnets and circuit board were considered as aluminium (likely an overestimate) and turbine blades, rubber o-ring, and other plastic parts are all grouped under the same material.

data were obtained from the user manual [7] of the wind turbine and were provided in terms of two power curves: high power production for low turbulence wind, and low values for highly turbulent conditions.

Wind regime data in the form of a frequency distribution were used, grouped into equivalent wind speed bins. For this study, 3 locations within 100 km of Edmonton were selected to represent the average conditions of the area specified by the functional unit. Wind regime values were taken for these locations from the Canadian Wind Energy Atlas at a height of 30 m [11]. These locations have wind regimes typical for the area. As seen in Table 7, the average of the six estimated power outputs (three locations with two different power curves) was used for the remainder of the study.

Note that a tower height of 30 m is three times taller than the tower provided by the manufacturer [7]. Although a 30 m tower may be uncommon for the Air X turbine, this assumption allows for a direct use of the wind atlas data without using height corrections which would require local surface roughnesses and other unknown values.

Using the power curve method and the above assumptions, the average monthly energy production was calculated to be 49 kWh per turbine. This translates into a continual operation power of 67.63 W, or, for a 400 W rated power turbine, a capacity factor of 0.17. In order to meet the functional unit, 4.77 turbines would be needed, however, the integer value of 5 turbines was used as an overestimate.

Equation (1) illustrates the method with which the net-energy input of a unit process was calculated based on the energy inputs

Table 6
Unit process considerations for the diesel system – diesel generator.

Unit process	Assumptions and considerations
UP1 generate power	Average generator performance is used to determine fuel consumption per kWh. See Section 4.6 on diesel generators. Energy loss due to generator efficiency is counted as an input. Refer to Table 3 for diesel fuel properties.
UP2 transport generator	Generator mass, based on average of 4 models is 90 kg [15,16]. With a lifetime of 10 years [35] the mass of 2 generators was transported 3000 km by large truck over the period of study. Given the on-demand operation of the generator, it is likely that the assumption of a 10 year lifetime is optimistic. This could have the effect of exaggerating the true benefits of the diesel generator system, however, it is assumed that this effect was small in contrast to energy and emissions associated with the fuel consumption process.
UP3 store diesel	No data are available describing the quantity of diesel spilled during refills or through leakage. Assumption: all vapour leaks and diesel spills can be avoided or are negligible.
UP4 produce generator	Generator composition can be approximated by equating the mass to be 60% steel, 35% aluminium, and 5% copper [21]. Based on lifetime: 2 generators are required to satisfy the functional unit time period of 20 years.
UP5 transport diesel	Diesel is transported to site from Edmonton by small truck. Calculations based on fuel requirement in litres and density of diesel 0.84 kg/l [35]. Note: diesel production values include transportation to an average location North American service station [25].
UP6 transport fuel tank	Storage volume is based on weekly fuel requirement. This volume is approx. 20 L so fuel storage tank is small. Assume transportation of plastic tank is negligible.
UP7 produce diesel	Calculated using aggregated data for production of diesel and total quantity of diesel consumption per functional unit. See Table 3 for diesel properties.
UP8 produce fuel tank	Storage tank volume is approximately 20 L. According to preliminary calculations: assume production of plastic tank is negligible.

and outputs of a process. It should be noted that, as energy from renewable sources is not included in this equation, the unit process "Generate Power" (Table 5) for the wind turbine system will have a negative energy input value.

$$UPI = E_i - E_o \qquad (1)$$

UPI – net-energy input for a unit process
E_i – total non-renewable energy input into the unit process
E_o – total energy output (electrical) from the unit process

In the case of wind power $E_i = 0$ because wind energy, which is renewable, was used to produce the electrical power.

The Air X composition of materials data presented in Table 8 was used for calculations in the unit process: Produce Air X.

Table 7
Results of wind power production estimation from three locations near Edmonton, Canada [7,11].

	High performance power curve energy (kWh/month)	Low performance power curve energy (kWh/month)	Average of power curves (kWh/month)
Location 1	66.9	42.4	54.6
Location 2	54.1	35.0	44.6
Location 3	59.2	38.9	49.0
Average of three locations			49.4

Table 8
Inventory data for Air X organized by mass of each material category considered.

Materials	Components	Mass per turbine (g)	Mass per F.U. (kg)	Energy input (kWh/f.u)	GHG emissions (kg CO_{2eq}/f.u.)
Stainless steel	Bolts, bearings, shaft, magnet base	876.3	4.4	78.5	28.2
Aluminium	Body, magnets,[a] circuit board[a]	3155.9	15.8	548.3	206.1
Copper	Wires in generator and 1 m cables	605.1	3.0	44.9	13.8
Steel	Internal support components	579.0	2.9	17.3	5.7
Plastic	Blades, nose cone, o-rings	736.3	3.7	46.7	15.8
TOTAL		5952.5		735.8	270.0

[a] Due to a lack of available data, an assumption was made to include magnets and circuit boards under the aluminium category due to its high energy input value.

4.5. Wind system: battery bank sizing

Variations in the battery bank size would alter the total energy inputs and emissions associated with this process and, therefore, could have significant impacts on the economic and environmental assessments in this report. For this reason, the battery bank size was determined based on the recommendations of an off-grid wind energy manual [12] produced by the government of Canada. This manual suggests that the battery bank capacity should be capable of providing three days of power before dropping below a state of 50% charged. Following this method, the monthly energy required to meet the functional unit of 162.5 kWh/month was first increased to compensated for the efficiency losses of the inverter and battery bank (listed in Table 5) to 235.5 kWh/month. This value was then divided into a daily rate and multiplied by 3 for the three storage days. Given the total energy storage requirement must be met by a 50% charge, the battery bank storage capacity was calculated to be 46.4 $kWh_{storage}$.

Furthermore, the functional unit requires 20 years of operation. Therefore, two sets of battery banks are used for all calculations based on a battery lifetime of 10 years [13,14]. For transportation calculations, the battery charge density listed in Table 5 was used to determine the mass of two battery banks. The calculated mass of one battery bank was 1428 kg.

4.6. Diesel system: generator performance

In order to determine generic performance for the diesel generator, data were collected from the average of 4 generator models of typical size for off-grid purposes [15,16]. The efficiency data for these generators were provided in the form of L/kWh at peak performance and at 50% capacity. As outlined in the section 3, the off-grid generator provides instantaneous power to the home as needed, and therefore, the generator was operating at various capacities. An average value of the 8 efficiencies (0.53 L/kWh) was used for this study [15,16], see Table 9 for the generator data.

These assumptions are likely to be gross overestimates of the generator performance and efficiency. It would require the generator to have a throttle control system to regulate the power production, it assumes that the generator will maintain the same efficiency regardless of the power output, and it does not include any idling time when diesel was used with no power output. Therefore, actual generator emissions and fuel consumption would likely be higher than presented in this paper. This value was used to calculate the quantity of fuel required to meet the functional unit. Note that the energy input into the unit process Generate Power was taken as the difference between the total chemical energy in the fuel and the energy required to meet the functional unit.

Table 9
Manufacturer provided data for four models of small diesel generators.

Generator	Fuel efficiency at 100% capacity (L/kWh)	Fuel efficiency at 50% capacity (L/kWh)	Mass (Kg)	Source
Duropower 4000 W	0.53	0.71	80	[15]
Duropower 6500 W	0.38	0.45	108	[15]
Duropower 7500 W	0.32	0.38	108	[15]
Hardy diesel 5500 W	n/a	0.91	42	[16]
Mean	0.53		85	
Standard deviation	0.2		31	

4.7. Inventory results

For complete results of the inventory assessment, refer to Figs. 3 and 4 for the unit process energy input values of the wind system and the diesel system respectively. Figs. 5 and 6 provide the CO_{2eq} emissions of each unit process for the two systems. As illustrated in Fig. 3, the total energy input for the wind system was −53kWh. This negative value reflects the fact that the wind turbine system produces more energy over its lifetime than was needed to produce the system. However, this value was small compared with other unit processes, therefore, even small levels of uncertainty in the other unit processes could affect this value dramatically.

5. Impact analysis

This study considers GHG emissions as the primary environmental impact to be investigated. This information is relevant for industries such as small-scale wind power which are focused on providing alternative energy sources that are more environmentally sound. This report intends to establish whether or not the

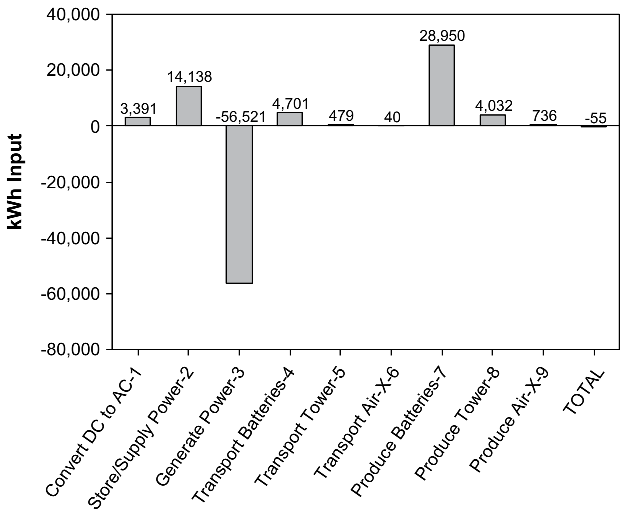

Fig. 3. Total kWh of energy input for each unit process of the wind system – wind system.

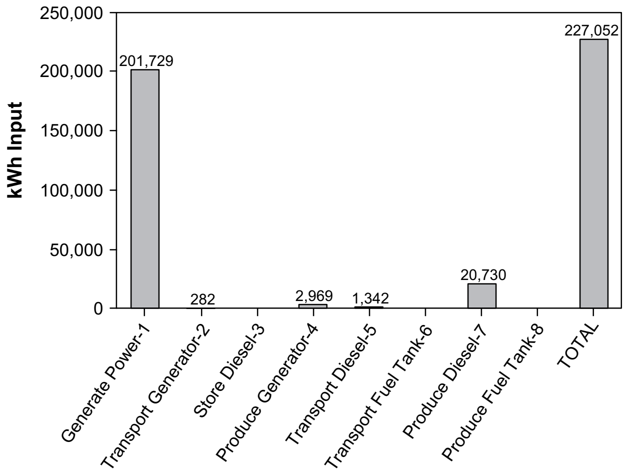

Fig. 4. Total kWh of energy input for each unit process of the diesel system.

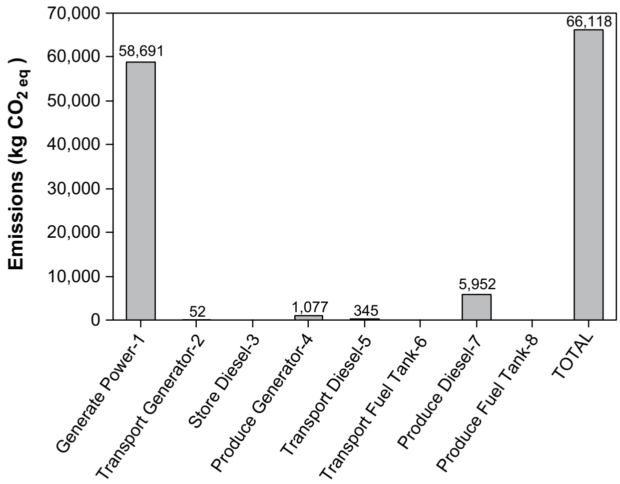

Fig. 6. Total of GHG emissions for each unit process of the diesel system.

benefits of small-scale wind power over diesel generators are significant when the entire life cycle is considered. This can be difficult to predict without an LCA, particularly in the case of off-grid wind systems which are heavily burdened by large battery banks. To illustrate the results, Fig. 7 portrays the total greenhouse gas emissions of the wind system and the diesel system in direct comparison. From this figure, it can be noted that although the data have a significant degree of uncertainty, the benefits of the wind system are clear. The wind powered system produces less than $^{1}/_{14}$ of the total greenhouse gas emissions that would be produced by the diesel generator. This is equivalent to a 93% emissions reduction.

6. Economic assessment

In terms of the environment, the impact analysis showed a significant benefit for the wind turbine system over the diesel generator. However, it is also important to understand the cost difference associated with the implementation of this system as it could play a significant role in determining the accessibility of this technology to potential users. For this reason, an economic assessment has also been included in this paper.

The simple sums of the system costs would indicate that the wind system was in fact the less expensive option. However, the wind turbine system has a large initial cost, whereas the expenses associated with the diesel fuel in the diesel system are spread out over the twenty-year period. Therefore, to account for these differences, the economic analysis performed in this study followed the Life-Cycle Cost methodology which considers parameters of inflation, interest, and year of purchase in order to account for the 'time value of money' on an investment [17]. For these calculations, an interest rate of 6% was used based on data from Statistics

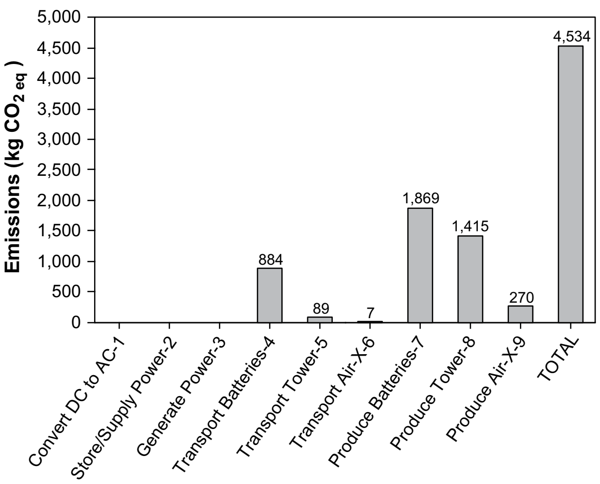

Fig. 5. Total of GHG emissions for each unit process of the wind system – wind system.

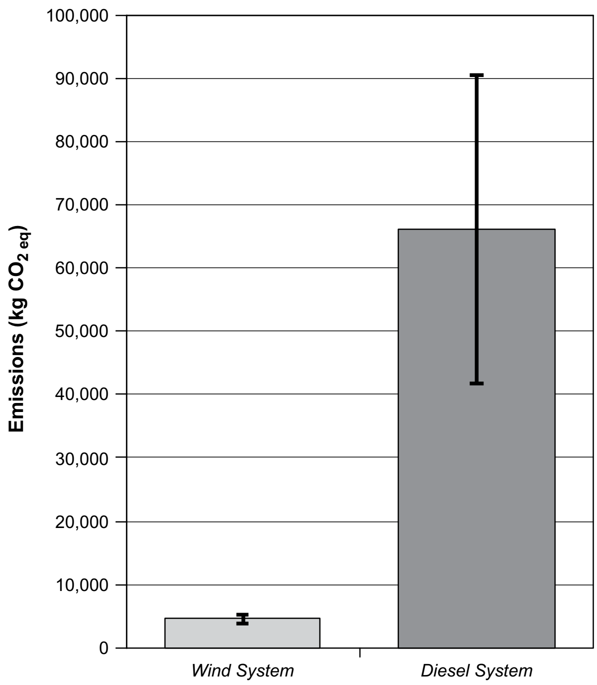

Fig. 7. Comparison of the total greenhouse gas emissions from both systems with 95% confidence range uncertainties.

Table 10
Results of the economic assessment and comparison of both systems.

Item	Cost/item (CAD)	Cost/functional unit (CAD)	Source	Year(s) of purchase
Wind system				
Air X turbine	800/turbine	4000	[36]	1
Inverter[a]	2500/inverter	5000	[37]	1 & 11
Tower	700/tower $_{\text{doubled for 30 m tower}}$[a]	7000	[36]	1
Battery bank	98.5/kWh$_{\text{storage capacity}}$	9140	[36]	1 & 11
Total		25,140		
Diesel system				
Diesel generator	1000/generator	2000	[36]	1 & 11
Diesel fuel	1.24/L	24,630	[38]	1–20
Total		26,630		
Total adjusted to "net-present cost"				
Total cost of the wind system		22,800		
Total cost of the diesel system		19,700		

[a] Note that given a lifetime of 10 years [13], two inverters are required to meet the functional unit requirement of 20 years.

Canada, and the inflation was approximated at 2% according to a report from the Bank of Canada [18,19].

This assessment was simplified by making the following assumptions. First, it was assumed that any differences in installation and maintenance costs between the two systems were negligible. In reality, the diesel system maintenance costs are likely much higher than the wind system, but no data were available to confirm this. Also, as the data were taken from retailers local to Edmonton, it was assumed that any price already accounted for the cost of transportation. Finally, as it was difficult to predict the cost of diesel over a 20 year period, it was assumed in this study that the price ($/L) of fuel will remain constant, increasing only proportionally to inflation.

The results of this analysis, which can be found at the bottom of Table 10, reveal that when accounting for the time value of money, the "net-present cost" of the diesel system was actually lower than the wind system by approximately 14%. This difference in cost was highly dependent on the price of diesel fuel which was selected in May 2008 at a period of relatively high oil prices. The drop in fuel prices notice since this economic analysis was performed will likely further impair the current economic disadvantage of the wind system. However, if the cost of diesel fuel increases beyond its 2008 value at any point over the 20 year period it is possible that the wind turbine system would become the more economically favourable option.

7. Improvement assessment

The purpose of this section was to determine which unit processes from each system contribute most significantly to the overall life-cycle environmental impacts of the system. This information is valuable, particularly if this product is to be redesigned, as it directly identifies which processes in a given system should be improved. As GHG emissions are the primary environmental impact considered for this study, the improvement assessment focused on emissions of this category.

Table 11
Considerations to improve processes of the wind system.

Unit process	Considerations
UP7, UP4 battery bank	Both processes could be dramatically improved if the number of batteries and mass of batteries could be reduced. This could be accomplished in many ways: alternative types of batteries may have lower life-cycle impacts or increased battery efficiency [39], installing wind turbines in a location with more wind resource and therefore lower batter requirement.
UP8 produce tower	Recycling or reusing tower materials was not considered and yet has great potential. Steel pipe has many uses and could be reused for another purpose or recycled. Alternatively, a taller tower would receive greater wind resource and thus reduce the number of turbines and towers required.
UP9 produce Air X	The majority of the Air X mass is aluminium. The manufacturer could implement a reuse program for the turbine body or could consider using less energy intensive materials when possible.

7.1. Wind generator system: A

Fig. 5 illustrates the total GHG emissions for each unit process. According to this information, the battery bank production was the most emission intensive process, followed by the tower production, then the battery bank delivery. The other system processes, including the production of the wind turbines, were essentially negligible in contrast to the three most intensive processes, collectively making up only 8% of the total emissions. Table 11 provides insight into how these processes could be improved.

7.2. Diesel generator system: B

As seen in Fig. 6, the diesel system was different from the wind system in the sense that essentially all of the GHG emissions were from one process: the electricity generation. When compared to the combustion emissions, the production of the generator and other components were essentially negligible. For this reason, if the diesel system is to be improved, the primary solutions would include efficiency gains for the generator or an alternative fuel. Biofuels with lower net GHG emission, for instance, could dramatically reduce the impacts of this unit process. However, it would be necessary to perform an in-depth life-cycle assessment that considers not only GHG emissions, but also land and water use, in order to determine whether or not true environmental benefits exist with the use of that fuel. Alternatively, small-scale wind turbines could be installed along side diesel generators to offset the majority of energy requirements, using the generator only for supplemental and backup power. This option would not only reduce the environmental impacts associated with the combustion of diesel, but could also operate with little or no battery bank storage capacity, thus eliminating the primary contributor to environmental impacts associated with the wind turbine system.

8. Conclusion

This study took two off-grid home energy systems, a wind turbine system and a diesel generator, and compared them along three different criteria:

1. Environmental impacts
2. Net-energy inputs
3. Economics

Firstly, with respect to the environmental impacts, there was a clear difference between the small wind turbine system and the diesel generator system. As mentioned earlier, the primary criteria used to distinguish the two systems was GHG emissions. According to that guideline, the Air X and battery bank system far outperforms the diesel generator by a factor of 14.6. In other words, a strong conclusion could be made to advocate for the use of wind power over diesel generators when GHG emissions are the primary concern.

Secondly, a similar conclusion can be drawn in terms of the net-energy inputs for the two systems. The diesel generator relies upon the energy of fossil fuels to produce electricity. This in turn causes the system to have a very large net-energy input requirement over the system's life cycle. The wind turbine system, however, makes use of wind to produce the electricity, thus input energy was only required to construct and transport the equipment. As shown in this study, even when including a large battery bank, the wind turbine system actually produces more energy over its life cycle than was required to produce the system.

Thirdly, when comparing the economics of the two systems, the results were considerably less clear. According to this study, even with the relatively high price of diesel fuel, the wind turbine system had a slightly higher net-present cost than the diesel system. Numerous factors, such as further increases in fuel prices over the 20 year life of wind turbine system, government subsidies, or decreases in turbine and battery bank costs could easily reverse this outcome.

Therefore, when all three criteria are considered together, the potential investor must decide whether the environmental benefits are worth the investment. At this point in time it is worth making a reminder that the specific wind turbine chosen for the study was one of the smallest available on the market, thus providing a minimum performance both economically and environmentally, given the effects of economy of scale. It is likely that small-scale wind power would be even more environmentally sound and economically favourable given a larger wind turbine, a stronger wind regime, or a smaller battery bank. Therefore, the results of this study may serve as a base line for the minimal environmental benefits that can be expected from installing a small wind turbine system as opposed to a diesel generator.

As the majority of homes in Canada are grid connected, future studies comparing grid-tied small wind turbines to grid provided electricity on both a GHG and economic level could be of even further interest. This would be another excellent application for life-cycle assessment methodologies.

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