Project Gryphon
A Comparative Life Cycle Assessment of Biodiesel- and Battery-Powered Ride-on Mowers

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by

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A SEEDS Project

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Executive Summary

This report is a summary of a life cycle assessment (LCA) that compares two ride-on mowers: A B5-biodiesel fueled Kubota F3680 and Li-ion battery-powered CXR-60. The LCA is limited to the product's Use phase which is recognized as having the most impact of all life phase for durable goods. The two mower systems are compared across four impact categories: Total primary fuel consumption, global warming, acidification and total toxicity potentials.

In all categories, the impact of the biodiesel mower is an order or, as in the case of energy use, orders of magnitude higher than that for the battery-powered system. The hydro source of electric energy is mainly responsible for the superior environmental performance of the battery mower.

Reported battery toxicity allocated to the Use phase was also found to be due to the combustible fuels used to generate electricity. Toxicity is not inherent to the use of the battery itself, so it should not be of concern in BC where electricity is generated mainly from hydro sources.

Economically, battery powered mowers could be more advantageous over their service life. Non-trivial savings could be made provided that the mowers are reliable and no capital investment is needed to upgrade the infra-structure to accommodate the new systems.

From the perspective of the general population of the university, students, professors and administrators, electric mowers would be a welcome change. The reduced noise and "green" image that electric mowers project to the community is an overwhelmingly positive one. For the operators and technicians, the people who will be using and maintaining the systems, battery mowers could be a source of nuisance. To them battery mowers are not as reliable or as powerful as the diesel ones. Also the charge capacity is not comparable to diesel mowers. These all are legitimate concerns but they could be mitigated by providing the operators with proper technical training and at least one trial system for them to test first hand.

A methodology for aiding management at Building Operations to make a decision is outlined. An algorithm that applies the hierarchical weighted scoring score method will be delivered before the middle of December, 2013.

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1.0 Introduction

The Building Operations has pledged to reduce it GHG emissions by 67% -based on its 2007 emissions- by the year 2020. In an effort to meet its commitment, the management has initiated a number of measures that ranged from encouraging behavioral driving patterns to replacing aging fleet vehicles with new higher efficiency vehicles and alternatively-powered ones. Kubota ride-on mowers and small four-wheel utility tractors, which are due for replacement by UBC standards, are looked on as an opportunity to attain emission reduction goals for this and later years. The options being considered are new diesel vehicles or electric equivalents.

Management at Building Operations has asked to have a comparative Life Cycle Assessment of the Kubota mowers/vehicles and their potential alternatives to aid in the decision making process. In addition to quantifying the environmental impacts of the vehicles, the study is to examine the economic consequences as well as the social impacts on the university population including the operators and the students. The task of executing the LCA study was trusted to students of the CEEN 523 course by the Sustainability office at UBC as a part of its continuing SEEDS program.

An LCA has four stages: (1) Goal and Scope, (2) Inventory Analysis, (3) Impact Assessment and (4) Interpretation. In Goal and Scope the objective of the study is stated and the system boundaries are clearly delineated. In inventory analysis energy and materials flows as well as emissions are tallied and characterized. In impact assessment, environmental burdens characterized in inventory analysis are classified and their mid-point impacts clarified. In the final stage of the study, the results of inventory analysis and impact assessment are interpreted in relation to the stated goal and scope.

There have been studies that compared electric (Battery-powered) to conventional diesel vehicles such as Hawkins and Singh (2012). Other studies like Sivaraman and Lindner (2004) addressed the environmental impacts of household (diesel, corded and battery) push mowers in the USA. Another relevant LCA study is one by the U.S. EPA that detailed the environmental and health impacts of Lithium-ion EV batteries. Some of the conclusions of this last study will be examined for their applicability to the present study and interpreted in the context of their geographic limitations. One more study that looked at the LCA of LPG powered riding (ride-on) mowers by Unnasch and Waterland (2011) is used here for its reference and use of GREET. More to come on the subject of GREET when discussing methodology in the LCI section. Owano (2012) draw attention to the serious impacts relating to material extraction and manufacturing of electric vehicles. More importantly, she points to the detrimental role that the source of electricity plays in determining the advantage, if any, of electric vehicles.

This LCA has for a focus the ride-on mowers whose sole function is to mow lawn areas within the UBC grounds and which are due to be replaced shortly by Building Operations. A parallel LCA study looks at small grounds-service four-wheel drive tractors. The results of that study are presented in a separate report.

Finally, Gryphon is the name given to the project by the Building Operations manager who commissioned the study. So, it is in deference to his wish that the name appears in the title of the report.

2.0 Goal and Scope

2.1 Objective

The objective of this study is to accurately characterize the environmental, social and economical impacts of two alternatives: a B5-bioDiesel fueled Kubota (model F3680) and a Lithium-battery powered (the CXR-60 zero-turn) ride-on mowers. Sealed Lead Acid (SLA) battery-powered mowers were excluded, though specified in the project statement, simply because they do not meet the functionality requirement of the Operations department, namely four to five hour mowing capacity. Also, it was felt that there are considerable difference between the mowers and the small four-wheel tractors that they warranted two separate studies. Combining the two studies would have meant much more uncertainty in the results.

On the other hand, as mentioned in the summary, the results arrived at here could easily be extended, with reasonable accuracy, to other comparably-sized gardening and service vehicles. That is, more general conclusions can be drawn from the results presented in this report.

2.3 Product Systems

The two systems that are compared here are the Kubota F3680 and the CXR-60. Both are ride-on mowers. The Kubota mower has a 36 hp engine and runs on B5-biodiesel, a mix of 5% bio fuel and 95% low sulfur diesel. Power is transmitted to the mowing deck via a PTO (Power take-off) axel. The deck comprises three steel cutting blades arranged in a row. The height of the mowing deck is hydraulically controllable. The width of the cutting path is 72 inches in width.

The battery powered mower, the CXR-60, is rated (by the manufacturer) as 36 hp mower. In reality, the mower is "equivalent" to a 36 hp diesel power. Equivalency here means equal output power at the wheels and cutting blades, taking into consideration the continuous operating horsepower and internal losses of the respective engines of both mowers. The CXR-60 is powered by a 4-module Lithium iron phosphate battery with a total storage capacity of 11.52 kWh. The mowing deck is smaller than that for the Kubota and results in a 60 inch wide cutting path (see Appendix C).

2.3 Intended Audience

The intended recipient of the study is UBC Fleet Inventory manager who is looking to make an informed decision, based on objective measure, regarding his next purchase of mowing systems and Ground service vehicles. So, in addition to determining and interpreting the environmental impacts of the mowing systems studied, a hierarchical algorithm for making a decision based on specific set of criteria is included. Weighting factors are determined by the decision maker and other stake-holders to reflect the relative importance of the decision criteria included in the algorithm. Finally a step by step procedure for scoring each system is outlined.

After review by the UBC SEEDS office, the study could potentially be made available for interested parties via UBC library. Library resources are accessible and searchable by internet. LCA practitioners could therefore have access and make use of the study.

2.4 Functional Units

The functional unit allows comparisons of equivalent systems. Emissions and impacts of product systems- mowers in this case- are normalized on the basis of functional unit. The main function of the Kubota F3680 is grass-mowing and to a much lesser degree for moving to and from the mowing spot. This latter functional represent a minute part and could be accounted through the overlap factor that is used to determine the area mowed per hour. Therefore, here only the mowing function is considered. Based on that, the functional unit chosen for this study is the equivalent of the surface area mowed by all four ride-on mowers at UBC in any given year, namely 8.267082 km^2.

This figure was obtained by multiplying the total lawn area where ride-on mowers are used by the frequency of mowing per year. For UBC, the mowing season extends over 25 calendar weeks, from the end of March through the middle of October. Grounds department records show scheduled weekly maintenance for lawn areas. That translates into a frequency of 25 mowings/lawn-area/year. The total lawn area was calculated by adding all larger (than 1000 m^2) grass areas. This area is consistent with theoretical values and estimates by some of the operators whose feedback was solicited through a written survey (see Appendix B).

2.5 System and Spatial Boundaries

A full LCA study of a product system is an examination of the environmental impacts incurred during all stages of life. A product's life stages include (1) Material Acquisition/Production, (2) Transportation, (3) Manufacturing, (4) Use and (5) End of Life. However, due in part to the complexity of the product system considered and the time limitation, only the "Use" phase of the life cycle is included in this study. Other reasons for restricting the study to one phase are the following:

- It is a comparative study of two systems that are relatively similar in their size, composition and construction.
- Very little data is available about the manufacturing and production processes involved that most of it would have had to be assumed. The results would then have been untrustworthy as to be useless to the recipient of the study or anyone else.
- Results from more exhaustive studies of comparable systems are consistent with the conclusions arrived at here. And
- There is a general agreement that for durable products, energy consumption and flows associated with the Use phase are more substantial than in the rest of the stages. Again that is consistent with the results of other studies, see [3] for an example.

As UBC replaces its fleet every seven years whereas the expected life of both the mower and the batteries are expected to last well beyond that, the end-of-life stage was also excluded. See figures 1 and 2 for representations of the life cycle boundaries and reference flows for both the Kubota F3680 mower and the CXR-60.

Another boundary to delineate here and which limits the applicability of the study is the spatial or geographic boundary to which this LCA is specific. The results and conclusions arrived at here wholly depend on the so-called electricity mix, that is the particular combination of primary energy sources used to generate electricity, in BC. British Columbia generates most of its electricity from hydro power. That is not typical for most of the rest of the world.

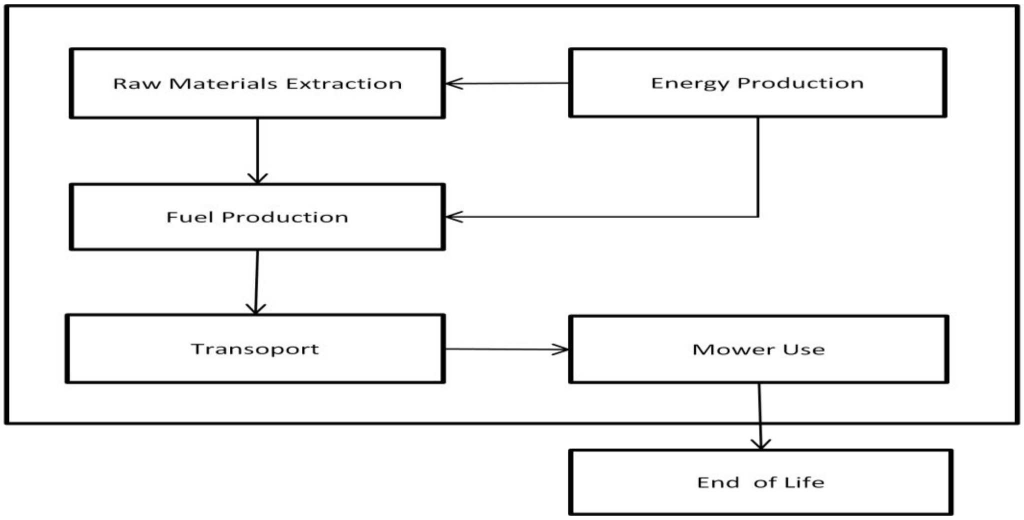


Figure 1. System boundary and reference flows for the Kubota F3680 mower

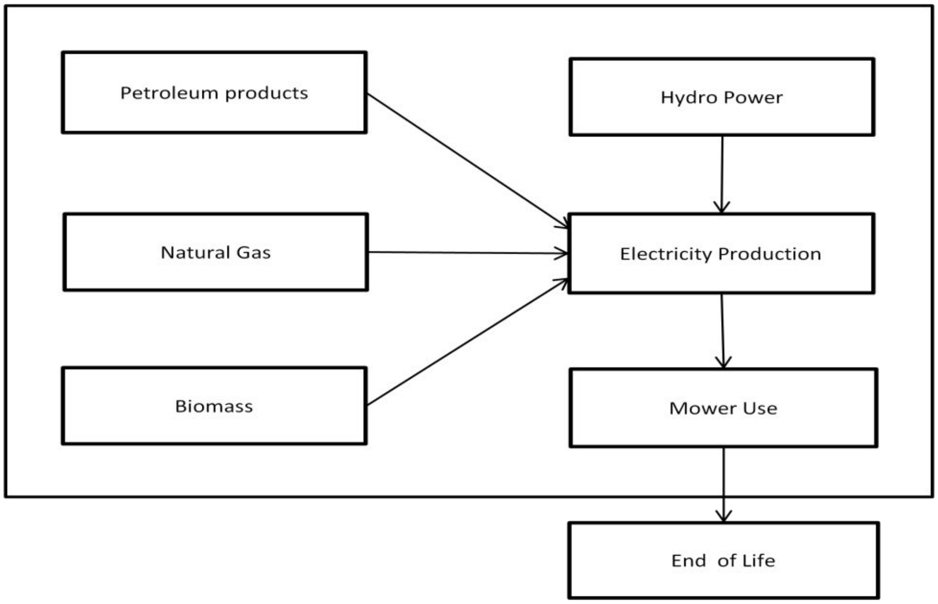


Figure 2. System boundary and reference flow for the CXR-60 mower

2.6 LCIA Impact Categories

Impacts can be categorized as either mid-point impacts or end-point impacts. The cause-and-effect relationships between emissions and mid-point effects are scientifically established. The causations of end-point categories are less certain. For these reasons, this study adopts the following mid-point categories to characterize:

- Total primary energy consumed (TPE) measured in MJ (mega Joules),
- Global warming potential (GWP) measured in kg CO2 equivalent,
- Acidification potential (ARP) in kg of SO2 equivalent, and

- Total toxicity (human) potential (TTP) in (kg/year)/(mg/m^3). Other impact categories were much less significant and therefore were omitted from the study.

It was concluded that the magnitudes of other mid-point impacts, such as Smog formation potential (SFP) and Eutrophication potential (EP) and others, are too small to matter. So they were omitted from graphs for clarity.

2.7 Data Sources

Data for this study were collected from two primary and secondary sources. Primary sources included Building Operations (managers and mower operators) and the manufacturer of one of the mowers. This latter source communicated general information about the product and answered questions directed to them by the author of the study. Some of the data was obtained in face to face meetings, emails, phone conversation and through surveys filled in by operator with firsthand experience of the one of the biodiesel mower studied.

Secondary sources included journal articles and published LCA studies, Standards, various environmental agencies and course handouts. Examples of data that were obtained from secondary sources are the impact factors (GWP, ARP and the like) and low heating values (LHV) of fuels none of which is dependent on geography or time.

3.0 Inventory Analysis

LCI is the stage of Life cycle that involves the quantification of inputs and emissions of the product system for each of the life stages analyzed [6]. In the context of this study, LCI is then the determination of the nature and quantities of inputs and emissions of the Use stage for the Kubota F3680 and the CXR-60 ride-on mowers.

3.1 Inputs and verifications

The input to the "Use" stage is the energy, in Mega Joule, supplied to the mower per functional unit. In the case of biodiesel mower, that meant determining the fuel used per functional unit and then transforming that into MJ. For the battery powered mower, it meant determining the KWh per functional unit first which then is transformed into MJ.

Fleet management at Building Operations provided the bulk of data used in the calculations of environmental loads. Specifically, they provided fuel logs which listed among other information the hour-meter reading at each fueling. The total volume used per year per mower and the corresponding number of service hours were easily extracted from the fuel logs. Next, the total area mowed was computed based on (1) the total surface lawn areas maintained, (2) an estimate of the percentage of that area in which ride on mowers are used and (3) the schedule for lawn maintenance. The aforementioned percentage is based on estimates by the operators. However, it is also consistent with theoretical values computed solely based on the number of mowers, engine powers and characteristics and theoretical mowing speed. All calculations are detailed in Appendix A.

For the Battery powered mower, the total energy per functional area was calculated based on (1) the battery stored energy per charging (total energy capacity), (2) the service time per single charge and (3) a theoretical mowed area per hour. Below are flow charts that outline how the total primary energy required per functional unit was computed in the case of the two mowers (see Appendix A).

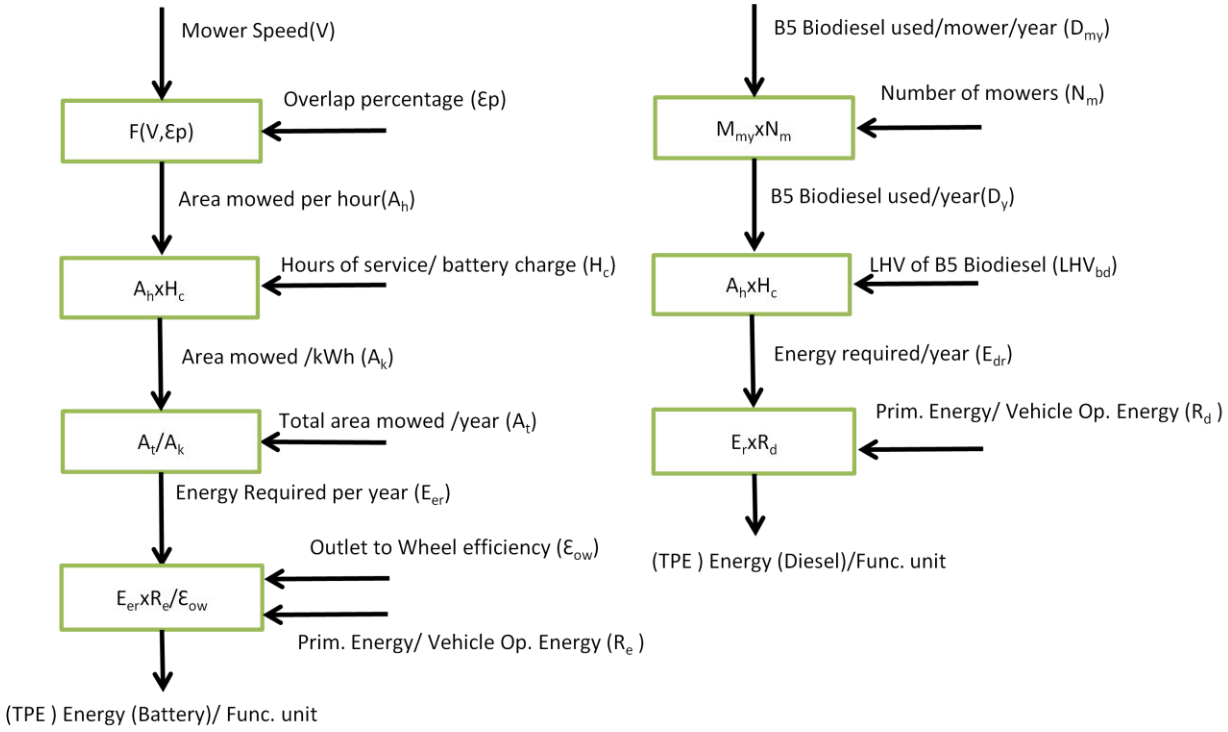


Figure 3. Flowcharts for computation of total primary energy for biodiesel and battery mowers

The meaning of some of the parameters that appear in the flow charts above is evident. However the source and meaning of others need to be elaborated. For example, Rd or Re, the ratios of primary to vehicle operation ratio were obtained from GREET (more on that below). The overlap percentage accounts for the fact that some lawn areas are covered twice. The overlap percentage could be increased to account for other mowing inefficiencies like going around plants etc. And finally, the outlet to wheel efficiency is the product of internal battery efficiency (90%), charger efficiency (90%) and battery maximum discharge (95%). The first two values were obtained from literature. The value for the maximum discharge (normally stated as the minimum battery charge) was obtained from the mower supplier. Actually it was claimed by the supplier that the battery could safely be discharged completely, however the minimum charge was set to 5% as a more realistic scenario.

1) For biodiesel mower
   - Biodiesel required per mower per year, D_m= 729 L/mower/year
   - Number of mowers, N_m=4
   - Low heating value of B5-Biodiesel, LHV_{bd} = 36.1 MJ/L
   - Primary Energy to Vehicle Operation Energy, R_d= 5056.3/4089.9 (Btu/mi)/(Btu/mi)
2) For battery mower
   - Mower Speed= 6km/hour (based on feedback from operators and manufacturer)
   - Overlap percentage= 10%
   - Hours of service per battery charge, H_t= 4 hours/11.52 kWh (supplier)

- Total Area mowed per year, A_t = 8.27 km^2 (one functional unit)
- Outlet to wheel efficiency, $\mathcal{E}_{ow}$= .77
- Primary energy to vehicle operation energy, R_e= 1959.3/1592.8 (Btu/mi)/(Btu/mi)

Note that the data provided by Building Operations for total mowed area biodiesel and the quantity of fuel consumed were consistent with theoretical values. See Appendix A for details.

By following the steps of the procedure outlined above, one obtains the total primary energy per functional unit for biodiesel and battery mowers as 129974 MJ and 16648 MJ respectively.

The mower speed in operation was estimated by a number of operators who filled in a survey that was prepared by the study author.

3.2 GREET Model and Emission Factors

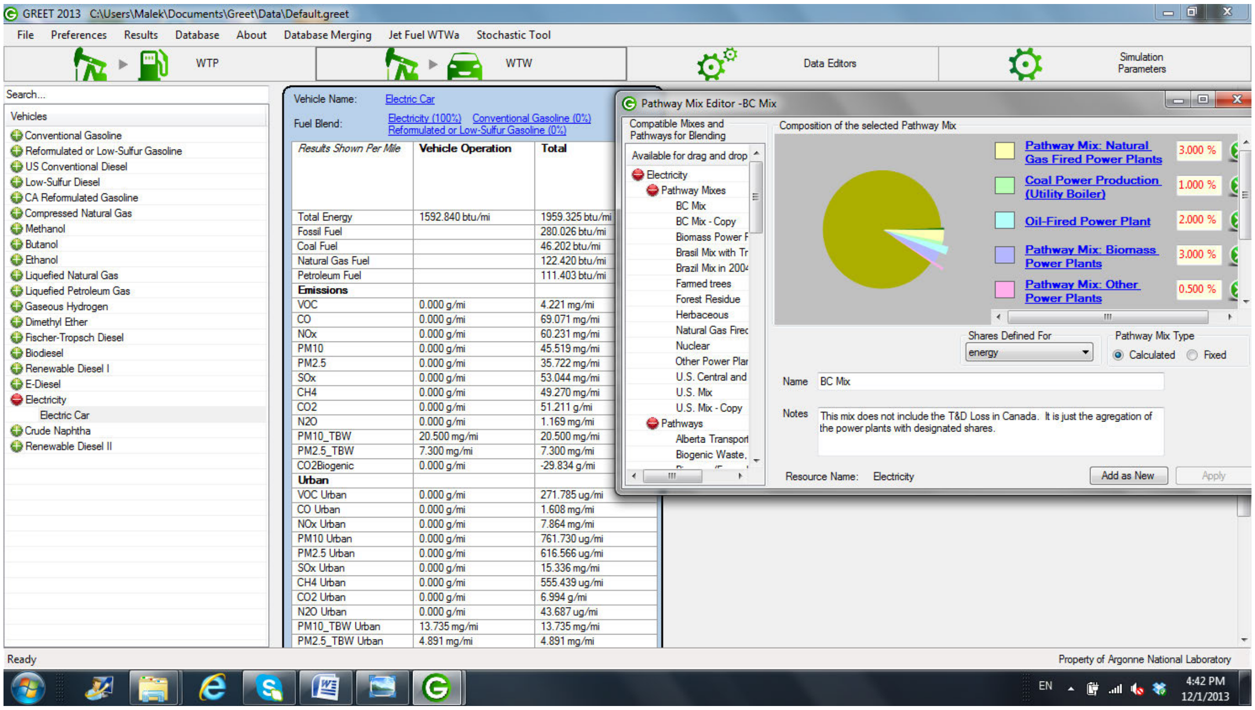
GREET is the U.S. Argonne National Laboratory life cycle modeling software for transportation. In this study, it was used to obtain the emission factors associated with both mower models considered here. In GREET, the user could choose between two modes WTP (Well to Pump) and WTW (Well to Wheel). The WTW mode generates for the total primary energy (TPE) which is the energy needed to extract, manufacture and transport the fuel as well as to operate the vehicle. The energy for operating the vehicle is stated along with the TPE both of which are expressed in Btu/mi.

In WTW mode, one could specify the type of vehicle and the fuel or fuel mix that is used as the inputs. The output is the emission factors (CO_2, CO, NO_x etc) stated in terms mg/mi (milligram/mile) or g/mi. GREET database includes a fair list of vehicles and fuel mixes that are already modeled. Unfortunately, mowers, B5-biodiesel and the BC electricity mix are not in the database.

To express emissions in more useful terms, namely in g/MJ or kg/MJ, the grams per mile values for each emission were divided by the Btu/mi for the fuel used. The resulting number for each type of emission is independent of the vehicle efficiency but depend on the energy consumed. For that reason, it was assumed that the CIDI car modeled in GREET and the mower, both of which use the same fuel- generate the same amount of emissions on per MJ consumed.

B5-biodiesel which is 5 percent by volume bio fuel was modeled as a mix of B20-biodiesel and low sulfur diesel. That means emission values for B5-biodiesel were interpolated between corresponding values for B20-biodiesel and 100 percent low sulfur diesel. The difference in the emission factors for all three is negligible. Transportation distances for the fuel were assumed the same as for the modeled fuels as no specific information was available for BC to warrant a correction.

The negligible difference between B20- and B5-biodiesels does not carry to the case of the electricity mixes. The BC electricity mix which combines 90 percent hydro with the other 10 percent coming from natural gas, biomass and other thermal sources generates emissions that are substantially different from the U.S. or Alberta electricity mixes. For that reason, it was necessary to model the BC electricity mix and add it to the database (see Figure 4 below). The vehicle was then paired with the new electricity mix to produce the emissions shown in Table 1 below.



Vehicle Name: Electric Car

Fuel Blend: Electricity (100%) Conventional Gasoline (0%) Reformulated or Low-Sulfur Gasoline (0%)

Results Shown Per Mile	**Vehicle Operation**	**Total**
Total Energy	1592.840 btu/mi	1959.325 btu/mi
Fossil Fuel		280.026 btu/mi
Coal Fuel		46.202 btu/mi
Natural Gas Fuel		122.420 btu/mi
Petroleum Fuel		111.403 btu/mi
Emissions		
VOC	0.000 g/mi	4.221 mg/mi
CO	0.000 g/mi	69.071 mg/mi
NOx	0.000 g/mi	60.231 mg/mi
PM10	0.000 g/mi	45.519 mg/mi
PM2.5	0.000 g/mi	35.722 mg/mi
SOx	0.000 g/mi	53.044 mg/mi
CH4	0.000 g/mi	49.270 mg/mi
CO2	0.000 g/mi	51.211 g/mi
N2O	0.000 g/mi	1.169 mg/mi
PM10_TBW	20.500 mg/mi	20.500 mg/mi
PM2.5_TBW	7.300 mg/mi	7.300 mg/mi
CO2Biogenic	0.000 g/mi	-29.834 g/mi
Urban		
VOC Urban	0.000 g/mi	271.785 ug/mi
CO Urban	0.000 g/mi	1.608 mg/mi
NOx Urban	0.000 g/mi	7.864 mg/mi
PM10 Urban	0.000 g/mi	761.730 ug/mi
PM2.5 Urban	0.000 g/mi	616.566 ug/mi
SOx Urban	0.000 g/mi	15.336 mg/mi
CH4 Urban	0.000 g/mi	555.439 ug/mi
CO2 Urban	0.000 g/mi	6.994 g/mi
N2O Urban	0.000 g/mi	43.687 ug/mi
PM10_TBW Urban	13.735 mg/mi	13.735 mg/mi
PM2.5_TBW Urban	4.891 mg/mi	4.891 mg/mi

🟨	Pathway Mix: Natural Gas Fired Power Plants	3.000 %
🟩	Coal Power Production (Utility Boiler)	1.000 %
🟦	Oil-Fired Power Plant	2.000 %
🟪	Pathway Mix: Biomass Power Plants	3.000 %
🟥	Pathway Mix: Other Power Plants	0.500 %

Shares Defined For: energy

Pathway Mix Type: ● Calculated ○ Fixed

Name: BC Mix

Notes: This mix does not include the T&D Loss in Canada. It is just the agregation of the power plants with designated shares.

Resource Name: Electricity

Figure 4. A screen shot of GREET showing emissions corresponding to BC electricity mix

Table 1. Summary of the emissions for both the biodiesel- and the battery-powered mowers

	TPE, Biodiesel (MJ)	129974	**TPE, Battery (MJ)**	16649
Emissions	**B5 Biodiesel mower**		**Battery powered mower**	
	Vehicle Operation	**Total**	**Vehicle Operation**	**Total**
	Energy(Veh. Op.) 4090 btu/mi	Energy consumed 5056 btu/mi	Energy(Veh. Op.) 1593 btu/mi	Energy Consumed 1959 btu/mi
VOC	88.0 mg/mi	124 mg/mi	0.00 g/mi	4.22 mg/mi
CO	539 mg/mi	592 mg/mi	0.00 g/mi	69.1 mg/mi
NOx	141 mg/mi	366 mg/mi	0.00 g/mi	60.2 mg/mi
PM10	9.0 mg/mi	48.8 mg/mi	0.00 g/mi	45.5 mg/mi
PM2.5	8.40 mg/mi	29.7 mg/mi	0.00 g/mi	35.7 mg/mi

SOx	2.23 mg/mi	149 mg/mi	0.00 g/mi	53.0 mg/mi
CH4	2.60 mg/mi	497 mg/mi	0.00 g/mi	49.3 mg/mi
CO2	322 g/mi	398 g/mi	0.00 g/mi	51.2 g/mi
N2O	12.0 mg/mi	13.0 mg/mi	0.00 g/mi	1.17 mg/mi
PM10_TBW	20.5 mg/mi	20.5 mg/mi	20.5 mg/mi	20.5 mg/mi
PM2.5_TBW	7.30 mg/mi	7.30 mg/mi	7.30 mg/mi	7.30 mg/mi
CO2Biogenic	0.000 g/mi	-190 mg/mi	0.00 g/mi	-29.8 g/mi

Customarily bio-fuels have been treated as carbon neutral. The minus sign attached to biogenic CO_2 in the table above serves to subtract the CO_2 emissions due to the bio-fuel portion of the fuel mix used in production and distribution of fuel.

4.0 Life Cycle Impact Assessment

The outputs of the LCI step, i.e. the emissions and the total energy consumed, are the inputs of the life cycle impact assessment. LCIA has three phases which are:

- Classification- This is the process of combining emissions that contribute to the same mid-point category. For example CO2, CH4, and NO_x among other emissions all contribute to global warming potential.
- Characterization- That is the quantification of the contribution of each of the emissions to the mid-point categories considered here.
- Valuation- That is assigning a weight to each impact category that reflects its importance in the estimation of the decision maker/s. Weighting allows for combining all impacts into a single score based on which a decision could be made.

This last step is avoided altogether here to avoid assuming the decision making responsibility when that clearly lies with the stakeholder who commissioned the study, i.e. Fleet management of Building Operations. So instead, a decision tree (a hierarchical scheme) and an algorithm are provided to the primary decision maker for them to assign weights as they see fit.

All LCA software packages, for example GhGenius and Gabi, have an LCIA component to them. In this study however, given the simplicity of the emissions, the classification and characterization steps were accomplished using an Excel spreadsheet. The results are shown in Tables 2 and 3.

Table 2. Mid-point impacts per functional area and TP energy consumed in case biodiesel mower

Total Primary Energy Consumed= 115922 MJ (Biodiesel Mower)

Pollutant	**Emissions factors (g/MJ)**	**Emissions (kg/year)**	**GWP**	**GW (kg CO2 Eq.)**	**ARP**	**ARP (kg SO2 Eq.)**	**TLV (mg/m^3)**	**TTP ($kg/year/mg/m^3$)**
VOC	0.0233	3.03	3	9.10	0	0.00	1800	0.0017
CO	0.1109	14.4	1.9	27.4	0	0.00	29	0.4969
NOx	0.0686	8.92	27	240.8	0.7	6.24	5.6	1.5924
PM10	0.0091	1.19	0	0.00	0	0.00	15	0.0793
PM2.5	0.0056	0.72	0	0.00	0	0.00	15	0.0482
SOx	0.0279	3.62	0	0.00	1	3.62	5.2	0.6962
CH4	0.0932	12.12	21	254.5	0	0.00	1000	0.0121
CO2	74.72	9711	1	9711	0	0.00	9000	1.0790
N2O	0.0024	0.32	310	98.3	0	0.00	50	0.0063
PM10_TBW	0.0038	0.50	0	0.00	0	0.00	15	0.0333
PM2.5_TBW	0.0014	0.18	0	0.00	0	0.00	15	0.0119
CO2Biogenic	-0.0357	-4.64	1	-4.64	0	0.00	9000	0.0005
				10336		**9.86**		**4.06**

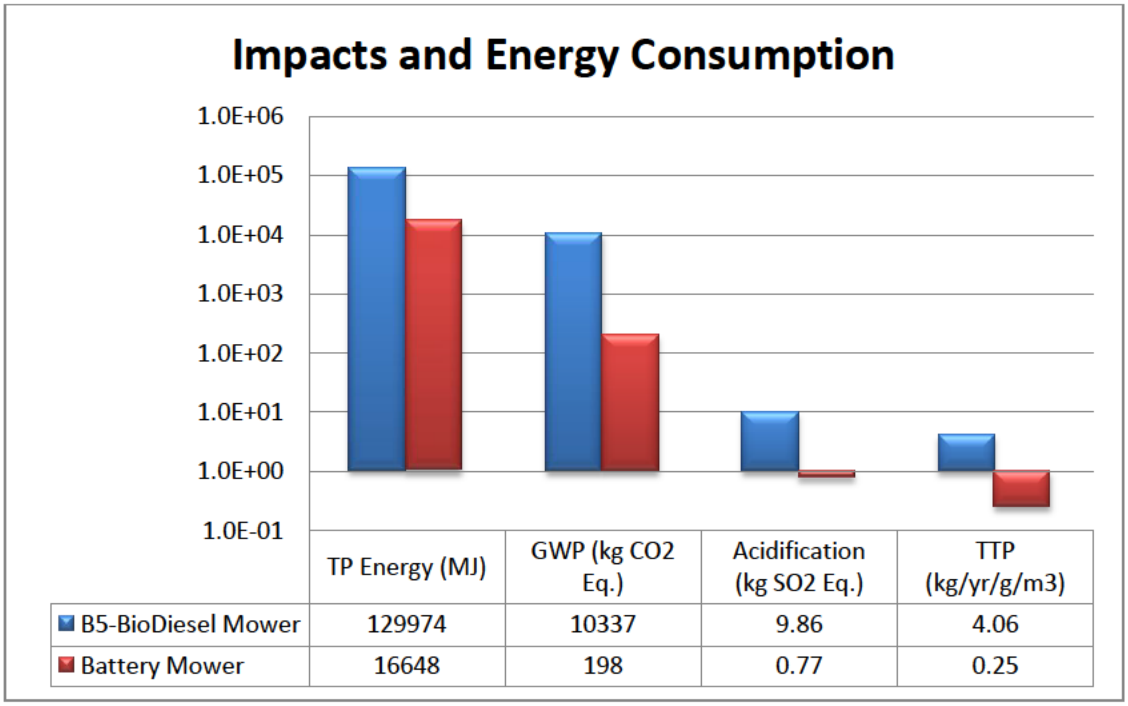
Table 3. Mid-point impacts per functional unit for the case of battery-powered mower

Total Primary Energy (TPE)= 16649 MJ (CXR-60 mower)

Pollutant	**Emissions factors (g/MJ)**	**Emissions (kg/year)**	**GWP**	**GW (kg CO2 Eq.)**	**ARP**	**ARP (kg SO2 Eq.)**	**TLV (mg/m^3)**	**TTP ($kg/year/mg/m^3$)**
VOC	0.0020	0.03	3	0.10	0	0.00	1800	0.00
CO	0.0334	0.56	1.9	1.06	0	0.00	29	0.02
NOx	0.0291	0.49	27	13.10	0.7	0.34	5.6	0.09
PM10	0.0220	0.37	0	0.00	0	0.00	15	0.02
PM2.5	0.0173	0.29	0	0.00	0	0.00	15	0.02
SOx	0.0257	0.43	0	0.00	1	0.43	5.2	0.08
CH4	0.0238	0.40	21	8.33	0	0.00	1000	0.00
CO2	24.7708	412.4	1	412.4	0	0.00	9000	0.05
N2O	0.0006	0.01	310	2.92	0	0.00	50	0.00
PM10_TBW	0.0099	0.17	0	0.00	0	0.00	15	0.01
PM2.5_TBW	0.0035	0.06	0	0.00	0	0.00	15	0.00
CO2Biogenic	*-14.43*	*-240.2*	*1*	*-240.2*	*0*	*0.00*	*9000*	*0.03*
				198		**0.77**		**0.32**

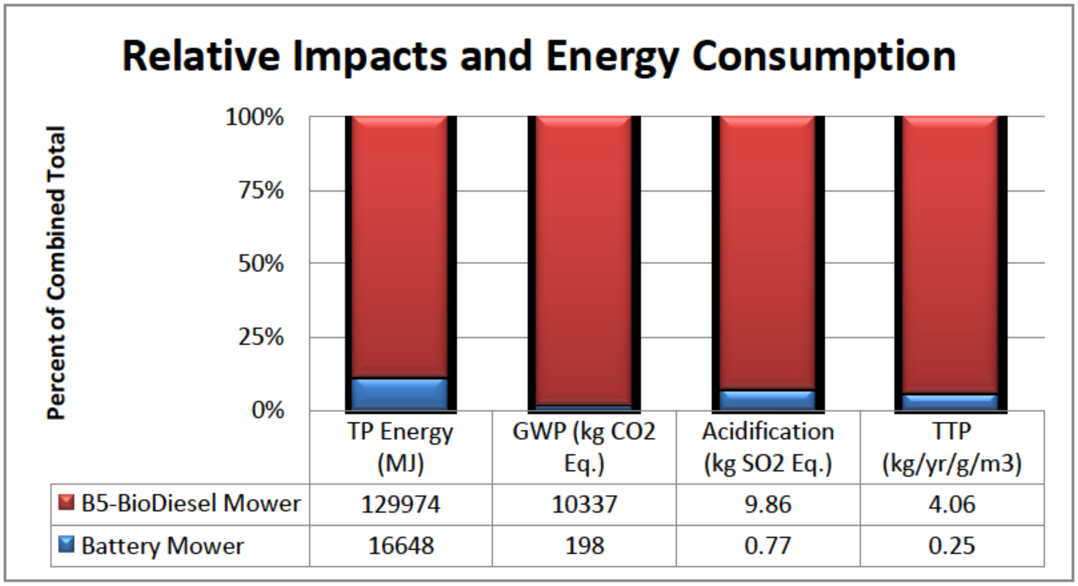
5.0 Results and Interpretation

The total primary energy (TPE) consumed and the mid-point impacts are shown graphically in Figures 3 and 4 for both of ride-on mowers. Mid-point impacts displayed are global warming (GWP), acidification (ARP) and total toxicity potentials (TTP).



	TP Energy (MJ)	GWP (kg CO2 Eq.)	Acidification (kg SO2 Eq.)	TTP (kg/yr/g/m3)
🟦 B5-BioDiesel Mower	129974	10337	9.86	4.06
🟥 Battery Mower	16648	198	0.77	0.25

Figure 5. Mid-point impacts and energy consumptions for Kubota F3680 and CXR-60 mowers



	TP Energy (MJ)	GWP (kg CO2 Eq.)	Acidification (kg SO2 Eq.)	TTP (kg/yr/g/m3)
🟥 B5-BioDiesel Mower	129974	10337	9.86	4.06
🟦 Battery Mower	16648	198	0.77	0.25

Figure 6. Relative mid-point impacts and energy consumptions for Kubota F3680 and CXR-60 mowers

In terms of energy consumption, the biodiesel mower consumes over 7.8 times the total TP energy necessary to operate the battery-powered mower. In fact in every mid-point impact category, the biodiesel mower contributes between 12 (for ARP) and 52 (for GWP) times as much as the battery mower.

It is worthwhile here to remind the reader that the attenuated impact of the battery mower is due for the most part to the fact that electricity is derived from hydro power. In the section “sensitivity analysis” we look at the impacts of using a different electricity mix.

Also, the impacts and energy consumed are limited to the Use stage of the mowers. However, as explained in Scope and as could be inferred from similar studies, the Use phase is the most energy-consuming and has the highest GWP impact.

One last note, if consumables (engine and transmission oils, oil filter, coolants etc) used for maintenance were included, the impact score of the biodiesel would get worse, but not by much. Oils, which amount to about 2.3 % of the biodiesel consumed, are either recycled or burned for fuel. Solid waste, filter inserts, amount to less than 4 kg per functional unit. As this LCA study is a comparative one, no further insight is gained by following through calculations of the exact emissions due to these consumables.

6.0 Sensitivity Analysis

LCA studies are as good as the data used to generate the inventory analysis and the LCIA. There were assumptions made for both types of mowers. In the case of the biodiesel mower, an overlap percentage ($\mathcal{E}_p$) of 10 percent was used and the drive between the work and the mower storage areas was neglected. However, neither of these two quantities would have affected the emissions of the biodiesel mower because those were based on the actual quantity of fuel used. On the other hand, revising $\mathcal{E}_p$ upward would result in a smaller area mowed per year and would entail redefining the functional unit to be proportionately smaller. That again does not affect the relative impacts of the two mowers, if all other parameters are kept fixed.

In the case of battery powered mower there were a few assumptions. One of which is the speed of the mower (V_m) when cutting the grass. It was assumed to be 6 km/h. A second parameter that was based on the supplier's claim is the service hours per single battery charge, H_c, which was reported to be between 4 and 5 hours. A third assumption which in part was based on values from literature deals with the internal losses of the battery, i.e. outlet to wheel efficiency $\mathcal{E}_{ow}$. If all these values were revised down, then it would mean more energy consumption and more emissions. To quantify these effects, the parameters are given the following values:

- Vm= 5 km (that is slow)
- Hc= 3 h/11.52 kW-h
- $\mathcal{E}_{ow}$ = .65 (it includes the transmission losses)

When the algorithm shown in Inventory Analysis section is executed, the new TP energy required per functional unit is 31536 MJ. The corresponding impacts are illustrated in Figure 5 below.

Next the influence of electricity mix is investigated. That is, if electricity used for the battery mower was produced at power plants representing the U.S. mix, and assuming the same TP energy demand as in the original scenario, the resulting impacts are shown in Figure 5. Impacts in Figure 5 are normalized relative to the biodiesel (diesel) case. Battery (BC, 6k) refers to the case where the mowing speed is 6km/h (the original scenario). While Battery (BC, 5k) refers to the case of a mower whose operating parameters are defined above.

This figure emphasizes the fact that the source of electricity plays a determining role on the environmental impacts, as was pointed out by Owano [7]. Assuming less efficient battery mower leads to increases in environmental impacts but they are negligible in comparison to changing the electricity mix.

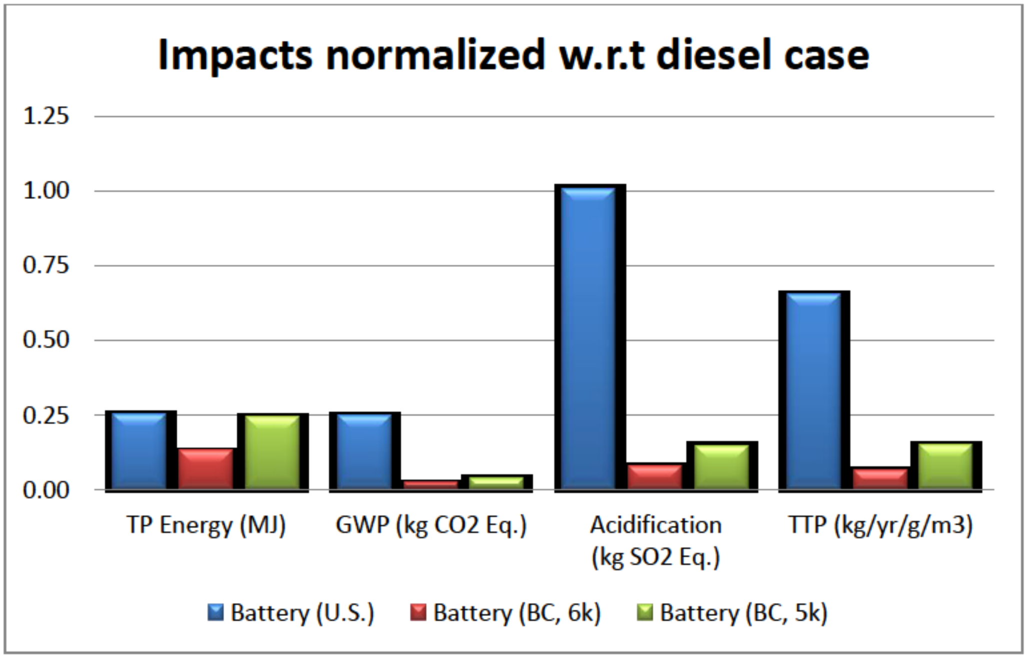


Figure 7. Impacts of battery-powered mower normalized relative to the biodiesel case

Finally, there is a question about the impacts attributed to the use of lithium batteries in vehicles in general. In the EPA paper[3], which is an exhaustive LCA study of Lithium ion batteries used in electric vehicles, their toxicity (eco-toxicity and HTP), particularly in the Use phase, is highlighted. On close examination, however, one concludes that the results of the EPA study are not applicable to the situation here. Without delving too much into the details of that study, the conclusion drawn there regarding battery toxicity will be re-iterated here. The paper states "the use stage human toxicity impacts primarily result from air emissions due to the combustion of fuels to supply electricity." In that study, the electricity is produced from combustion of coal (60%), biomass (25%) and natural gas (15%).

That is far from being the case here. The EPA study authors' conclusion is hardly surprising, as electricity is a carrier and not a source of energy. So anytime, when the electricity is produced from combustion of a fuel, and the combined efficiency from raw material to wheel is less than the efficiency of a standard fuel vehicle, it is expected that the electric option would have more severe global impacts. Again, in British Columbia, over 90 percent of electricity is derived from hydro.

7.0 Cost Analysis

The cost of ownership for both systems over their UBC-lifetime is calculated next. It is based on a service life of seven years which reflects the frequency at which UBC replaces its vehicles. The total cost is expressed in terms of present value (PV) or 2013 dollars.

- The purchase price of the Kubota biodiesel mower is based on a price furnished by the Fleet manager at UBC and it includes "all the bells and whistles" asked for by the Grounds dept.

- The cost of maintenance is based on average per-vehicle maintenance cost provided by UBC Fleet manager. Only the parts cost was included in the analysis here. Labor, facilities and utilities costs allocated on per vehicle basis in departmental budgets are excluded from the analysis here.
- The purchase price of the CXR-60 is based on a price quote by the supplier (Appendix B). It includes the cost of the lithium iron phosphate battery of 11.52 kWh charge capacity (LEM80 Battery Module), the charger (LEMC-30 36 V), and of the crating and shipping. The quoted (basic) mower price was increased by 25 percent as to allow for the inclusion of equivalent “bells and whistles” to those in the Kubota mower.
- The annual cost of parts needed for maintenance of the CXR-60 is assumed to be half that of the Kubota. That is a reasonable conclusion given that battery-powered mowers have a lot less moving parts than the equivalent biodiesel mowers.
- The battery which constitutes a substantial cost ($9860) is not expected to be replaced during the service life of the mower at UBC. The battery specifications show a life expectancy of 10 to 12 years or 1500 charge cycles. That is equivalent to 6000 service hours that is 3.4 times the expected service hours (1758 h) per mower in seven years. So, unless the battery is defective to start with, the battery could be reasonably expected to last the service life of the mower.
- Carbon tax refunds, due to the use of battery-powered mowers, are assumed to be credited to the budget of Building Operations at the rate of $30 for every tonne of CO2 eq. that is reduced.
- The applicable rate of return that is assumed to be 5 percent accrued annually. This is the net rate of return after accounting for inflation.
- Finally, all capital costs associated with outfitting Building Operations facilities with charge stations/outlets and/or upgrading their electric networks are not included in this analysis.

The results of the cost analysis are summarized in Table 4. They indicate net savings of 5516 dollars that could be realized by switching from biodiesel to battery powered mower.

Table 4. Cost of ownership over 7 years

Cost Analysis	**Purchase Price**	**Cost of Energy ($/year)**	**Maintenance Cost ($/year)**	**Carbon Tax refund ($)**	**Cost of Ownership (in 2013 $)**
Kubota Diesel Mower	22500	999	1200	0	**35223**
Battery-Powered Mower CXR-60	26430	42	600	76	**29706**

8.0 Social Aspects for Considerations

The third dimension of this study is the social aspect. Namely what are the social implications of adopting a battery-powered ride-on mower? The stakeholders are many and each group has its own priorities. There are the operators using the mowers, the manager/s at Building Operations, UBC executives and UBC personnel and students.

The question of whether or not to adopt battery powered mowers is hardly worth asking for UBC directors, personnel and students. Battery mowers are "green" and nearly silent, unlike their diesel equivalents which generate so much noise that is at odds with the campus life. More importantly, battery mowers are consistent with the goals and image UBC wants to project to the community and the world.

Based on the limited feedback to the survey distributed to the operators, those who will be using the mowers, the first priority should be given to the reliability and fuel capacity of the mower. Some operator answers seemed to imply comfortable familiarity with the diesel mowers. This last observation could be interpreted to mean that diesel mowers are a "known quantity", so they require less effort to use and maintain them. All these are legitimate concerns, but not reasons to stay with diesel powers. After all, even the operators recognize the positives of battery mowers in terms of their reduced environmental impacts and much less noisy operation. There is no reason why battery powered mowers should be less reliable in term of their technology. But unfamiliarity with them could mean increased effort by the maintenance technicians and operators.

Managers at Building Operations could do a lot to dissipate the concerns of the operators and technicians while still pursuing a change toward environmentally friendly mowers and vehicles. Gradual adoption by buying replacing one mower could be a safe way to test the technology and gain acceptability at the same time. Also, Arranging for formal training might ease the adaptability of battery mowers.

9.0 Decision Making Tool

Battery-powered mowers have two distinct advantages -environmental and economical- over their diesel counterpart. Yet, they are not the clear choice to make as far as Building Operations management is concerned. Reliability and adequacy of battery mowers are not yet established as there is no firsthand experience with these mowers. Acceptability by the operators is also a key. These are only a few concerns among others that management has to grapple with before making a decision.

A hierarchical weighted scoring method is advised in this case. A decision "tree" is illustrated in Figure 5 where factors to score are listed. An algorithm that mirrors this tree as well as an explanation for how to use it will be provided to Fleet manager to aid him in coming to a decision. The algorithm will be delivered in the next 15 days.

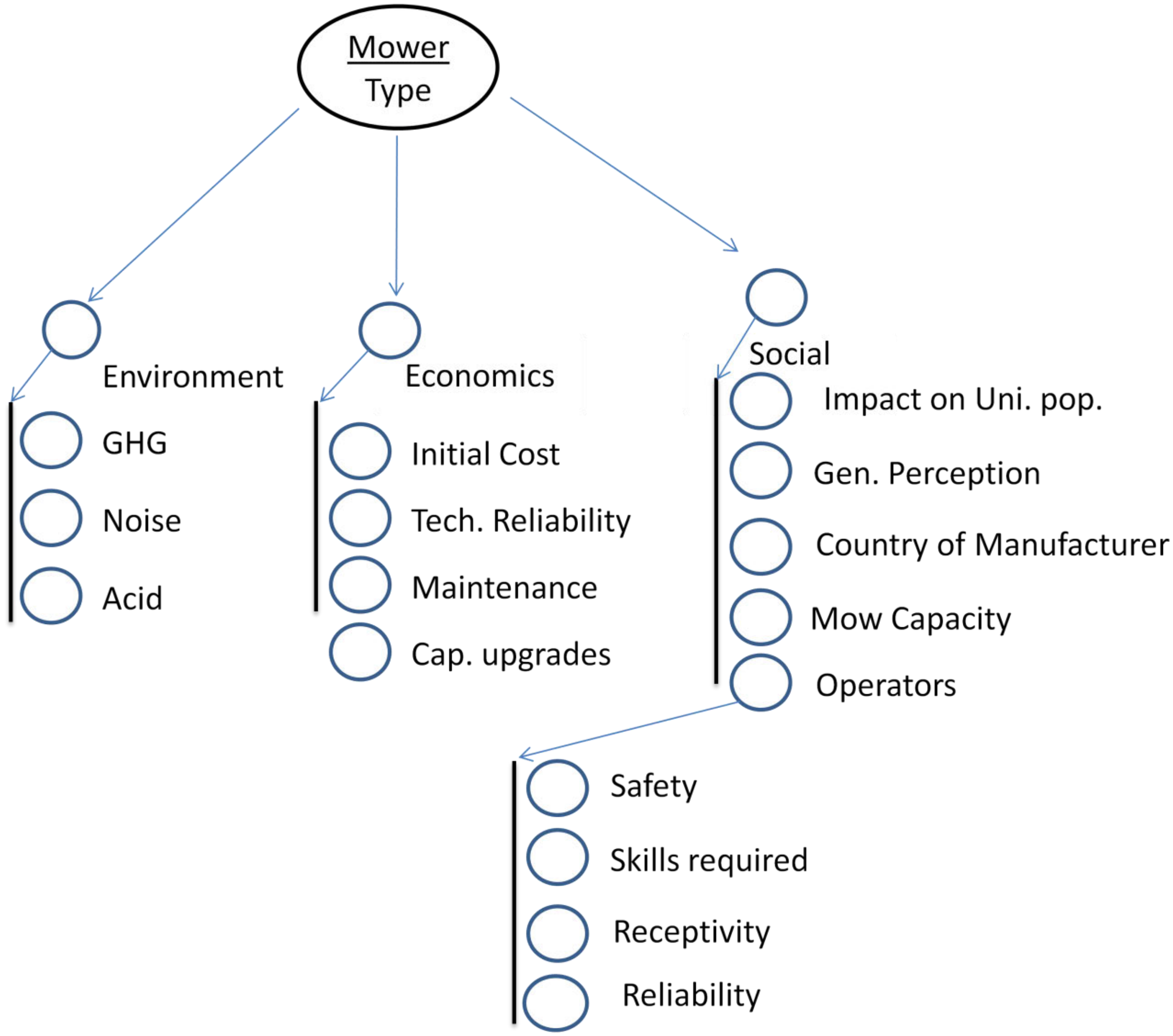


Figure 8. Hierarchical decision-making method

10. Conclusion and Recommendations

This LCA study confirms the improvement in environmental performance that is associated with the employment of battery-powered mowers. It is expected that the replacement of the four mowers will reduce GHG by about 10 tonnes per year. The Eco and human toxicity that is reported in LCA literature and attributed to the Use phase is traced to combustible fuels used to generate electricity. That is a non issue for electricity generated in British Columbia. Toxicity is not then inherent to the battery and therefore is deemed safe for use.

Also, Battery-powered ride-on mowers have a lower cost of ownership compared with the diesel-fueled mowers. The cost advantage is realized over the projected service life (7 years) and amount to over $5500 per mower. These figures do not reflect possible costs of upgrading facilities to enable charging of the mowers. That is, it is assumed that Building Operations have enough capacity and charge stations to accommodate four more mowers in addition to the existent fleet of electric vehicles.

While a decision is not provided a method for making a decision is included in the study and will be followed by a computer algorithm to be delivered by the middle of December, 2013.

Employee training and sharing in the decision-making are key to successful adoption of new technologies in the workplace. Having one battery-powered mower put in service achieves many objectives. For one thing, it allows testing the technology in real setting and makes tangible the positive points of silent and green mowers.

Further LCA studies could look at other vehicles that are due for replacement as well as emissions associated with maintenance operations.

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Appendix A: Calculations

I. Diesel consumption

Parameters

Engine net power, P_{net} : 26.3 kW

Continuous operating power, $P_{cont.}$, kW

LHV of B5 biodiesel: 36.0588 MJ/L or 43.34 MJ/kg

Variables

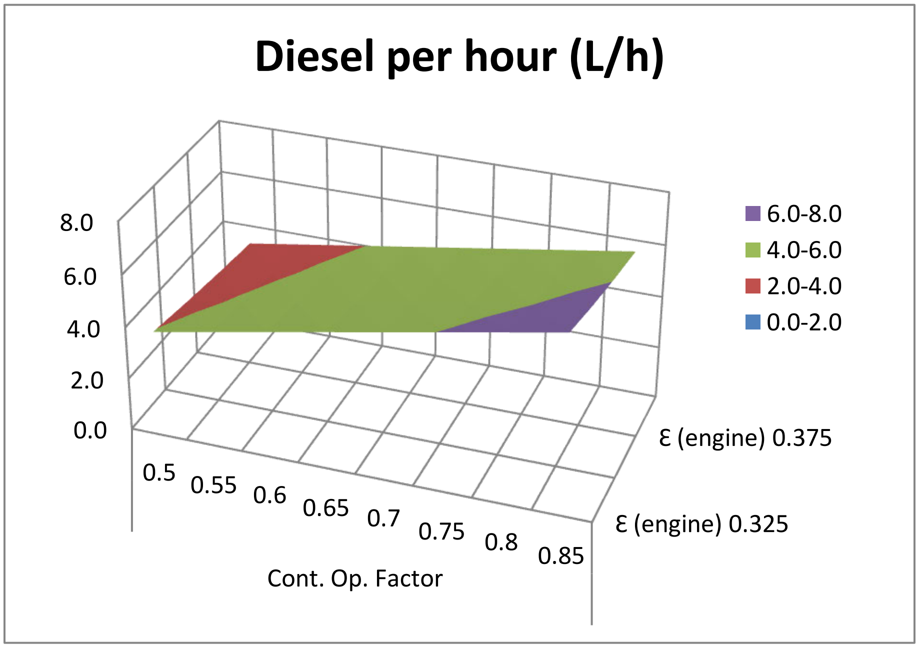
$R_{co} = P_{cont}/P_{net} = [.5 \text{ to } .85]$

$\varepsilon_E = [0.3 \text{ to } 0.4]$

Formula

$V_h = [\, R_{co} \times P_{net} \times 3600/(LHV_{bd} \times \varepsilon_E \times 1000)]$

Figure 9. Theoretical diesel consumption per hour per mower, V_h



II. Area mowed per hour

Parameters

Mowing deck width, W_d: 60 inches or 72 inches

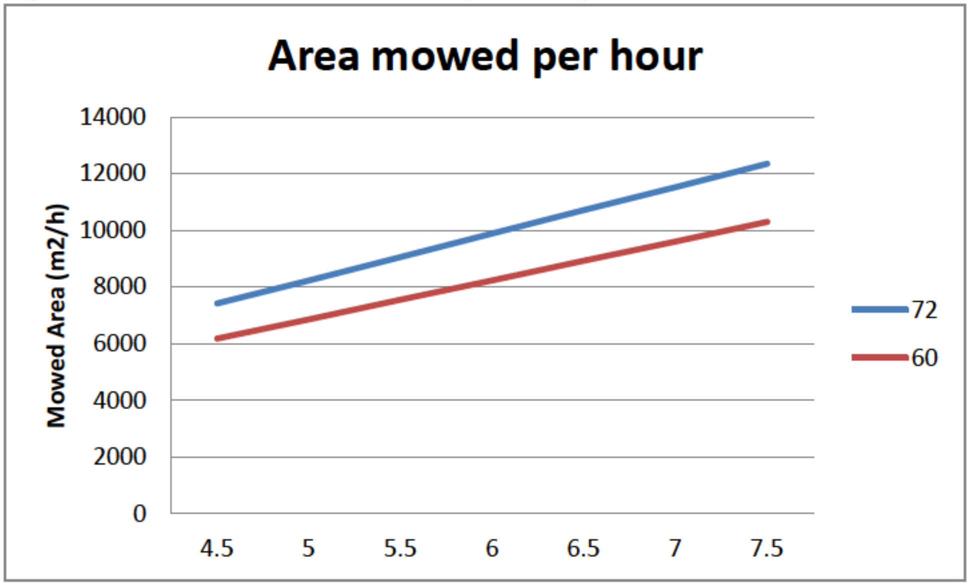
Variables

Mower Speed, V_m =[4.5 to 7.5 km/h]

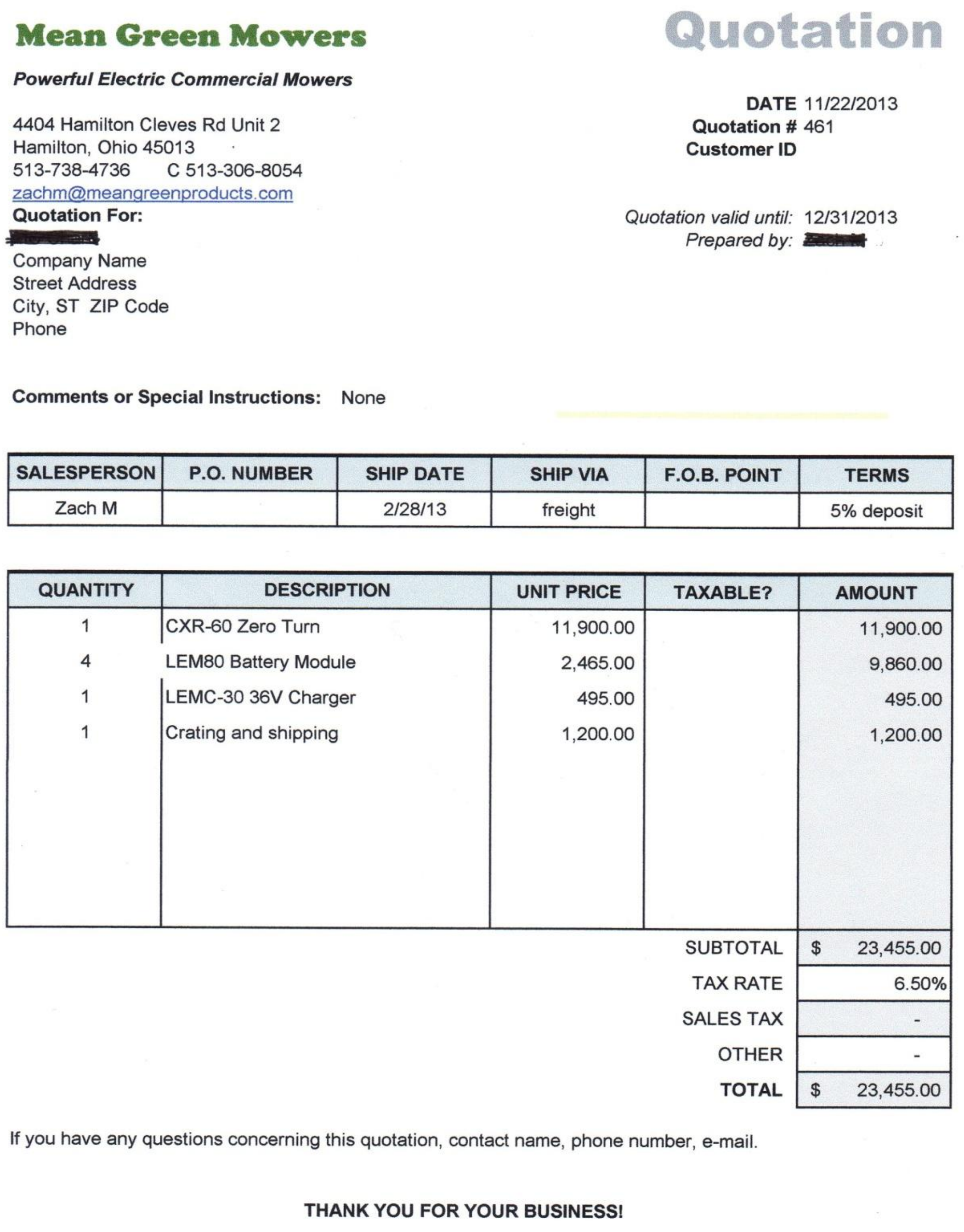
Formula

$A_h = V_m \times 1000 \times W_d \times (2.54/100)$, in m^2/h

Figure 10. Theoretical area-mowed per hour per mower as function of mower speed, A_h



Appendix B: Price Quote



Mean Green Mowers

Powerful Electric Commercial Mowers

4404 Hamilton Cleves Rd Unit 2
Hamilton, Ohio 45013
513-738-4736 C 513-306-8054
zachm@meangreenproducts.com

Quotation

DATE 11/22/2013
Quotation # 461
Customer ID

Quotation For:
[redacted]
Company Name
Street Address
City, ST ZIP Code
Phone

Quotation valid until: 12/31/2013
Prepared by: [redacted]

Comments or Special Instructions: None

SALESPERSON	P.O. NUMBER	SHIP DATE	SHIP VIA	F.O.B. POINT	TERMS
Zach M		2/28/13	freight		5% deposit

QUANTITY	DESCRIPTION	UNIT PRICE	TAXABLE?	AMOUNT
1	CXR-60 Zero Turn	11,900.00		11,900.00
4	LEM80 Battery Module	2,465.00		9,860.00
1	LEMC-30 36V Charger	495.00		495.00
1	Crating and shipping	1,200.00		1,200.00

SUBTOTAL	$ 23,455.00
TAX RATE	6.50%
SALES TAX	-
OTHER	-
TOTAL	$ 23,455.00

If you have any questions concerning this quotation, contact name, phone number, e-mail.

THANK YOU FOR YOUR BUSINESS!

Appendix C: CXR-60 Specifications

	WBX-33	**CXR-52**	**CXR-60(62)**
Deck Size	33"	52"	60"
Voltage	36 Volts	36 Volts	36 Volts
Batteries	LEM40, 60, or 80	2-4ea LEM80s	2-4ea LEM80s
Acres Cut/Charge	LEM40 (2acres), LEM60 (3acres), LEM80 (4acres)*	2ea LEM80s (3acres), 3ea LEM80s (5acres), 4ea LEM80s (7acres)*	2ea LEM80s (3acres), 3ea LEM80s (5acres), 4ea LEM80s (7acres)*
Mow Time/Charge	LEM40 (2hrs), LEM60 (3hrs), LEM80 (4hrs)*	2ea LEM80s (2hrs), 3ea LEM80s (3hrs), 4ea LEM80s (4hrs)*	2ea LEM80s (1.75hrs), 3ea LEM80s (2.65hrs), 4ea LEM80s (3.5hrs)*
Blades/Deck	2	3	4
Battery Recharge Time	2hrs-Overnight	2hrs-Overnight	2hrs-Overnight
Speed	4-5 mph	7-8 mph	7-8 mph
Operational SAVINGS/hr (compared to gas, includes battery depreciation & maintenance)	$5.09/hr	$7.02/hr	$7.02/hr
Battery life	up to 1500 Charge cycles (6000 hrs with 1ea LEM80) or 10-12 years	up to 1500 Charge cycles (6000hrs with 4ea LEM80s)or 10-12 years	up to 1500 Charge cycles (5250hrs with 4ea LEM80s)or 10-12 years
EMISSIONS	ZERO	ZERO	ZERO
Sound Level	73 db (gas engine 88 db)	78 db (gas engine 92 db)	82 db (gas engine 95-100 db)
Peak Horsepower	16 HP	36 HP	36 HP
Weight	365lbs (compared to 480lbs gas mower)	720lbs (compared to 860lbs gas mower)	780lbs (compared to 910lbs gas mower)

* Varies with LEM size, terrain, operator performance, and grass height/thickness

NOTE: LEMs can be exchanged in about one minute to extend the run time of any of the Mean Green Mowers!

Appendix D: Survey

Life Cycle Assessment

Background

In effort to aid UBC achieve its goal of zero carbon footprint, the Grounds department is considering alternatives to the current diesel-powered vehicles. To make an enlightened decision, it was decided that a triple-bottom line (environmental-social and economic) Life Cycle Assessment (LCA) may be necessary. This LCA study is particularly focused on ride-on mowers like Kubota F3680 or equivalent mowers that are used by the ground department to maintain grassy areas.

Management has made it clear that your input matters to its decision. We, the LCA authors (names deleted), also think that your input is most relevant and practical to us. So please take a few minutes to fill in this survey and return it to us via Adam. Alternatively, you could email us and ask for a softcopy to fill in online and emailed it back to us. Make sure to indicate "Mowers Survey" in the subject line of the email. You could also fill in the hard copy you receive, scan and email it to us. The email address is:

(Email addresses deleted)

We thank you in advance for your time and effort.

Staff Survey

First Name (optional):_______________________

Title/ Job (optional): ________________________________

Years at UBC (optional):________________

Grass Mowing Specifics

Used Kubota F3680 or equivalent mowers at UBC?

What percentage of grassy areas would you estimate these mowers are used for? Use your best judgment. ___________%.

How fast do you go when mowing grass? ____6km/h (fast walking pace), ___8 km/h (jogging pace)

What do you like about diesel mowers? ____

Have you operated a battery-powered ride-on mower? If so which brand and model? _____________

Would you prefer a battery-powered mower? Please explain why YES or NO _____________________

____

Please List your concerns, like and dislikes regarding diesel and battery powered mowers of the class described here. Please consider the following factors when filling the table below:

Operation, maintenance, convenience, noise, impact on health

	Diesel Mower (like)	Diesel Mower (Dislike/ Concern)	Battery powered (Like)	Battery Powered Mower (Dislike/ Concern)
1				
2				
3				
4				

What would you pick as your top three criteria for deciding on a replacement for the Kubota F3680 and similar vehicles/mowers? And why?

1____

2____

3____

Other comments (feel free to add relevant information that we may have neglect to ask about)