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POLICIES AND SUPPORT IN RELATION TO LCA

Quantification of the environmental and economic benefits of the electrification of lawn mowers on the US residential market

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Abstract

Purpose Gasoline-powered lawn mowers and garden equipment are emitting 30 million tons of pollutants yearly in the USA, accounting for a quarter of all non-road gasoline emissions. While the US market is dominated by gasoline-powered lawn mowers, this study offers an assessment of the environmental implication and cost of electrifying the lawn mower industry.

Methods First, the lifecycle environmental footprint and total cost of ownership of electric-powered mowers are calculated and compared to those of conventional gasoline-powered counterparts, using life cycle assessment (LCA) and life cycle costing (LCC) methodologies. A multi-indicator impact assessment is notably conducted, using the SimaPro software (v8.5), the ReCiPe methodology (H), and the ecoinvent database (v3.4) completed with data from the GREET model for the use phase. Second, an extrapolation model is computed to interpret the results at a national and regional scale, considering the proper energy mix in each US state. The combination of LCA and LCC results, mapped out in a two-dimensional chart, allows a clear visual representation of the environmental and economic trade-offs between the gasoline and electric solutions.

Results and discussion The findings indicate a reduction of 49.9% and 32.3% of CO_2 emissions, respectively, for push and riding mowers, by using the electric solution instead of the conventional one over their lifecycle. Yet, the total cost of ownership is slightly higher (4.7–10.6%) for the electric solutions, even if the operating costs are lower. And as the initial buying price of the electric solution is more expensive than the gasoline solution of the same category, this could be a real hindrance for consumers who do not systematically consider the overall lifecycle cost when comparing mowers. In this line, the quantification of a suitable financial incentive to support the electrification of the lawn mower market is of utmost importance and appears as a promising line for future work.

Conclusions The present results are significant in at least two major respects for the potential electrification of lawn mowing equipment. First, they show how an increased market share of electric mowers can contribute to cutting down greenhouse gas emissions. Second, such quantitative results can be useful for decision-makers in businesses and state governments to take appropriate ecological actions, e.g., in the development of adequate financial incentives or green policy to support the energy transition in this sector, and thus tackle global warming.

Keywords Electrification · Lawn mowing industry · Environmental savings · Life cycle assessment · Life cycle costing · Extrapolation model · US market · US energy mix

1 Introduction

1.1 Context and motivations

The importance of balancing economic growth with environmental protection, including resource preservation and carbon dioxide emission mitigation, is increasingly recognized by academics, industries, and policymakers. According to the United Nations Environment Programme (2019),

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there are more and more opportunities and solutions to tackle global warming. In fact, green technologies, renewable energy, or electric mobility are increasingly operational and affordable options to drive down the emissions of carbon dioxide. Yet, greenhouse gases (GHG) emissions continue to rise: 55 GT of CO_2 eq. in 2018, representing a rise of 1.5% by year on average for the past decade. It is projected that GHG emissions must fall by 7.6% a year from 2020 to 2030 to avoid an ecological crisis, i.e., to avoid raising temperatures by more than 2 °C, which would result in non-reversible damages to human habitat and environment. Reducing GHG emissions to mitigate climate change at regional and global levels, and to limit warming under the 2 °C target of the Paris Agreement (Edwards and Celia 2018), is actually a key challenge of the twenty-first century (Intergovernmental Panel on Climate Change 2014). Meanwhile, it is increasingly acknowledged that electricity-powered solutions, coupled with low-carbon electricity sources, offer great potential for cutting carbon emissions and exposure to tailpipe emissions from fossil fuel combustion (Hill et al. 2006; Hawkins et al. 2013; Transport Environment 2017). Electrification of transport could actually reduce the CO_2 emissions attributed to this sector by 72% by 2050 (United Nations Environment Programme 2019). While decarbonizing the road transport sector through electrification of automotive vehicles is gaining traction at diverse levels (e.g., green policies with financial incentives encouraging the purchase of electric cars; original equipment manufacturers widening their portfolio of electric vehicles; researchers, engineers, and designers working at improving the performance of electric batteries), little attention has been paid to the potential environmental impact savings from electrifying the lawn mower industry.

Gasoline-powered lawn mowers and garden equipment (GLGE) are important contributors of GHG (notably carbon dioxide, methane, and nitrous oxide), as well as air pollutant emissions (such as volatile organic compounds, carbon monoxide, nitrogen oxide, airborne particulate matter, and sulfur oxides) (Banks and McConnell 2015). According to the Environmental Protection Agency (Environmental Protection Agency 2019a), around 30 million tons of pollutants are emitted by such agricultural equipment every year in the USA, accounting for more than a quarter of all non-road gasoline emissions. Such equipment is commonly used in residential neighborhoods, schools, parks, and other public spaces, exposing workers and other pedestrians directly to the emitting source of toxic exhaust and fine particulate matter, in addition to ground contamination (i.e., environmental damage to the grass). On this basis, it has been suggested that communities and environmental and public health officials should create policies and programs to protect the public from GLGE air pollutants and promote non-polluting alternatives (Banks and McConnell 2015). It is estimated that around 5 million walk-behind power mowers and 1.25 million riding mowers were sold in the USA in 2018 (Statista 2019a). Further, this market is expected to keep expanding in the next decade (Grand View Research 2017), with between 5 and 6 million gas-powered walk-behind mowers being sold in the US market each year (Fact MR 2019; Statista 2019b). In all, it can be estimated that approximately 50 million walk-behind (or push) mowers plus 12.5 million tractor-type (or riding) lawn mowers are used in the USA on a yearly basis, based on a 10-year lifetime and statistics on purchased lawn and garden tools from 2008 to 2018—figures that are well-aligned with the population of GLGE provided by the EPA in their evaluation of US national emissions from lawn and garden equipment (Banks and McConnell 2015). Gasoline lawn mowers represent 76% of the lawn mower market share in 2016, and electric- (corded) and battery-powered (cordless) ones count, respectively, for 16% and 8% (Technavio 2017). The benefits of switching petroleum-powered machines for electric counterparts are promising (Charif 2013), including the following: no tailpipe emissions, potential GHG emission reduction, lower operating cost, higher energy efficiency, reduction in noise pollution, and fewer maintenance operations. Yet, in the agricultural and gardening sector, compared to the automotive vehicle industry (Diamond 2009; Hidrue et al. 2011; Nordelöf et al. 2014; Archsmith et al. 2015; Girardi et al. 2015; Roy et al. 2016; Kendall et al. 2019), there is a lack of in-depth investigation on quantifying the possible environmental savings and economic repercussions of electrifying the mower market (Carbon Fund 2019; Home Guides 2019).

1.2 Research questions and objectives

With this background, and in the context of transition towards more renewable energy sources, we want to quantitatively validate the hypothesis that going for the electrification of lawn mowers on the US residential market leads to environmental and economic benefits. Importantly, this study aims to provide new relevant insights in regard to the three following research questions (RQ): (RQ1) to what extent are electric-powered lawn mowers a commendable alternative to gasoline-powered ones from the economic and environmental perspectives at the US national scale? (RQ2) What are the environmental savings if the electric mowers market share increased by a given percentage, according to the electricity mix in each US state? (RQ3) How to set up an appropriate financial incentive(s) to support the green purchase of electric mowers? The main objectives of this research are therefore the following: (i) to evaluate the life cycle environmental and economic performance of electric-powered lawn mowers compared to that of conventional gas-powered ones, at a regional and national scale in the USA, considering the proper energy mix for each case; and (ii) to provide a sound basis to quantify the right financial incentive—considering the customers' willingness to pay for electric lawn mowers, and different possible levers such as carbon tax, subsidy, and governmental or commercial rebates—to promote the adoption of electric-powered lawn mowers.

The research approach deployed in this study involves a combination of several methods. First, the environmental impact and lifecycle cost of generic gasoline-powered push and riding mowers are compared with electric-powered counterparts, using the lifecycle assessment (LCA) and lifecycle costing (LCC) methodologies (Environmental Protection Agency 2006). Then, an extrapolation model is developed to interpret the results at the scale of US states, i.e., to quantify the overall potential environmental benefits through an increase of the market share of electric lawn mowers by a given percentage. This extrapolation model includes the following elements: number of lawn mowers sold by year and by type in the USA, distribution of lawn mowers currently in use in each US state according to US demographics, usage intensity modeling, differentiation of electricity mixes between regions and associated emissions models, appropriate fuel, and electricity prices, as further detailed in the materials and methods section. Economic and environmental trade-offs between gasoline- and electric-powered solutions are particularly highlighted. Eventually, based on the estimated potential environmental benefits of this shift from conventional gas-powered lawn mowers to electric ones, quantitative elements are provided to support the setup of a suitable incentive (e.g., subsidy, tax reduction, or carbon tax) that can stimulate green purchase, in order to increase the market share of electric mowers.

2 Methods

2.1 Life cycle assessment and life cycle costing: goal, scope, and functional unit

Life cycle assessment (LCA) is the most recognized approach to evaluate the environmental impacts of a product, process, or activity throughout its life cycle (ISO 14,040 2006; ISO 14,044 2006). Life cycle costing (LCC) is the equivalent of LCA for economic assessment. Combining LCA and LCC allows trade-off analysis (e.g., cost of impact reduction) between products (Kwak and Kim 2013; Saidani et al. 2019). The goal here is to compare the relative environmental and economic performances of gasoline and electric mowers (considering both generic riding and push models) throughout their life cycle. To make a sound comparison, both electric and gasoline push systems are evaluated against the same function unit (FU): mowing a 0.25 acre (i.e., 1000 m^2) surface area (average residential grass surface area), 1 h per week (performance), 26 times per year (mowing season), for 10 years (average lifespan under appropriate maintenance) with a generic 2.5 horsepower push lawn mower in the USA. For the riding mower, we consider an average use of 1.5 h per week to cover a range of yards from 0.3 to 2 acres. As illustrated through Fig. 1, the system boundaries of this study include (in-scope) the manufacturing, use, and maintenance phases, all considered with a high level of details, as further described in sect. 2.3. Note that the electric riding mower is operating on a lead-acid battery, while the generic push mower is using a lithium-ion battery, to have similar mowing performance (in terms of powers) than their gasoline counterparts (see further details and supporting references in the first paragraph of sect. 2.3. related to the life cycle inventory). While the impact of materials processing for parts and components manufacturing is included in the scope of the LCA (as illustrated in Fig. 1), the assembly and end-of-life phases are out of scope of the present study, due to lack of data available, and assuming a negligible contribution of these two phases over the 10-year lifetime, notably in comparison to the usage, maintenance, and manufacturing phases (Nordelöf et al. 2014; Girardi et al. 2015; Roy et al. 2016; Saidani et al. 2020).

2.2 Life cycle impact assessment categories and software

The life cycle software SimaPro 8.5 with the ecoinvent database 3.4 (2017) (Wernet et al. 2016), plus the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) life cycle model (Argonne National Laboratory 2018) (Wang et al. 2020), is used to perform the environmental impact assessment. Global warming potential (GWP) score (in CO_2 eq.) and additional environmental indicators (provided by the ReCiPe methodology (Goedkoop et al. 2008) implemented in SimaPro) quantifying the impact on human health, natural ecosystem, and resource depletion, are considered to compare the environmental performance of gasoline mowers with their electric counterparts. Using different metrics is suitable here as it enables the analysis and identification of possible impact transfers (which cannot be seen applying, e.g., only the GWP score, which solely takes into account the emissions of GHG). Actually, in addition to their contribution to global warming, both mowing solutions have to be compared regarding the specific impacts they cause on human health and nature, including ecosystem damage and resource depletion. In parallel, a lifecycle costing analysis is conducted to compare the total cost of ownership of each system, considering initial cost, fuel, and electricity prices, as well as maintenance costs.

2.3 Supporting data for life cycle inventory and life cycle impact assessment

Generic bills of materials provided directly by original equipment manufacturers, or scaled from published articles and reports, have been utilized and completed with more specific information available in the literature. For instance,

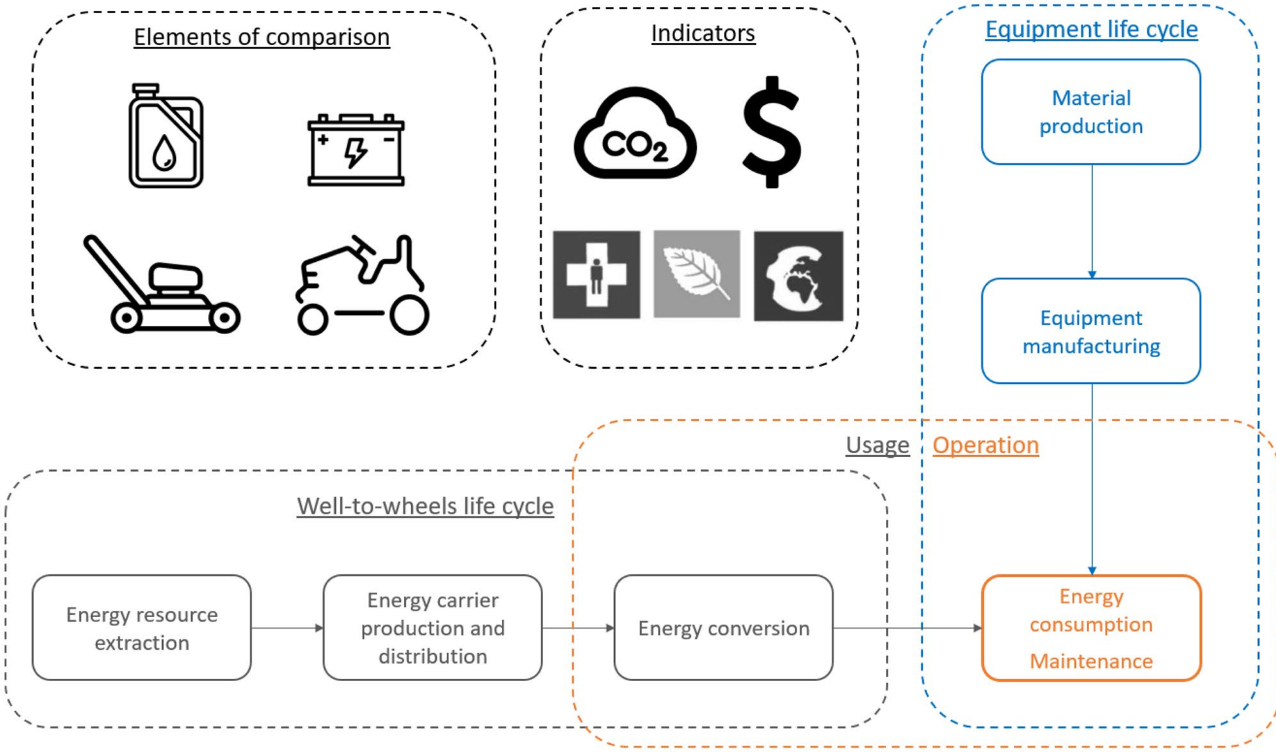

Fig. 1 Scope and system boundaries of the comparative LCA and LCC

data from the Argonne National Laboratory and their module for battery LCA in the GREET model (Wang et al. 2020) have been extracted to get a detailed material composition and cradle-to-gate performance of the lithium-ion (Environmental Protection Agency 2013; Ellingsen et al. 2014; Gaines and Dunn 2014) and lead-acid batteries (Sullivan and Gaines 2012; Liu et al. 2015; Chen et al. 2017). Note that a similar bill of materials is considered for both electric- and gasoline-powered systems except regarding the important differentiation related to their powertrains, i.e., internal combustion engine for the gasoline push and riding mowers vs. lithium-ion or lead-acid battery package for the electric ones. Additional details, including the life cycle inventory of the lawn mowers assessed, are available in Table 1 (Appendix).

Further, particular attention has been given to the use phase of both systems (e.g., fuel consumption and electric mix, as electricity can be produced from a variety of sources with different environmental costs). The main cost to operate a push or riding mower is fuel cost (gasoline) or electricity cost. The US Department of Energy's eGallon tool (Choose Energy 2019; Energy 2019) provides average gasoline and electricity rates in the USA. In 2019, the average price of (residential) electricity for US households was about 12 cents ($0.12) per kilowatt-hour (Choose Energy 2019; Energy 2019; NPR 2019). The average price of fuel used in a typical gasoline-powered mower in the USA is $2.60 per gallon (Alternative Fuels Data Center 2019; Environmental Protection Agency 2019b), which is equivalent to approximately $0.70 per liter. These average values are used for the life cycle costing comparison and for the extrapolation at the US scale. Related to the environmental footprint of operating a lawn mower, both the production and consumption of gasoline and electricity are considered in the impact assessment, ensuring a comprehensive and well-to-wheel approach (Ma et al. 2012): tank-to-wheels corresponding to the mower in-use phase of the LCA, and well-to-tank covering the production and transport of fuel feedstock or electricity. According to the GREET model, the well-to-tank GHG impacts of regular gasoline is 2.87 kg CO_2 eq./gal., and the tank-to-wheels (burning gasoline and associated emissions) is 8.887 kg CO_2 eq./gal. For the GHG related to electricity generation, as different US states produce electric power through various energy sources, the EPA's Power Profiler (2019b) and the Emissions & Generation Resource Integrated Database (eGRID) (Environmental Protection Agency 2020a) emissions factors are used to calculate the emissions allocated to battery charging. For the extrapolation, specific emissions factors are considered for each US state according to their electricity mix. Note that the emission of an average 0.5 kg CO_2 eq./kWh is used at the US nation scale (Carbon Fund 2019; Environmental Protection Agency 2019b).

The average lifespan of lawn mower is around 10 years under proper maintenance (Lan and Liu 2010; Charif 2013; Home Guides 2019; Hunker 2019). The average growing season in the USA is 26 weeks, and typical lawn mower owners mow their yards once a week (Sivaraman and Lindner 2004; Banks and McConnell 2015). As such, the functional unit assumes a 10-year lifetime and the system boundaries integrate realistic maintenance operations and scenarios, as detailed hereafter. Standard lawn mower tune-ups focus on the engine, performing the three following tasks (Angies List 2019; Popular Mechanics 2019a): cleaning or replacing the air filter, changing the oil, and replacing the spark plug (on an annual basis to ensure an easy start). It is also recommended to sharpen or replace the blades once a season to maintain proper cutting performance. Tune-up prices range from $70 for gasoline-powered push mowers to $140 for riding mowers (The Lawn Mower Guy 2020), with slight variations for electric-powered ones (Today's Mower 2019). The national average estimate cost for lawn mowing and maintenance is between $214 and $322 a year (Home Advisor 2019). For the electric mowing systems, most lithium-ion batteries have a rated lifetime of somewhere between 500 and 1500 charge cycles (Stanford 2010; Popular Mechanics 2019b). As lithium-ion batteries can lose about 20% of their capacity after 1000 charge cycles (Battery University 2019; Popular Mechanics 2019c), the following rules are used for battery replacement: (i) after a 5-year usage period and (ii) after 1000 charge cycles, if reached before this 5-year time window. The estimated number of push and riding lawn mowers by state have been calculated (extrapolated) based on the repartition (number) of household with a yard by state, using data providing the overall number of household in 2018 (Statista 2019c), on which the number of apartments (i.e., households without a yard) has been deducted (NMHC 2019). Similar estimates are obtained (same order of magnitude) by the use of ratio based whether on the population and land area by state (State Symbol USA 2019; World Population Review 2019), or on the number of car registration by state (Statista 2019d).

3 Results

3.1 Quantification of the environmental impact and total cost of ownership

A first finding, using the global warming potential (GWP) score obtained through LCA, indicates a reduction of 49.9% and 32.3% of CO_2 emissions, respectively, for the push and riding mowers, by using the electric solution instead of the conventional gasoline-powered one, over a 10-year lifecycle, as illustrated through Fig. 2. Even if the manufacturing and maintenance impacts are slightly higher for the electric solution (mainly due to the battery impact), the environmental impact savings of the electric mowers during the use phase regarding the GHG emissions outperformed the gasoline solutions. Approximately 1.0 and 0.36 Mt of CO_2 emissions could be avoided respectively per riding and push mower switch from

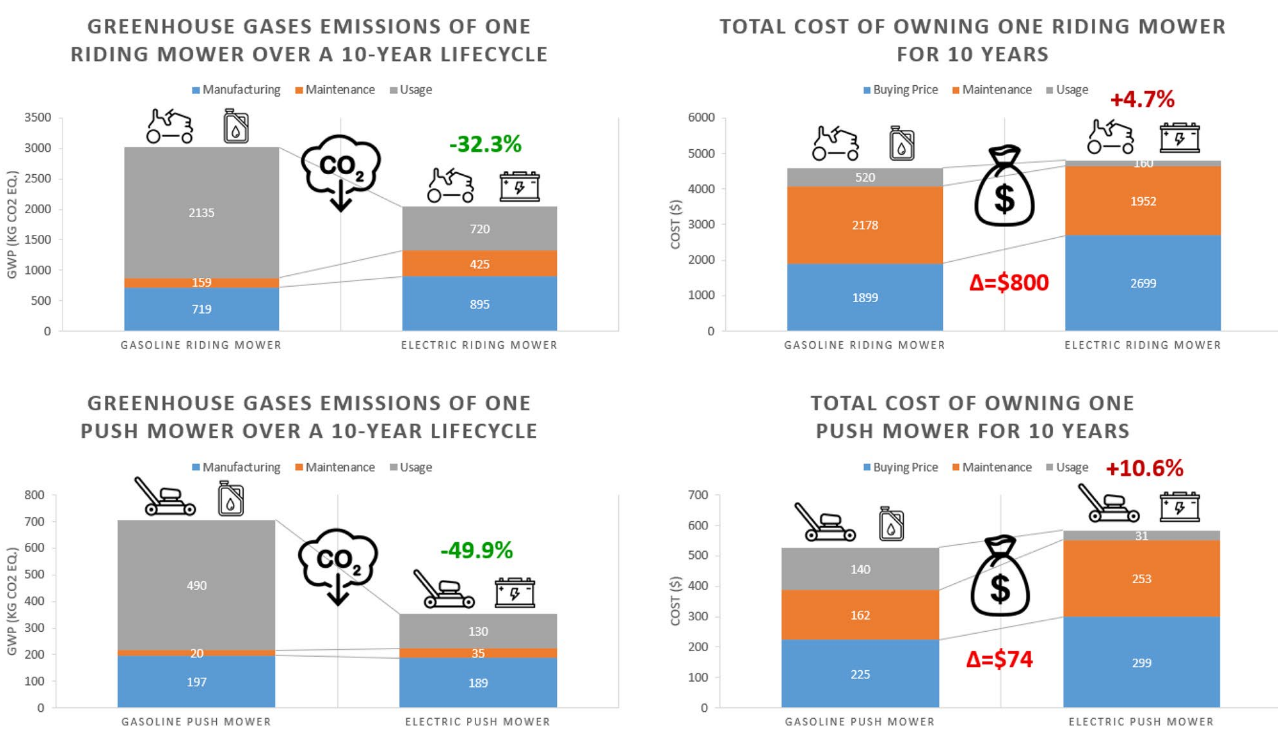

Fig. 2 Comparing greenhouse gases emissions and total cost of ownership

gasoline to electric-powered one over their lifecycle. By comparison, a typical passenger US vehicle emits about 4.6 Mt of CO_2 per year (referring here to the emissions attributed to the use phase) (Environmental Protection Agency 2019c). Yet, the average total cost of ownership, assuming the same lifetime, is respectively \$214 and \$56 higher for the electric riding and push mowers compared to their gasoline-powered counterparts. On the one hand, the operating costs for the electric-powered lawn mowers are lower than the operating costs of the gasoline solutions. On the other hand, the initial buying price of an electric riding mower is on average \$800 more expensive than the gasoline equivalent, and \$74 higher for the electric push mower compared to the conventional gasoline walk-behind mowing solution. As such, this could be a real hindrance for consumers who do not systematically consider the total cost of ownership (over a 10-year period) when comparing lawn mowers and buying products.

The combination of LCA and LCC results, mapped out in a two-dimensional chart in Fig. 3, allows a clear visual representation of the environmental and economic trade-offs between the gasoline-powered and electric-powered lawn mowers. Note also that, for the electric mowers, the impact attributed to the use phase depends on the electricity generation sources. Here, the US average mix has been used. In the following sub-section, the potential impact savings at a US state level are more specifically analyzed.

Although contributing to mitigating the GHG emissions is a good argument in favor of the electric mowing solutions, it must be ensured at the same time that there is no negative impact transfer, especially here with the impact related to the manufacturing and use of batteries. The key takeaways of the complementary multi-indicators analysis are as follows. Overall, the electric mowing solutions (both riding and push models), including the environmental impact induced by the batteries and their replacements, perform better than the generic gasoline solutions, as illustrated in Fig. 4.

However, the gasoline mowers outperform the electric ones in terms of environmental footprint performance for the following indicators: human toxicity, ecotoxicity, freshwater eutrophication, and metal depletion (mainly because of (i) li-ion and lead-acid batteries and their replacements, (ii) the current US electrical mix). But in absolute terms, this impact surplus is not significant compared to the fairly large benefits for human health and ecosystem damage mitigation, according to the following midpoint indicators, and as quantified in Fig. 4: global warming potential, ozone depletion, and fossil depletion indicators. The numerical data resulting from the LCA and used to generate the bar charts of Fig. 4 are available in Tables 2 and 3 (see Appendix).

To consolidate the LCA results and associated interpretations, sensitivity analyses have been carried out on maintenance operations with their associated cost and impact, including variability on the consumables, repair parts for the motor, and replacement frequency for the battery. Five scenarios are considered, as described in Table 4 (see Appendix) and illustrated in Fig. 5. Results show that, even under extreme maintenance scenario (worst case scenario), the electric mowing solutions are still a greener alternative than the gasoline systems over the 10-year lifecycle described in the functional unit of the LCA.

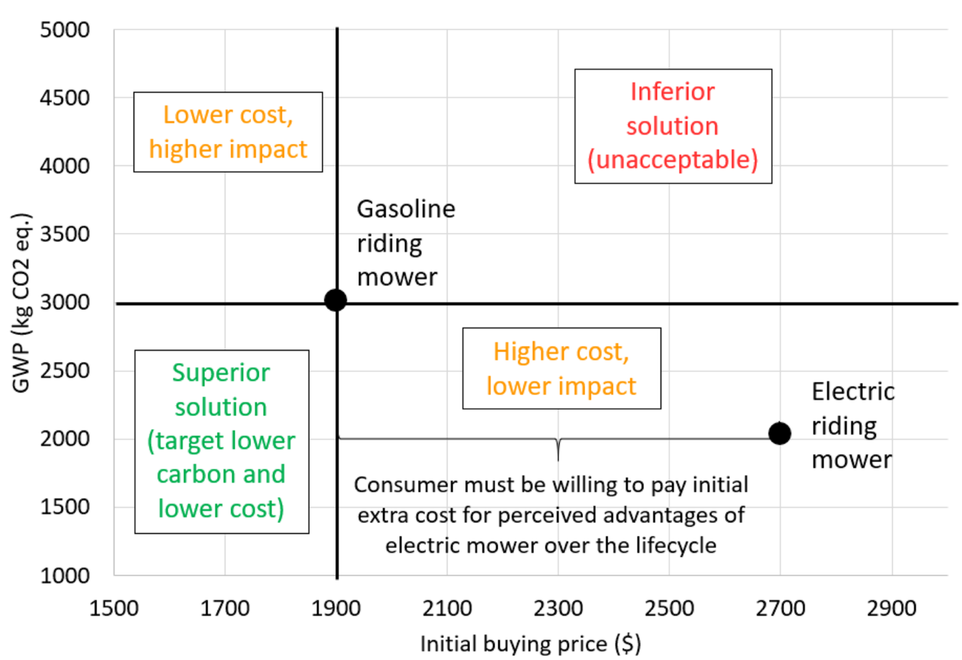

Fig. 3 Visualizing trade-offs between lifecycle impact and costs

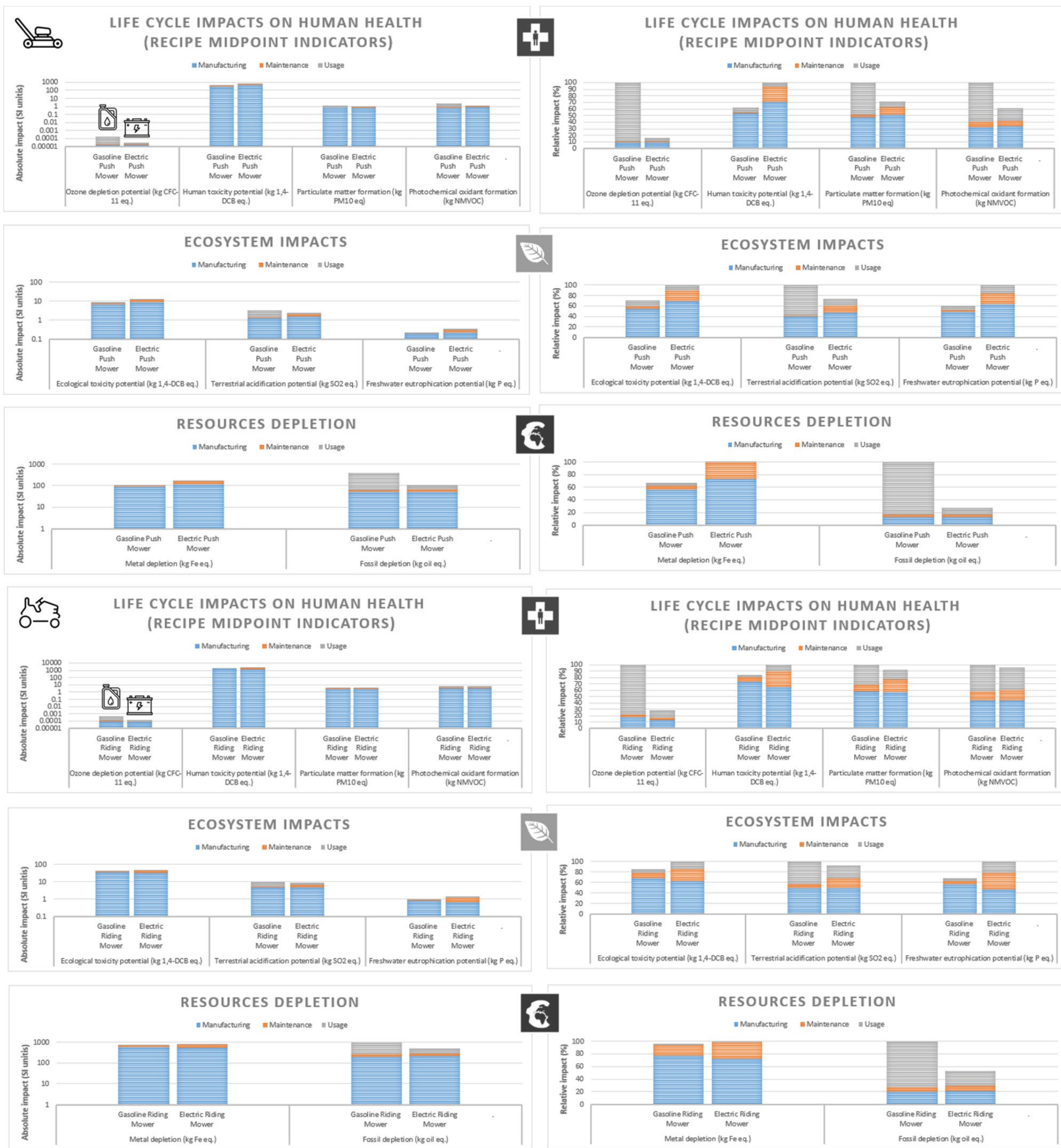

Fig. 4 Comparative life cycle impacts on human health, ecosystem, and resource depletion

3.2 Extrapolation at the scale of US states

In the USA, the lawn mowing industry is currently dominated by gasoline mower solutions. The split between gasoline and electric mowers in the USA is following a market share of 76% for gasoline equipment and 24% for electric equipment (Technavio 2017). Here, based on the quantitative results of the comparative lifecycle GHG emissions between the two solutions, an extrapolation is made at the national and state scale to evaluate the

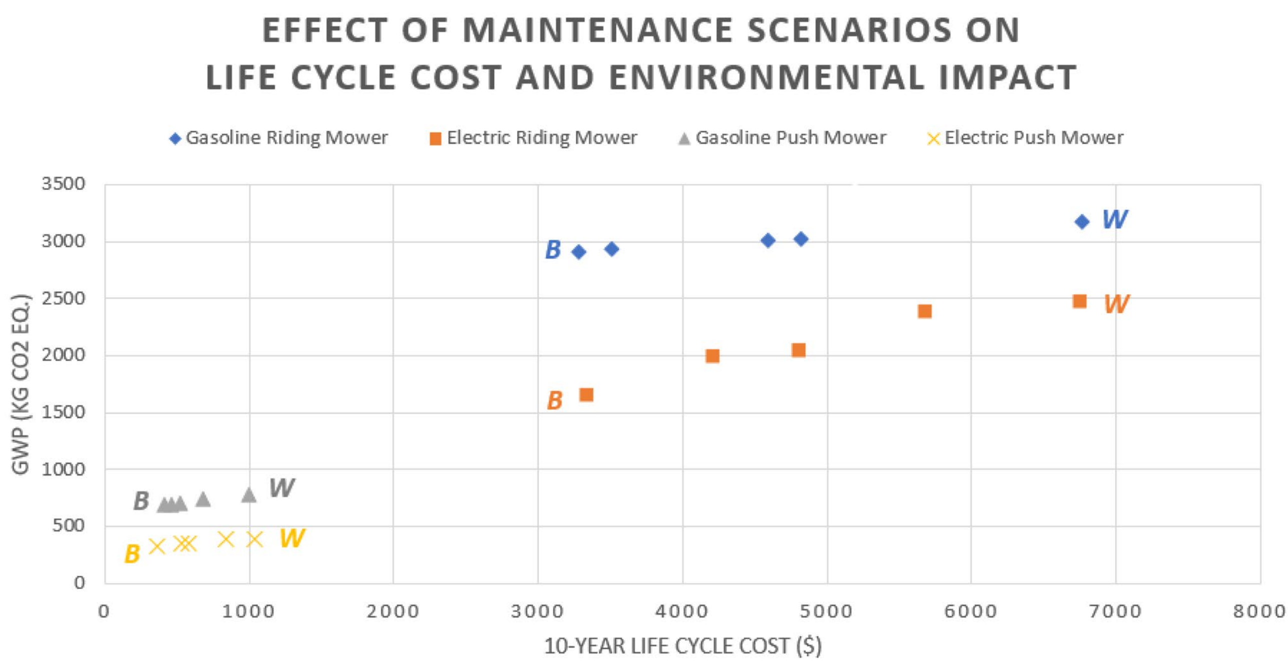

Fig. 5 Sensitivity analysis on maintenance phase (B = best case; W = worst case)

potential mitigation in global warming by increasing the market share of electric mowers. To estimate the number of mowers used in each state, the overall number of riding and push mowers in use in the USA (aforementioned in the introduction) has been distributed proportionally according to the number of households with a yard in each US state (combining datasets from reports on lawn mowers market size in the USA (Grand View Research 2017; Fact MR 2019; Statista 2019a, 2019b), official statistics from the Simmons National Consumer Survey and the US Census Bureau (Statista 2019e), and a 2015 report from the EPA (Banks and McConnell 2015) on gasoline-powered lawn mowers and garden tractors).

It has been found that switching from gasoline-powered lawn mowers to electric-powered ones can contribute to environmental impact savings in terms of CO_2 emissions nationwide, as shown in Fig. 6. At the US national scale, increasing the market share of electric mowers by 10% (including both push and riding mowers) could lead to an estimated amount of avoided GHG emissions of 0.3 Mt of CO_2 eq. on a yearly basis. The graphs in Fig. 7 show the results for a 10-year lifetime, according to the functional unit of the comparative LCA.

To understand the significance of the CO_2 reduction potential in practical terms, according to the EPA (2020b) Greenhouse Gas Equivalencies Calculator, this amount is equivalent to the GHG emissions from 63,694 passenger vehicles driven for 1 year. It also represents the GHG emissions avoided by 104,639 t of waste recycled instead of landfilled, or by 64 wind turbines running for a year. With the current average US electricity mix, a market share of 50/50 would avoid annually the emissions of 7.75 Mt CO_2 eq., and a full electrification of the mowing industry would save 22.65 Mt of CO_2 eq. over 10 years. These environmental savings are more or less significant, according to the electricity mix used in each state. For instance, as illustrated in Fig. 6, using an electric mower in West Virginia (WV), which relies mostly on electricity generated from coal, has a more significant impact than operating and recharging a mower in Washington (WA) or Vermont (VT), where the electricity generation comes mainly from renewable energy, notably hydroelectricity (Environmental Protection Agency 2019c). Interestingly, by keeping the same functional unit, over a 10-year lifecycle, the electric mowing solution appears to be an environmentally friendlier alternative than the gasoline one even in the US states with the worst electricity mix in terms of GHG emissions. The overall potential impact savings for each state, and its relevance to consider incentives or advertising for electric solutions, depend both on the electricity mix and the number of mowers in use in each state.

Considering consumers' willingness to pay extra cost for lifecycle advantages of the electric solution,

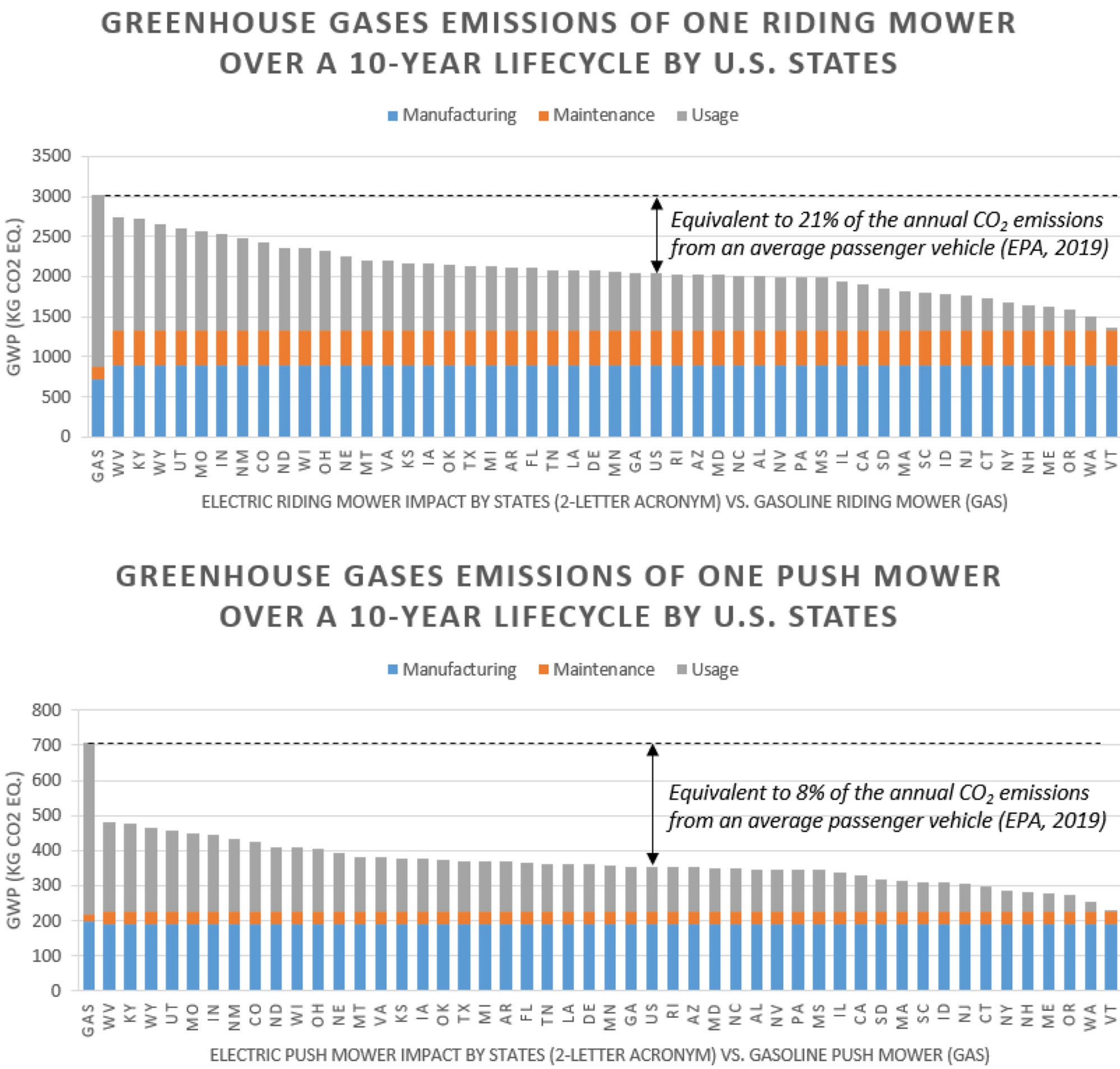

Fig. 6 Extrapolated greenhouse gases emissions by US states

the quantification of the appropriate instruments (e.g., regulatory approaches, economic incentives, or market-based policies), to support the electrification of the lawn mower market is a promising and timely topic for further research (van der Bergh 2013; Miller 2018). A relevant question to address in future work is then, for instance, how to increase the market share of electric lawn mowers by at least 50% by 2030 for the State of Illinois? As both government and original equipment manufacturers may provide economic incentives to encourage the purchase and use of electric-power solutions over petroleum-based ones, a relevant question is how much of a monetary discount or subsidy is necessary to encourage this purchase of greener lawn mowers? Such incentives already exist in the automotive sector to promote green vehicles, e.g., federal tax credits and state incentives of up to $7500 for new plug-in vehicles to offset the higher purchasing price of these vehicles (Fuel Economy 2019; Environmental Protection Agency 2020c). Actually, even if it can be projected that the penetration of electric cars in the USA is likely

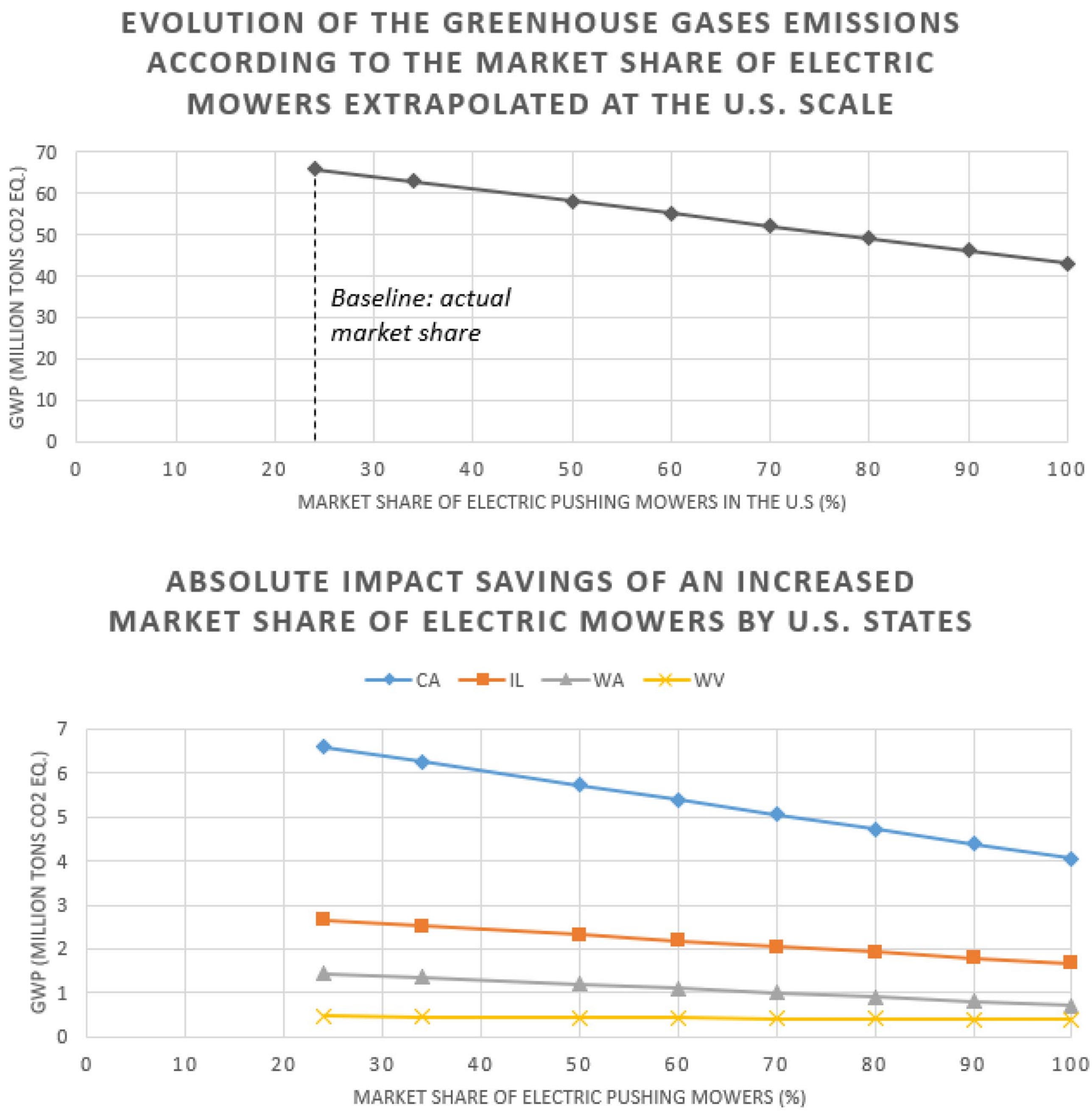

Fig. 7 GHG emissions reduction by increasing the market share of electric mowers in the USA

to influence the demand for electric mowing solutions positively, "price" is the number one purchase motivator when it comes to acquiring a lawn mower, "trusted brand" being second, and "features" third (HBS Dealer 2012). Note that, as incentives for EVs are changing constantly depending on the state (Alternative Fuels Data Center 2019; Energy Sage 2019), and therefore the presented quantitative analysis by state and related potential impact savings is suitable to define appropriate incentives. Last but not least, we argue that the identification and quantification of appropriate economic instruments for supporting the mower market electrification should be based on lifecycle environmental externalities, as quantified in the present study.

4 Discussion

4.1 Electrification of the automotive industry and related impact assessment

To date, most academic research and grey literature have been focused on the comparison between conventional and electric vehicles, including numerous comparative life cycle assessments (Nordelöf et al. 2014; Velandia Vargas et al. 2019). Numerous studies have indeed quantified the potential environmental benefits of using an electric over a conventional vehicle in various regions, e.g., in Canada (Roy et al. 2016), or in Italy (Girardi et al. 2015). For instance, electric vehicles (EVs) powered by the present European electricity mix offer a 10 to 24% decrease in global warming potential (GWP) relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km (Hawkins et al. 2013). Yet, due to the prevalent use of lithium-based batteries, EVs can lead to non-desirable increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts (Hawkins et al. 2013). From the economic side, comparing the annual fuel cost of driving a typical gasoline vehicle and typical battery electric vehicles in the USA, it has been found that the gasoline vehicle is on average 2.3 times costlier than the battery electric vehicle: the average cost to operate an EV in the USA is $485 per year, while the average for a gasoline-powered vehicle is $1117 (Sivak and Schoettle 2016).

4.2 Current debate and challenges in the life cycle assessment of electric solutions

In all, EVs are often promoted to reduce greenhouse gas (GHG) emissions from the transportation sector, as well as to be a greener alternative than traditional internal combustion engine vehicles (Yang et al. 2019). However, this topic is still subjected to some debates, e.g., see the arguments between Tessum et al. (2014) and Oron (2015) on the soundness (relevance and validity) of their models, scenarios, and assumptions to evaluate the environmental impacts of EVs. To make sure that the reader can assess the scientific soundness of the present study and its conclusion, great attention has been paid both to explain: (i) how the comparative LCAs between electric and gasoline mowers have been performed, and (ii) how the potential reduction of GHG at a regional and national level has been estimated. Being transparent on the sources of data used and justifying the assumptions made with solid supporting references is fundamental to provide the reader—e.g., a decision-maker in the lawn mowing industry or a policymaker—with unbiased, well-founded, traceable, and sound guidance and recommendations. In fact, findings comparing gasoline- and electricity-powered means of transportation are sensitive to assumptions regarding, e.g., the electricity source, the equipment lifetime, and associated maintenance operations such as battery replacement schedules for the electric equipment (Hawkins et al. 2013). For instance, the environmental impacts and economic costs allocated to the use phase of electric solutions significantly depend on the parameters of their site of operation (Egede et al. 2015). It is then of the utmost importance to specify the appropriate power mix (and its associated environmental footprint) to generate the electricity that is used for recharging the batteries. Also, while the present analysis considered the average costs for fuel and electricity at the US national scale, future work could investigate and quantity the actual benefits by State, for households when switching from a conventional gasoline mower to an electric solution. Concretely, states with lower electricity costs (e.g., LA, Oklahoma) can even be more favorable for the electric option than states with higher electricity costs (e.g., CA, MA) from a total cost of ownership standpoint (Energy Information Administration, 2021). Further, conducting a multi-indicator environmental approach was essential here, considering possible rebound effects and thus avoiding negative impact transfers when it comes to recommending a solution over another based on environmental impact savings.

4.3 Existing studies on lawn mowers and present contributions

On the one hand, an extensive number of comparative LCA between gasoline-, hybrid-, and electric-powered vehicles has been performed in the automotive industry by academics, industrialists, and governmental agencies. On the other hand, the existing literature of comparative LCA between gasoline- and electric-powered lawn mowers is scarce: one published article, two academic reports, and one communication from an original equipment manufacturer have been found on this topic, all having their own limitations. Table 5 (see Appendix) provides a comparative overview and critical analysis of these studies. In comparison, the present study provides: (i) an up-to-date life cycle assessments (LCAs) on lawn mowers with recent bills of materials, usage, and maintenance data on lawn mowers, in addition to the latest life cycle impact assessment methods and tools, as further detailed in the materials and methods section; (ii) a more comprehensive environmental impact assessment, considering two one-to-one life cycle analysis and costing comparison (between both electric and gasoline riding and push mowers), representing more accurately the overall US lawn mower market (including manufacturing, usage, and maintenance phases with a high level of details, and with a distinction between lead-acid (PbA) and lithium-ion (li-ion) batteries); and (iii) an extrapolation at the scale of the US lawn mower market with the quantification of potential environmental savings at the national and state levels.

5 Conclusions

The current context and momentum on energy transition (Williams et al. 2012; Dangerman and Schellnhuber 2013) is an opportunity for the lawn mower industry to further deliver sustainable and environmental benefits. This research work can help industrial practitioners and policymakers to quantitatively realize the (environmental) opportunities and (economic) challenges of replacing conventional lawn mowers by electric-powered ones. In fact, the broader impacts of our work have the potential to provide informed and sound recommendations that can be useful to stakeholders who make decisions in the field of electrification (i.e., replacing the use of fossil fuels with renewable electricity) in the gardening and agricultural industry, especially in long-term strategic (e.g., supporting green purchases) and political decisions (e.g., national or regional guidelines). From a research perspective, this work provides a valuable and transparent approach for future research (e.g., in other regions or on other products) addressing the shift from one energy source to another, considering both the environmental impact and economic stakes, respectively, through LCA and LCC.

In addition to the potential environmental savings that have been quantified in this study for the electric mowing solution, note that there are other arguments promoting electric mowers nationwide. In comparison with electric vehicles (EVs) and related long-distance driving anxiety, for most residential customers, there is no fear of running out of power for the mowing solutions. To recharge the batteries of electric-powered mowers, every user has several electric outlets at home, and it does not lead to further infrastructure costs for the community (contrary to the necessity of deploying plug-in stations for EVs all across the territory). Also, as new consumers are increasingly looking for lawn equipment that is easier to use and causes less environmental impact, original equipment manufacturers are extending their portfolio of electric-powered models. Interestingly, renewable sources (solar, wind, hydro) used for electric generation are projected to be increasingly exploited (Weis et al., 2016; UNEP 2019; Visual Capitalist 2019). From an environmental standpoint, as more renewable electricity enters the grid, the environmental impacts of electric-powered solutions will further diminish. From an economic perspective, as the costs of renewable energy fall lower and lower with advancements in technology and policy, it can be projected that the price of electricity will decrease as well (Caldeira and Brown 2019; UNEP 2019).

Likewise, regarding the current environmental impact attributed to the lithium-ion or lead-acid batteries for the electric-powered solutions, ongoing technological improvement of battery chemistry, the perspective of reusing batteries for storage purposes, and the development of a recycling industry for EV batteries should lead to improvements in their sustainability (International Energy Agency 2017; Rigamonti et al. 2017; Transport Environment 2017). Note that the lithium-ion batteries that currently power EVs are difficult to dispose of and are harmful to the environment, with inconsistent regulations on their disposal (Roy et al. 2016). Advanced recycling of lithium-ion batteries could be a solution to relieve supply constraints and mitigate the environmental impact of virgin material production (Dai et al. 2019). Contrary to lithium-ion batteries, lead-acid (PbA) batteries are classified by the EPA as hazardous waste, and almost all (97%) PbA battery waste in the USA since the 1990s has been recycled. Also, while rules for battery replacement, based on the number of charging/discharging cycles and number of years in use, have been used in this study, additional sensitivity analysis could be performed to examine further the influence of battery duration on the LCA and LCC results. Indeed, even by losing a non-negligible percentage of its capacity after hundreds of cycles, the remaining capacity of a battery can still be sufficient to operate a mower or drive a car in practice, and thus extend its lifespan (Girardi et al. 2020). Last but not least, when there will be less uncertainty and more data available related to the end-of-life fate and recovery options for electric-powered mowers and their associated batteries, the scope of this study could be extended by considering a complete cradle-to-grave analysis, or even a cradle-to-cradle assessment in a circular economy perspective with the integration of multiple life cycles (Stucki et al. 2021).

Appendix. Supporting data

Table 1 Life cycle inventory

	Gas riding mower	Electric riding mower	Gas push mower	Electric push mower
Bill of materials (material: kg)	All equipped (198 kg) Steel: 122 Cast iron: 32 Rubber: 14 Plastics 14 (10 PP, 2 ABS, 1 PVC, 1 PA) Copper:4 Aluminum: 4 Stainless steel: 4 (blades) Oils: 2 Filters: 2 (0.1 stone groundwood pulp for paper filter, 0.5 aluminum oxide for substrate, 1 steel, 0.4 polyethylene)	Batteries excluded (164 kg) Steel: 107 Cast iron: 25 Rubber: 14 Plastics: 10 (8 PP, 1 ABS, 0.5 PVC, 0.5 PA) Copper: 2 Aluminum: 2 Stainless steel: 4 (blades) Battery detail (4 × 26.5 kg): see composition for a representative lead-acid battery in Sullivan and Gaines (2012)	All equipped (30 kg) Steel: 16.5 Aluminum: 5 PP: 3.5 ABS: 0.5 PVC: 0.1 PA: 0.1 Copper: 1 Air filter: 0.5 Rubber: 1 Blades: 1 Oil: 1	Battery excluded (25 kg) Steel: 14.5 Aluminum: 4 PP: 3 ABS: 0.5 PVC: 0.1 PA: 0.1 Copper: 1 Rubber: 1 Blade: 1 Battery detail (2 kg): see composition for a representative li-ion battery in Gaines and Dunn (2014)
Motor	20 hp (14.9 kW)	75 Ah, 48 V DC, lead-acid battery	2.5 hp (1.9 kW)	5.0 Ah, 40-V DC, lithium-ion battery
Buying price	$1899	$2.699	$224	$299
Maintenance (baseline scenario)	Blades × 9 Oils × 9 Filters × 9 Deck belt (1) Motor belt (1)	Blades × 9 (36 kg) Battery pack (1)	Engine oil (4 L) Extra blades (4 × 1 kg) Spark plug (4) Air filter (4)	Extra blades (4 × 1 kg) Battery pack (1)
Associated cost of replacement parts (per year for the ride-on, overall for the push ones)	Blades $42 Oils$9 Air filters$26 Oil filter $19 Delivery$50 Labor$70 Spark plug, deck and engine belt change, at year 5: $234 Total (10-year): $2178	Blades $42 Delivery$25 Labor$52.5 Battery pack replacement, plus shipping at year 5: $636 (4 × 159$) Labor for battery change: $140 Total: $1952	Blades $84 (4 × 21) Oils$18 Air filters $20 (4 × 5) Delivery $20 (overall, 2 orders) Spark plug replacement: 20$ (4 × 5) Labor done by user (no cost) Total: $162	Blades $84 Independent Li-Ion 5.0 Ah Battery: $149.00 Delivery 20$ (overall, 2 orders) Labor done by user (no cost) Total: $253
Use phase	Mowing time per year: 40 h. Lawn size: 0.3 to 2 acres. Lifetime: 400 h (10 × 40 h) Fuel type: E10 gasoline Fuel rate: 1.89 L/h (0.5 gal) Tier level: Class II, Under 18.6 kW (Spark Ignit.). Gas motor efficiency: 25%. 9 kWh energy input per hour of mowing	Mowing time per year: 40 h. Lawn size: 0.3 to 2 acres. Lifetime: 400 h (10 × 40 h) PbA battery losing charges: 50–92 With 67% efficiency, energy required for one full charge is 5.4 kWh. 3.6 kWh lead-acid (PbA) battery for 1-h runtime (up to 2 acres per charge)	Mowing season per year: 26 weeks. Mows per week: 1. Mowing speed (mph): 2. Lawn size 0.25 acre (1000 m^2). Calculated mowing time (h) 1. Fuel consumption (gal/ac): 0.830 (approx. to 1 L per mowing)	Li-ion battery losing charges: 80–90% (charge/discharge efficiency). Elec motor efficiency: 60% Energy outlet to wheel efficiency per charging: 54%. 1 kWh energy consumption per hour of mowing

Table 2 Numerical values associated with Fig. 4 for the push mowers

Indicators	Mower	Absolute impact			Relative impact		
		Manufacturing	Maintenance	Usage	Manufacturing	Maintenance	Usage
Ozone depletion potential (kg CFC-11 eq.)	Gasoline push mower	1.70E−05	3.34E−06	1.68E−04	9.02E+00	1.77E+00	8.92E+01
	Electric push mower	1.72E−05	2.74E−06	1.05E-05	9.14E+00	1.46E+00	5.55E+00
Human toxicity potential (kg 1,4-DCB eq.)	Gasoline push mower	3.21E+02	1.39E+01	4.43E+01	5.25E+01	2.27E+00	7.25E+00
	Electric push mower	4.32E+02	1.37E+02	4.20E+01	7.07E+01	2.24E+01	6.87E+00
Particulate matter formation (kg PM10 eq.)	Gasoline push mower	6.00E−01	5.00E−02	6.24E−01	4.71E+01	3.92E+00	4.90E+01
	Electric push mower	6.42E−01	1.52E−01	1.18E-01	5.04E+01	1.19E+01	9.26E+00
Photochemical oxidant formation (kg NMVOC)	Gasoline push mower	7.30E−01	1.70E−01	1.34E+00	3.27E+01	7.60E+00	5.97E+01
	Electric push mower	7.44E−01	1.84E−01	4.38E-01	3.33E+01	8.23E+00	1.96E+01
Ecological toxicity potential (kg 1,4-DCB eq.)	Gasoline push mower	6.97E+00	4.40E−01	1.51E+00	5.54E+01	3.50E+00	1.20E+01
	Electric push mower	8.65E+00	2.56E+00	1.37E+00	6.87E+01	2.03E+01	1.09E+01
Terrestrial acidification potential (kg SO2 eq.)	Gasoline push mower	1.28E+00	9.00E−02	1.87E+00	3.95E+01	2.78E+00	5.77E+01
	Electric push mower	1.52E+00	4.40E−01	3.99E-01	4.69E+01	1.36E+01	1.23E+01
Freshwater eutrophication potential (kg P eq.)	Gasoline push mower	1.80E−01	1.00E−02	3.41E-02	4.91E+01	2.73E+00	9.29E+00
	Electric push mower	2.34E−01	7.40E−02	5.89E-02	6.38E+01	2.02E+01	1.61E+01
Metal depletion (kg Fe eq.)	Gasoline push mower	8.92E+01	1.08E+01	6.86E+00	5.60E+01	6.76E+00	4.31E+00
	Electric push mower	1.15E+02	4.24E+01	1.40E+00	7.25E+01	2.66E+01	8.81E−01
Fossil depletion (kg oil eq.)	Gasoline push mower	5.05E+01	1.14E+01	3.27E+02	1.30E+01	2.93E+00	8.41E+01
	Electric push mower	5.14E+01	1.26E+01	4.17E+01	1.32E+01	3.23E+00	1.07E+01

Table 3 Numerical values associated with Fig. 4 for the riding mowers

Indicators	Mower	Absolute impact			Relative impact		
		Manufacturing	Maintenance	Usage	Manufacturing	Maintenance	Usage
Ozone depletion potential (kg CFC-11 eq.)	Gasoline riding mower	8.13E−05	1.96E−05	3.66E−04	1.74E+01	4.19E+00	7.84E+01
	Electric riding mower	6.32E−05	1.27E−05	5.79E−05	1.36E+01	2.72E+00	1.24E+01
Human toxicity potential (kg 1,4-DCB eq.)	Gasoline riding mower	1.58E+03	1.48E+02	9.65E+01	7.30E+01	6.83E+00	4.45E+00
	Electric Riding Mower	1.42E+03	5.14E+02	2.33E+02	6.56E+01	2.37E+01	1.07E+01
Particulate matter formation (kg PM10 eq.)	Gasoline riding mower	2.52E+00	4.83E−01	1.36E+00	5.77E+01	1.11E+01	3.12E+01
	Electric Riding Mower	2.46E+00	8.95E−01	6.53E−01	5.65E+01	2.05E+01	1.50E+01
Photochemical oxidant formation (kg NMVOC)	Gasoline riding mower	3.04E+00	1.05E+00	2.91E+00	4.34E+01	1.50E+01	4.15E+01
	Electric riding mower	3.09E+00	1.16E+00	2.42E+00	4.41E+01	1.66E+01	3.46E+01
Ecological toxicity potential (kg 1,4-DCB eq.)	Gasoline riding mower	3.45E+01	4.71E+00	3.29E+00	6.87E+01	9.38E+00	6.55E+00
	Electric riding mower	3.15E+01	1.11E+01	7.61E+00	6.27E+01	2.22E+01	1.51E+01
Terrestrial acidification potential (kg SO2 eq.)	Gasoline riding mower	4.74E+00	7.00E−01	4.07E+00	4.99E+01	7.36E+00	4.28E+01
	Electric riding mower	4.71E+00	1.82E+00	2.21E+00	4.95E+01	1.92E+01	2.32E+01
Freshwater eutrophication potential (kg P eq.)	Gasoline riding mower	8.20E−01	9.35E−02	7.42E−02	5.61E+01	6.40E+00	5.08E+00
	Electric riding mower	6.77E−01	4.59E−01	3.26E−01	4.63E+01	3.14E+01	2.23E+01
Metal depletion (kg Fe eq.)	Gasoline riding mower	5.76E+02	1.24E+02	1.49E+01	7.74E+01	1.66E+01	2.01E+00
	Electric riding mower	5.38E+02	1.98E+02	7.77E+00	7.24E+01	2.66E+01	1.04E+00
Fossil depletion (kg oil eq.)	Gasoline riding mower	1.98E+02	6.24E+01	7.13E+02	2.04E+01	6.41E+00	7.32E+01
	Electric riding mower	2.08E+02	7.29E+01	2.31E+02	2.14E+01	7.49E+00	2.38E+01

Table 4 Sensitivity analysis on the maintenance phase

Maintenance scenarios	Gas ride-on mower	Electric ride-on mower	Gas push mower	Electric push mower
Best case (B) (ideal conditions)	Replacement: Blades × 4 Oils × 4 Filters × 4 (once every 2 years) No spark plug, deck, and motor belt replacement	Replacement: Blades × 4 (once every 2 years) No battery pack replacement	Replacement: Blades × 1 Oils × 1 Filters × 1 Spark plug × 1 (once a lifetime)	Replacement: Blades × 1 (once a lifetime) No battery replacement
Intermediate better case	Blades × 4 Oils × 4 Filters × 4 (once every 2 years) 1 spark plug, plus deck, and motor belt	Blades × 4 (once every 2 years) 1 battery pack (once a lifetime)	Blades × 2 Oils × 2 Filters × 2 Spark plug × 2 (twice during lifetime)	Blades × 2 (twice during lifetime) 1 battery (once a lifetime)
Average case (baseline)	Blades × 9 Oils × 9 Filters × 9 (once every year) 1 spark plug, plus deck and motor belt	Blades × 9 (once every year) 1 battery pack (once a lifetime)	Blades × 4 Oils × 4 Filters × 4 Spark plug × 4 (once every 2 years)	Blades × 4 (once every year) 1 battery (once a lifetime)
Intermediate worse case	Blades × 9 Oils × 9 Filters × 9 (once every year) 2 spark plug, plus deck and motor belt	Blades × 9 (once every year) 2 battery packs (twice a lifetime)	Blades × 9 Oils × 9 Filters × 9 Spark plug × 9 (once every year)	Blades × 9 (once every year) 2 batteries (twice a lifetime)
Worst case (W) (extreme usage conditions)	Blades × 18 Oils × 18 Filters × 18 (twice a year) 2 spark plug, plus deck and motor belt	Blades × 18 (twice a year) 2 battery packs (twice a lifetime)	Blades × 18 Oils × 18 Filters × 18 Spark plug × 18 (twice a year)	Blades × 18 (twice a year) 2 batteries (twice a lifetime)

Table 5 Comparative overview and critical analysis of existing LCAs on lawn mowers

Studies	Sivaraman and Linder 2004	Lan and Liu 2010	Charif 2013	Basco 2014
Types of mowers	Gasoline and electric push mowers	1 gasoline push mower, and 1 electric auto mower	1 biodiesel riding mower, and 1 li-ion battery riding mower	1 gasoline push mower
Scope of the LCA	Limited to the mowers' use phase	Full life cycle from cradle to grave	Limited to the mowers' use phase	Full life cycle from cradle to grave
Functional unit	Mowing 2000 m^2, 8 years, 26 times per year, 1.2 h a week, in the USA	Mowing 1000 m^2, 10 years, 25 times per year, 1 h a week, in Sweden	Mowing 8270 m^2, 25 times per year, for 7 years, in Vancouver	Time scope: 5.5 years Fuel consumption: 5 gal/year
Methods Software	Environmental impact from Eco-Indicator 99 and CML. SimaPro 5.1	Environmental impact from Eco-Indicator 99 and EPS2000. SimaPro	Environmental impact from GREET model	Traci N.A
Results	Gasoline: 2.5e + 03 kg CO_2 eq Electric: 1.4–1.6e + 02 kg CO_2 eq	For the gasoline push mower: Use: 173 kg CO_2 eq Manufacturing: 112 kg CO_2 eq	Biodiesel: 10.3e + 04 kg CO_2 eq Battery: 2.0e + 02 kg CO_2 eq	Manufacturing: 125 kg CO_2 eq Use: 210 kg CO_2 eq (Use and manufacturing phases have the highest env impacts.)
Limitations	Assumption that all other life stages than the use phase have the same impacts	LCA made for the OEM Husqvarna Usage and maintenance impacts seem a bit low	In this case study, electricity generated mainly from hydro power (Vancouver, Canada)	LCA made by the OEM Briggs & Stratton. Lack of transparency on the data used

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