Environmental Impact Assessment of Autonomous Transportation Systems

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Abstract

The transportation industry has been leading efforts to fight climate change and reduce air pollution. Autonomous electric vehicles (A-EVs) that use artificial intelligence, next-generation batteries, etc., are predicted to replace conventional internal combustion engine vehicles (ICEVs) and electrical vehicles (EVs) in the coming years. In this study, we performed a life cycle assessment to analyze A-EVs and compare their impacts with those from EV and ICEV systems. The scope of the analysis consists of the manufacturing and use phases and a functional unit of 150,000 miles*passenger was chosen for the assessment. Our results on the impacts from the manufacturing phase of the analyzed systems show that the A-EV systems have higher impacts than other transportation systems in the majority of the impacts categories analyzed (e.g., global warming potential, ozone depletion, human toxicity-cancer, etc.) and on average, EV systems were found to be the slightly more environmentally friendly than ICEV systems. The reason for high impacts in A-EV is due to additional components such as cameras, sonar, radar, etc. In comparing the impacts from the use phase, we also analyzed the impact of automation and found that the use phase impact of A-EVs outperforms EV and ICEV in many aspects including global warming potential, acidification, smog formation, etc. To interpret the results better, we also investigated the impacts of electricity grids on the use phase impact of alternative transportation options for three representative countries with different combinations of renewable and conventional primary energy resources such as hydroelectric, nuclear and coal. The results revealed that A-EVs used in regions that have hydropower based electric mix become the most environmentally friendly transportation option than others.

Keywords: Comparative life cycle analysis, Transportation systems, Autonomous vehicles, Electric vehicles, Internal combustion engine vehicles

1. Introduction

The effects of burning fossil fuels on climate change have grown enormously since the industrial revolution [1]. Currently, seven billion tons of carbon dioxide are released into the atmosphere each year [2]. The United States of America alone has emitted nearly a quarter of greenhouse gas emissions globally [3]. The 30-year national inventory conducted by the United States Environmental Protection Agency found that transportation was responsible for the largest greenhouse emissions of all use sectors [3]. Upon further investigation, we found that a typical passenger vehicle with gross weight <8500 lbs, emits 4.6 metric tons of carbon dioxide per year, leading to 57% of the total transportation emissions [4]. Given the increase in personal vehicle usage, the potential impacts of transportation systems on environmental degradation are becoming more apparent.

In recent years there has been a consistent trend by the government and industry to reduce greenhouse gas emissions with a wide adaptation of electric vehicles (EV) [5]. Since 2018, over one million EVs have been sold worldwide [6]. Growing demand for EVs parallels the fusion of several technologies, including hybrid EVs, fuel-cell EVs, and plug-in hybrid EVs [7]. EVs maintain traffic demands quietly, and efficiently while decreasing air pollution and dependency on fossil fuels [6]. EVs also offer competitive advantages over internal combustion engine vehicles (ICEVs) in lower maintenance requirements because they have fewer moving parts [8,9]. To date, the life cycle assessment (LCA) methodology has been adopted to analyze the environmental impacts of EVs and ICEV [10–12]. The manufacturing of chemicals in batteries (e.g., Lithium-ion, nickel manganese cobalt, lead-acid), energy sources (e.g., coal, wind, solar), and disposal of vehicles are all crucial aspects of potential environmental impacts of an EV's life cycle [13]. Shafique et al. found that EVs have more environmental impacts than ICEVs due to the usage of larger material proportions [14]. This trend is common in LCA literature and is commonly associated with the material composition of the batteries used in electric vehicles [15–17]. It is also noted that improvements in battery chemistry and manufacturing are needed for more environmentally sustainable EV technology that can outperform ICEV [18].

To optimize the global emissions in the transportation sector, one interesting alternative is increasing the efficiency of EVs in their usage phase by transitioning into fully autonomous driving [19,20]. Autonomous electric vehicles (A-EV) represent one of the biggest technological advancements in the transportation sector [21]. A-EVs utilize artificial intelligence, cameras, laser imaging, detection, ranging systems, and radar sensors to perceive the surrounding environment and use artificial intelligence to control the actuators for vehicle control with or without human input [22,23]. The National Highway Traffic Safety Administration has defined six levels of automation such as level zero is no automation, level one is driver assistance, level two is partial automation, level three is conditional automation, level four is high automation and level five is full automation [24]. The full automation system is anticipated to improve driving safety, energy utilization, sustainability, and traffic congestion [21]. Daily driving an autonomous vehicle can increase energy utilization by up to 200%, zero greenhouse gas emissions during travel, and decreased stagnate emissions in traffic are all expected [25].

While A-EVs have attracted significant scientific attention, numerous studies have also been conducted to assess the environmental sustainability of A-EVs as well [11,26–30]. Vahidi et al. studied the energy-saving potential of A-EV technology [26]. Ross et al. considered the effect of A-EVs in different scenarios [27]. So far, Gawron et al. have provided an LCA of A-EV sensing and computing systems [11]. Brown et al. highlighted the major factors determining the A-EV's environmental impacts [31] while Cox et al. conducted an LCA of A-EV at a different operational level by considering changes to driving patterns by applying exponential smoothing of the driving cycle [28]. However, the existing literature on A-EV still has gaps since there is no comprehensive LCA study providing comparisons between A-EV systems and EV and ICEV and detailed analyses on various levels of automation.

In this study, we performed an LCA to provide a direct comparison between ICEV, EV, and A-EV technologies. For A-EV systems, we categorized the vehicles from level zero through two (A-EV1) and level-three-through five (A-EV2). A-EV1 refers to where a human monitors the driving environment with a level of autonomy including features such as cruise control and lane assist. A-EV2 refers to an automated system that monitors the driving environment with features such as environmental detection, automation through geofencing, and complete automation. We focused on assessing the impact of increased automation on reducing usage emissions. To interpret the results more clearly, we investigated the impacts of electricity grids in Poland, Norway, and France.

2. Methods

2.1 Goal and Scope

The goal of this study was to compare the life cycle environmental impacts of ICEVs, EVs, and A-EVs. The results of the LCA will help inform policy and lawmakers in their decision-making to achieve the zero-carbon emission target [2]. The LCA work in this study was performed following the recommended practices of the ISO (International Standards Organization) 14040:2006 and 14044:2006 standards [32,33].

The cradle-to-use phase system boundary includes the production of raw materials, the materials, and energy used in the manufacturing and use phase of three vehicle types. We excluded the end-of-life phase from the system boundary due to limited data available [11]. For a fair comparison, a functional unit of 150,000 miles*passenger (about 241,402 km*passenger) was chosen to compare the environmental performance of ICEVs, EVs, and A-EVs during the vehicle's lifetime [14]. The data for materials and energy was extracted from Ecoinvent V. 3.8 Database [34]. For the quantification of environmental impacts associated with the manufacturing and use phase, GaBi ts 10.0 software was used [35]. We employed Tools for the reduction and assessment of chemical and other environmental impacts (TRACI) used in this study [36]. TRACI allows for quantifying stressors that have potential effects providing insights into the processes and their environmental impacts. Ten midpoint environmental categories were modeled using the TRACI impact assessment model: acidification (kg $SO_{2\text{-}eq}$), ecotoxicity (CTU_e), eutrophication (kg N_{eq}), global warming potential (kg $CO_{2\text{-}eq}$), human toxicity cancer (CTU_h), human toxicity non-cancer (CTU_h) human health particulate air (kg $PM_{2.5\text{-}eq}$), ozone depletion air (kg $CFC11_{eq}$), resources (MJ surplus energy), and smog air (kg $O_{3\text{-}eq}$).

2.2 Modeling Approach

The framework for this study can be seen in Figure 1. For this study, vehicle inventories were divided into engines, batteries, additional autonomous components, and energy use. It was assumed that the remaining materials used in all vehicles (e.g., steel, aluminum, plastics) are the same. Both electric and autonomous vehicles engines and batteries are assumed to be the same electric motors and lithium-ion batteries. ICEV engines included additional parts such as cast iron, aluminum, and copper. The batteries in internal combustion vehicles are most commonly lead-acid batteries [11]. Autonomous vehicles need additional components such as cameras, sonar, radars, laser imaging, detection, and ranging sensors, a global positioning system with an inertial navigation system, dedicated short-range communication equipment, computers, harnesses, and structure [11]. The engine composition used in standard, electric and autonomous vehicles was used to build inventories, respectively.

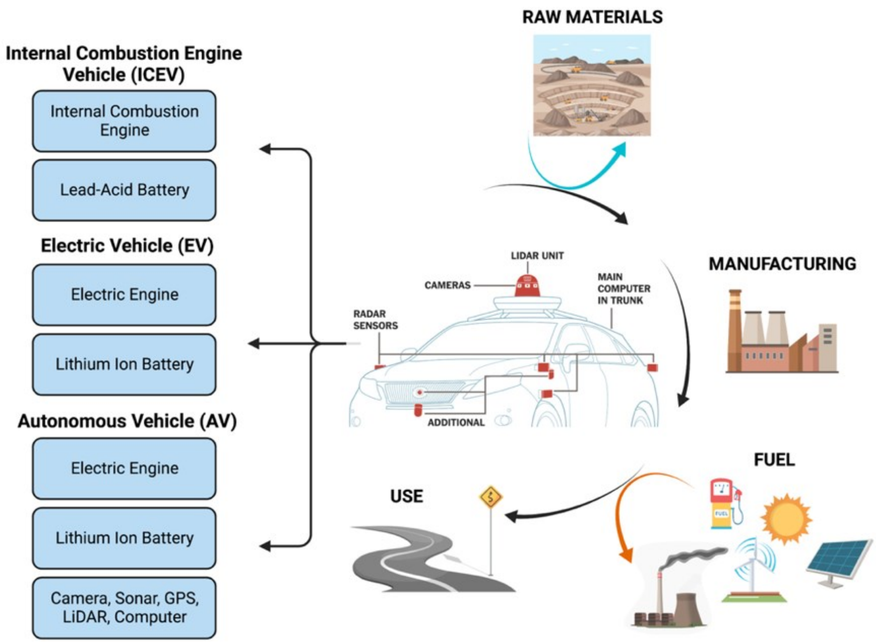

Figure 1. System boundary and components of distinct types of vehicles.

2.3 Life cycle inventories

The life cycle inventories were categorized into manufacturing and use phase components and shown in Table 1. The manufacturing phase includes engines, batteries, additional parameters, and energy utilized during the production of three different vehicle types [9,11,14,37]. The choice of lead-acid and lithium-ion batteries was justified due to their wide adaptation in combustion and electric vehicles. Battery inventories were adapted from literature [38]. The energy used during the manufacturing of ICEV, EV, and A-EVs varies. The electricity required for the manufacturing of EVs and A-EVs is more than the ICEVs since both EVs and A-EVs require advanced equipment and infrastructure [16]. The average electricity consumption for compact car manufacture was calculated to be 20 MJ/kg of vehicle [15]. The average mass of the ICEV and EV/A-EVs is considered as 1355 kg and 1450kg [15]. In the use phase, fuel and electricity consumption were chosen at 21.79 kilometers (km) per liter for ICEV [14], 206 Wh/km for EV [9], and 177.16 Wh/km for A-EV [11].

Table 1 Inventories for manufacturing and use phase of ICEV, EV, and A-EVs types. For the use phase, A-EVs were categorized into A-EV1(automation levels zero through two) [11] and A-EV2 (automation levels three through five) [27]. * indicates electricity utilized for A-EV1, and ** indicates energy utilized for A-EV2 types during the use phase.

Phase	Components	ICEV			EV			A-EV
		Materials	Units	Mass	Materials	Units	Mass	Mass
Manufacturing Phase	Engines	Cast Iron	kg	102.27	Copper	kg	4.50	4.50
		Aluminum	kg	61.36	Steel	kg	23.90	23.90
		Steel	kg	20.45	NdFeB	kg	1.30	1.30
		Plastic	kg	9.20	X	X	X	X
		Rubber	kg	9.20	X	X	X	X
		Copper	kg	2.05	X	X	X	X
	Battery	PbSb 2.5%	kg	1.12	Battery cell	kg	152.30	152.30
		Lead	kg	0.01	Anode	kg	59.00	59.00
		Sulfuric Acid	kg	0.80	Cathode	kg	65.00	65.00
		Water (Deionized)	kg	0.86	Separator	kg	3.30	3.30
		Paper/Glass	kg	0.38	Electrolyte	kg	24.00	24.00
		Polypropylene	kg	1.04	Cell container	kg	1.00	1.00
		Distilled Water	kg	0.00	Battery case	kg	81.00	81.00
		Pulp Paper	kg	0.40	BMS	kg	9.40	9.40
		Foil	kg	0.00	Cooling	kg	10.00	10.00
		Iron	kg	0.04	X	X	X	X
	Additional	X	X	X	Cast Iron	X	X	0.20
		X	X	X	Aluminum	X	X	9.40
		X	X	X	Copper	kg	X	0.70
		X	X	X	Steel	kg	X	0.30
		X	X	X	Glass	kg	X	0.10
		X	X	X	Rare earth	kg	X	0.20
		X	X	X	Plastic	kg	X	1.60
		X	X	X	Electronics	kg	X	3.90
	Energy	Electricity	GJ	27	Electricity	GJ	29	29
Use Phase	Energy Use	Petroleum	lit/km	0.046	Electricity	Wh/km	206	177* 103**

2.4 Limitations and uncertainty

The variation in inventory data may influence the LCA results substantially. To interpret the results, we investigated the impact of the electricity grid by analyzing the data for three representative countries with different combinations of renewable and conventional primary energy resources such as Norway (92% of electricity is supplied from hydropower plants) [39], Poland (87% of electricity is from coal) [40], and France (74.5 % of electricity is provided by nuclear plants) [41]. Note that the electricity data was representative of 2019 inventories. Sensitivity analysis was carried out using the one-variable-at-a-time method by varying one parameter at a time to determine the sensitivity of parameters to variation in input.

3. Results and Discussion

3.1 Life Cycle Impact Assessment

Figure 2 compares the environmental performance of three transportation technologies based on their manufacturing phase impacts. The data shows that in most of the impacts analyzed, the A-EV systems have slightly higher impacts than other transportation systems, and EV systems were found to be more environmentally friendly than ICEV systems. The reason for higher impacts for A-EV is the increased impacts from cameras, sonar, radar, global positioning systems, laser imaging, detection, and ranging systems, dedicated short-range communication equipment, and computers needed for autonomy. A-EVs were found to have better environmental performance in acidification impact categories. The higher acidification impacts of ICEVs are due to the usage of platinum group metals used in catalytic converters [9,16]. In the following impact categories, the ICEV systems were found to be better than EV systems: global warming potential, ozone depletion, human health particulate, and resource depletion. The reason for higher impacts for EV systems in these categories is attributed to energy used for manufacturing. Battery production is responsible for the higher energy usage in the EV production stage. These results were consistent with the previous LCA study findings [9,14,16]. Similar to our findings, Shafique et al., also found that lithium-ion batteries used in the EVs contributed majorly (more than 45%) to the production phase global warming potential, ozone depletion, and fossil fuel depletion impacts [14]. The European Environmental Agency conducted an LCA study on EVs and found that the energy used for battery production in the manufacturing stage emits about twice as much NOx, SO_2, and PM emissions as ICEV production [16]. This study also reported that the production stage impacts of EVs were more than ICEVs in global warming potential, human health particulate air, and resource depletion categories [16].

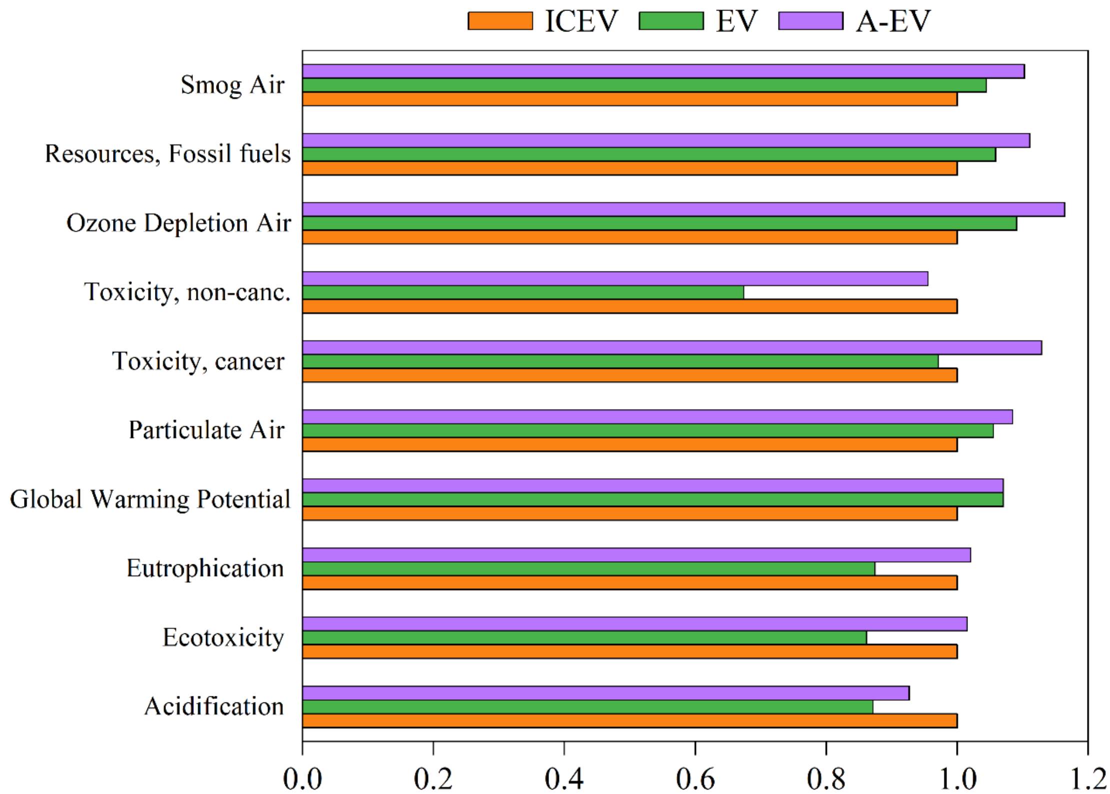

Figure 2. Normalized impacts of vehicle production. Results from each impact category have been normalized to impacts from ICEV for normalization.

Figure 3 provides a comparison between ICEV, EV, and two types of A-EV systems (A-EV1 and A-EV2) based on use phase environmental impacts. First, we found that the ICEVs have higher impacts during the use phase than EV and A-EV systems in three significant impact categories such as global warming potential, ozone depletion, and resource depletion. As EVs and A-EVs have nearly zero exhaust emissions, most of the associated air-related emissions are contributed to electricity consumed by EV motors. Therefore, for EVs and A-EVs, the upstream processes due to the combustion-based power generation system where the electricity is generated were found to be the primary reasons for air-related emission [42,43]. Note that pollutants, such as CO_2, N_2O, and CH_4, as well as solid particulate matter, have a considerable impact on climate change and particulate matter formation (e.g., $PM_{2.5}$ and PM_{10}) [44]. Other contaminants include different metal elements, NOx, and phosphate, which promotes eutrophication [45], and sulfur dioxide (SO_2) starts the acidification process (nickel, beryllium, cobalt, vanadium, copper, and barium, etc.) [46]. These results are consistent with the literature. Shafique et al. found that use phase global warming potential, ozone, and resource depletion impacts of ICEVs are almost three times greater than EV [14]. Another comparative study also reported that the use phase global warming potential and resource depletion impacts of ICEVs is about three times higher than EVs [17]. A comparison of ICEV and A-EV also revealed that applying potential operational effects for A-EV could result in roughly 10% lower global warming potential impacts than ICEV [11]. Second, in the acidification and formation of smog categories, we observed minor differences in the use phase associated impacts of A-EV1 and ICEV. We also noted that increasing automation to A-EV2 resulted in a ~40% reduction of impacts compared to A-EV1 in these impact categories. This is mostly because greater levels of automation are boosting fuel efficiency. Massar et al. also found that increasing automation levels by more than 60% could minimize environmental impacts [30]. Last but not least, we found that the impacts of A-EVs are nearly two to three times higher compared to ICEV in human health particulate, ecotoxicity, eutrophication, and human toxicity categories. The reason for particulate matter formation is associated with electricity production. On average, the global electricity mix contains an average of ~37% of primary energy from coal-fired power plants [47]. Therefore, even with significant improvement in fuel efficiency of A-EV2, fine particulate matter was still 2.5-fold higher than ICEVs. The higher impacts in ecotoxicity impact are due to the additional metal consumption of A-EV and EV systems. Heavy metals, the anthropogenic sources, including coal mining and combustion, are mainly associated with ecotoxicity [48]. The high eutrophication impacts are related to water discharges from mining activities required for electricity generation [16]. The production of electricity from coal power plants utilized for batteries during the use phase of the EV and A-EVs is responsible for the greater human toxicity impacts [9]. These results were also confirmed in the literature [9,14,16,49].

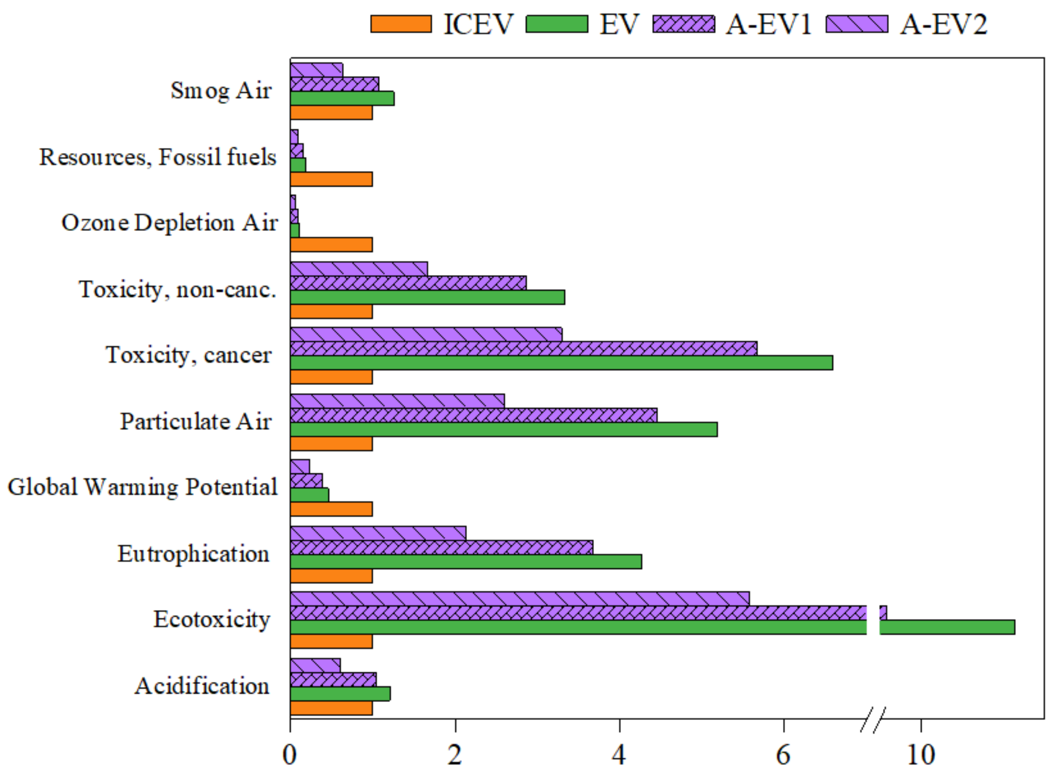

Figure 3. Normalized impacts of use phase. The impact from each environmental category was normalized to the impacts from ICEV.

Table 2 provides the cradle-to-end-of-use impacts that consist of manufacturing and use phase impacts. The combined normalized environmental impacts of EV and A-EVs were lower than ICEV in the global warming potential, ozone depletion, and resource depletion categories. Previous research yielded comparable results in these categories [9,14,15,17]. According to our findings, for all transportation systems, the use phase contributes more than 70% and the production phase contributes around 30% in the majority of impact categories. Shafique et al., also reported that the use phase impacts of ICEV and EVs account for ~50- 80% of total life cycle impacts across all impact categories[14]. We observed lower contributions of the use phase on total impacts in other studies, which was attributed to differences in the electricity mix employed in those studies [17,50].

Table 2 Normalized combined (production and use phase) environmental impacts of ICEV, EV, and A-EVs per 150,000 miles per passenger. The environmental impacts are normalized with respect to ICEV combined impacts (shown in the last column).

		EV	A-EV1	A-EV2	ICEV	ICEV (150,000 miles*passenger)
Impact categories	Acidification	1.14	1.02	0.67	1.00	1.70E+02 (kg $SO_{2\text{-eq}}$)
	Ecotoxicity	3.86	3.51	2.34	1.00	2.14E+05(CTU_e)
	Eutrophication	2.66	2.42	1.61	1.00	6.56E+01 (kg N_{eq})
	Global warming	0.50	0.44	0.28	1.00	8.59E+04 (kg $CO_{2\text{-eq}}$)
	Human health particulate	3.32	2.94	1.91	1.00	2.69E+01 (kg $PM_{2.5\text{- eq}}$)
	Human tox., cancer	3.38	3.07	2.06	1.00	7.57E-04 (CTU_h)
	Human tox., non-can	1.86	1.81	1.27	1.00	6.02E-03 (CTU_h)
	Ozone depletion	0.12	0.11	0.07	1.00	1.85E-02 (kg CFC 11_{eq})
	Resources	0.20	0.18	0.11	1.00	1.53E+05(MJ energy)
	Smog Air	1.22	1.08	0.71	1.00	1.95E+03 (kg $O_{3\text{-eq}}$)

3.2 Sensitivity Analysis

LCA results show significant variabilities in comparison to the A-EV system alternative's environmental performances, which is primarily attributed to differences in electricity consumption during their use phase. Depending on where electricity is produced, those impacts change. For example, the global warming potential impact of 1 kWh of electricity produced in Norway is about ~45 times more environmentally friendly than the same amount of electricity produced in Poland. As such, energy-intensive processes like photovoltaic panel production, chip manufacturing, etc., are also more environmentally friendly in Norway than in Poland [51]. Thus, it is crucial to consider the impact of various electricity grids of different countries to provide a detailed comparison between A-EV, EV, and ICEV systems.

The influence of electricity from different countries with various primary energy sources such as coal, hydroelectric, and nuclear on the environmental performance of alternative transportation options is shown in Figure 4. We found that the composition of the electricity mix highly affects the usage phase impacts, and with a grid dominated by renewable energy like hydropower plants, A-EV1 and A-EV2 will have the least impact in almost ten assessed impacts categories. Furthermore, using A-EVs using a coal-dominated grid such as Poland is worse than using the current mix of the electricity grid. However, using a grid dominated by nuclear power like France will have similar impacts as using a renewable-dominated grid, except for ozone depletion. Considering the usage of EVs and A-EVs is primarily focused on reducing the global warming impacts along with the reduced release of ozone-depleting substances, the use of A-EVs and EVs in nuclear power grid would have a higher impact. It can be traced back to higher chlorofluorocarbon used during uranium enrichment, the source for nuclear plants [52]. EVs and A-EVs would be most feasible in grids dominated by renewable energy.

We found similar observations in the literature. Pipitone et al. compared the electricity mix of European, Norway, and Poland on the life cycle environmental performance of ICEV and EVs

[17]. The findings from this study show that by considering renewable energy dominated grid (i.e., Norway), EVs have significantly lower use phase environmental impacts compared to European and Poland electricity grids [17]. Another study also found that switching the electricity source in electric automated minibuses from a European electricity mix to a 100% renewable energy source can reduce the global warming potential impacts by 58% [50].

4. Conclusions

A comparative environmental impact assessment of ICEV, EV, and A-EV was undertaken using the TRACI method. Based on the evaluation of vehicle manufacturing, we found that the A-EV systems have higher impacts than other transportation systems in most of the impacts categories analyzed (e.g., global warming potential, ozone depletion, human toxicity, cancer, etc.) and on average, EV systems were found to be the slightly more environmentally friendly than ICEV systems. This is due to the excess materials needed for manufacturing the A-EV system. The results for the usage phase show that EV and A-EV have larger impacts than ICEV in acidification, ecotoxicity, eutrophication, human health particulate air, human toxicity (cancer), human toxicity (non-cancer), and smog air. A-EV has less impact in all impact categories than EV. Increasing to A-EV2 decreases the impacts compared to A-EV1 by 40%, showing that using automation will significantly decrease the impacts associated with EVs. To clearly interpret the results, we also investigated the impacts of electricity grids used in the United States, Poland, Norway, and Franc on use phase impacts of ICEV, EV, and A-EV transportation systems. The use of a renewable grid-primarily contributed by hydropower plants can make the use of EVs and A-EVs feasible with less impact on ten categories. Furthermore, the nuclear-based renewable grid is not effective in reducing ozone-depleting gas emissions.

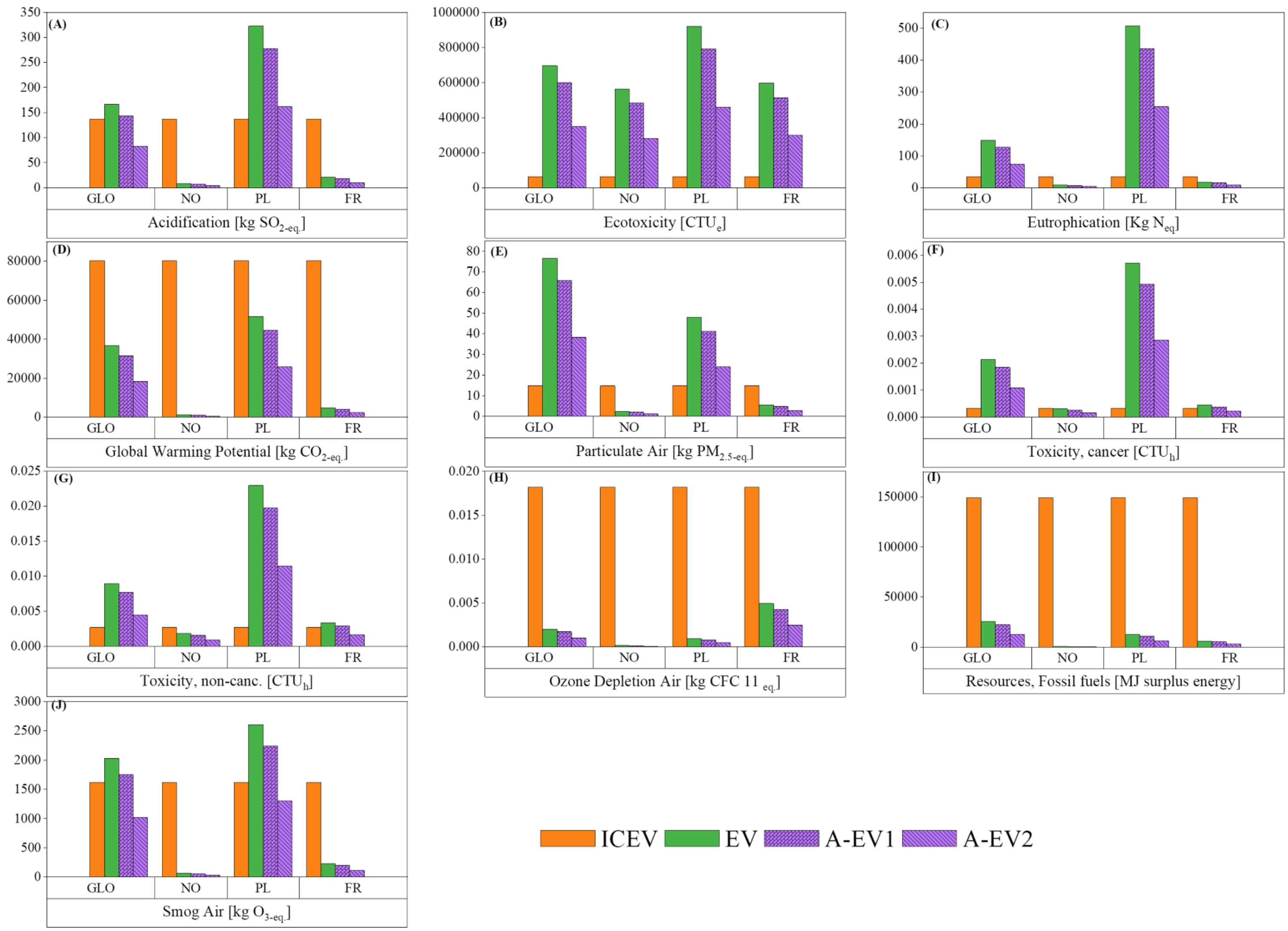

Figure 4. The use phase impacts of alternative transportation systems based on different electricity grids of distinct locations, such as Norway (NO), Poland (PL), and France (FR). Note that the baseline analysis was done based on global average (GLO) of electricity mix. The impact from each environmental category was normalized to the impacts from ICEV.

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Author Contributions
Conceptualization, I.C.; Methodology, S.H, E.E., C.A., A.R., and D.R..; Data curation, S.H, E.E., C.A., A.R., and D.R.; Writing—original draft, S.H, E.E., C.A., A.R., and D.R.; Writing—review & editing, A.R., V.G., S.D., and I.C.; Visualization, C.A., A.R., and D.R. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement
Data is available upon a reasonable request.

Conflict of Interest
The authors declare no conflict of interest.

Abbreviations

Abbreviations	**Description**
A-EV	Autonomous electric vehicles
A-EV1	Autonomous electric vehicles with automation from level zero through two
A-EV2	Autonomous electric vehicles with automation from level-three through five
EV	Electric vehicles
ICEV	Internal combustion engine vehicles
LCA	Life cycle assessment
TRACI	Tools for the reduction and assessment of chemical and other environmental impacts
PM	Particulate matter
NOx	The gases of nitric oxide and nitrogen dioxide
BMS	Battery management system

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