ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20240725130415

Original scientific paper
Received: 2024-07-25, Accepted: 2024-08-13

Application of Life Cycle Assessment to Determine the Influence of Electricity Mix Profile and Driving Mode on the Environmental Impact of Electric Battery Vehicles

Jelena Topić Božič*, Ante Čikić, Simon Muhič, Boris Kraševec

Abstract: Transportation electrification is one of the key strategies in the sustainable energy transition. Life cycle assessment was performed to evaluate the environmental impact of different electricity mixes with higher uptake of renewable energy sources and various driving modes on the use of battery electric vehicles (BEVs). The results showed that the values for categories global warming, fine particulate matter formation, ozone formation, human health, and fossil fuel scarcity decreased by 15.8 %, 11.3 %, 25.3 %, and 12.9 %, respectively, in the Green 2030 scenario compared to the baseline. When the driving mode was considered, the impact decreased by 27.7 %, 36.9 %, 21.3 %, and 24.4 %, respectively, in the lowest use in the current production scenario. In the categories of land use and mineral resource scarcity, a 6.9 % and 2.1 % increase in the values was observed in Green 2030 scenario, showcasing the trade-off in different environmental impact categories.

Keywords: battery electric vehicles; driving mode; electricity use; electricity production mix; life cycle assessment; transportation

1 INTRODUCTION

In 2019, the European Green Deal (EGD) was released to tackle climate and environmental challenges. EGD aims to achieve zero net emissions of greenhouse gases in 2050 [1, 2]. The energy transition is the core objective of policies aimed at decarbonization and can be achieved by the accelerated deployment of renewable energy (RE) technologies and energy efficiency measures [3–5]. As energy use is responsible for most global greenhouse gas emissions (GHGE), transitioning to a more sustainable energy system is crucial [6]. Transportation electrification is one of the key strategies in the sustainable energy transition [7] as transportation still largely relies on liquid fuels mainly derived from oil (95 %) [8].

Road transportation remains a significant source of air pollution, primarily via exposure to particulate matter ($PM_{2.5}$), nitrogen oxides (NO_X), CO, and sulfur dioxide (SO_2)[9–11]. Electric vehicles (EVs) offer some advantages over traditional vehicles as EVs do not emit tailpipe pollutants, CO_2, or NO_X and reliability as the number of engine elements in EV is smaller, leading to cheaper maintenance and fewer breakdowns [11,12]. On the other hand, significant battery-related challenges remain, such as the driving range, which is typically limited from 200 to 350 km with full charge, long charging time, and battery costs [11]. The electrification roadmap is facing several challenges as the vehicle types are diverse in terms of purposes, sizes, and travel modes, leading to variable energy demands in consumption modes, amounts, and costs. Additionally, the benefits of transportation electrification will be greater if EVs deployment takes place in parallel with the decarbonization of the power system and increases the share of renewable energy sources (RES) [7].

Recently Mirz et al. showed that the CO_2 equivalent emissions differ greatly depending on the country where the EV is used. The results showed that life cycle of CO_2 equivalent emissions of an exemplary electric car and a lifetime usage of 200000 km in selected countries were in the range of 16.1 t (Norway) to 41 t (Poland) [12]. Similarly, Shafiqe and Luo undertook a comparative life cycle assessment for the top 10 countries of EV sales, assessing current and future electricity mixes. The results showed that the overall performance of the EV. The results showed that overall performance of the EV is highly dependent on the electricity mix consumed during their production and use phase. The results showed that EVs in China with 2019 and 2025 electricity mix have a higher impact than others. EV with 2030 Norway electricity mix was an optimal choice and had the lowest environmental impact in most categories [13]. Burchart-Korol et al. compared the environmental impact of cars in Poland and Czech Republic. The results showed that the environmental indicators in all impact categories were higher for EVs in Poland than in the Czech Republic due to different electricity mix. In scenarios with a reduced share of coal among the sources of energy used for electricity production, a decrease in the values of environmental indicators was observed. When EV and internal combustion engine vehicles (ICEV) were compared, GHGE and fossil fuel depletion values were lower for EV [14]. On the other hand, in the categories terrestrial acidification, freshwater eutrophication, human toxicity, and particulate matter formation, values were higher in the case of EV [14]. Similarly, Del Pero et al. showed that using EVs significantly reduces climate change due to the absence of exhaust gas emissions. The advantages are even greater when a higher share of RES is introduced in electricity production. However, the manufacturing of EV compared to ICEV requires larger use of metals, chemicals, and energy; therefore, the resulting impact in categories acidification, human toxicity, particulate matter, photochemical ozone formation, and resource depletion are higher in the case of EV [15].

EVs are recognized as pillars bridging the gap towards renewable energy systems [16]. The deployment of EVs has been growing over the past ten years. Still, the penetration rates of EVs remain relatively low, corresponding to 1 % of the global car stock in 2019 [7], which can be attributed to several issues, including the high cost of infrastructure, the prices of EV, the scarcity of charging stations, and the limited range of EVs [17]. However, to reduce the environmental impact in the transport sector, the role of lifestyle should be considered, and emphasis should be put on policy and strategy development to reduce travel demand [18].

The transport's share of final energy use in Slovenia remains high, representing the sector with the highest share (41 %), followed by manufacturing and construction (25 %), households (22 %), service activities (9 %), and other users (3 %) [19]. Muhič et al reported that the share if the end energy use in transport was 39.5 % in 2014 [20]. Fig. 1 shows the final energy use by sector in 2014 – 2021 [21]. The final energy use in 2014 – 2021 was on average 4758.0 ktoe, above the 2030 NECP target set at 4426 ktoe. The year 2020 was the only year that the final energy use was slightly below the 2030 NECP target (4405.7 ktoe) which can be attributed to the lockdowns during the Covid-19 pandemic.

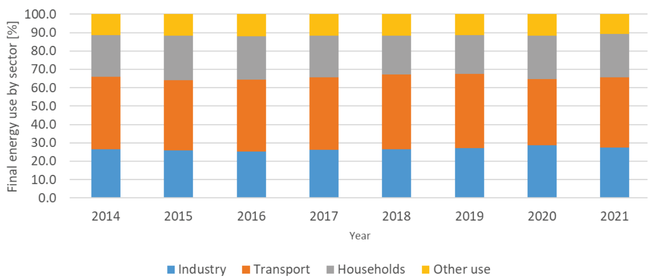

Figure 1 Final energy use by sector in Slovenija for the period 2014 – 2021 [21]

One of the main sources of GHGE in Slovenia is road traffic, as cars contribute 20 % of all GHGE. Due to Slovenia's smaller share of public transport to achieve a 67 % reduction, significant vehicle fleet electrification is needed [22]. The latest data shows that the number of newly registered battery EV and hybrid EV is increasing. The number of registered battery and hybrid EV has reached 5448 and 1617 in 2021, representing 3.4 % share of electric cars in first registrations [22]. Based on the latest available data for 2021, the number of newly registered EV in Slovenia is above the country's baseline (25.7 % difference) but below moderate (8.8 % difference) and ambitious (34.2 % difference) national climate and energy plan (NECP) scenario projections [22]. Similarly, a total number of batter EV and plug in hybrids in 2021 is above the baseline NECP projections (14.0 % difference) and slightly below moderate (2.2 % difference), and below ambitious (16.2 %) NECP scenario projections [22].

The widespread rollout of electric cars faces several technical and socio-economic challenges. The direction of the future transportation system is affected by political, economic, social, technological, and environmental reasons [16]. Adopting EVs to existing networks may increase peak demand for electricity, causing network congestion and requiring additional investment in the electricity grid infrastructure. Additionally, the environmental cost of the use of EVs is low only if the RES penetration in the considered system is significant. Decarbonization measures in Slovenia support the introduction of EVs. The main incentives and legislation include [23]:

- Registration tax benefits: BEVs pay minimum rate of 0.5 %;
- Purchase subsidies for private individuals and legal entities;
- Other financial benefits include Eco Fund long-term loans for the purchase of electric cars at a subsidized rate set by the Bank of Slovenia;
- Company tax benefits: for EVs used as company cars, there is zero benefit-in-kind tax;
- VAT benefits: Legal entities can claim VAT deductions for purchasing, servicing, and spare parts.

This study aimed to perform life cycle assessment (LCA) focusing on the use phase of the EV in Slovenia to evaluate the environmental impact of using BEV under different electricity scenarios. Different electricity mixes were considered, including scenarios with higher uptake of RES in 2030 and phasing out dependence on fossil fuels in the electricity mix.

2 MATERIALS AND METHODS

(LCA) is a standardized methodology based on ISO 14044 and 14040 standards for evaluation of the environmental impact of products and processes. LCA consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [23, 24]. LCA defines the boundaries of the study, which typically include processes such as manufacturing (extraction of raw materials, transport to the factory, manufacturing of components, transportation), construction, operation and maintenance, and disposal [26].

2.1 LCA Software and Methods

This study utilized the software SimaPro 9.5. with Ecoinvent 3.9.1 database for foreground processes. ReCiPe Midpoint (H) was the impact assessment method used [26, 27].

2.2 System Definition and Boundaries

The study's primary goal is to evaluate and compare the potential environmental impact of using electric cars with different modes of driving and electricity production mix scenarios for Slovenia.

In electricity scenarios, all input and output data were related to the 1 kWh of produced electricity for the electricity generation scenarios. The functional unit (FU) was defined as 1 kWh of produced electricity.

For the electric car a defined FU was a journey of 1 km with an electric passenger car which is a process. All input and output data were related to the 1 km of journey with a compact electric car.

2.3 Life Cycle Inventory

This LCA uses Ecoinvent 3.9.1 data about electricity generation in Slovenia to report environmental impact of producing 1 kWh of electricity in Slovenia. The ReCiPe midpoint and CED methods were used to calculate environmental impacts. Slovenia has three primary electricity generation sources: nuclear, hydroelectric, and thermal power plants. Three electricity mix scenarios were modeled:

1) SI_2020 mix (Slovenia electricity generation sources with different shares without import – year 2020): Wind 0.04 %, Pump Hydro 1.4 %, Hydro 28.6 %, Lignite 24.6 %, Gas 0.15 %, Nuclear 37.1 %, Oil 0.01 %, Biogas CHP 0.5 %, Lignite CHP 2.5 %, Gas CHP 2.3 %, Oil CHP 0.05 %, Biomass CHP 0.5 %, and Solar 2.3 %.
2) SI_2030 mix (additional uptake of solar power without import with shares): Wind 0.04 %, Pump Hydro 1.2 %, Hydro 25.7 %, Lignite 22.1 %, Gas 0.14 %, Nuclear 33.3 %, Oil 0.01 %, Biogas CHP 0.5 %, Lignite CHP 2.5 %, Gas CHP 2.0 %, Oil CHP 0.05 %, Biomass CHP 0.04 %, and Solar 12.1 %.
3) SI_Green2030 mix (reduction in coal electricity): Wind 0.04 %, Pump Hydro 1.4 %, Hydro 28.6 %, Gas 0.15 %, Lignite 13.4 %, Nuclear 37.1 %, Oil 0.01 %, Biogas CHP 0.5 %, Lignite CHP 2.5 %, Gas CHP 2.3 %, Oil CHP 0.05 %, Biomass CHP 0.5 %, and Solar 27.9 %.

For the electric car, the available dataset for 1 km of transport with an electric car, available in the Ecoinvent database, 3.9.1, with a global geographical denomination, was used. A vehicle lifetime of 150000 km and an average battery lifetime of 100000 km were assumed. The study focused on the use phase – the environmental impact of using a car for transportation concerning the electricity mix scenarios described above and the driving profile. Different electricity use representing different driving styles was modeled and electricity use scenarios were chosen based on the available literature data [28, 29]:

1) Baseline: The process is available in the Ecoinvent 3.9.1 database, which models 0.199 kWh of electricity used for a journey of 1 km.
2) Low use: 0.150 kWh of electricity for a journey of 1 km;
3) Moderate use: 0.250 kWh of electricity for a journey of 1 km;
4) High use: 0.300 kWh of electricity for a journey of 1 km.

3 RESULTS AND DISCUSSION

3.1 LCA of the Impact of Electricity Mix on the Use of Electric Car

Tab. 1 shows the environmental impact in midpoint impact categories generated by a 1 km journey with an electric car in three hypothetical electricity mix scenarios. The baseline electricity production mix for Slovenia (year 2020) and two scenarios modeling an increased PV share (SI_2030) and reduction in coal electricity (SI_Green2030).

Table 1 Environmental impact of using electric car with hypothetical electricity mix scenarios (Functional unit is 1 km journey).

Impact category	Unit	SI_2020	SI_2030	SI_Green2030
Global warming	kg CO_2 eq	0.159446016	0.153873439	0.134273449
Stratospheric ozone depletion	kg CFC11 eq	0.000000050	0.000000049	0.000000049
Ionizing radiation	kBq Co-60 eq	0.057741176	0.052568903	0.057574530
Ozone formation, Human health	kg NO_x eq	0.000525799	0.000513405	0.000466363
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.000597861	0.000563428	0.000446451
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.000599567	0.000587325	0.000540361
Terrestrial acidification	kg SO_2 eq	0.001669117	0.001555614	0.001180641
Freshwater eutrophication	kg P eq	0.000205132	0.000191823	0.000147501
Marine eutrophication	kg N eq	0.000019359	0.000018455	0.000015856
Terrestrial ecotoxicity	kg 1,4-DCB	1.235851020	1.309610056	1.317791213
Freshwater ecotoxicity	kg 1,4-DCB	0.027746272	0.028594659	0.027652181
Marine ecotoxicity	kg 1,4-DCB	0.036160349	0.037180793	0.035865067
Human carcinogenic toxicity	kg 1,4-DCB	0.029285870	0.028743272	0.026581153
Human non-carcinogenic toxicity	kg 1,4-DCB	0.468926516	0.463877112	0.420506987
Land use	m^2a crop eq	0.005248252	0.005283378	0.005614444
Mineral resource scarcity	kg Cu eq	0.001920566	0.001951656	0.001960755
Fossil resource scarcity	kg oil eq	0.040475825	0.039326098	0.035270061
Water consumption	m^3	0.001164947	0.001167766	0.001170062

In the impact category of global warming, values were higher in non-green scenarios. However, with the modeled phased-out thermal power plant in the Green scenario, a 15.8 % decrease was observed. Similarly, LCA analysis from Koroma et al. showed that global warming potential (GWP) decreases with increased RES share. In scenarios with moderate and high RES share, the GWP decreased by 36 % and 53 %, respectively, compared to the reference scenario (0.170 kg CO_2 eq.). The moderate and high RES scenarios modeled decreased coal and lignite share and increased wind electricity production with other RES (PV) increases [31]. Results from Shafique and Luo showed that the use phase results were mainly dependent on the electricity mix in accordance with our results. In future 2030 energy mix scenarios, Norway had the lowest GWP (13.251 kg CO_2 -eq), and South Korea had the highest GWP (35.179 kg CO_2 -eq) because a higher proportion of Norway's electricity is generated from RES. The results showed that integrating RES into electricity generation positively impacts the environmental impact of EV production and use; however, the study focused on a limited number of indicators, with mineral resource scarcity not taken into account [13].

Similarly to Shafique and Luo [13], the modeled increase in RES has a positive impact also on ozone formation (11.3 % decrease), fine particulate matter formation (25.3 % decrease), and fossil resource scarcity (12.9 %) in our study. Petrauskienė et al. recently conducted a comparative LCA of BEV and ICEVs fuelled with petrol and diesel. In addition, the LCA of BEV under different electricity mix scenarios for Lithuania (2015 – 2050) was carried out. The research assumed ICEV and BEV could drive 150000 km as the baseline. The environmental impacts were calculated for such a life cycle, ensuring that no battery replacement is required. The results showed that throughout the whole life cycle, the BEV of the 2015 electricity mix performed better in impact categories ionizing radiation and fossil depletion, while both ICEVs had a lower impact in climate change, human toxicity, and metal depletion, with impact on climate change being 26 % and 47 % higher than that of ICEVs fuelled with petrol and diesel, respectively. The difference in impact was attributed to the effect of the BEV's operation phase, which amounts to 70 % of the total burden, where the electricity of 2015 is produced with natural gases (41.7 %) and oil (5 %) [32].

In scenarios with higher penetration of RES, the GHG emissions become lower than that of ICEVs. In 2050 mix scenarios, where the main sources of electricity are PV (45.6 %) and wind (33.6 %), the impact of use phase is expected to reduce by 64 % and 73 % in terms of climate change and fossil depletion, respectively [32], which is in accordance with our results as phasing out coal and increasing PV has a positive impact on global warming, fossil resource scarcity and particulate matter formation. On the other hand, an increase in PV results in a higher impact in category mineral resources depletion, with 1.6 % and 2.1 % in SI2030 and SI_Green2030 scenarios, respectively. Similarly, an increase in impact category land use was also observed, with a 6.9 % increase in the SI_Green2030 scenario, compared to baseline 2020 scenarios. Increases in both categories can be attributed to the higher PV share in the electricity mix.

Recently, modeling of electricity scenarios mixes with different shares of photovoltaics (PV) for Slovenia showed that a significant increase in PV results in a 50 % in 2030 and 150 % in 2050 increase in the category of mineral resource scarcity compared to the 2020 baseline scenario for 1 kWh of electricity produced [33], highlighting that the values of mineral resource scarcity could be higher when EV are used in high PV electricity mix. PV causes negligible environmental impacts during the use phase; however, the material acquisition and consumption of metals is associated with the manufacturing phase [34]. Similarly, a higher impact in metal depletion indicators was observed for BEV compared to ICEV in the current and future energy mix scenarios due to the production of the battery. Furthermore, due to the larger use of metals, chemicals, and energy for the production of powertrains, BEV had a higher impact in the category of human toxicity [32].

3.2 Life Cycle Assessment of the Impact of the Driving Mode on the Use of Electric Car

The electricity use of BEV depends on several characteristics, among them driving environment (e.g., street characteristics, ambient temperature, road gradient) as well as driving style (e.g., aggressive, calm, driving during peak hour) and vehicle internal characteristics such as loading [29,30,35,36]. In the research conducted by Braun & Rid, it varied from 0.158 kWh per 1 km to 0.75 kWh per 1 km, depending on the road type, driving style, and traffic concentration [29]. If the electricity use varies, it is expected that the environmental impact of using BEV will also depend on the driving characteristics and environment [37].

The effect of driving mode on the environmental impact in selected impact categories of the use of BEV under different electricity scenarios is shown in Fig. 2. It can be observed that in the categories global warming, fine particulate matter formation, ozone formation, human health and fossil fuel scarcity, the impact is higher when electricity use is higher, according to available literature data [38]. The global warming category's values differ from 0.123 to 0.196 kg CO_2 eq., depending on the electricity use and mix scenarios. The lowest value observed was in 0.15 kWh per 1 km scenarios under Green 2030 electricity mix scenarios. The percentage difference between the lowest and the highest value was 46.0 %.

An important aspect to be considered is dependency not only on the yearly electricity mix but also the variation in the time of the day and season, highlighting the impact of the charging time on the environmental impact of the BEV [38]. On the other hand, categories of land use and mineral resource scarcity show the reverse trend. A higher share of RES (PV) and higher electricity use result in higher values in both impact categories due to land needed to install PV panels and the materials for battery production.

The lowest values observed were in 0.15 kWh per 1 km scenarios under the current electricity scenario with values 0.005 m^2a crop eq. and 0.0019 kg Cu eq., respectively. The percentage difference between the lowest and highest value in land use and mineral resource scarcity categories was 13.0 % and 6.3 %, respectively. The results support the premise that BEVs' impact heavily depends on the use phase of energy and the electricity mix used for charging [39]. Available data shows that BEVs have better environmental performance compared to ICEV in terms of CO_2 emissions during their entire life cycle [40]; however, the electricity mix is one of the most crucial parameters, as using a mix based entirely on RES delivers a completely different result than energy mix based on fossil fuels [36].

The environmental impacts of BEVs depend on several factors, which can be divided into external and internal factors. Among external factors, user driving mode, comfort requirements (i.e., air-conditioning, heating), and charging behavior are vital as they affect the electricity use required for 1 km of transport. Surrounding conditions such as climate, topography, and type of road also affect the electricity use required for 1 km of transport [36].

CO_2 emissions during their entire life cycle [40]; however, the electricity mix is one of the most crucial parameters, as using a mix based entirely on RES delivers a completely different result than energy mix based on fossil fuels [36]. The environmental impacts of BEVs depend on several factors, which can be divided into external and internal factors. Among external factors, user driving mode, comfort requirements (i.e., air-conditioning, heating), and charging behavior are vital as they affect the electricity use required for 1 km of transport. Surrounding conditions such as climate, topography, and type of road also affect the electricity use required for 1 km of transport [36].

On the other hand, categories of land use and mineral resource scarcity show the reverse trend. A higher share of RES (PV) and higher electricity use result in higher values in both impact categories due to land needed to install PV panels and the materials for battery production.

The lowest values observed were in 0.15 kWh per 1 km scenarios under the current electricity scenario with values

0.005 m^2 a crop eq. and 0.0019 kg Cu eq., respectively. The percentage difference between the lowest and highest value in land use and mineral resource scarcity categories was 13.0 % and 6.3 %, respectively. The results support the premise that BEVs' impact heavily depends on the use phase of energy and the electricity mix used for charging [39]. Available data shows that BEVs have better environmental performance compared to ICEV in terms of CO_2 emissions during their entire life cycle [40]; however, the electricity mix is one of the most crucial parameters, as using a mix based entirely on RES delivers a completely different result than energy mix based on fossil fuels [36]. The environmental impacts of BEVs depend on several factors, which can be divided into external and internal factors. Among external factors, user driving mode, comfort requirements (i.e., air-conditioning, heating), and charging behavior are vital as they affect the electricity use required for 1 km of transport. Surrounding conditions such as climate, topography, and type of road also affect the electricity use required for 1 km of transport [36].

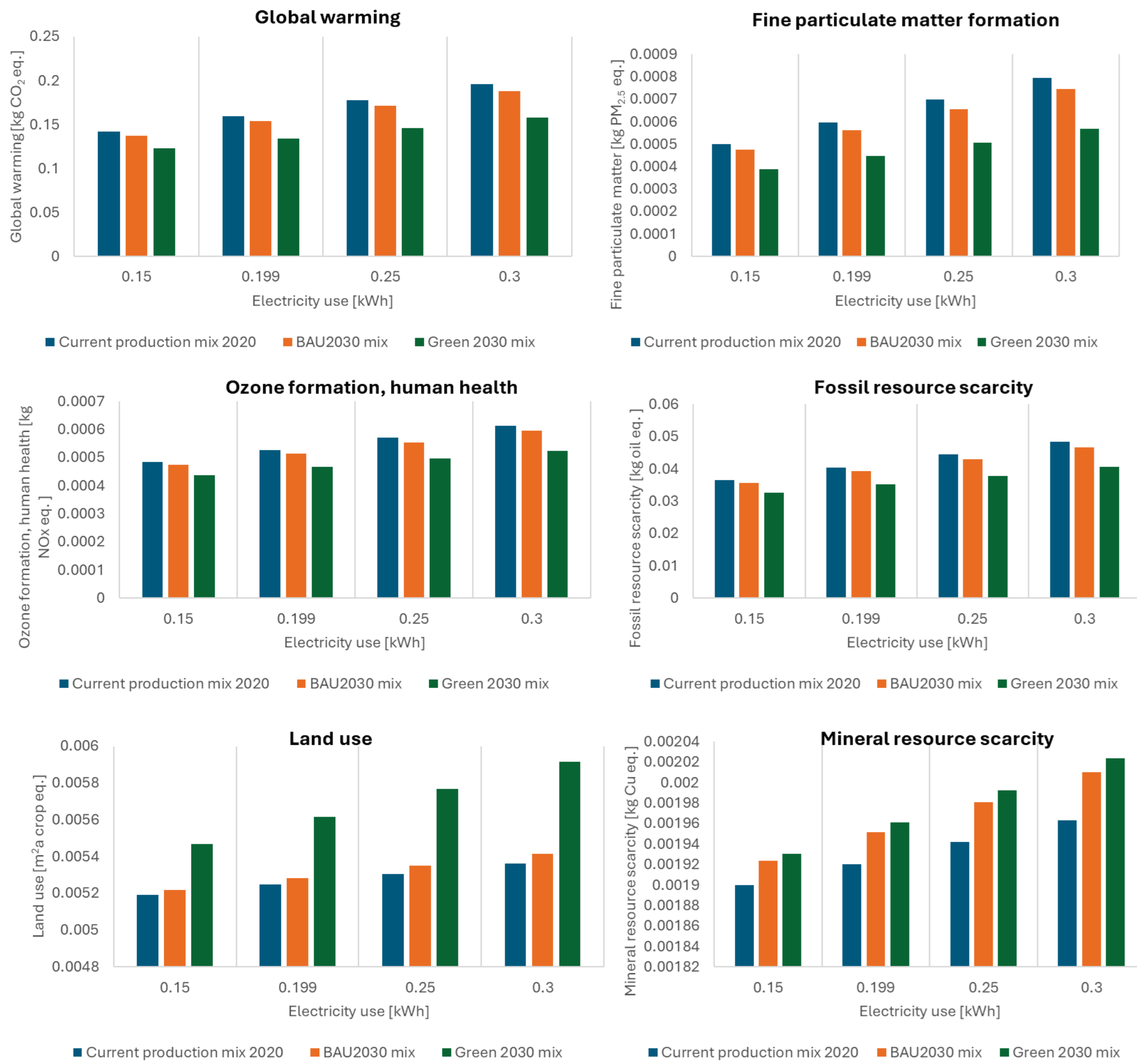

Figure 2 Environmental impact of driving mode under different electricity mix scenarios

BEVs are seen as a way to significantly reduce the world's dependence on fossil fuels and GHG emissions. A higher level of RES is also needed for a more sustainable transportation sector to promote EVs and RES diffusion [40]. The intermittency of some RES (namely PV and wind) hinders high penetration in the electrical grid [41], and higher penetration of BEV could result in increased peak loads under a simple charging strategy, requiring extra investment in generation and transmission capacity. However, if charging strategies are implemented, BEVs can potentially be charged at off-peak times when otherwise unwanted energy (i.e. excess energy in the system) can be used to charge the vehicle batteries. In such strategies, BEVs could be potentially used as a distributed storage mechanism for absorbing excess renewable energy [42]. Another vital aspect to be considered is the end-of-life of electric batteries, which pose a threat to the environment and are also a valuable source of various metals. With more sustainable practices in which recovered battery waste would be used in manufacturing batteries, the environmental impact could be potentially reduced; however, much more research is needed to strive towards all three pillars of sustainability – social, environmental, and economic [43–45].

4 CONCLUSIONS

The research utilized the LCA approach to determine the environmental impact of electricity mix and driving mode on the use of BEV. The analysis of future energy mix scenarios provides insight into how government measures could yield different results, showcasing the importance of evaluating plans and policies to select sustainable pathways for future transport systems. The values for categories global warming, fine particulate matter formation, ozone formation, human health, and fossil fuel scarcity decreased by 15.8 %, 11.3 %, 25.3 %, and 12.9 %, respectively with an increase in RES in the Green 2030 scenario compared to the baseline. On the other hand, in the categories of land use and mineral resource scarcity, a 6.9 % and 2.1 % increase in the values was observed, showcasing the trade-off in different environmental impact categories under various scenarios. Similarly to the impact of the energy mix, the result showed that different electricity use for 1 km journey showcases the driving modes, and topology has a vital role in the environmental impact of the use of BEVs. The values for categories global warming, fine particulate matter formation, ozone formation, human health, and fossil fuel scarcity decreased by 27.7 %, 36.9 %, 21.3 %, and 24.4 %, respectively when comparing the lowest and highest electricity use in the current production scenario.

The introduction of BEVs could result in several positive impacts including lower vehicle operating costs, reduced CO_2 emissions, and the ability to support and contribute to grid power quality and stability if the proper infrastructure is adopted. The market share of BEVs is still relatively small due to high investment cost compared to conventional cars, small driving ranges and the limited availability of charging infrastructure. Incetives policies are crucial for wider adoption of BEVs and could include purchase subsidies, registration tax benefits and ownership tax benefits.

5 REFERENCES

[1] European Commission. (2019). *The European Green Deal*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640

[2] Hainsch, K., Löffler, K., Burandt, T., Auer, H., Crespo del Granado, P., Pisciella, P., & Zwickl-Bernhard, S. (2022). Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal? *Energy*, *239*, 122067. https://doi.org/10.1016/j.energy.2021.122067

[3] Neofytou, H., Nikas, A., & Doukas, H. (2020). Sustainable energy transition readiness: A multicriteria assessment index. *Renewable and Sustainable Energy Reviews*, *131*, 109988. https://doi.org/10.1016/j.rser.2020.109988

[4] Đurđević, D., Balić, D., & Jurić, Ž. (2019). Socio-Economic Aspects in Satisfying Energy Demands by Different Technologies of Heat and Electricity Generation. *Tehnički Vjesnik*, *26*(6), 1803–1813. https://doi.org/10.17559/TV-20180525214147

[5] Bošnjaković, M., Galović, M., Kuprešak, J., & Bošnjaković, T. (2023). The End of Life of PV Systems: Is Europe Ready for It? *Sustainability*, *15*(23), Article 23. https://doi.org/10.3390/su152316466

[6] Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza Noel Simas Barbosa, L., Fasihi, M., Khalili, S., Traber, T. & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, *227*, 120467. https://doi.org/10.1016/j.energy.2021.120467

[7] Yuan, M., Thellufsen, J. Z., Lund, H., & Liang, Y. (2021). The electrification of transportation in energy transition. *Energy*, *236*, 121564. https://doi.org/10.1016/j.energy.2021.121564

[8] de Blas, I., Mediavilla, M., Capellán-Pérez, I., & Duce, C. (2020). The limits of transport decarbonization under the current growth paradigm. *Energy Strategy Reviews*, *32*, 100543. https://doi.org/10.1016/j.esr.2020.100543

[9] Bonsu, N. O. (2020). Towards a circular and low-carbon economy: Insights from the transitioning to electric vehicles and net zero economy. *Journal of Cleaner Production*, *256*, 120659. https://doi.org/10.1016/j.jclepro.2020.120659

[10] Hossain, M. S., Kumar, L., Islam, M. M., & Selvaraj, J. (2022). A Comprehensive Review on the Integration of Electric Vehicles for Sustainable Development. *Journal of Advanced Transportation*, *2022*(1), 3868388. https://doi.org/10.1155/2022/3868388

[11] Sanguesa, J. A., Torres-Sanz, V., Garrido, P., Martinez, F. J., & Marquez-Barja, J. M. (2021). A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities*, *4*(1), Article 1. https://doi.org/10.3390/smartcities4010022

[12] Hirz, M., Brunner, H. & Nguyen, T. T. (2022). Greenhouse Gas Emissions of Electric Cars—A Comprehensive Evaluation. *Tehnički Glasnik*, *16*(2), 280–287. https://doi.org/10.31803/tg-20220407135956

[13] Shafique, M., & Luo, X. (2022). Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective. *Journal of Environmental Management*, *303*, 114050. https://doi.org/10.1016/j.jenvman.2021.114050

[14] Burchart-Korol, D., Pustejovska, P., Blaut, A., Jursova, S., & Korol, J. (2018). Comparative life cycle assessment of current and future electricity generation systems in the Czech Republic and Poland. *The International Journal of Life Cycle Assessment*, *23*(11), 2165–2177. https://doi.org/10.1007/s11367-018-1450-z

[15] Pero, F. D., Delogu, M., & Pierini, M. (2018). Life Cycle Assessment in the automotive sector: A comparative case study of Internal Combustion Engine (ICE) and electric car. *Procedia Structural Integrity*, *12*, 521–537. https://doi.org/10.1016/j.prostr.2018.11.066

[16] Capuder, T., Miloš Sprčić, D., Zoričić, D., & Pandžić, H. (2020). Review of challenges and assessment of electric vehicles integration policy goals: Integrated risk analysis approach. *International Journal of Electrical Power & Energy Systems*, *119*, 105894. https://doi.org/10.1016/j.ijepes.2020.105894

[17] Alanazi, F. (2023). Electric Vehicles: Benefits, Challenges, and Potential Solutions for Widespread Adaptation. *Applied Sciences*, *13*(10), Article 10. https://doi.org/10.3390/app13106016

[18] Brand, C., Anable, J., Ketsopoulou, I., & Watson, J. (2020). Road to zero or road to nowhere? Disrupting transport and energy in a zero carbon world. *Energy Policy*, *139*, 111334. https://doi.org/10.1016/j.enpol.2020.111334

[19] SURS. (2023). *Energy statistics, 2022*. https://www.stat.si/StatWeb/en/News/Index/11405

[20] Muhič, S., Čikić, A., Pištan, J., Stojkov, M., & Bošnjaković, M. (2018). Transport emissions and electric mobility in private transport in the Republic of Slovenia. *Tehnički Glasnik*, *12*(2), 98–103. https://doi.org/10.31803/tg-20180508162744

[21] ARSO. (2024). *Final energy consumption by sector | Okoljski kazalci*. https://kazalci.arso.gov.si/en/content/final-energy-consumption-sector-6

[22] ARSO. (2022). *Number of electric vehicles | Okoljski kazalci*. https://kazalci.arso.gov.si/index.php/en/content/number-electric-vehicles?tid=14
[23] European Commission. (2024). *Incentives and Legislation | European Alternative Fuels Observatory*. https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/slovenia/incentives-legislations
[24] ISO 14044:2006. https://www.iso.org/standard/38498.html
[25] ISO 14040:2006. https://www.iso.org/standard/37456.html
[26] Bošnjaković, M. & Tadijanović, V. (2019). Environment impact of a concentrated solar power plant. *Tehnički Glasnik*, *13*(1), 68–74. https://doi.org/10.31803/tg-20180911085644
[27] Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y
[28] RIVM. (2018). *The Dutch National Institute for Public Health and the Environment: LCIA: the ReCiPe model | RIVM*. https://www.rivm.nl/en/life-cycle-assessment-lca/recipe
[29] Braun, A., & Rid, W. (2017). Energy consumption of an electric and an internal combustion passenger car. A comparative case study from real world data on the Erfurt circuit in Germany. *Transportation Research Procedia*, *27*, 468–475. https://doi.org/10.1016/j.trpro.2017.12.044
[30] Braun, A., & Rid, W. (2017). The influence of driving patterns on energy consumption in electric car driving and the role of regenerative braking. *Transportation Research Procedia*, *22*, 174–182. https://doi.org/10.1016/j.trpro.2017.03.024
[31] Koroma, M. S., Brown, N., Cardellini, G., & Messagie, M. (2020). Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios. *Energies*, *13*(23), Article 23. https://doi.org/10.3390/en13236236
[32] Petrauskienė, K., Skvarnavičiūtė, M., & Dvarionienė, J. (2020). Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. *Journal of Cleaner Production*, *246*, 119042. https://doi.org/10.1016/j.jclepro.2019.119042
[33] Dimnik, J., Topić Božič, J., Čikić, A., & Muhič, S. (2024). Impacts of High PV Penetration on Slovenia's Electricity Grid: Energy Modeling and Life Cycle Assessment. *Energies*, *17*(13), Article 13. https://doi.org/10.3390/en17133170
[34] Gargiulo, A., Carvalho, M. L., & Girardi, P. (2020). Life Cycle Assessment of Italian Electricity Scenarios to 2030. *Energies*, *13*(15), Article 15. https://doi.org/10.3390/en13153852
[35] Mamala, J., Graba, M., Mitrovic, J., Prażnowski, K., & Stasiak, P. (2023). Analysis of speed limit and energy consumption in electric vehicles. *Combustion Engines*, *195*(4), 83–89. https://doi.org/10.19206/CE-169370
[36] Egede, P., Dettmer, T., Herrmann, C., & Kara, S. (2015). Life Cycle Assessment of Electric Vehicles – A Framework to Consider Influencing Factors. *Procedia CIRP*, *29*, 233–238. https://doi.org/10.1016/j.procir.2015.02.185
[37] Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A., & van Vuuren, D. P. (2018). Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environmental Science & Technology*, *52*(8), 4989–4995. https://doi.org/10.1021/acs.est.8b00261
[38] Rupp, M., Handschuh, N., Rieke, C., & Kuperjans, I. (2019). Contribution of country-specific electricity mix and charging time to environmental impact of battery electric vehicles: A case study of electric buses in Germany. *Applied Energy*, *237*, 618–634. https://doi.org/10.1016/j.apenergy.2019.01.059
[39] Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, *17*(1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x
[40] Franzò, S., & Nasca, A. (2021). The environmental impact of electric vehicles: A novel life cycle-based evaluation framework and its applications to multi-country scenarios. *Journal of Cleaner Production*, *315*, 128005. https://doi.org/10.1016/j.jclepro.2021.128005
[41] Asiaban, S., Kayedpour, N., Samani, A. E., Bozalakov, D., De Kooning, J. D. M., Crevecoeur, G., & Vandevelde, L. (2021). Wind and Solar Intermittency and the Associated Integration Challenges: A Comprehensive Review Including the Status in the Belgian Power System. *Energies*, *14*(9), Article 9. https://doi.org/10.3390/en14092630
[42] Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews*, *19*, 247–254. https://doi.org/10.1016/j.rser.2012.11.042
[43] Guzek, M., Jackowski, J., Jurecki, R. S., Szumska, E. M., Zdanowicz, P., & Żmuda, M. (2024). Electric Vehicles—An Overview of Current Issues—Part 1—Environmental Impact, Source of Energy, Recycling, and Second Life of Battery. *Energies*, *17*(1), Article 1. https://doi.org/10.3390/en17010249
[44] Dunn, J., Kendall, A., & Slattery, M. (2022). Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. *Resources, Conservation and Recycling*, *185*, 106488. https://doi.org/10.1016/j.resconrec.2022.106488
[45] Slattery, M., Dunn, J., & Kendall, A. (2021). Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resources, Conservation and Recycling*, *174*, 105755. https://doi.org/10.1016/j.resconrec.2021.105755

Authors' contacts:

Jelena Topić Božič, Assistant Professor
(Corresponding author)
Rudolfovo – Science and Technology Centre Novo mesto,
Podbreznik 15, 8000 Novo mesto, Slovenia
Faculty of Industrial Engineering,
Šegova ulica 112, 8000 Novo mesto, Slovenia
jelena.topic.bozic@rudolfovo.eu

Ante Čikić, Full Professor
University North, Department of Mechatronics,
104. Brigade 3, 42000 Varaždin, Croatia
ante.cikic@unin.hr

Simon Muhič, Full Professor
Faculty of Industrial Engineering,
Šegova ulica 112, 8000 Novo mesto, Slovenia
Rudolfovo – Science and Technology Centre Novo mesto,
Podbreznik 15, 8000 Novo mesto, Slovenia
Institute for Renewable Energy and Efficient Exergy Use,
INOVEKS d.o.o, Cesta 2. grupe odredov 17,
1295 Ivančna Gorica, Slovenia
simon.muhic@inoveks.si

Boris Kraševec, Assistant Professor
Faculty of Industrial Engineering,
Šegova ulica 112, 8000 Novo mesto, Slovenia
boris.krasevec@fini-unm.si