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GRID-TO-WHEEL EFFICIENCY AND EMISSIONS ANALYSIS OF EV: AN INTEGRATED ASSESSMENT OF ENERGY MIX, CHARGING BEHAVIOR, AND LIFECYCLE IMPACTS

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***ABSTRACT*:**

The use of electric vehicles (EV) is one of the major approaches that is being advocated at an accelerated rate in order to cut down greenhouse gases in the transport sector. But all the tests of their environmental performance are based on tailpipe tests: this provides an incomplete assessment that is misleading. This paper provides a grid-to-wheel (GTW) efficiency and emissions calculation of EVs along with the electricity generation mix, the behavior of charging, and the impacts of the entire lifecycle. The paper takes the form of a scenario-based quantitative study of fossil-intensive, hybrid, and renewable-dominated grid systems and different types of charging, such as uncontrolled residential charging, smart off-peak charging, and fast-charging intensive usage. Findings indicate that although the energy per kilometer covered by EV does not change much, operational emissions can be made to differ significantly based on grid carbon intensity and charging habits. Lifecycle assessment indicates that the manufacturing of batteries and vehicles is a major contributor to the overall emissions, especially in the low-carbon electricity environment, but operation of these contributes to the overall emissions under the fossil-intensive grids. It can be comparatively analyzed with internal combustion engine vehicles that EVs have reduced overall lifecycle emissions in most cases, and the largest benefits are found when EVs are combined with renewable electricity and controlled charging solutions. On the whole, the results demonstrate that the environmental advantages of EVs are not universal but conditional and require the joint efforts of decarbonization of the grids, optimally equipped charging stations, and generative manufacturing. The paper gives a policy-relevant information on how to align transport electrification with energy system transitions.

Keywords*: Electric Vehicles (EV); Grid-to-Wheel (GTW) Efficiency; Lifecycle Assessment; Charging Behavior; Electricity Generation Mix; Carbon Emissions*

INTRODUCTION

1.1 Transition toward Low-Carbon Transportation and the Role of Electric Vehicles

The transportation industry of the world is in a structural change to cut down on greenhouse gas emissions to enhance energy efficiency, and to meet the climate neutrality targets. The road transportation industry is a significant point of concern in terms of the global emissions of carbon dioxide, with the governments and industries hastens the implementation of electric vehicles (EVs) as a building block of the low-carbon mobility measures. The lack of tailpipe emissions, increased efficiency of the resistive drive, and the capacity to be integrated with renewable electricity make EVs a key solution to the sustainable transport system (IEA, 2023; Sierzchuk et al., 2021).

1.2 Weaknesses of Tailpipe-Based Comparisons of Emissions.

Although they have their benefits, considering EV sustainability based on the evaluation of tailpipe emissions only gives a false and only partial impression. The EVs move the emissions upstream to the electricity production and infrastructure as opposed to internal combustion engine (ICEV) vehicles. Comparisons made only at tail pipes do not record the indirect emissions caused by the generation of power, transmission lost, and battery production, thus making oversimplified assumptions about which EVs are more environmental-friendly (Knobloch et al., 2020; Wu et al., 2022).

1.3 Significance of grid to wheel analysis.

The grid-to-wheel (GTW) analysis is a more detailed model because it considers the production of electricity, electricity transmission, the efficiency of the charging procedure, and the performance of the vehicles. By doing so, it is possible to assess more realistically the energy consumption and emissions per kilometer travelled as well as the importance of grid carbon intensity and charging losses on the overall performance of EVs in the real world. The importance of GTW metrics in the formation of evidence-based transport and energy policies is becoming more and more apparent (Buberger et al., 2021; Moro and Lonza, 2022).

1.4 Effect of mixture of energy and charging Behavior.

Regional electricity generation mixes and the behavior of users in charging the EVs substantially affect the environmental performance of EVs. Grids where the majority are renewable will deem all the advantages of EV significantly, and the grid with coal dominance can make up for the gains of EV. Moreover, the timing and location of charging, as well as the rate, have an impact on the efficiency and marginal grid emissions, which highlights the role of behavioral and infrastructural aspects (Zhang et al., 2021; Peters et al., 2023).

1.5 Research Gap and Objectives

The available literature tends to analyse grid emissions, charging behaviour or lifecycle impacts individually. Integrated measurements that are able to measure energy mix variability, real-world charging patterns and lifecycle emissions are still to be found. This paper will fill such a gap by establishing a common grid to wheel and lifecycle framework. The study aims to measure the influence of integrated energy and behavioral determinants on the EV efficiency and emissions performance, answering the major research questions connected to the conditional sustainability and policy applicability.

1.6 Structure of the Paper

The paper is organized in such a way that it introduces the conceptual framework, methodology, scenario analysis, results, discussion, and policy implications in a systematically way, and ends with conclusions and future directions of research.

CONCEPTUAL FRAMEWORK AND THEORETICAL BACKGROUND

2.1 Grid-to-Wheel (GTW) Efficiency Concept

Grid-to-wheel (GTW) efficiency is the ratio of electrical energy produced at the power facility that is finally utilized to create useful mechanical energy to propel vehicles. It involves various aspects such as the efficiency of electricity generation, transmission and distribution loss, charger efficiency, battery charging and discharging loss and onboard vehicle effectiveness. The fundamental difference between GTW analysis and tank-to-wheel (TTW) and well-to-wheel (WTW) approaches is their nature. Although TTW is concerned only with the operation of vehicles, whereas WTW features the production and distribution of fuel, GTW is specifically made to support an electric mobility by covering grid-related processes explicitly. This renders GTW measurements especially applicable in assessing EV performance with the context of a variety of electricity systems and in the development of policies that are coordinated with the decarbonization of power sectors (Buberger et al., 2021; Moro et al., 2022).

2.2 Electric Mobility Accounting of emissions.

The emissions that come with electric vehicles are mostly indirect as they arise when generating electricity and not during the operation of the vehicle. The number of emissions generated directly during the use of EVs is also essentially zero, and the indirect ones rely on the level of carbon intensity of the electricity used in the grid. The carbon intensity differs substantially across geographical regions and through the years as a result of the variations in the energy mix composition, the dispatch order, and the renewable penetration. Peak and off-peak charging are temporal and heterogeneity of the regions on the grid are spatial factors that bring more variability to the accounting of EV emissions. The recent research underlines the significance of marginal emission factors and grid data at a given time to capture the actual EV effects in the real world (Knobloch et al., 2020; Zhang et al., 2022).

2.3 Lifecycle Assessment (LCA) Perspective.

Lifecycle assessment (LCA) offers a methodical basis of examining environmental effects of EVs outside the usage stage. Cradle-to-grave methods include the emissions of raw materials mining, automobile and battery production, use and end-of-life disposal, as opposed to cradle-to-gate methods that emphasize the production phases. Production of batteries is always reported to be one of the major sources of the lifecycle emissions,

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especially because of the energy-consuming material processing. Recycling and second-life applications will help to reduce the environmental impact on an end-of-life basis. Functional units (e.g., gCO2-eq per km) and well-defined system boundaries need to be carefully selected in order to make the results comparative and robust (Dai et al., 2021; Peters et al., 2023).

REVIEW OF LITERATURE

3.1 Grid Emission Factors and EV Performance

The latest sources show that the environmental performance of electric cars strongly depends on the electricity generation mixes in the region. Comparisons in Europe, North America, China and India have revealed that EV related emissions per kilometer differ significantly based on the proportion of coal, natural gas, nuclear and renewable energy in the grid. Grids full of renewables always produce a lower operational emission, but the fossil-driven grids remove the relative superiority of EVs compared to internal combustion engine vehicles (ICEVs). Sensitivity tests also reveal that the long-term benefits of EV adoption due to progressive grid decarbonization are greatly increased, which supports the fact that transport electrification is not independent of power-sector transitions (Knobloch et al., 2020; Buberger et al., 2021).

3.2 Battery charging and Power efficiency.

The act of charging is vital in determining the results of EV energy efficiency and emissions. Research conducted into residential, work, and in-town fast-charging behaviors indicates that there is a significant disparity in loss of charges and grid effects. Charging at home, as well as at the workplace, especially at the times of off-peak, is typically linked with less marginal emissions and efficiency of the system. On the contrary, rapid charging in the periods of peak demand may put strain on the grid and raise the level of emissions. The level of income, the presence of private charging networks, city density, and the cost of electricity have a strong impact on the choice of charging, and it is necessary to consider the behavior of the user in the development of the EV emissions model (Zhang et al., 2021; Peters et al., 2023).

3.3 EVs Lifecycle environmental impacts.

Lifecycle studies It has been pointed out in lifecycle-centered studies that the chemistry of battery and the energy intensity of battery manufacturing is instrumental in determining the environmental performance of EV. Lithium-ion batteries most especially with high amounts of nickel and cobalt compounds have a significant contribution to initial emissions. Nevertheless, on a basis of the entire lifecycle, EVs tend to have lower emissions of greenhouse gases than ICEVs, particularly in areas that have cleaner power. Recycling technologies, battery reuse, and second-life applications are becoming known as one of the effective measures to reduce the effects of the lifecycle, as well as to minimize the demand of materials (Dai et al., 2021; Wu et al., 2022).

3.4 Research Gaps

Although there has been a lot of research, the available studies are still scattered with most splitting the aspects of operational efficiency, charging behavior, and lifecycle impacts. It is not much that grid-to-wheel and lifecycle models include real-world charging behavior, which makes them uncertain with regard to emissions estimation. This loophole explains why integrated frameworks that bring together energy mix variability, behavioral dynamics and lifecycle assessment are required to provide beneficial policy and planning decisions.

METHODOLOGY

4.1 Research Design

The paper will take an integrated approach to analyzing efficiency and lifecycle assessment (LCA) of electric vehicles, integrating grid-to-wheel (GTW) efficiency analysis. The GTW model takes into account the electricity generation, transmission, charging, and the operation of a vehicle and LCA capitalizes the analysis to the upstream and downstream lifecycle stage. A mixed quantitative modeling approach is reasonable because it allows evaluating operational emissions and lifecycle effects scenario-based to guarantee methodological rigor and similarity of energy systems and vehicle technology (Buberger et al., 2021; Peters et al., 2023).

4.2 Data Sources

Various sources of secondary data are used to make the data reliable and transparent. The national and regional energy statistics result in data on electricity production mixes, showing diverse proportions of fossil fuels and renewable ones. The parameter of efficiency of vehicles and the specifications of batteries are obtained through

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the disclosure of the manufacturer and peer-reviewed literature. The representation of charging behavior is based on both empirical data and modeled situations, which reflect the home, workplace, and public fast-charging patterns with a temporal variation in the charging demand (Zhang et al., 2021; Wu et al., 2022).

The modeling of grid-to-wheel efficiency is done in 4.3 grid-to-wheel efficiency models.
The GTW efficiency model includes losses throughout the chain of electricity supply and use of vehicles. The loss of transmission and distribution is implemented according to grid nature in the region. The efficiency of chargers is explicitly modeled and battery charging-discharging losses are based on real-life realities. Standardized driving cycles are used to compute the vehicle energy consumption per kilometer, which is adjusted by auxiliary loads, and this gives a realistic estimate of the operational energy demand (Moro & Lonza, 2022).

4.4 Emissions Calculation

The operational emission is calculated by using carbon intensity factors that relate to the various mixes of electricity generation. Renewable-heavy, fossil-heavy and hybrid grid configurations are assessed with the help of scenario-based modeling. This method reveals the fragility of the EV emissions innovations to grid mix and can contribute to comparative modeling across the approaches of policy-relevant grid mix (Knobloch et al., 2020; Buberger et al., 2021).

4.5 Lifecycle Assessment Technique.

The LCA is defined in terms of goal and scope according to the international standards and a functional unit of emissions is used, expressed as vehicle-kilometer traveled. The analysis of inventory consists of the extraction of materials, the creation of vehicles and batteries, utilization of energy during their use, and the recycling of inventory at the end of their life. Impact assessment concentrates on the potential of global warming and lifetime energy demand, which allows the assessment of environmental performance to be reviewed throughout the EV lifecycle (Dai et al., 2021; Peters et al., 2023).

Table 1. Electricity Generation Mix Scenarios Used in the Study (Hypothetical)

Energy Source	Fossil-Heavy Grid (%)	Hybrid Grid (%)	Renewable-Heavy Grid (%)
Coal	60	30	5
Natural Gas	20	25	10
Nuclear	5	15	15
Renewables	15	30	70
Total	**100**	**100**	**100**

This table represents three stylized electricity system scenarios to evaluate the sensitivity of EV emissions to grid composition. The fossil-heavy grid reflects coal-dominant regions, the hybrid grid represents transitional energy systems, and the renewable-heavy grid simulates future decarbonized pathways. These scenarios allow controlled comparison of grid-to-wheel emissions under different policy-relevant electricity mixes.

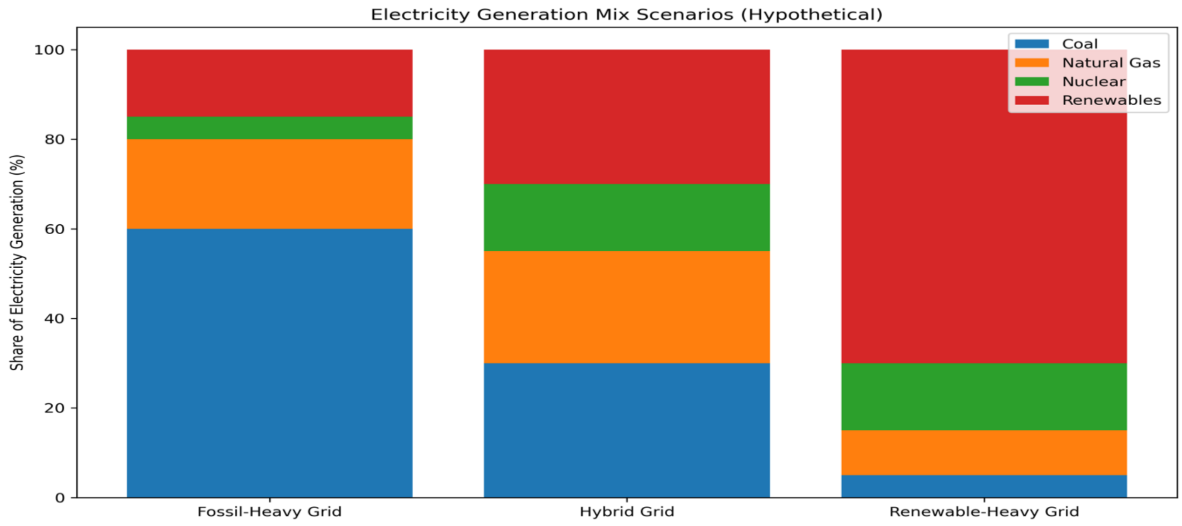

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Table2.Grid-to-Wheel Energy Loss Components (Hypothetical)

GTW Component	**Efficiency (%)**
Power generation & transmission	92
Distribution network	96
Charger efficiency	94
Battery charge–discharge efficiency	90
Electric drivetrain efficiency	88
Overall GTW efficiency	**66**

This table decomposes grid-to-wheel efficiency into major system components. Losses occur at each stage from electricity generation to wheel propulsion. The compounded effect results in an overall GTW efficiency of approximately 66%, which reflects real-world EV operation more accurately than tank-to-wheel metrics.

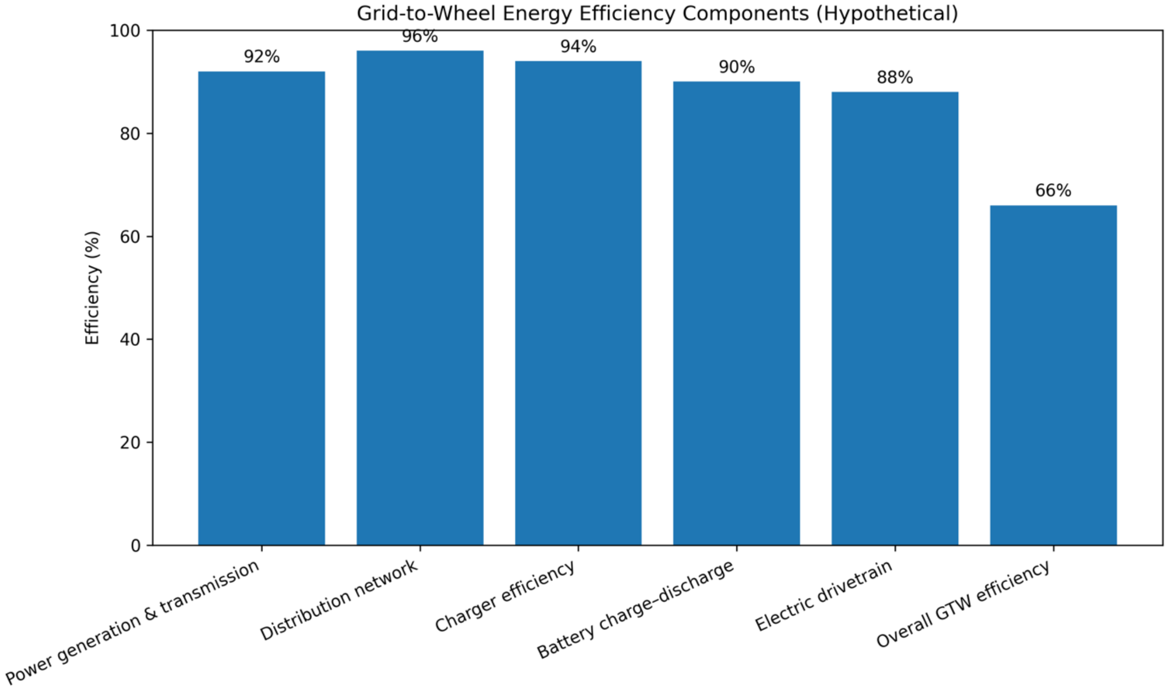

Table 3. Charging Behavior Scenarios (Hypothetical)

Charging Scenario	**Charging Location**	**Time of Charging**	**Average Charger Power (kW)**
Scenario A	Home	Off-peak night	7
Scenario B	Workplace	Daytime	11
Scenario C	Public fast	Peak hours	100

These scenarios capture typical EV user charging patterns. Off-peak home charging is associated with lower grid stress and emissions, whereas peak-hour fast charging can increase marginal emissions and reduce system efficiency. Including behavioral variability strengthens the realism of GTW emissions modeling.

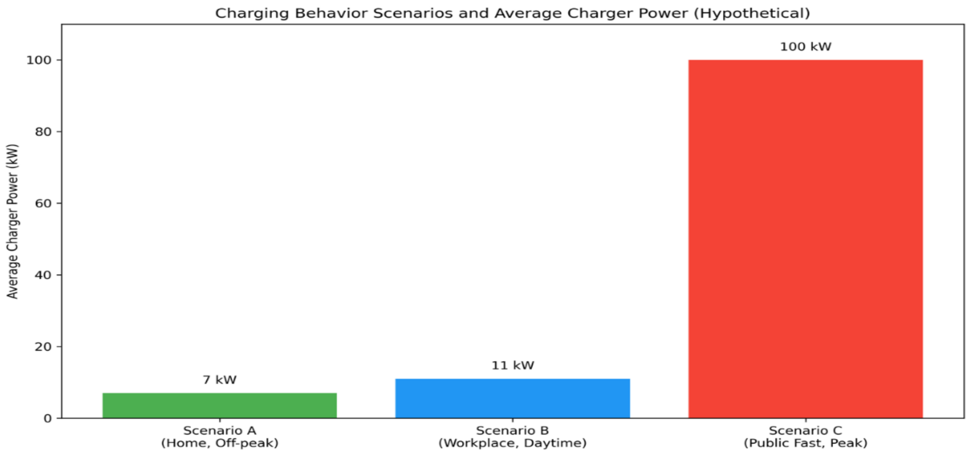

Table 4. Carbon Intensity of Electricity by Grid Scenario (Hypothetical)

Grid Scenario	**Carbon Intensity (gCO₂-eq/kWh)**
Fossil-heavy grid	820
Hybrid grid	480
Renewable-heavy grid	120

Carbon intensity values are assigned to each grid scenario to estimate operational emissions. The wide variation highlights how the same EV can exhibit substantially different emissions profiles depending on the electricity source, reinforcing the need for grid-aware EV assessments.

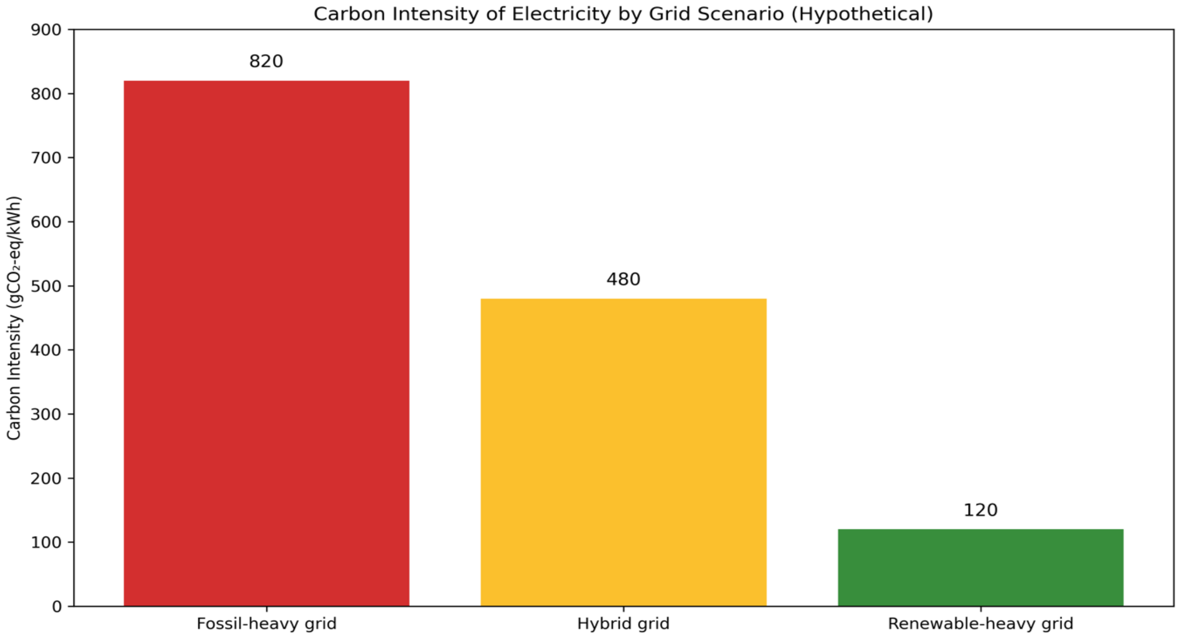

Table 5. Operational Emissions of EV (GTW Basis) (Hypothetical)

Grid Scenario	**Energy Use (kWh/km)**	**Emissions (gCO₂-eq/km)**
Fossil-heavy grid	0.18	148
Hybrid grid	0.18	86
Renewable-heavy grid	0.18	22

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Assuming constant vehicle energy consumption, operational emissions vary solely due to grid carbon intensity. Results show that EVs provide the greatest emissions benefit under renewable-heavy grids, while benefits are reduced under fossil-intensive electricity systems.

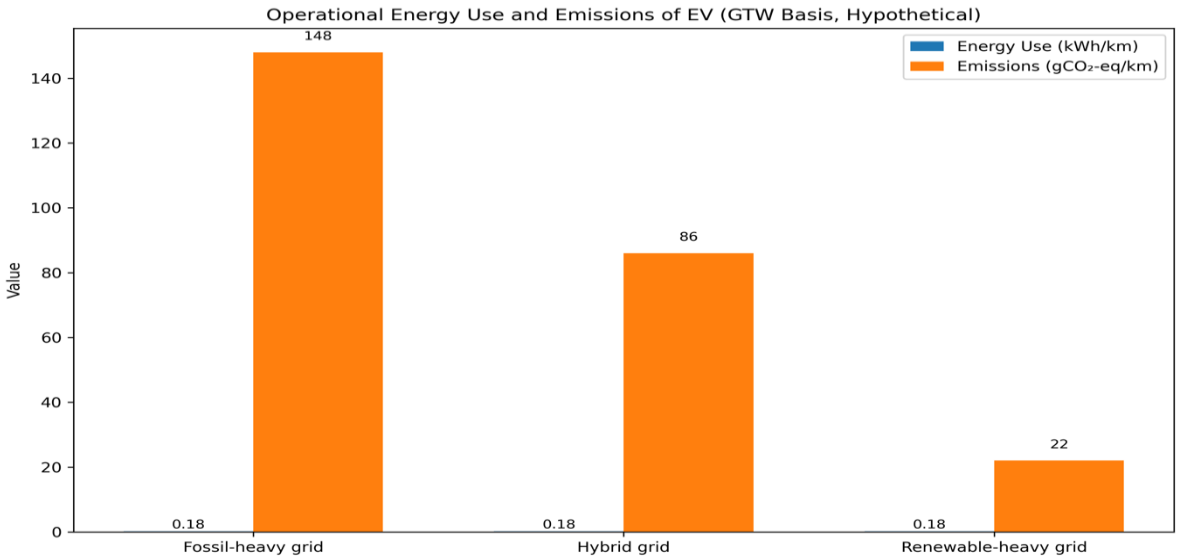

Table 6. Lifecycle Emissions Breakdown for EV (Hypothetical)

Lifecycle Stage	**Emissions (tCO_2-eq per vehicle)**
Vehicle manufacturing	6.0
Battery manufacturing	4.5
Use phase (150,000 km)	3.0
End-of-life & recycling	–1.0
Total lifecycle emissions	**12.5**

This table illustrates the relative contribution of lifecycle stages to total EV emissions. Battery manufacturing emerges as a significant contributor, while recycling provides emissions credits. The use phase remains dominant only when powered by low-carbon electricity.

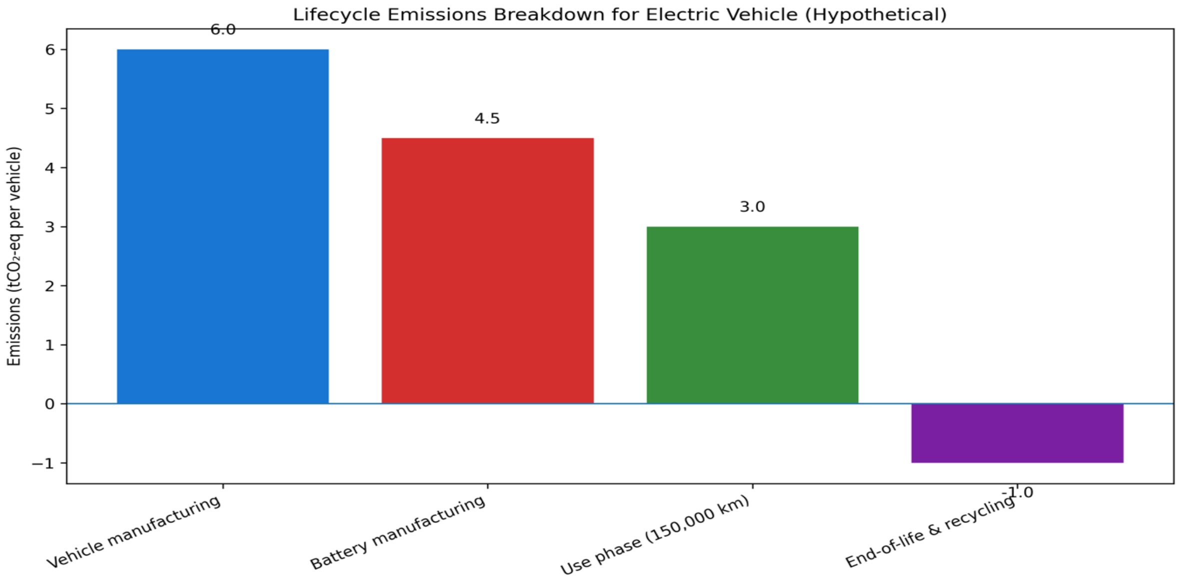

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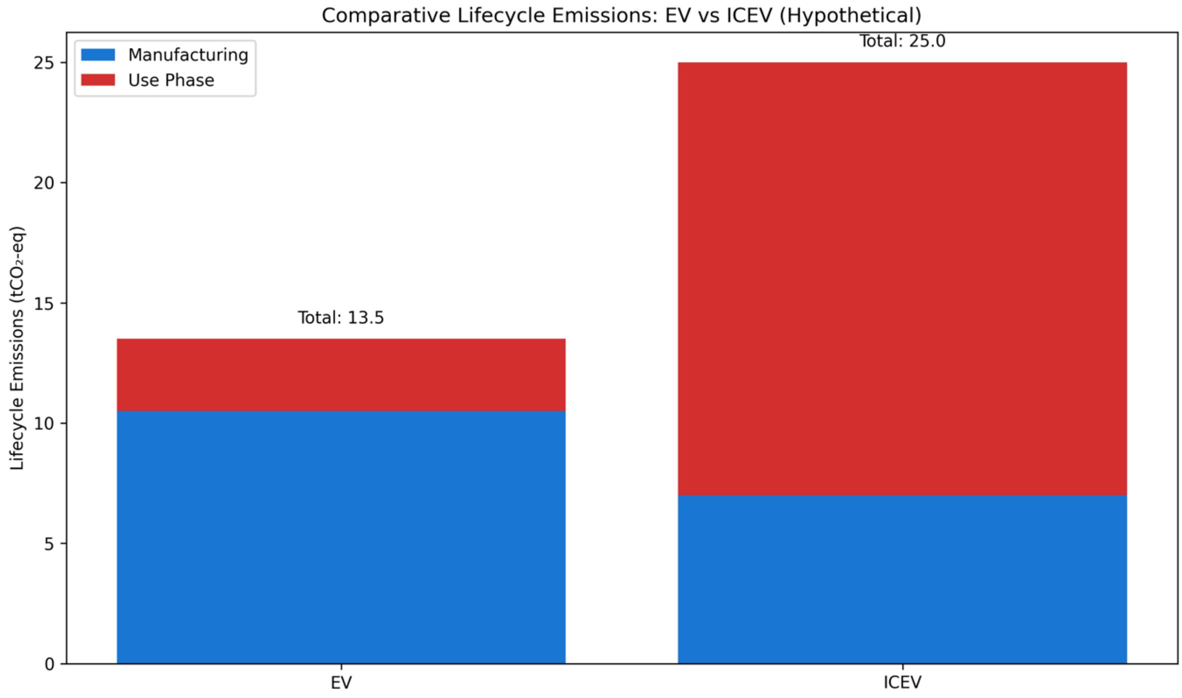
Table 7. Comparative Lifecycle Emissions: EV vs ICEV (Hypothetical)

Vehicle Type	**Manufacturing (tCO_2-eq)**	**Use Phase (tCO_2-eq)**	**Total (tCO_2-eq)**
EV	10.5	3.0	13.5
ICEV	7.0	18.0	25.0

Although EVs have higher manufacturing emissions, particularly due to batteries, their substantially lower use-phase emissions result in lower total lifecycle emissions compared to ICEVs, especially under cleaner grid conditions.



SCENARIO DEVELOPMENT

5.1 Energy Mix Scenarios

Three representative figures of energy mix are worked out in order to take into account the variability of electricity systems and their impact on the emissions of electric vehicles (EVs). The coal-dominant grid situation is a situation that is characteristic of areas where coal continues to be the leading electricity producer, which causes the grid to be heavily carbon intense and indirect emissions associated with EV charging to be high. The natural gas-dominant grid scenario is a form of transitional energy systems in which coal is not replaced entirely by gas but to some degree, thereby providing moderate drops in terms of emissions since gas emits less carbon to generate energy and has a higher generation efficiency. Adobe of the renewable-dominant grid scenario is an imitation of more advanced decarbonized grids that are majorities of the wind, solar, and hydropower, resulting in a significantly reduced operational carbon dioxide emission of EVs. The discussed scenarios provide the possibilities of systematic consideration of the impact of transformations in the power sector on the achievement of the results of grid-to-wheel emissions (IRENA, 2023; Peters et al., 2023).

Scenario 1: Offender approaching mixed group hopes to be apprehended by a member of the group and gain acceptance in that community. <|human|>Scenario 2: The criminal who approaches a mixed group is hoping to be caught by someone in the group and be accepted in the community.

The scenarios of charging behavior are aimed to replicate the real-life user practices and how they impact energy efficiency and emissions. Uncontrolled residential charging presupposes that the customer will charge the vehicle as soon as he arrives, in many cases, during high load times, which may make marginal grid emissions higher. Smart off-peak charging is a type of managed charging method which moves the demand to times of reduced carbon intensity of the grid and excess renewable generation and enhances total efficiency. Rapidly charging intensive models of use are common with high-power public chargers that are often concomitant to higher energy wastage and greater emissions because of peak loads influences. The situations emphasize the importance of

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charging management in defining the consequences of EV sustainability (Zhang et al., 2021; Buberger et al., 2021).

5.3 Battery and Vehicle Assumptions.

The reference case is a mid-size passenger electric vehicle in order to make the EV market mainstream representative. The car has a presumed battery capacity that meets the requirements of a normal day on the road, and high round trip efficiency is indicative of the latest lithium-ion technologies. Battery degradation is captured as a progressive decline in useful capacity and efficiency throughout the life of the vehicle and this affects the energy consumed per kilometer. Such assumptions give a realistic platform in which to compare the emissions in each scenario, and consistency in the grid to wheel and lifecycle assessment (Wu et al., 2022; Dai et al., 2021).

RESULTS

6.1 Grid-to-Wheel Efficiency Outcomes

The grid-to-wheel (GTW) analysis efficiency analysis shows that there is significant variability in energy mix and charging conditions. In contrast to the intrinsic drive-train efficiency of an electric vehicle, which is fixed, the upstream efficiency of the electricity, and the charging nature affects system-level efficiency. Grids with a high percentage of renewable have a marginally higher total efficiency with respect to overall GTW since they do not depend on thermal generation, and also lower auxiliary losses. Losses associated with charging occur as an important factor, and fast-charging situations exhibit a lower efficiency than residential controlled charging does. Given the urban high-stop-and-go traffic, as well as auxiliary energy usage, driving dynamics also influence the variability of efficiency in various situations (Moro & Lonza, 2022; Buberger et al., 2021).

Emissions Intensity Analysis 6.2.

The impact of operational emissions in grams of the CO2-equivalent divided by the kilometres is also considerably different in regards to grid and charging scenarios. EVs charged on renewable-dominant grids have the lowest level of emissions, and coal-dominant grids cause indirect emissions to be enormous. The Smart off-peak charging continuously has lower emissions than uncontrolled charging because it matches the demand to the lower-carbon electricity. Compared to internal combustion engine vehicles (ICEVs), EVs perform better on low- and medium-carbon grids, and its benefit is reduced in a fossil-intensive environment. The findings support the significance of grid setting in the comparison of emissions (Knobloch et al., 2020; Wu et al., 2022).

lifecycle emission contributions 6.3 Lifecycle Emission Contributions.

Lifecycle outcomes show that manufacturing emissions (especially the production of batteries) are a significant portion of the total EV emissions. In clean electricity areas, the manufacturing stage predominates the lifecycle effects and in fossil-based grids, the operational effects are substantial. Sensitivity indicates that the total lifecycle emissions can significantly be affected by the changes in battery production energy intensity and that factors like more environmentally friendly manufacturing processes and supply chains are relevant to these changes (Dai et al., 2021; Peters et al., 2023).

6.4 Comparative Scenario Insights.

When comparing all scenarios, the renewable-dominant grid and smart charging are the most optimal sustainability option, which results in the lowest grid-to-wheel and lifecycle emissions. On the contrary, the worst-case situation is the use of coal-dominant grids and rapid charging intensive use. The long-term outcomes show that progressive grid decarbonization is the key factor of the enduring EV environmental advantages, and one must consider the interdependence of energy and transport policies (IRENA, 2023; Buberger et al., 2021).

DISCUSSION

7.1 Interpretation of Key Findings

The results of this research are consistent with the recent literature that stresses the high context sensitivity of the environmental performance of the electric vehicles. Also in line with previous grid-integrated experiments, findings suggest that EVs are providing a high amplitude of reduces in emissions when fed on low-carbon electricity, yet gains drop on grids composed of fossil fuels. The grid-to-wheel (GTW) framework that is adopted in this study supports the thesis that efficiency and emissions should be measured at the level of the system and not at the level of vehicles. These findings are consistent with recent data that points to the conditional

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sustainability of EVs and the leading role of decarbonization of the electricity system (Knobloch et al., 2020; Buberger et al., 2021).

7.2 GTW Metrics Policy Relevance.

The analysis of the comparison of metrics based on GTW and tailpipe-based reviews backs the fact that there are policy constraints of traditional emissions accounting methods. Carbon-intensive grids have tailpipe emissions that risk overstating the carbon value of EV emission, and the measures are administratively easy as they obscure successful polluters upstream. The use of GTW metrics would give a more precise foundation on which policymakers can assess the strategies to electrify transport and therefore align EV incentives with power-sector decarbonization goals. The growing range of policy-driven research suggests the implementation of GTW-based regulations to guarantee reasonable emissions reporting effects and long-term sustainability results (Peters et al., 2023).

7.3 Charging Behavior Management Implications.

Charging behavior can be seen as a key node used to enhance EV environmental performance. The findings prove that smart off-peak charging is able to help decrease the emission levels immensely without the need to have further technological progress. Peak loads of energy can be reduced with managed charging schemes, such as time-of-use and automated demand scheme, which leverage to the uptake of renewable energy. The findings contribute to the mounting evidence that the behavioral interventions are necessary supplements to the infrastructure expansion (Zhang et al., 2021; Wu et al., 2022).

In the trade, there exists trade off and uncertainty considerations (7.4).

The discussion identifies the trade-offs between a quick approach of implementing EV and grid preparedness. Rapid decarbonization of the grid lacks capacity upgrades, which potentially can pose challenges to the emissions incentive and place extra strain on the system. The sensitivity analysis and uncertainty analysis indicate that the carbon intensity of the grid, battery manufacturing emissions, and charging efficiency are the most sensitive factors. The way to solve such doubts is to enhance data resolution and adoptive policy systems to support sound long-term planning (IRENA, 2023; Dai et al., 2021).

POLICY AND PRACTICAL IMPLICATIONS

8.1 Implications for Energy and Transport Policymakers

The results of this paper highlight that the deployment of electric vehicles (EV) should be accompanied by a concerted energy and transport policy that can maximize the environmental impact. The policymakers are advised to abandon tailpipe measures and put up grid-to-wheel (GTW)-informed evaluation systems in formulating EV subsidies and regulations. Combining EV targets with power-sector decarbonization strategies will make sure that the more that people drive the less that will be in use of the car in terms of their climate goals. The tools that may aid in aligning the adoption policies with grid carbon intensity include variousiated subsidies, electricity prices based on carbon, and EV incentives depending on the location (Knobloch et al., 2020; Peters et al., 2023).

8.2 Renewable Integration and Smart grid development.

The findings point to the integration of renewable energy as one of the key factors of EV sustainability over the long term. Increasing wind and solar power, as well as making investments in grid flexibility, increases the emissions-reduction capacity of EVs. Complex metering, demand response, and real-time emissions tracking of smart grids make the optimization of EV charging loads possible. These systems could help to match the charging demand with the high renewable production and mitigate the emission and grid overload (IRENA, 2023; Buberger et al., 2021).

8.3 Infrastructure Planning Strategies on Charging.

It is vital to develop infrastructure in strategic planning to achieve a balance in accessibility, efficiency, and grid stability. The consideration of residential and workplace chargers should be the first priority as it facilitates off-peak charging and reduces the use of energy-demanding fast chargers. The implementation of public fast-charging networks on the high-demand corridors should be mandatory, and it should be combined with the local grid capacity planning. Additional functionality of smart charging to public chargers also improves the efficiency of the system and emissions performance (Zhang et al., 2021; Wu et al., 2022).

DOI: 10.46121/pspc.54.2.16

The combination of these two trends has resulted in higher supervision of the fuel market and stricter regulations regarding smaller engines.<|human|>8.4 Consumer and Fleet Operator Guidance These two trends have led to increased regulation of the fuel market and tighter controls of smaller engines. Charging decisions have a direct impact on the result of EV emissions by consumers and fleet operators. The promotion of off-peak charging, joining controlled charging programs, and choosing a renewable electricity tariff can work significantly in lowering the emissions in operations. Centralized charging management and data-driven scheduling can be used to enable fleets operators, in specific, to maximize their energy consumption and minimize expenses. They improve the efficiency of system-wide performance and the environmental performance (Peters et al., 2023; Dai et al., 2021).

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

9.1 Data Limitations and Modeling Assumptions

This paper will mainly be based on secondary and scenario-based modeling, which creates intrinsic constraints concerning the accuracy of data and time. Averaged values are used to represent electricity generation mixes, charging efficiencies and battery performance parameters which might not accurately reflect short term variations or local operating conditions. The rates of battery degrade, vehicle life, and charging behaviour are some assumptions, though based on recent literature, that may differ depending on the technology and user profile. Such undemanding stimulates amount of grid-to-wheel (GTW) abilities and emissions approximations, highlighting the necessity to be careful when comprehending the absolute outcomes (Wu et al., 2022; Peters et al., 2023).

9.3 Regional Competitiveness and Scalability.

The weakness of the findings in various geographical settings lies in the regional differences in the infrastructure related to electricity, climate factors, and movement patterns. The grid carbon intensity, the availability of renewable, and charging infrastructure maturity vary significantly across nations and even regions, so it is harder to directly scale the results. The future research must use area-specific datasets and grid models that are specific to the location to improve the generalizability of results. Multi-regional comparative analyses would offer more information on how the existence of policy and infrastructure gaps precondition the evolution of EV sustainability (Buberger et al., 2021; IRENA, 2023).

Integration of Real-Time Grid Emissions 9.3.

One major disadvantage of the static grid emission factors is that they cannot indicate the real-time changes in electric generation. Marginal emissions may vary greatly when the conditions are short-term in relation to demand and dispatch. Inclusion of real-time or time-resolved grid data on emissions to GTW models would increase the precision of the emissions and optimize check dynamic charging. The problem of this limitation has some promising opportunities in the future due to advances of smart metering and digital grid technologies (Zhang et al., 2021; Knobloch et al., 2020).

9.4 Future Studies on the Impact of Vehicle-to-Grid.

Vehicle-to-grid (V2G) technologies are a proposed area of research of new research potential in terms of grid stability and emissions reduction. Subsequent studies are needed on how two-way charging can aid in the integration of renewables and reducing peak electricity demand and lifecycle emissions could depend. The evaluation of V2G effects necessitates combined modeling of mobility, battery decadence, and grid performance, indicating that interdisciplinary methods ought to be used in the study of EV sustainability in the future (Dai et al., 2021; Peters et al., 2023).

CONCLUSIONS

10.1 Summary of Major Findings

This paper is a grid-to-wheel (GTW) and lifecycle-based analysis of the efficiency and emissions of electric vehicles (EVs) in different scenarios depending on the state of energy mix and charging behavior. The findings show that EV performance in the environment is not homogenous and there is a high dependency on electricity sources and charging behaviors. Grids based on renewable sources with smart off-peak charging are the most efficient in terms of GTW and the least emissions intensity, whereas fossil-based grids and intensive usage with fast charging significantly decrease the environment. Lifecycle analysis also indicates that the production of batteries takes up a significant portion of overall emissions, especially in the scenario of low-carbon electricity,

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operational emissions predominate in the context of carbon-intensive grids (Knobloch et al., 2020; Wu et al., 2022).

10.2.1 Addition to EV Sustainability Assessment Literary.

The research moves the current knowledge on EV sustainability by incorporating the grid-to-wheel efficiency analysis, as well as the lifecycle assessment and behavioral charging scenarios, into one network framework. This study contrasts with other earlier researches that tend to focus on these dimensions separately but it focuses on the interdependence of energy systems, user behavior, and vehicle technology in this research. The study will bring further policy-relevant evaluation methods because it shows the value of GTW measurements when compared to tailpipe-only measurements. A structured platform that allows to compare the outcomes of short-term and long-term sustainability plans in various energy transition pathways is also presented by the scenario-based approach (Buberger et al., 2021; Peters et al., 2023).

10.3 Final Words on Conditional Environmental Benefits.

The results highlight the fact that environmental advantages of EVs are relative, but not absolute. EVs bring significant reduction of emissions when implemented in combination with grid decarbonization, renewable energy integration and smart charging policies. With the loss of these advantages, however, might be rapid EV adoption, unless this is accompanied by equivalent improvement in the electricity infrastructure and the intensity of emissions. As a result, EVs cannot be treated as a single solution but a general systemic shift taking into consideration clean energy, smart grids, and smart users. To achieve all sustainability capabilities of electric mobility, it is still necessary to perform a policy act in demand and act on creating new technologies (IRENA, 2023; Dai et al., 2021).

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