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FROM ICONS OF THE PAST TO A SUSTAINABLE FUTURE: 9E PERFORMANCE EVALUATION IN ELECTRIC/HYBRID CONVERSION OF ANADOL VEHICLES

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ABSTRACT

This study presents a comprehensive evaluation of the hybrid and electric conversion of the Anadol A1, a culturally iconic vehicle in Turkey's automotive history, through a 9E analysis covering energy, exergy, environment, and economic dimensions. The aim is to combine nostalgic design with modern technologies for sustainable mobility. The electric model emerged as the most efficient and environmentally friendly option, with an energy consumption of 64.1 MJ and emissions of 8 kg CO2 per 100 km. However, the battery production energy cost of 750 MJ reveals a limitation in its sustainability profile. The hybrid model offers a balanced trade-off between energy efficiency and cost-effectiveness, with 127.35 MJ of total energy use and 10.8 kg of CO2 emissions. In contrast, the conventional internal combustion engine (ICE) model demonstrated the lowest sustainability performance. This research highlights how integrating classic design with contemporary technology can facilitate sustainable innovation in the automotive industry.

Keywords: Electric vehicles, hybrid vehicles, 9e analysis, sustainability.

1. INTRODUCTION

Fossil fuels are used as a primary energy source in many areas, especially in the transportation sector, due to their high concentration in energy production and easy availability. However, the carbon dioxide (CO2) and other greenhouse gases produced by the combustion of these fuels are a major cause of global climate change. This has increased interest in renewable energy sources and encouraged the development of alternative technologies to internal combustion engine (ICE) vehicles in the transport sector. ICE technology is based on pistons that generate energy by compressing and burning the fuel-air mixture in the combustion chamber. This energy is transmitted to the crankshaft, which provides mechanical motion. The efficiency of ICEs varies according to engine design, fuel type and operating conditions. However, due to their high fuel consumption and exhaust emissions, ICEs pose significant problems in terms of environmental sustainability (Mi & Mansur, 2017).

Electric vehicles (EVs) are a type of vehicle that operate using electric motors in place of fossil fuel engines, with rechargeable lithium-ion batteries serving as the primary energy source. The operation of electric motors is based on the conversion of electric energy from the battery into rotating mechanical motion through the use of magnetic fields. EVs offer an environmentally friendly alternative, with zero exhaust emissions and high energy efficiency. However, the limited range of EVs and the lack of charging infrastructure represent significant obstacles to their widespread adoption (Özbay et al., 2020).

Hybrid electric vehicles (HEVs) present a novel solution that integrates the benefits of both technologies by employing both internal combustion engines and electric motors. The operational principle of HEVs is predicated on the utilization of the electric motor at low speeds or under light load, with the internal combustion engine activated at high speeds. Additionally, the regenerative braking system facilitates the conversion of kinetic energy released during braking into electrical energy, which is utilized to charge the battery. This feature enhances energy efficiency and reduces environmental impact (Doğan et al., 2016). Hybrid electric vehicles (HEVs) exhibit reduced fuel consumption and emission values in comparison to internal combustion engine (ICE) vehicles. Plug-in hybrid electric vehicles (PHEVs) represent an advanced iteration of HEV technology. PHEVs are equipped with larger batteries that can be recharged from the grid, enabling fully electric driving over short distances. The internal combustion engine is only activated if the battery is depleted, thereby further reducing fossil fuel consumption and emissions. In regions where charging infrastructure is well-developed, PHEVs are considered a more economical and environmentally friendly option than both ICEs and HEVs (Urooj & Nasir, 2024).

In the contemporary automotive sector, electric vehicles (EVs) and hybrid electric vehicles (HEVs) are undergoing a period of significant transformation on a global scale. The demand for electric vehicles is increasing rapidly due to a number of factors, including the tightening of global environmental policies, the adoption of carbon neutrality targets and the limited availability of fossil fuels. Hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) in particular play a critical role in the transition to sustainable transportation solutions by balancing energy efficiency and range anxiety. Innovations in regenerative braking, energy management systems and battery technologies further enhance the performance of these vehicles and reduce their environmental impact. In his study, Mengi (2018) converted a 1.3-litre vehicle with a diesel engine into an electric vehicle and compared the performance of both vehicles. The study concluded that the conversion process results in a more environmentally friendly vehicle without any loss of performance. In their study, Mizushima and Oguma (2023) improved the dynamic performance of the electric supercharged SI engine by more than 20% with a fuel consumption of approximately 2.5% in a target compact 12-V HEV with an electric supercharged SI engine.

The Anadol, Turkey's inaugural mass-produced automobile, was manufactured between 1966 and 1984, and was distinguished for its utilization of glass fiber-reinforced polyester bodywork (Anadolturkey, 2025). The Anadol brand encompasses a range of models, each designed to cater to distinct purposes and periodic requirements: These include the 'Anadol A1', a two-door car with a very lightweight design; the 'Anadol SL', a family car with a sedan body type; the 'Anadol STC-16', Turkey's first sports car; the 'Anadol SV', a five-door car; the 'Anadol Böcek', a car with off-road capabilities; and the 'Anadol P2', a pickup truck used for commercial purposes (Figure 1).

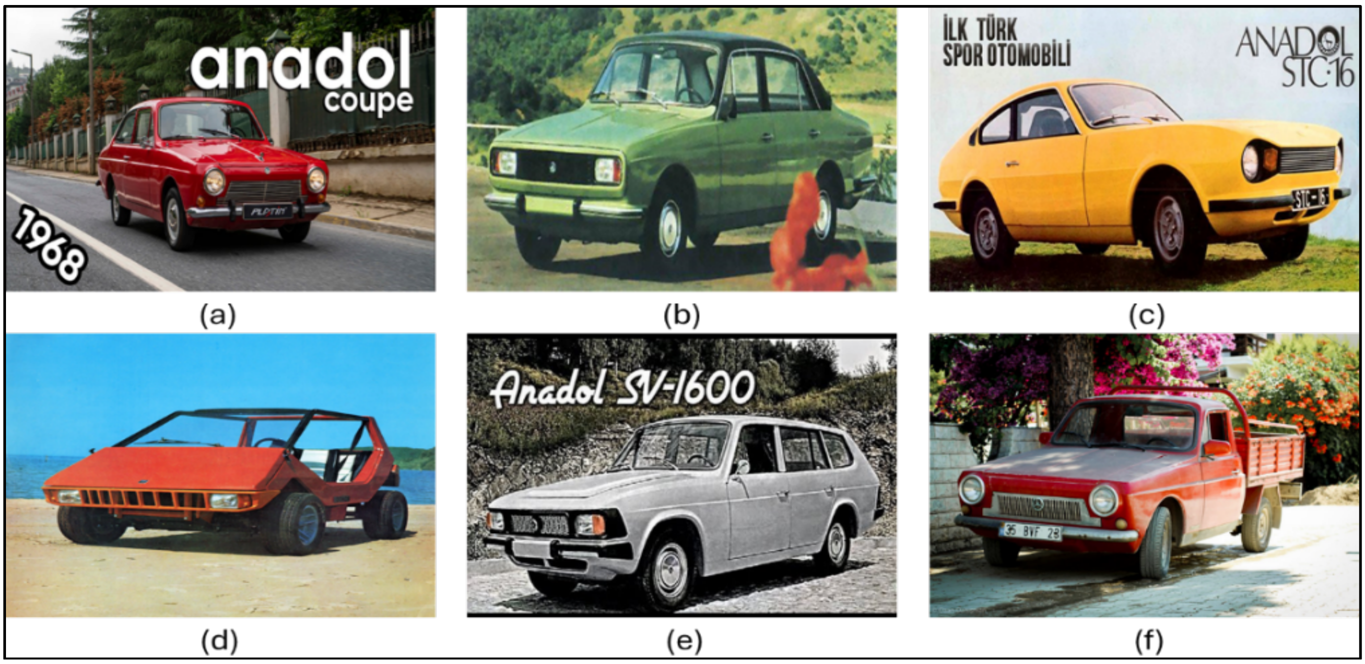


Figure 1. Anadol Models; (a): A1, (b): SL, (c): STC-16, (d): Böcek, (e): SV, (f): P2

This study proposes a novel approach in the domains of energy efficiency, environmental sustainability and cost effectiveness by addressing the electric and hybrid conversion of the Anadol A1 model. A more comprehensive evaluation is made with 9E analysis, in contrast to similar studies in the literature.

2. METHODOLOGY

In this study, 9E (energy, exergy, economy, energo-economics, energo-economics, exergo-economics, environment, energo-environment, exergo-environment, exergo-environment and emergy) analyses were first performed for full electric and rechargeable hybrid electric vehicle models with internal combustion engine. Then, the sustainability index was calculated by performing life cycle and economic sensitivity analysis.

The equations utilized in the analysis are delineated in Table 1 (Sreenath et al., 2021; Ünal et al., 2022; Koç et al., 2022; Khan et al., 2023; Maruf et al., 2023; Sabbaghi et al., 2024; Kumar et al., 2024; Han et al., 2025).

Table 1. Equations Utilized

Type of Analysis	Description	Equation	Equation Number
Energy	Involves the study of the energy input and output of the system. It is based on the law of energy conservation.	$Efficiency = \frac{Output\ energy}{Input\ energy}$	(1)
Exergy	Evaluates the quality dimension of energy utilization. It shows how thermodynamically efficient the energy transformations within the system are. It analyzes energy losses as well as exergy destruction.	$Efficiency_{exergy} = \frac{Useful\ exergy\ output}{Total\ exergy\ input}$ $Exergy\ destruction = Input\ exergy - Output\ exergy$	(2)
Economy	Examine the cost-effectiveness of the energy system.	$Simple\ payback = \frac{Total\ initial\ cost}{Annual\ net\ income}$ $Net\ present\ value = \sum_{year=1}^{n} \frac{Annual\ income\ - Annual\ cost}{(1 + discount\ rate)^{year}}$	(3)
Energo-economy	Energy efficiency and cost effectiveness of systems are evaluated together.	$ECOE = \frac{Energy\ consumption}{Cost}$	(4)
Exergo-economy	Analyzes the cost-effectiveness of the system by relating the exergy losses in the energy system to the economic value.	$EXCOE = \frac{Exergy\ consumption}{Cost}$	(5)

Environment	Evaluates the environmental impacts of energy production and utilization processes.	$CO_2 = Fuel\ consumption \times Emission\ factor$	(6)
Energo-environment	Evaluates the environmental impacts of energy production and consumption systems.	$ECE = \frac{Energy\ consumption}{CO_2\ emission}$	(7)
Exergo-environment	Evaluates the environmental impact of exergy losses in the system.	$EXCE = \frac{Exergy\ consumption}{CO_2\ emission}$	(8)
Emergy	Relates the environmental contribution of energy and natural resources in the system to an economic value. It takes into account the total amount of energy consumed (both direct and indirect) for the production of energy.	$Emergy = Energy\ consumption \times Emergy\ conversion\ factor$	(9)

The equations employed in the study were selected for systematic analysis of energy, exergy, economic and environmental impacts. Energy equations determine the energy input and output of vehicles, while exergy equations evaluate the thermodynamic efficiency of energy transformations. The economic equations analyse cost-effectiveness, while the environmental equations evaluate emissions and environmental impacts. Energy equations analyse the sustainability of systems by relating natural resource consumption to economic value.

The motor types and their characteristics are shown in Table 2 (Urooj & Nasir, 2024; Mengi, 2018; Mizushima & Oguma, 2023).

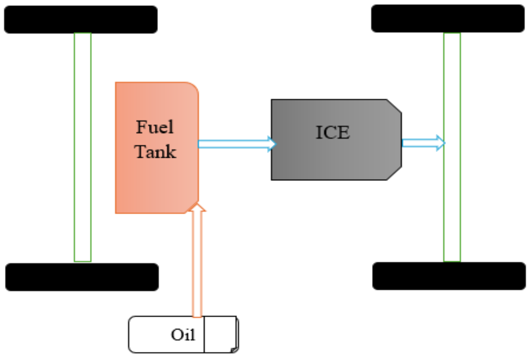
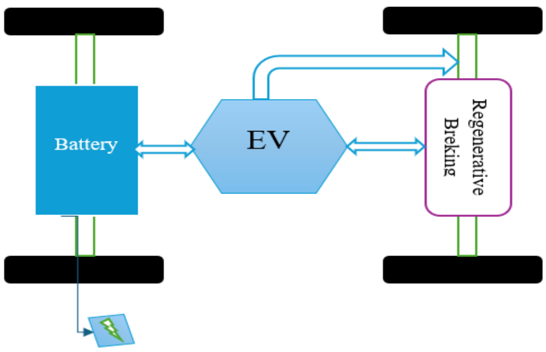
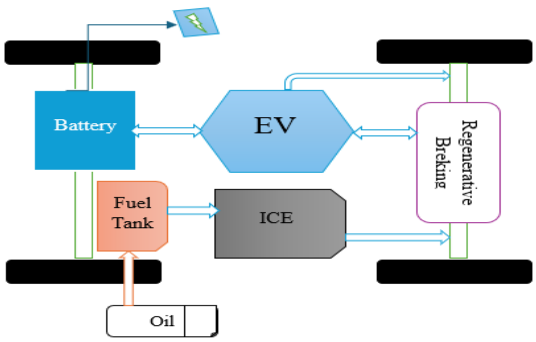
Engine type	**Schematic representation**	**Specifications**
Internal Combustion Engine (ICE)		• fuel type gasoline, • 1300 cc engine displacement, • 63 HP engine power, • 7.5 l/100 km fuel consumption, • 25% mechanical efficiency
Electric Vehicle (EV)		• 134 HP engine power, • 90% mechanical efficiency, • 50 kWh lithium-ion battery with a range of 250 km, • quick charging with 80% charge in 30 minutes, • regenerative braking system
Plug-in Hybrid Electric Vehicle (P-HEV)		• 30% internal combustion, 70% electric motor, • complex (series-parallel) strategy, • rechargeable, • 35% mechanical efficiency

Table 2. Engine Types and Their Characteristics

In the context of the analysis, the ICE was selected as the primary reference point, serving as a baseline model compatible with the vehicle design of the era. The EV is a contemporary solution to the requirements of sustainability, with zero emissions and high energy efficiency. The PHEV is regarded as a transitional technology, representing both urban and intercity efficient use scenarios.

The complex (series-parallel) hybrid configuration enables the vehicle to operate in series mode at low speeds in urban areas, utilizing the electric motor to power the vehicle, while the internal combustion engine charges the battery. At higher speeds, the internal combustion engine functions directly to power the wheels, thereby facilitating a transition to parallel mode. This configuration is regarded as offering the most balanced solution in terms of fuel consumption and carbon emissions, providing maximum efficiency in urban (series mode) and intercity (parallel mode) use.

The methodology follows a two-step approach: First, performance indicators based on 9E principles were calculated using data from published literature and simulation results. Second, sustainability was assessed through a composite index integrating energy, emissions, and cost dimensions. The normalization of indicators was carried out using minmax scaling, and sensitivity analysis was performed to evaluate robustness. No structured MCDM framework (e.g., AHP, TOPSIS) was used, which is noted as a limitation.

The methodology of this study is designed to comprehensively evaluate the environmental, economic and thermodynamic aspects of energy systems. The 9E analysis approach used provided a basis for determining the environmental friendliness and economic viability of hybrid and electric conversion. The results have made the scope and interactions of all the outputs analyzable and provided guiding insights for the sustainable transformation of Anadol vehicles.

3. RESEARCH & FINDINGS

The objective of this study is to integrate contemporary drivability standards with a nostalgic design, with a focus on the electric and hybrid conversion of the Anadol A1. Utilizing innovative energy and environmental analysis methodologies, the economic and thermodynamic merits of this conversion are examined.

It is estimated that 1 liter of gasoline contains 34.2MJ of energy (Energyeducation, 2025). Gasoline has 80% exergy potential, while electricity has 95% exergy potential (Flórez-Orrego et al., 2014; Nazerifard et al., 2023). The cost of 1 liter of gasoline is approximately 45 ₺, while 1 kWh of electricity costs approximately 2 ₺ (EPDK, 2025a; EPDK, 2025b). Gasoline has an emission value of 2.31 kg CO2/l, while this value is 0.4 kg CO2/kWh for electricity (Yalılı Kılıç et al., 2021; ETKB, 2025). The emergy conversion factor for fossil fuels is 50.3 MJ/l, 3.6 MJ/kWh for grid electricity, and 15 MJ/kWh for the production of lithium-ion batteries with a lifetime of 300 thousand km, which is a one-time energy cost for electric vehicles (Energy and carbon conversions 2023 update, 2025). The results of the 9E analysis based on these data are given in Table 3.

Analysis type	**Internal combustion engine**	**Electric vehicle**	**Hybrid vehicle**
Energy (MJ/100 km)	256.5 (total) 64.1 (useful)	72 (total) 64.8 (useful)	127.35 (total) 44.57 (useful)
Exergy (MJ/100 km)	51.3	61.56	38.3
Economy (₺/100 km)	337.5	100	171.25
Energo-economy (MJ/₺)	0.76	0.72	0.74
Exergo-economy (MJ/₺)	0.15	0.62	0.22
Environment (kg CO_2/100 km)	17.33	8	10.8
Energo-environment (MJ/kg CO_2)	14.81	9	11.8
Exergo-environment (MJ/kg CO_2)	2.96	7.7	3.55
Emergy (MJ/100 km)	377.25	72.25	233.6

Table 3. 9E Analysis Results

The 9E analysis results indicate that electric vehicles offer significant environmental and economic advantages. While the internal combustion engine vehicle demonstrates the highest values in total energy consumption, the electric vehicle is notable for its zero emissions and low operating costs. Hybrid vehicles offer a balanced solution between energy efficiency and carbon emissions. The potential for further reduction in the environmental impact of such vehicles is suggested by the findings of this study, which indicate that optimisation of regenerative braking and energy management strategies, especially in hybrid systems, may be a fruitful avenue for future research. The high emergy values resulting from the battery production processes of electric vehicles are a point to be considered in sustainability policies.

Life cycle analysis is a method that examines the environmental impacts of a product from production to disposal. In the life cycle analysis for internal combustion, hybrid and electric vehicles, the following data were used: 15 MJ/kWh energy consumption for the production of electric vehicle batteries, 300000 km lifetime of lithium-ion batteries, 2.31 kg CO2/l gasoline emission and 0.4 kg CO2/kWh electricity generation value of internal combustion engines. The analysis yielded results indicating that the total energy consumption for battery production in electric vehicles amounts to 750 MJ. Furthermore, the analysis revealed that internal combustion engine vehicles generate 17.33 kg of CO2 emissions per 100 km, whereas electric vehicles emit 8 kg of CO2. While electric vehicles demonstrate low emissions over their lifetime, their high initial energy and environmental cost due to battery production is a significant drawback. Hybrid vehicles offer a balanced environmental impact between the production and use phases.

Economic sensitivity analysis is a tool that can be used to assess the impact of changes in fuel and energy prices on the cost-effectiveness of vehicles. This analysis is illustrated in Figure 2 for nine distinct scenarios involving a 20% fluctuation in gasoline and electricity unit prices.

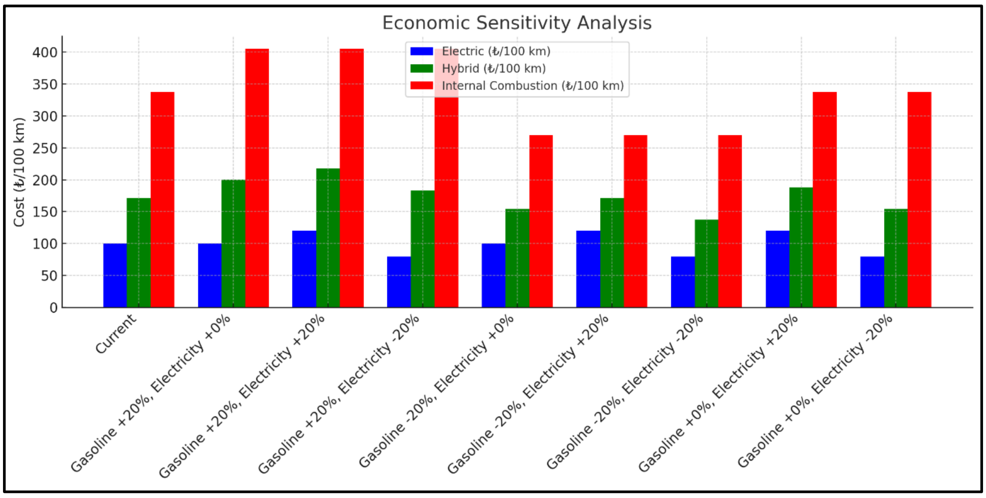


Figure 2. Economic Sensitivity Analysis (₺/100 km)

The cost changes in different scenarios demonstrate that electric vehicles are economically advantageous in all scenarios. Conversely, hybrid vehicles exhibit heightened sensitivity to price fluctuations, while internal combustion vehicles emerge as the most cost-disadvantageous option, particularly in the context of escalating gasoline prices.

To assess the overall sustainability performance of the evaluated vehicle types, a composite Sustainability Index (SI) was developed. The 9E indicators served as foundational inputs for sustainability assessment, especially focusing on energy consumption, CO_2 emissions, and economic cost. These were synthesized into a composite index (SI) through a normalized inverse formula, enabling cross-comparison and integrative sustainability evaluation. The SI is computed using the Equation 10 (Maruf et al., 2023; Khan et al., 2023):

$$Sustainability\ index = \frac{1}{3}\left(\frac{E_{min}}{E} + \frac{C_{min}}{C} + \frac{CO_{2min}}{CO_2}\right) \tag{10}$$

where E, C, and CO_2 represent the energy consumption (MJ/100 km), cost (₺/100 km), and carbon emissions (kg/100 km) of the vehicle, respectively, while E_{min}, C_{min}, and CO_{2min} are the lowest values among all evaluated options. This formulation results in a dimensionless index ranging from 0 to 1, with higher values indicating better sustainability.

Based on this approach, the electric vehicle (EV) achieved the highest sustainability score (1.000), followed by the hybrid model (0.609), while the internal combustion engine (ICE) model scored the lowest (0.336). This method provides a transparent, interpretable, and comparative metric for assessing the multi-dimensional aspects of vehicle sustainability (Fig. 3).

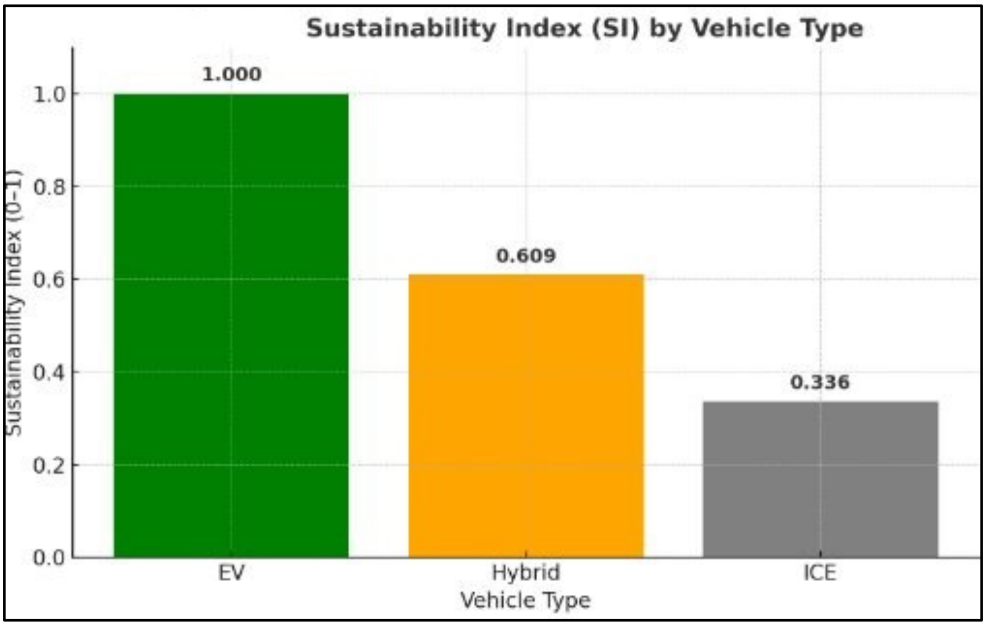


Figure 3. Sustainability Index

The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) evaluates the energy consumption and emissions of vehicles according to four different speed zones (low, medium, high, very high speed). This procedure is designed to more accurately simulate real-world operating conditions. The impact of each speed zone on energy consumption and CO_2 emissions is calculated as a percentage contribution to the total trip. These percentages were determined according to WLTP standards (BM, 2025).

- Low Speed: 13% (19 km/h average speed - city low speed)
- Medium Speed: 36% (39 km/h average speed - normal city speed)
- High Speed: 36% (56 km/h average speed - acceleration outside the city)
- Extra High Speed: 15% (91 km/h average speed - highway conditions)

The energy consumption in each region according to the WLTP speed zones (Fig. 4) is calculated by Equation 11. In this context, EC_{region} denotes the energy consumption in each speed zone, while EC_{total} signifies the total energy consumption. The term $percentage_{region}$ refers to the percentage contribution of the respective speed zone.

$$EC_{region}(MJ) = EC_{total}(MJ) \times percentage_{region} \quad (11)$$

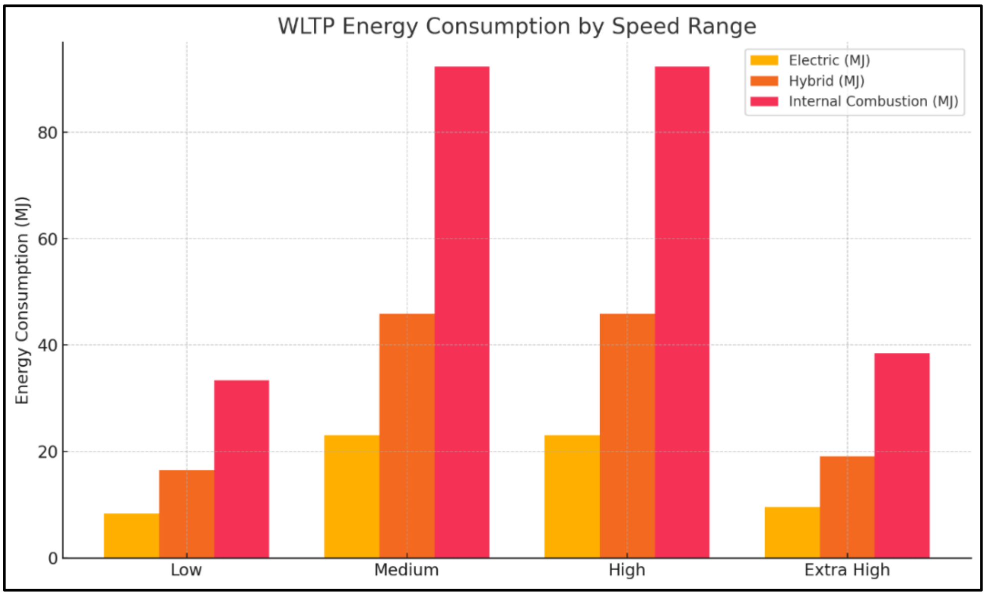


Figure 4. Energy Consumption by WLTP Speed Zones (MJ)

The electric vehicle demonstrates the lowest energy consumption at each velocity (8.33 - 23.08 - 23.08 - 23.08 - 9.61 MJ), while the internal combustion engine vehicle exhibits the highest values (33.35 - 92.34 - 92.34 - 38.48 MJ).

The carbon emission in each region according to the WLTP speed zones (Fig. 5) is given by Equation 12. In this equation, $CO_{2,region}$ denotes the CO_2 emission in each speed zone, and $CO_{2,total}$ signifies the total CO_2 emission.

$$CO_{2,region}(kg) = CO_{2,total}(kg) \times percentage_{region} \tag{12}$$

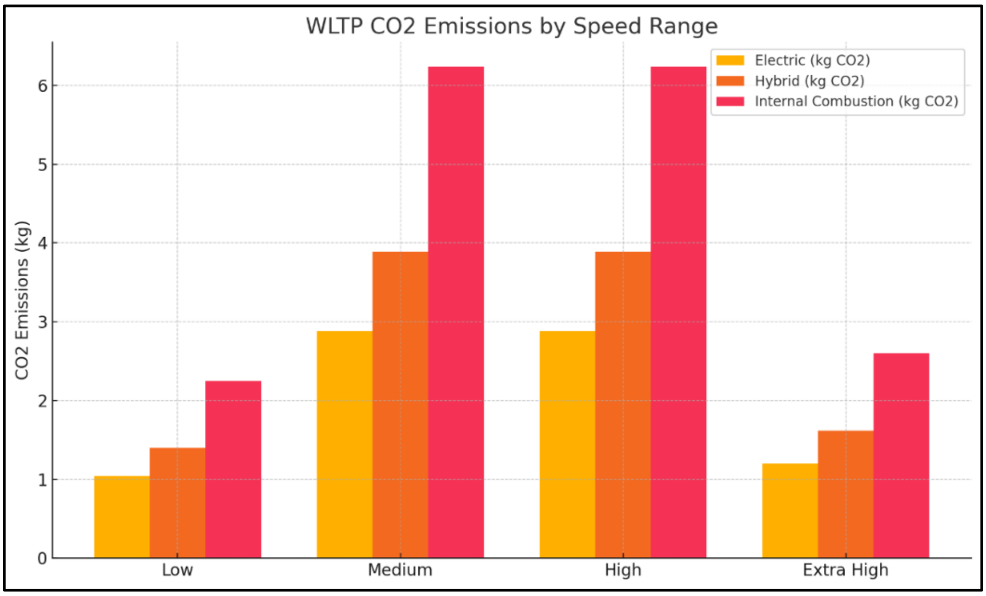


Figure 5. Carbon Emissions by WLTP Speed Zones (kg)

The electric vehicle is notable for its near-zero emission values (1.04 - 2.88 - 2.88 - 1.20 kg), while the hybrid model demonstrates balanced performance (1.40 - 3.89 - 3.89 - 1.62 kg).

The following comparison is made of internal combustion, hybrid and electric vehicles in terms of energy savings and cost advantages in long-term use (average 10 years - 150000 km). Electric vehicles are shown to be the most economical option, with a total energy cost of approximately 9600 ₺. The total energy cost of hybrid vehicles is calculated as 21375 ₺, and for internal combustion vehicles, it is 67275 ₺. While electric vehicles produce approximately 1200 kg CO2 for 150000 km, this value is 1620 kg in hybrid vehicles and 2600 kg CO2 in internal combustion vehicles. In the long term, electric vehicles have been shown to offer a cost advantage of 57675 ₺ and a reduction of 14000 kg CO2 over 10 years. The conclusion drawn is that electric vehicles offer a cost-effective and environmentally friendly alternative in the long term, given their low energy consumption and emission advantage. Conversely, hybrid vehicles emerge as a viable transitional technology, adeptly balancing economic and environmental considerations.

The findings unequivocally underscore the merits of electric vehicles, particularly their energy efficiency and zero emissions, while hybrid models proffer a balanced approach between environmental impacts and cost effectiveness. With regard to energy consumption per 100 km, the electric model achieved the lowest values (64.1 MJ), while the hybrid model's features such as regenerative braking systems minimized energy losses. However, the high emergy values resulting from battery production in electric models increase the environmental cost of this technology. Hybrid systems offer versatility in urban and intercity use, making them a strong alternative.

4. CONCLUSION

This study presented a comprehensive analysis of the conversion of the Anadol A1 with electric and hybrid systems. The findings in terms of energy efficiency, environmental impacts and economic viability have important implications for fossil fuel consumption reduction and renewable energy integration.

The study's findings can be summarized as follows:

- The internal combustion engine exhibited the least sustainable performance, with a total energy consumption of 256.5 MJ and 17.33 kg CO_2 emissions per 100 km.
- In comparison, the electric model emerged as the most environmentally sustainable option, exhibiting an energy consumption of 64.1 MJ and emissions of 8 kg CO_2 per 100 km.
- The hybrid model was found to offer a balanced solution between energy and economy, with a total energy consumption of 127.35 MJ and 10.8 kg CO_2 emissions per 100 km.
- The additional energy consumption of 750 MJ from battery production was identified as a significant factor increasing the environmental cost of the electric model.

Hybrid vehicles function as a crucial intermediary in the transition to electric vehicles. This is particularly beneficial for users experiencing range anxiety, as hybrid models offer a more practical solution for both urban and intercity journeys. While electric vehicles demonstrate high energy efficiency, hybrid models emerge as a user-friendly alternative in regions where charging infrastructure is limited. In addition, the effective role of hybrid vehicles in saving energy and reducing carbon emissions is attributable to regenerative braking and mixed operating modes.

Government incentives and regulations are critical to accelerating the adoption of electric and hybrid vehicles. The provision of incentives, including investments in charging station infrastructure for electric vehicles, the implementation of carbon taxes, and the reduction of tax rates, has been identified as a key factor in facilitating the widespread adoption of these technologies. Tax incentives for the purchase of electric vehicles and the benefits of hybrid vehicles based on their low fuel consumption have been shown to significantly reduce the total cost of ownership of these vehicles. It is evident that incentive policies are a pivotal instrument in accomplishing sustainable transportation objectives.

The revival of a nostalgic model such as the Anadol with modern technologies not only provides environmental and economic benefits but also creates social awareness. The adoption of electric and hybrid conversion solutions offers a viable solution that addresses the needs of the future while preserving the values of the past. Such initiatives are instrumental in paving the way for innovative approaches in the domestic automotive sector, thereby raising environmental awareness and contributing to the realization of sustainable development goals. Moreover, the revival of an iconic brand like Anadol creates a cultural impact that supports the harmony between nostalgia and modernity in different segments of society.

This study combines a classic design with modern technologies and concludes with an innovative perspective on the environmental and economic dimensions of energy systems. The adoption of renewable energy-oriented solutions has yielded insights that have led to innovation in the local automotive sector. The development of a sustainable transportation strategy has supported economic gains and contributed positively to the environment by reducing the carbon footprint.

The following recommendations are offered for future studies:

- Investigate new materials and techniques to reduce the environmental costs of battery technologies.
- Further optimisation of regenerative braking in hybrid systems.
- Further analysis of drivability in different urban and intercity scenarios.
- While the WLTP procedure offers a standardized framework, alternative test cycles such as the FTP-75 (used in the US) or the NEDC (formerly used in Europe) may yield different results due to variations in acceleration patterns, average speeds, and load assumptions. For instance, the NEDC often underestimates real-world emissions and energy use, potentially overstating the efficiency of EVs and PHEVs. A brief comparative evaluation of such procedures could be a fruitful avenue for future work.

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