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RESEARCH ARTICLE **RENEWABLE ENERGY**

Estimation of the Storage Capacity of Electric Vehicle Batteries under Real Weather and Drive-mode Conditions: A Case Study

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ABSTRACT

In line with Libya's strategic shift towards renewable energy and efforts to reduce carbon emissions, and considering that the transportation sector is the second-largest contributor to environmental pollution after the electricity sector, this study aims to explore the feasibility of adopting electric vehicles (EVs) as a strategic solution to enhance environmental sustainability and reduce dependence on fossil fuels. This research analyzes the energy consumption of electric vehicles under real-world climatic and operational conditions, focusing on the impact of wind resistance, road incline, rolling resistance, and acceleration resistance on energy efficiency. The Brak-Sabha highway in southern Libya was selected as a case study, where an 83 km simulated journey over 60 minutes was assessed under four distinct weather conditions: stormy, cold, hot, and rainy, considering both daytime and nighttime driving. In the present stydy, the energy consumed in electric vehicles was classified into two levels: high voltage (400 volts) to operate the electric motor and its accessories, and low voltage (12 volts) to operate the auxiliary devices. The results indicate that wind resistance had the most significant impact on energy consumption, accounting for 74.8% of total resistance, followed by road incline (14.4%), rolling resistance (10.3%), and acceleration resistance (0.5%). The study also revealed that auxiliary systems, such as heating, cooling, and lighting, significantly increase energy consumption, reaching 3.61 kWh during winter nighttime driving, whereas the lowest recorded consumption was 1.86 kWh during daytime summer trips. In the worst operational scenario, total energy consumption surged from 18,476.63 Wh under normal conditions to 86,800 Wh, reflecting a 370% increase, emphasizing the substantial impact of extreme weather conditions on energy usage. The findings highlight the necessity of optimizing driving strategies and energy management to enhance electric vehicle efficiency and extend operational range.

تقدير سعة تخزين بطاريات المركبات الكهربائية في ظل الظروف الجوية والتشغيلية الحقيقية: دراسة حالة

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الكلمات المفتاحية

السيارات الكهربائية
تحليل استهلاك الطاقة
بطاريات الية الفولتية
بطاريات منخفضة الفولتية
بطاريات السيارات الكهربائية

الملخص

تماشياً مع استراتيجية ليبيا في التحول نحو الطاقات المتجددة وتحقيق الاستدامة، والجهود الدولية المبذولة للحد من انبعاثات الكربون، وباعتبار قطاع النقل هو اكبر مستهلك للطاقة وثاني أكبر مساهم في التلوث البيئي، هدفت هذه الدراسة إلى استكشاف جدوى تبني المركبات الكهربائية كحل استراتيجي لتعزيز الاستدامة البيئية والحد من استنزاف الوقود الأحفوري، عن طريق محاكاة استهلاك الطاقة للمركبات الكهربائية في ظل الظروف المناخية والتشغيلية الحقيقية. تم اختيار طريق براك-سبها في جنوب ليبيا كحالة دراسية، حيث تم تقييم رحلة بطول 83 كم على مدى 60 دقيقة في ظل أربعة ظروف جوية مختلفة: عاصفة وباردة وساخنة وممطرة، مع الأخذ في الاعتبار متطلبات القيادة في النهار والليل. كما تم في هذا البحث تصنيف الطاقة المستهلكة في المركبات الكهربائية الى نوعين، عالية الفولتية (400 فولت) لتشغيل المحرك الكهربائي وملحقاته، ومنخفضة الفولتية (12 فولت) لتشغيل الاجهزة المساندة. تشير النتائج إلى أن مقاومة الرياح كان لها التأثير الأكثر أهمية على استهلاك الطاقة، حيث شكلت 74.8٪ من إجمالي الطاقة المستهلكة عالية الفولتية، تليها انجدار الطريق (14.4٪)، ومقاومة التدحرج (10.3٪)، ومقاومة التسارع (0.5٪). وكشفت الدراسة أيضًا أن الأنظمة المساعدة، مثل التدفئة والتبريد والإضاءة، تزيد بشكل كبير من استهلاك الطاقة، حيث قدرت الطاقة المستهلكة 3.61 كيلووات ساعة أثناء القيادة ليلاً في الشتاء، في حين كان أقل استهلاك حوالي 1.86 كيلووات ساعة أثناء الرحلات النهارية في الصيف. كما قامت الدراسة بمحاكاة أسوء سيناريو من الظروف الجوية والقيادة، حيث سجل ارتفع إجمالي استهلاك الطاقة من 18.477 كيلووات ساعة في الظروف العادية إلى 86.800 كيلووات ساعة، مما يعكس زيادة بنسبة 370٪، مما يؤكد التأثير الكبير للظروف الجوية القاسية على استخدام الطاقة. وتسلط النتائج الضوء على ضرورة تحسين استراتيجيات القيادة وإدارة الطاقة لتعزيز كفاءة المركبات الكهربائية وتوسيع نطاق التشغيل.

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https://doi.org/

Introduction

The demand for transportation has experienced a substantial increase over the past decade, primarily attributable to global population growth, with projections indicating that the number of internal combustion engine (ICE) vehicles will escalate from 1.7 to 2 billion by the year 2040 [1]. As per the 2023 data, the transportation sector remains predominantly dependent on petroleum products, which constitute approximately 91% of its aggregate energy consumption, comprising about 106.41 EJ of petroleum derivatives, 5.25 EJ of natural gas, 4.18 EJ of biofuels, and 1.65 EJ of electricity utilized. The transportation sector is recognized as the most environmentally detrimental among all sectors, contributing around 8.4 $GtCO_2$ emissions in 2023, thereby accounting for approximately 21% of the total global CO_2 emissions [2]. In the context of Libya, the transportation sector is an essential element of the nation's infrastructure, characterized by a highway network that spans roughly 1,759,540 square km and encompasses over 83,200 km of roads, of which 47,590 km are paved. According to the Ministry of Transport and Communications (2023), the number of vehicles registered in Libya has reached 5,483,760. Furthermore, the transportation sector emerges as the predominant consumer of fuel within the country, exhibiting an annual consumption of approximately 5,545 thousand tons of fuel, which results in the emission of 18.246 million tons of CO_2 each year [3].Thus, the transportation sector is the largest consumer of energy and the second largest contributor to environmental pollution [4] These statistics underscore the pressing necessity for the enhancement of Libya's transportation infrastructure and illustrate the sector's potential to contribute to the nation's obligations in reducing greenhouse gas emissions, as it is a signatory to the Paris Agreement on Climate Change (2015). Moreover, the transition towards renewable and environmentally sustainable energy sources is congruent with Libya's 25-year energy strategy (2025-2050), which aspires to elevate the proportion of renewable energy to exceed 50% of the overall energy mix by 2050 [5]. Achieving carbon neutrality within the transportation sector stands as one of the principal objectives for realizing the targets set forth by the Paris Climate Agreement, with electric vehicles (EVs) anticipated to play a crucial role in facilitating this transition [6]. The automotive industry has experienced a series of remarkable transformations and advancements over the years, commencing with the inception of the first steam-powered vehicle prototype in the year 1679, which, despite its innovative design, demonstrated exceedingly low efficiency levels coupled with significantly high emission rates that raised environmental concerns. The evolution of automotive technology continued its trajectory of improvement until the year 1876, when the illustrious inventor Nikolaus Otto successfully engineered the first internal combustion engine (ICE), a groundbreaking mechanism that operates predominantly on fossil fuel resources such as various petroleum derivatives including gasoline and diesel, as well as natural gas. Furthermore, there has been a notable shift towards the increased utilization of renewable fuels, exemplified by the incorporation of biodiesel within compression ignition engines, alongside the application of methanol in spark ignition engines, which reflects a growing awareness of the need for more sustainable energy sources. In the year 1966, General Motors made a significant leap forward in automotive innovation by unveiling the first-ever hydrogen-powered vehicle, thereby establishing itself as a pioneer in the realm of alternative fuel technologies and contributing to the early development of cars that operate on hydrogen as a clean energy source. In the year 1888, the Flocken Elektrowagen emerged as a groundbreaking invention, recognized as the inaugural electric automobile, which was ingeniously equipped with a modest yet effective one-horsepower electric motor coupled with a rechargeable lead-acid battery system, allowing it to achieve an impressive maximum velocity of roughly 9 miles per hour, a remarkable feat for its time. Throughout the subsequent century, the field of electric vehicle research has undergone profound transformations and advancements, culminating in a significant surge in the commercial availability and acceptance of electric vehicles (EVs), thereby revolutionizing the automotive industry as a whole. In recent years, the electric vehicle market has experienced an unprecedented and robust growth trajectory, reflecting a burgeoning demand and increased consumer interest in sustainable transportation solutions, as evidenced by various statistical analyses and market reports [7]. In the year 2023, the global market for electric vehicles experienced a remarkable surge, with sales figures reaching an impressive total of 13.9 million units, which astonishingly constitutes approximately 20% of all automotive sales worldwide. Over the span of five years, from 2018 to 2023, the global annual growth rate for electric vehicles manifested at an extraordinary rate of roughly 46%, with notable variances observed across different regions, including a striking 53% growth rate in Europe, a commendable 49% in China, and a slightly lower yet significant 32% in the United States. According to projections made by the International Energy Agency (IEA), it is anticipated that by the year 2030, the total number of electric vehicles in circulation will escalate dramatically to a staggering 226 million, representing an increase of approximately 39.8 million vehicles when compared to the figures recorded in 2023. Such statistics serve as compelling evidence of the robust expansion occurring within the global electric vehicle market, thereby indicating a profound and transformative shift within the transportation sector towards the adoption of more sustainable and environmentally conscious technologies [8].

This research is aligned with Libya's ambitious aspirations for achieving sustainable growth within the transportation sector, as well as implementing effective strategies aimed at mitigating the adverse environmental impacts associated with traditional vehicular reliance. Central to the advancement of electric vehicle technology are batteries, which stand as the fundamental component driving development in this arena, given that they represent the most critical element influencing vehicle efficiency, overall performance, and ultimately, consumer satisfaction. Factors such as battery capacity, charging efficiency, charging duration, and the overall lifespan of batteries emerge as pivotal aspects that significantly impact consumer trust and reliance on electric vehicles when juxtaposed with conventional internal combustion engine vehicles. Furthermore, the ongoing advancements in battery technology, which encompass enhancements in energy density, reductions in production costs, and improvements in reliability, are absolutely essential for propelling the transition to electric-driven transportation solutions and concurrently diminishing societal reliance on fossil fuel sources. The continuous innovation in battery design and manufacturing methodologies lays the foundational groundwork necessary for catalyzing a substantial transformation within the electric vehicle industry, thereby reinforcing its integral role in shaping the future landscape of sustainable transportation solutions [9]. Scientists have significantly escalated their endeavors aimed at the development of innovative technologies that are specifically designed to enhance the overall efficiency of electric vehicle (EV) batteries, with the overarching goal of maximizing both comfort and performance while also taking into account the increasing demand for the charging infrastructure required for these vehicles, particularly along major thoroughfares in urban environments. A multitude of comprehensive studies have been undertaken to ascertain the most optimal locations for the establishment of public EV charging stations; however, it is essential to recognize that selecting these locations based merely on the travel patterns exhibited by EV drivers across various metropolitan areas may inadvertently lead to a disproportionate distribution of charging stations, which could result in elevated demand during specific peak times while leaving certain stations underutilized during off-peak periods [10]. When electric vehicles are charged utilizing renewable energy sources or other low-carbon energy alternatives, their lifecycle emissions are markedly lower when compared to the emissions produced by vehicles powered by fossil fuels, culminating in a substantial reduction of greenhouse gas emissions that can reach as high as 93% [11]. This notable reduction plays a critical role in advancing the objectives set forth by sustainable development goals (SDGs) and in the pursuit of achieving net-zero emissions, which is becoming increasingly imperative in the context of global climate change. In light of this pressing issue, several nations have proactively instituted strategies and policies that are aimed at bolstering sustainable development objectives and ensuring compliance with the stipulations of the Paris Climate Agreement, which includes measures such as the prohibition of the sale of internal combustion engine (ICE) vehicles, thereby rendering the transition towards electric vehicles not only beneficial but indeed inevitable. For example, the United Kingdom has enacted legislation that prohibits the sale of gasoline and diesel-powered vehicles by the year 2030, while the European Union has outlined a comprehensive plan to impose a ban on such vehicles by the year 2035. Electric vehicles have demonstrated considerable efficacy in the reduction of fossil fuel consumption as well as the mitigation of greenhouse gas emissions. Nevertheless, the availability of charging stations continues to be a pivotal factor that significantly influences the rates of adoption for electric vehicles. The charging equipment that is utilized varies considerably based on numerous factors, including charging duration, battery capacity, battery type, and the specific characteristics of electric vehicle supply equipment (EVSE). Indeed, the durations for charging can vary widely, ranging anywhere from a brief 15 minutes to an extensive 20 hours, contingent upon these various parameters. While more affordable electric vehicles—excluding high-end models such as those produced by Tesla—typically provide a driving range of approximately 100 to 120 km per full charge, the principal challenge that persists is the insufficient number of charging stations available to meet the burgeoning demand for electric vehicles [12]. The scarcity of fast-charging stations has emerged as an increasingly daunting global challenge, particularly in light of the limited driving range that many electric vehicles possess, coupled with the pressing need for reduced charging times. The absence of adequate charging infrastructure represents a significant barrier for potential users, thereby necessitating meticulous planning with regard to the deployment of charging stations. A variety of critical factors must be taken into account when strategizing the placement of these stations, including the driving behavior patterns of EV owners, the configuration of the power distribution network, the economic viability of such projects, and the overarching safety of the energy system [13].

The process of conducting a thorough review of previous academic studies is not merely a procedural formality but rather an indispensable and fundamental step in establishing a robust scientific foundation that underpins and supports the overarching research framework of any scholarly inquiry. This particular section is dedicated to summarizing a variety of research initiatives that have specifically concentrated on the area of electric vehicles (EVs), while simultaneously analyzing and reflecting upon the notable achievements as well as the persistent challenges that are encountered within this rapidly evolving field of study. In a notable study undertaken by Mansour et al., the researchers meticulously assessed and analyzed energy consumption patterns in both fuel cell vehicles (FCVs) and electric vehicles (EVs) under a variety of different operational conditions, which included a comprehensive examination of the impact that the heating, ventilation, and air conditioning (HVAC) system has on energy usage in the context of New York City. The results derived from this investigation clearly indicated that the operation of the HVAC system leads to a substantial increase in energy consumption, quantified as a 33% rise in electric vehicles and an even more significant 55% increase in fuel cell vehicles. Furthermore, the study highlighted that a 20% decline in battery efficiency could result in a considerable reduction in driving range, specifically by 34.5%, thereby illuminating the critical fact that the deterioration of battery health exerts a markedly greater negative influence on the performance of electric vehicles in comparison to fuel cell vehicles. These significant findings underscore the pressing need for the formulation and implementation of comprehensive policies aimed at enhancing energy efficiency within the broader transportation sector [14]. In a separate yet equally compelling study, Lee et al. investigated the influence of ambient temperature on both energy efficiency and driving range in electric vehicles. Their research revealed that particularly low temperatures, specifically at -15°C, correspondingly increase energy consumption by a striking 35.4% when compared to moderate temperature conditions, such as those at 24°C. The study identified that optimal energy efficiency was achieved at temperatures within a specific range, notably between 20°C and 30°C. Additionally, the operation of the HVAC system was found to further exacerbate battery energy consumption, resulting in increases of 5.4% during the summer months and 12.0% during winter, which collectively detrimentally impacted the overall energy efficiency of the vehicles in question. This study confirmed that real-world energy efficiencies observed were, in fact, higher than previously reported values, thereby emphasizing the critical importance of taking into account ambient temperature fluctuations as well as HVAC usage when assessing the energy efficiency and driving range of electric vehicles [15]. Additionally, a comprehensive study conducted by Hang et al. focused on investigating the effects of extreme temperature environments on the energy consumption behaviors of battery electric vehicles (BEVs) within the specific context of Tianjin, China. Over the course of eight months, researchers collected extensive data from eight different electric vehicles, and the results revealed that vehicle speed emerged as the most significant factor influencing energy consumption, demonstrated by an impressive average correlation coefficient of 0.785. Moreover, the findings indicated that energy consumption exhibited a decrease of 5.4% during high-temperature conditions, whereas, conversely, it experienced an increase of 13.3% during low-temperature conditions. Furthermore, the study elucidated that air conditioning (AC) energy consumption surged by 17.12% in high-temperature environments and spiked dramatically by 47.48% in low-temperature settings, thereby showcasing the profound impact that climatic conditions have on the operational performance of electric vehicles [16]. Lastly, a pivotal study by Liu et al. was conducted to rigorously examine the effects of road gradients on energy consumption patterns, utilizing advanced methodologies such as GPS tracking data in conjunction with a Digital Elevation Model (DEM). The findings from this research revealed that energy consumption in electric vehicles exhibited variability ranging between 5% and 8%, with a particular emphasis placed on the critical role that braking systems play in enhancing energy efficiency when navigating inclines and declines in topography [17]. A comprehensive study conducted by Świeczko et al. meticulously measured the rolling resistance in electric vehicles (EVs) and its consequential impact on energy consumption, providing significant insights into this critical aspect of automotive engineering. The findings from this extensive research indicated that an impressive reduction of rolling resistance by as much as 50% could potentially lead to a noteworthy 15% decrease in energy consumption, thereby underscoring the importance of optimizing this variable; furthermore, the study included a thorough analysis that examined the multifaceted effects of various factors such as tire design, road pavement conditions, and environmental influences on the overall performance of vehicles, particularly emphasizing electric vehicles [18].

In a related research endeavor, Iora et al. [19] developed an intricate model aimed at estimating energy consumption and the driving range associated with electric vehicles, with a particular emphasis placed on the influence of ambient temperature and the energy consumed by accessories within the vehicle. The findings from this comprehensive analysis revealed that the need for cabin heating during low-temperature conditions exerts a significant impact on the overall performance of the vehicle; consequently, the vehicle was subjected to testing until the battery was fully depleted across a broad spectrum of ambient temperatures. The results demonstrated that the ambient temperature exerted a pronounced effect on the driving range, with the maximum achievable range exceeding 150 km at a comfortable temperature of 20°C, which notably decreased to approximately 85 km at 0°C, and further diminished to merely 60 km at an even lower temperature of -15°C. Additionally, the study highlighted the phenomenon of desert winds sweeping across unobstructed roadways as a contributing factor that can exacerbate aerodynamic resistance, thereby accentuating the necessity to incorporate these environmental effects into any comprehensive analysis of energy consumption. In another relevant investigation, Tran et al. conducted a thorough analysis of energy consumption patterns in electric vehicles, placing particular emphasis on the sensitivity of energy consumption metrics to variations in wind speed and direction. This meticulous study confirmed the hypothesis that energy consumption in electric vehicles is highly contingent upon prevailing weather conditions, especially the influence of wind, thereby making accurate predictions of energy consumption essential for optimizing both the efficiency and the driving range of electric vehicles [20]. Furthermore, Abousleiman et al. undertook the development of a sophisticated dynamic model specifically designed for analyzing battery energy consumption within the context of electric vehicles, applying this model to a 2013 Fiat 500e, which resulted in demonstrably high levels of accuracy, as evidenced by an average error margin of less than 1.5% over an extensive driving distance of more than 340 km. This significant achievement underscores the model's reliability and its paramount importance in enhancing energy efficiency as well as contributing to the advancement of electric vehicle technology [21]. Lastly, a study conducted by Hyodo et al. concentrated on the formulation of a mathematical equation intended to estimate energy consumption in electric vehicles, which was grounded in the rigorous collection of high-precision GPS data. This innovative methodology was specifically applied to a Mitsubishi i-MiEV, which has a weight of 1100 kg and is equipped with a 16 kWh battery capacity, allowing for a measured driving range of 160 km. The results yielded a strikingly high correlation between the estimated values and the actual measured data, with an error margin consistently remaining below 1.5%, thereby demonstrating the remarkable accuracy of the model and its considerable potential to enhance energy consumption estimations while also supporting the development of essential infrastructure, such as roads and charging stations, necessary for the future of electric mobility [22].

This study aims to develop a comprehensive framework for estimating the storage capacity of electric vehicle (EV) batteries under real-world weather and operating conditions, analyzed on a per-minute basis. This represents the scientific contribution of this research, as the effect of relative wind direction concerning vehicle movement on energy consumption in electric vehicles has not been thoroughly investigated. A simulated journey of 83 kilometers with an estimated duration of 60 minutes was conducted, considering climatic and topographical conditions along the route under multiple scenarios: a nighttime trip and a daytime trip under four different weather conditions—stormy, cold, hot, and rainy.

The remainder of this study is structured into four sections. The second section provides fundamental information about the study area. The third section outlines the methodology used to analyze EV energy consumption and determine battery capacity. The fourth section presents and discusses the graphical representation of the obtained results. Finally, the fifth section summarizes the study's key conclusions, followed by a list of references used in this research.

Basic Information about the Study Area

The study area is the road connecting the cities of Brack Alshatti and Sabha in southern Libya, spanning approximately 83 km with an average travel time of 60 minutes under normal driving conditions. The route extends from Brack Alshatti, located at 27.533° N latitude and 14.271° E longitude, to Sabha, situated at 27.037° N latitude and 14.428° E longitude. The road traverses diverse topographical features, including elevations and depressions, which pose challenges for energy consumption estimation, particularly for electric vehicles (EVs) that are highly influenced by slope resistance. Additionally, the route contains several turns with varying degrees, leading to frequent speed fluctuations that directly impact energy consumption. The road also includes four security checkpoints distributed along its length, which necessitate short stops that influence driving range and energy efficiency. Given its strategic importance as a major transportation corridor linking northern and southern Libya, the route experiences continuous and high traffic volumes for passenger and freight transport, further emphasizing its role as a critical transport artery in the region. Figure 1 illustrates the study area.

Fig.1: Study area.

The region is characterized by a hot desert climate in summer and a cold, dry climate in winter. During summer daytime, the average high temperature reaches 39°C, while the average low temperature is 26°C. In winter, temperatures drop significantly, with an average low of 7°C and an average high of 19°C. These temperature variations contribute to additional energy consumption, which in turn affects battery storage capacity estimation. Figures 2–4 present hourly climatic data for Brack City in 2022, illustrating the following, respectively: Global Horizontal Solar Radiation Intensity, and Wind Speed and Direction, and Ambient Air Temperature.

Methodology

In this study, the energy consumption of electric vehicles was analysed, and the required battery capacity was determined to meet the journey's demands under real-world weather and operational conditions. Meteorological data were obtained from the meteorological station at Wadi Al-Shati University - Brack, while topographic data were collected using GIS, providing precise insights into environmental factors such as ambient air temperature, wind speed, and direction, which directly impact the energy consumption of electric vehicles. The data were processed and analysed using Microsoft Excel. As a case study, a simulation was conducted for a journey along the Brack-Sabha road, covering a distance of 83 km with an estimated travel time of 60 minutes, considering various weather and topographic conditions under multiple scenarios, including a nighttime trip and a daytime trip under four different climate conditions: stormy, cold, hot, and rainy. Figure 5 presents a schematic diagram of the research methodology adopted in this study.

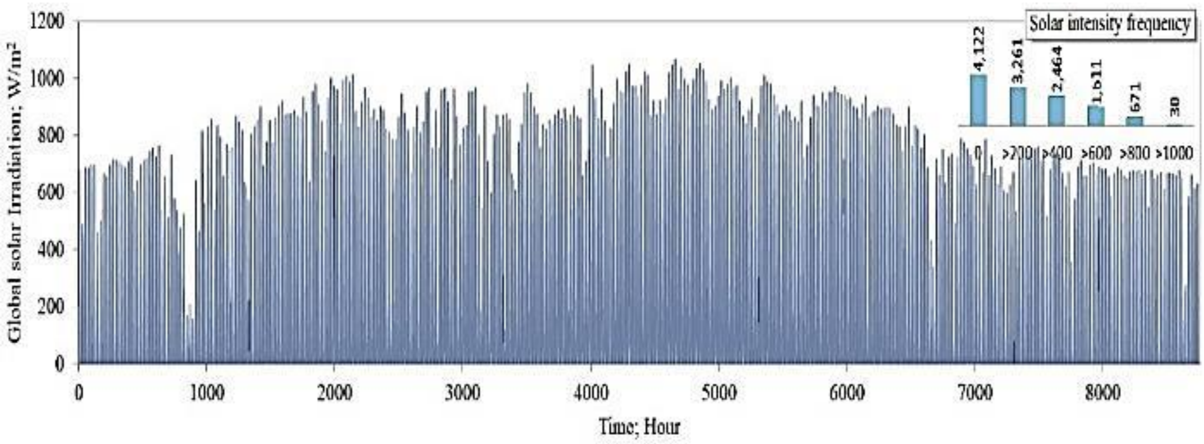

Fig.2: Hourly global horizontal solar radiation intensity and frequency distribution.

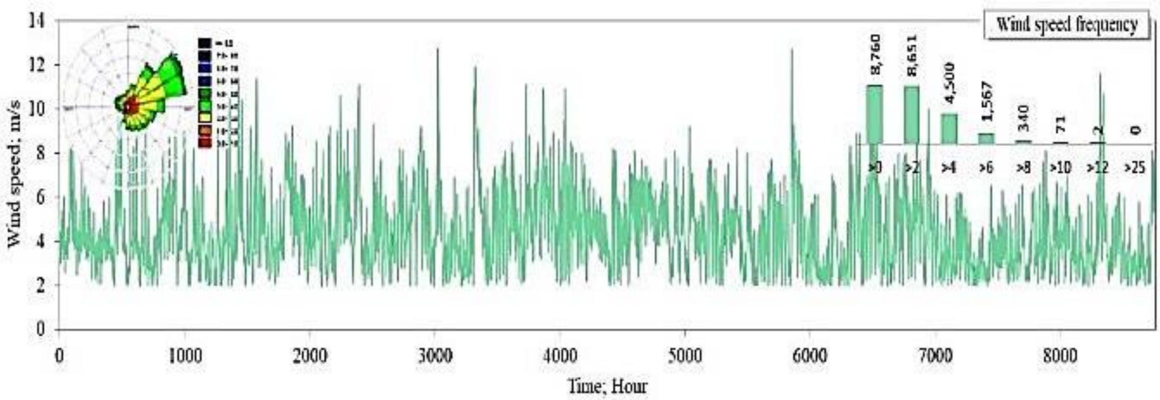

Fig.3: Hourly wind speed and direction with frequency distribution.

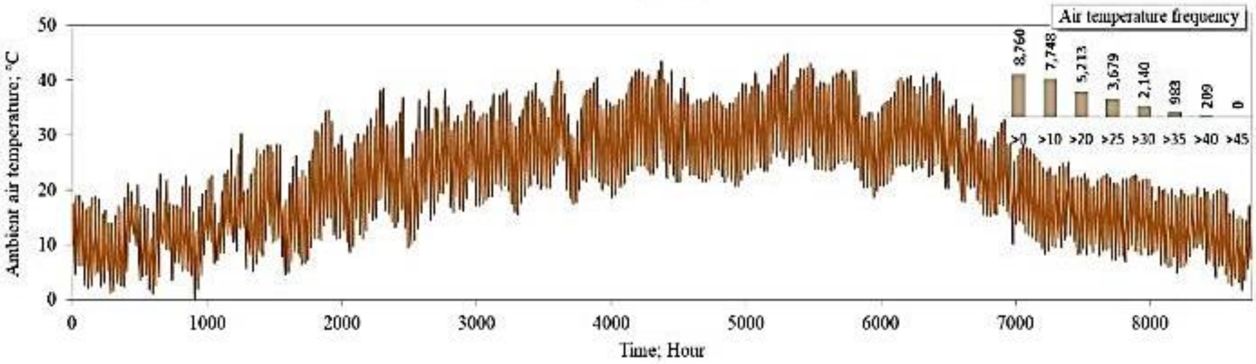

Fig.4: Ambient air temperature and frequency distribution.

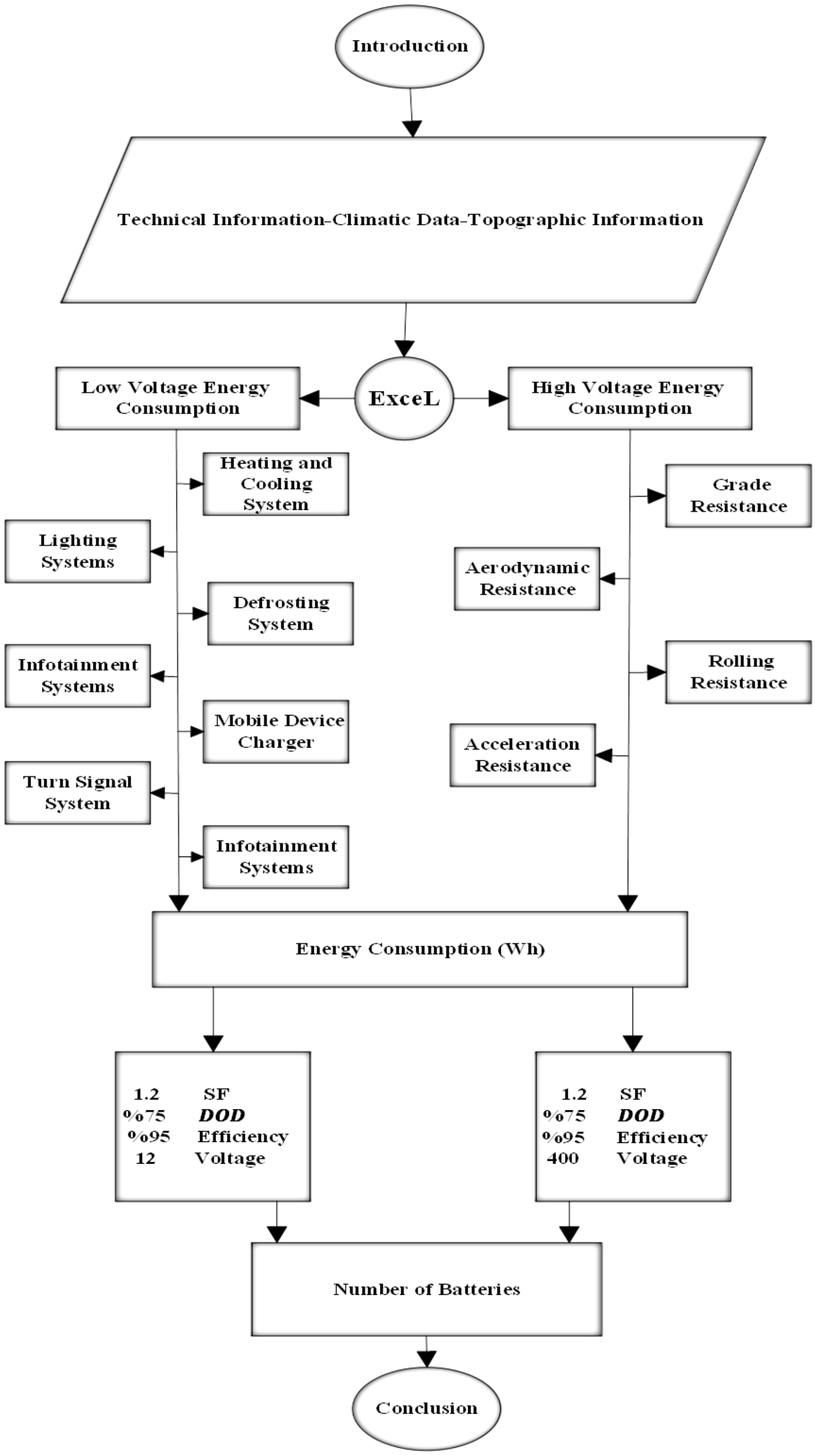

Fig.5: Research methodology.

Unlike previous studies, this research classifies the consumed energy into two types based on battery capacity: high-voltage energy (400V) (E_{HV}), which powers the electric motor and its accessories [26], and low-voltage energy (12V) (E_{LV}), which operates the auxiliary devices. Consequently, the total energy consumption in electric vehicles (E_{total}) can be estimated using Eq.1 [27].

$$E_{total} = E_{HV} + E_{LV} \quad (1)$$

The high-voltage energy consumption (E_{HV}) is represented by the rolling resistance (E_{Roll}), acceleration resistance (E_{Acc}), wind resistance (E_{Wind}), and gradient resistance (E_{Deg}), as expressed in Equation (2).

$$E_{HV} = E_{Roll} + E_{Acc} + E_{Wind} + E_{Deg} \quad (2)$$

Meanwhile, the low-voltage energy consumption (E_{LV}) includes the heating and cooling system (E_{AC}), lighting systems (E_L), infotainment systems (E_I), defrosting system (E_D), mobile device charger (E_{Ch}), turn signal system E_S), braking system (E_B), and other auxiliary devices (E_O), as expressed in Equation (3).

$$E_{LV} = E_{AC} + E_L + E_I + E_D + E_{Ch} + E_O + E_S + E_B \quad (3)$$

The Instantaneous Energy Level in Battery

The instantaneous State of Charge in the batteries are calculated using eqns 4 and 5 for both charge ($SoC_{ch}(t)$) and discharge ($SoC_{Dis}(t)$) mode, respectively, and for both batteries (LV and HV) [29-31]:

$$SoC_{Dis}(t) = SoC(t - \Delta t)(1 - \sigma) - E_{LV,HV}(t)\eta_b \quad (4)$$

$$SoC_{ch}(t) = SoC(t - \Delta t)(1 - \sigma) + \left(\frac{P_S(t)}{\eta_{inv}}\right)\eta_b \quad (5)$$

Where: Δt states for the time interval, σ is self-energy consumption (1%), $E_{LV,HV}$is the energy consumption for both batteries at a certain time t, η_b is the battery efficiency (95%) and η_{inv} is the inverter efficiency (85%). These efficiencies assumed to be constant during the simulation time [32].

Environmental Aspects

It must be mentioned in this regard that, the infrastructure in Libya is not ready to receive electric vehicles under the current conditions of the electric power generation system, due to the decline in generation efficiency (23%) [33], in addition to the high CO_2 emission factor, which averages about 1.037 $kgCO_2/kWh$ [34]. Therefore, government must begin establishing charging stations that operate with renewable and cleaner energies [35-37].

Results and discussion

Estimation of High-Voltage Energy Consumption

Wind Resistance

It represents the force opposing the vehicle's motion due to wind resistance while driving. This resistance is a crucial factor affecting the energy efficiency and driving range of electric vehicles. As the vehicle speed increases, wind resistance rises significantly, requiring the electric motor to consume more energy to overcome this force. Therefore, aerodynamic vehicle design, which aims to reduce the drag coefficient (Cd), is essential for improving performance and efficiency [28].

$$E_{air} = \frac{1}{2}\rho\, C_D\, A \int_0^T V_{car}(t)(V_{car}(t) + V_{wind}(t)\, Cos\theta(t)\,)^2\, dt \quad (6)$$

Where: E_{air} = Energy consumed due to wind resistance (J), ρ = Air density, equal to 1.275 kg/m³, C_D = Aerodynamic drag coefficient, equal to 0.25, A = Frontal area of the vehicle (m²), V_{car} (t) = Vehicle speed (m/s), V_{wind} (t) = Wind speed (m/s), θ(t) = Wind direction angle relative to the vehicle's movement, T = Time elapsed (s) [25].

Gradient Resistance

Gradient resistance is the force that hinders the movement of a vehicle when ascending an inclined road. This resistance results from the effect of gravitational force and is considered one of the primary factors influencing energy consumption in electric vehicles [22]. The gradient resistance is calculated based on the vehicle's weight and the road inclination angle. Equation (7) illustrates the calculation of the grade resistance affecting the electric vehicle.

$$E_{grade} = m\, g \sin\beta \int_0^T V_{car}(t)dt \quad (7)$$

Where: E_{grade} = Energy consumed due to grade resistance (J), m = Vehicle mass (kg), g = Gravitational acceleration (constant value of 9.81 m/s²), β = Inclination angle relative to the horizontal, T = Time (s) [25].

Rolling Resistance

Rolling resistance is the force that opposes the motion of a vehicle's wheels as they roll on the road surface. It results from the deformation of the tires and the road due to the vehicle's weight and friction between them. Rolling resistance is one of the key factors affecting the energy consumption efficiency of electric vehicles, as a portion of the battery's energy is required to overcome it. Equation (6) illustrates the calculation of rolling resistance in electric vehicles [27].

$$E_{roll} = m \times \tau \times g \times cos\beta \times \int_0^T V_{car}(t)dt \quad (8)$$

Where: E_{roll} =represents the energy consumed due to rolling resistance in Joules (J), τ is the rolling resistance coefficient, which is equal to 0.005 [22].

Acceleration Resistance

Acceleration resistance is the force acting on a vehicle during speed increase, resulting from the vehicle's total mass and the effort required to change its motion state according to Newton's Second Law. This resistance is one of the key factors influencing energy consumption in electric vehicles, as additional battery energy is required to accelerate the vehicle. Equation (7) represents the calculation of acceleration resistance in electric vehicles [28].

$$E_{acc} = m \times \delta \times \int_0^T a(t)V_{car}(t)dt \quad (9)$$

Where: E_{acc}= Energy consumed due to acceleration (J), δ = Rotational inertia factor, equal to 1, a = Linear acceleration of the vehicle (m/s²) [22].

Estimation of Low-Voltage Energy Consumption

The energy consumption of auxiliary devices in electric vehicles was estimated using the mathematical formulas outlined in Equation (10), which integrate the rate of energy consumption and elapsed time [21].

$$E_{LV} = \frac{1}{3600}\sum_{i=1}^{n} E_{aux,i}\, t_i \quad (10)$$

Where: n represents the number of auxiliary devices, $E_{aux,i}$ represents the power consumption of device (i) in watts, t_i refers to the operating duration of device (i).

To accurately determine energy consumption in electric vehicles, certain key parameters must be defined. Table (1) presents the values used in the simulation formulation and analysis, which were applied in the equations to calculate energy consumption while driving between two points [21].

Table 1: Values used in simulation formulation and analysis.

Description	Symbol	Value	Unit
Aerodynamic Drag Coefficient	C_D	0.25	-
Frontal Area	f_a	2.25	m²
Rolling Resistant Coefficient	f_r	0.005	-
Vehicle Mass	m	1500	kg
Gravitational Acceleration	g	9.8	m/s²
Air Mass Density	ρ	1.275	kg/m³
Rotational Inertia Factor (mass factor)	δ	1	-

Results and Discussion

High-Voltage Energy Consumption

A dataset reflecting energy consumption in electric vehicles was collected and analysed based on various factors such as wind resistance, acceleration, gradient, and rolling resistance. This data was examined to establish the relationship between different variables and energy consumption.

Wind Resistance

Figure 6 illustrates the relationship between time (min) and wind speed (m/s) during a journey under the influence of steady northern winds.

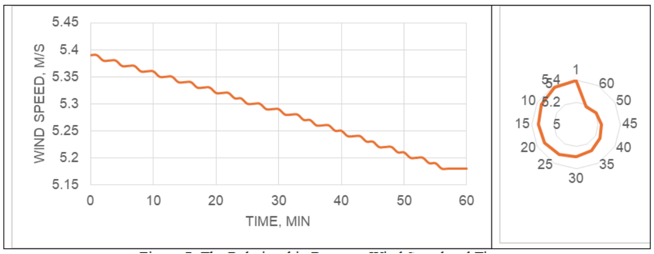

Fig.6: Instantaneous wind speed.

The curve shows a slight decrease in wind speed over time, starting at approximately 5.4 m/s and gradually decreasing to 5.2 m/s by the end of the 60-minute journey, representing a total reduction of 0.2 m/s. The data indicates a momentary wind speed variation of 0.05 m/s, reflecting a relatively stable atmospheric condition throughout the journey.

Figure 7 illustrates the minutely wind direction over the 60-minute trip duration.

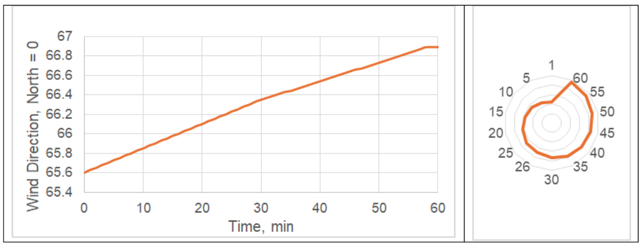

Fig.7: Instantaneous wind direction.

It shows that the wind direction starts at 65.6° north and gradually increases to 66.9° north by the end of the journey, indicating a slight change in wind direction of 1.3° throughout the trip. The analysis demonstrates a relatively stable wind direction with a slight eastward inclination, which may have a minimal impact on the vehicle's aerodynamics and energy consumption, as the angle of influence remains nearly constant without significant fluctuations. This slight variation in wind direction could result in a minor effect on air resistance and, consequently, energy consumption, reinforcing the reliability of the model used in analyzing the dynamic performance of the electric vehicle under wind influence.

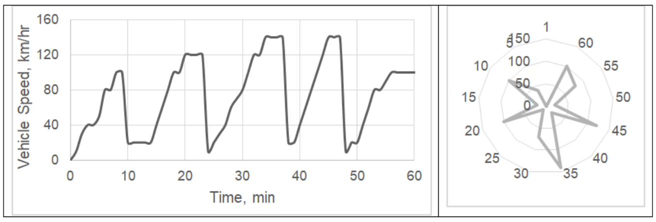

Fig.8: Instantaneous vehicle speed.

Figure 8 illustrates the relationship between vehicle speed (km/hr) and time (min) over a 60-minute journey. The curve exhibits significant speed variations due to factors such as security checkpoints, turns, and road elevation changes. Initially, the speed increases gradually from zero to approximately 140 km/hr within the first 10 minutes, indicating a natural acceleration phase at the start of the journey. A sharp speed drop occurs at the 10-minute mark, coinciding with the first security checkpoint, requiring the vehicle to stop or significantly reduce its speed. Between 10-20 minutes, after passing the first checkpoint, the speed rises again but experiences a slight dip due to the presence of a traffic island and a right turn. Another noticeable decrease occurs at the second security checkpoint. From 20-40 minutes, the speed remains relatively stable with minor fluctuations caused by road elevation changes on a straight path. At the 40-minute mark, another sharp drop in speed aligns with the third security checkpoint. In the period from 40-50 minutes, the speed undergoes substantial variations due to three consecutive turns, with one of them involving a steep ascent, further reducing the vehicle's speed. After clearing the turns and elevations, between 50-60 minutes, the speed stabilizes gradually. A final drop at 50 minutes is linked to the fourth security checkpoint, followed by a steady speed until the journey's end.

Figure 9 illustrates the relationship between wind resistance energy consumption (Wh) and time (min).

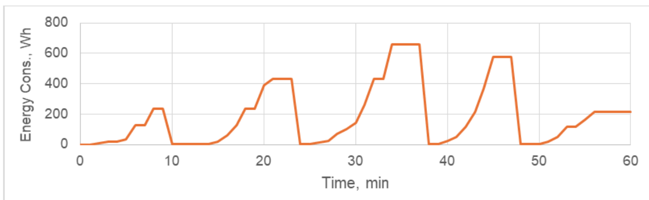

Fig.9: Energy consumption in wind resistance.

The curve shows significant variations in energy consumption due to changes in vehicle speed and relative wind speed and direction, influenced by security checkpoints and road curves. A gradual increase in energy consumption is observed as speed increases, reaching approximately 200 Wh at the ninth minute, coinciding with high vehicle speed before a sharp decrease at the first security checkpoint, where energy consumption drops significantly to near zero due to stopping or slowing down. Energy consumption rises again as speed increases gradually, reaching 300 Wh at the 15th minute. Between the 20th and 30th minutes, a continuous rise in energy consumption is observed, peaking at 600 Wh due to high speeds on a straight road section. After the second security checkpoint, energy consumption increases progressively due to passing curves (affecting relative wind direction) and increasing speeds, reaching approximately 500 Wh before the 47th minute. After passing the curves, the curve stabilizes at an energy consumption range of 300-400 Wh until the end of the journey.

Acceleration Resistance

Figure 10 illustrates the relationship between acceleration resistance (Wh) and time (min), showing repeated variations in acceleration due to frequent speed changes influenced by surrounding conditions.

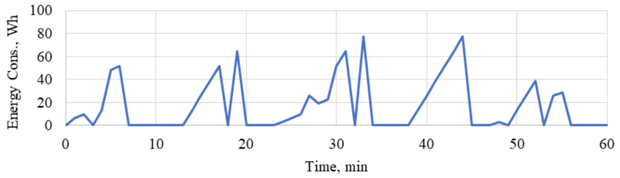

Fig.10: Instantaneous acceleration during the trip.

The journey begins with a gradual acceleration, reaching approximately 80 Wh, followed by a drop to zero due to speed reduction. Energy consumption then gradually increases to around 60 Wh as speed rises, before dropping to zero again after a turn at the 20th minute due to deceleration. Throughout the journey, repeated acceleration peaks are observed, reaching 70 Wh due to increased speed on the straight road. A sharp drop to zero occurs at the 40th minute, corresponding to a security checkpoint. Subsequently, acceleration peaks of up to 8 Wh appear while navigating curves and elevation changes, indicating additional efforts required for speed adjustments. In the final minutes of the journey, acceleration decreases as speed stabilizes, ultimately reaching zero at the end of the trip.

Gradient Resistance

Figure 11 illustrates the relationship between gradient resistance and time, where the curve shows a gradual decrease in gradient resistance from 700 Wh to 100 Wh over 60 minutes.

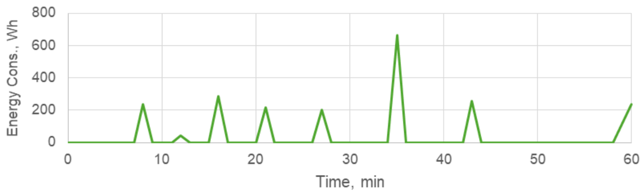

Fig.11: Instantaneous Gradient Resistance and Time.

The decline occurs at a rapid rate during the initial phase (0-20 minutes) due to changes in operating conditions or loads. In the mid-phase (20-40 minutes), the rate of decrease slows down as the system stabilizes. Finally, in the last phase (40-60 minutes), the decline occurs at a much slower rate as the system reaches a state of equilibrium.

Rolling Resistance

Figure 12 illustrates the relationship between energy consumption due to rolling resistance and time over a 60-minute journey. The curve shows a clear variation in energy consumption, which is influenced by speed fluctuations, stops, and road characteristics. Initially, there is a gradual increase in energy consumption as speed rises, reaching a peak of approximately 40 Wh, followed by a slight drop due to speed reduction at the first security checkpoint. The curve then exhibits moderate peaks ranging between 20-30 Wh, resulting from frequent speed changes caused by turns and minor road elevation variations. A relatively stable energy consumption of 25 Wh is observed when the vehicle maintains a steady speed for a short period. Later, a significant increase in energy consumption is noted, reaching a peak of 50 Wh due to high-speed driving on a straight road. Towards the end of the journey, energy consumption stabilizes gradually at 40 Wh, indicating stable driving conditions and relatively constant speed.

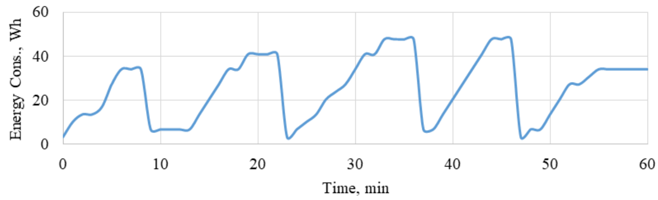

Fig.12: Instantaneous rolling resistance.

Figure 13 illustrates the total forces acting on the electric vehicle throughout the journey.

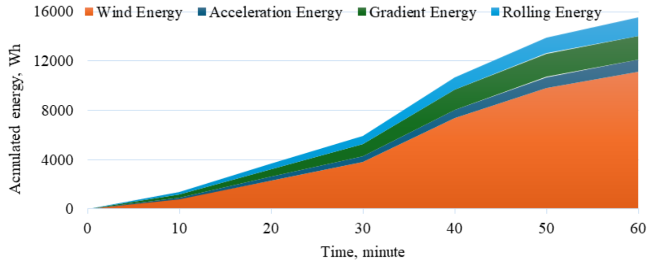

Fig.13: Cumulative high-voltage energy consumption.

Figure 13 reveals that the total resistance energy consumption of the electric vehicle during the trip amounted to 14,866.63 Wh. Wind resistance contributed the highest share at 74.8% (11,126.38 Wh), emphasizing the significant impact of aerodynamics on energy consumption, particularly at high speeds. Gradient resistance accounted for 14.4% (2,137.35 Wh), highlighting the influence of terrain on energy demand, as resistance increases when climbing inclined roads. Rolling resistance represented 10.3% (1,525.74 Wh), demonstrating the persistent effect of tire-road friction on overall energy consumption. Lastly, acceleration resistance had the least impact, contributing only 0.5% (77.16 Wh), indicating that acceleration phases were not a primary factor in energy consumption compared to other resistances.

Low-Voltage Energy Consumption

The energy consumption of auxiliary devices is significantly influenced by weather conditions and driving circumstances (daytime or nighttime). Table (2) presents real measurements of electric energy consumption for auxiliary components in a 2020 Hyundai Sonata during multiple trips between the cities of Brack and Sabha, simulating various driving conditions and different weather scenarios. Table 2 shows that the total energy consumption of auxiliary devices in electric vehicles varies depending on the time period (daytime or nighttime) and the season (winter or summer). The highest energy consumption occurs during nighttime winter trips, reaching 3.61 kWh, due to the heavy reliance on heating, lighting, and defrosting systems. This is followed by daytime winter trips, with a total consumption of 2.56 kWh, as the heating system operates throughout the journey. Nighttime summer trips

Table 2: Measurement of energy consumption for auxiliary components in the electric vehicle.

Auxiliary Devices	Daytime Trip Winter (kWh)	Daytime Trip Summer (kWh)	Nighttime Trip Winter (kWh)	Nighttime Trip Summer (kWh)	Power Consumption (W)	Operating Time (min)
Heating System	2.0	0	2.5	0	2500	60
Cooling System	0	1.5	0	1.5	1500	60
Lighting	0.1	0.05	0.6	0.3	100-600	60
Infotainment System	0.25	0.25	0.25	0.25	250	60
Defrosting System	0.15	0	0.2	0	500-800	15
Turn Signals	0.006	0.006	0.006	0.006	40	3
Braking System	0.013	0.013	0.013	0.013	80	10
Mobile Device Charging	0.05	0.05	0.05	0.05	50	60

consume less energy, totaling 2.11 kWh, as the cooling system operates alongside the lighting system, while daytime summer trips record the lowest consumption at 1.86 kWh. The heating system, which operates for 60 minutes, relies on electric heaters, leading to high consumption in winter, especially at night due to heat loss and lower ambient air temperatures. In contrast, the cooling system operates for 60 minutes during summer. LED lighting, which runs for 60 minutes, consumes more energy at night, particularly in winter, as there is a higher likelihood of using high-beam headlights compared to summer, while daytime lighting use is mostly limited to dashboard illumination. Meanwhile, the infotainment system, operating for 60 minutes, remains stable in its energy consumption, unaffected by external factors. The defrosting system operates for 15 minutes during winter, consuming more energy at night due to increased condensation on the windshield, while it remains inactive in summer. Turn signals (LED), operating for 3 minutes, consume minimal energy due to their intermittent use, keeping their consumption unchanged across seasons. The braking system (ABS), operating for 10 minutes, maintains stable energy consumption as it relies on electric brake pumps and sensors that activate when needed. Finally, mobile device charging, which operates for 60 minutes, remains constant throughout the journey, consuming minimal energy, regardless of external conditions. This analysis highlights the importance of optimizing auxiliary device energy management in electric vehicles to minimize energy losses, enhance operational efficiency, and extend driving range.

Sensitivity Analysis of Energy Consumption

A comprehensive sensitivity analysis was performed on various resistance factors influencing energy consumption in electric vehicles, taking into account the peak recorded wind velocity in Libya as well as the most pronounced road gradient at elevated vehicle velocities reaching up to 120 km/h. The subsequent figures delineate the influence of these extreme conditions on the sensitivity of energy consumption.

Figure 14 illustrates that an increase in road gradient leads to a rapid rise in energy consumption as the travel distance increases, reaching 2500 W at 2500 m. This indicates that electric vehicles require more energy to ascend steep roads, which in turn reduces their actual driving range.

Figure 15 illustrates the impact of road gradient on energy consumption at high speeds, where consumption reaches its peak at the steepest incline and speeds exceeding 120 km/h, surpassing 120,000 W. This highlights the significant effect of road gradient on the efficiency of electric vehicles.

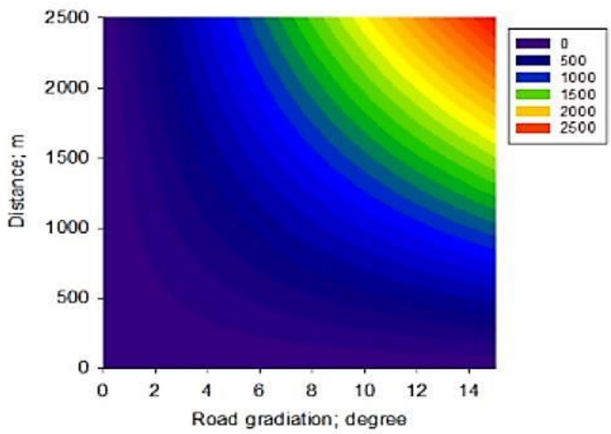

Fig.14: Impact of energy cons. based on gradient and distance.

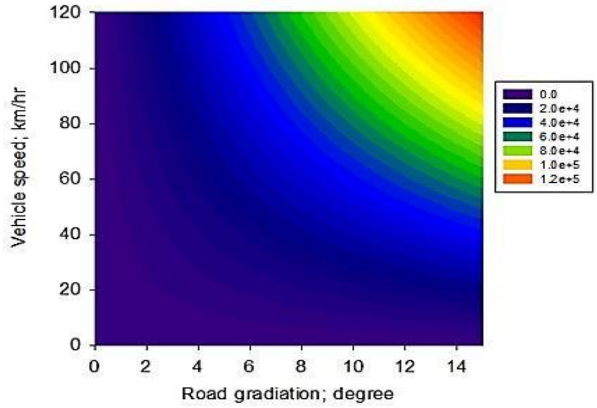

Fig.15: Impact of energy cons. based on gradient and vehicle speed.

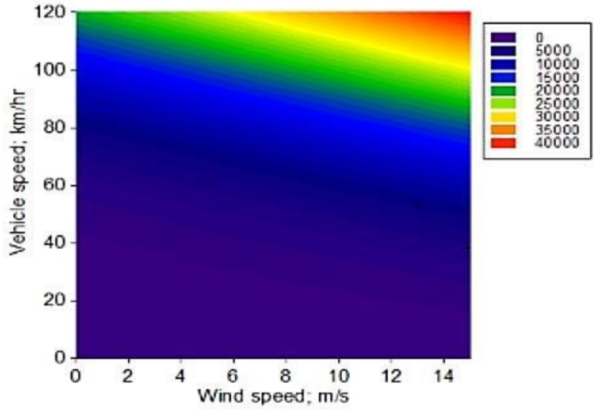

Fig.16: Impact of energy cons. due to wind resistance.

The results in Figure 16 indicate that an increase in wind speed leads to a significant rise in energy consumption, particularly at high speeds of 100 km/h and above, where consumption reaches 40,000 W. While the effect remains limited at lower speeds, aerodynamic resistance increases with wind speed, resulting in higher energy consumption.

Figure 17 illustrates the analysis of the impact of road gradient on energy consumption at different speeds, where the effect remains limited at low speeds of up to 40 km/h. However, energy consumption rises to over 2500 W at high speeds of 100 km/h and above. This demonstrates that rolling resistance on steeply inclined roads leads to high energy consumption, reducing the overall efficiency of the electric vehicle.

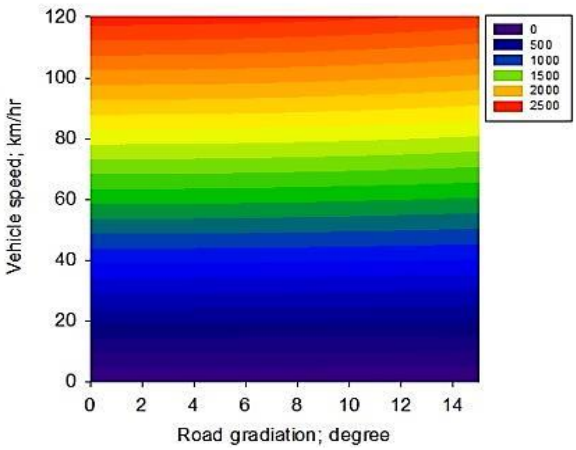

Fig.17: Impact of energy cons. due to rolling resistance.

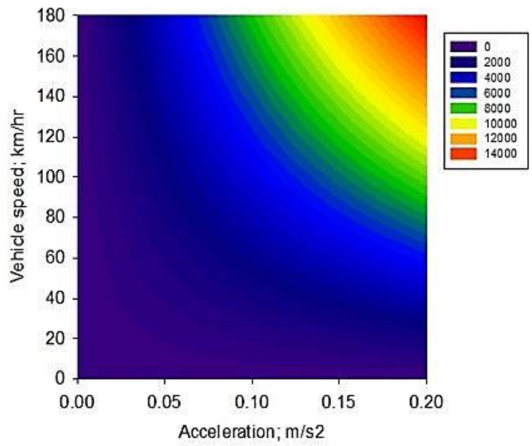

Fig.18: Impact of energy cons. due to acceleration resistance.

Figure 18 illustrates the analysis of the impact of acceleration on energy consumption. The results indicate that an increase in acceleration significantly raises energy consumption, particularly at high speeds exceeding 150 km/h, where it reaches 14,000 W. In contrast, energy consumption remains lower at mild acceleration levels below 0.05 m/s². This suggests that aggressive acceleration consumes a substantial amount of energy and negatively impacts the driving range of electric vehicles. Therefore, optimizing driving strategies and energy management systems in electric vehicles is essential to minimize energy loss and enhance operational efficiency.

Comparison between normal energy consumption and maximum consumption in worst-case conditions

Figure 19 illustrates a visual comparison between normal energy consumption (Image 1) and peak consumption under worst-case operating conditions (Image 2) for various systems in an electric vehicle, distinguishing between high-voltage energy consumption (HV) and low-voltage energy consumption (LV). The results indicate that wind resistance was the most influential factor, with its consumption rising from 11,126.38 Wh under normal conditions to 40,000 Wh in extreme conditions, a 259% increase. This was followed by gradient resistance, which increased from 2,137.35 Wh to 20,000 Wh, marking an 835% increase. Rolling resistance consumption also surged from 1,525.74 Wh to 5,000 Wh, reflecting a 227% increase. Meanwhile, acceleration resistance exhibited the most dramatic rise, escalating from 77.16 Wh to 14,000 Wh, an astounding 18,034% increase, highlighting the substantial impact of aggressive acceleration on energy consumption. Regarding auxiliary system consumption (LV), its energy demand rose from 3,610 Wh in normal conditions to 7,800 Wh in extreme conditions, representing a 116% increase, with heating and cooling systems being the primary contributors. Consequently, total energy consumption (HV+LV) increased from 18,476.63Wh

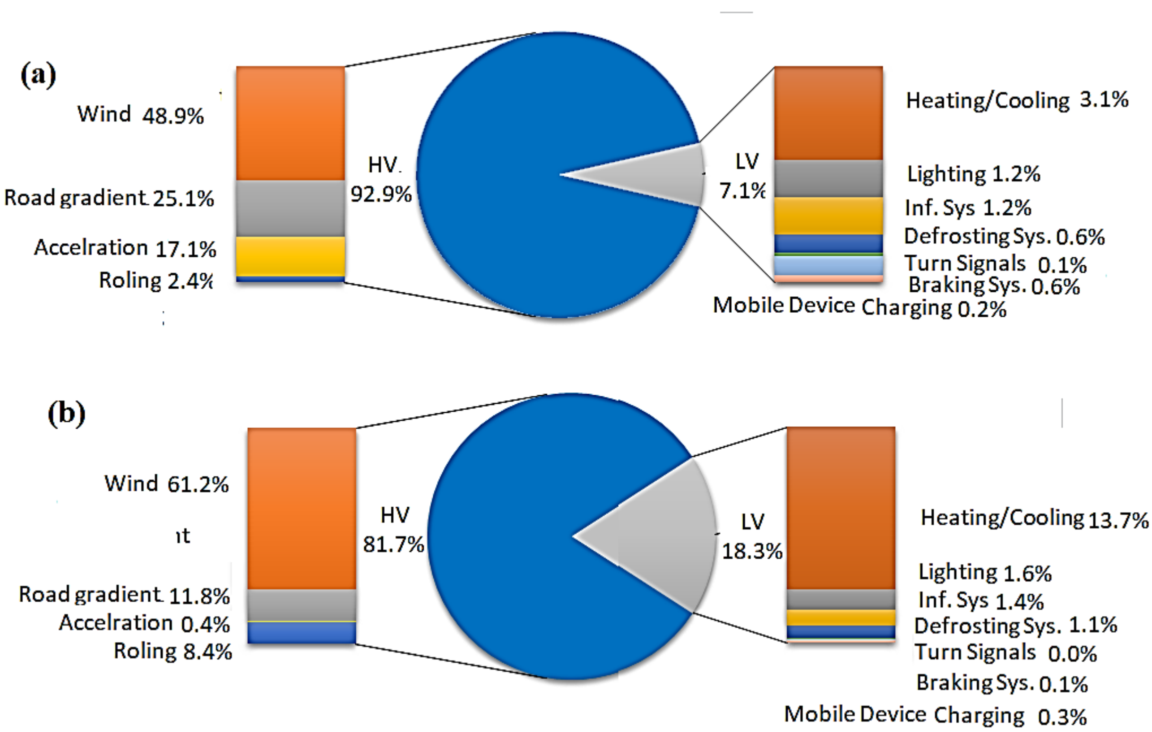

Fig.19: Comparison between the worst-case consumption (a) and the normal consumption (b).

under normal conditions to 86,800 Wh under worst-case conditions, reflecting a 370% overall increase. These findings emphasize the critical importance of optimizing driving strategies and energy management to counteract challenging environmental conditions and enhance the range and efficiency of electric vehicles.

Conclusions

1- The findings indicated that the energy consumption associated with electric vehicles is profoundly influenced by meteorological conditions, as diminished temperatures elevate energy usage due to the requisite for cabin heating, whereas headwinds considerably affect the aerodynamic efficiency of the vehicle, resulting in an escalation of energy consumption.

2- The research revealed that aerodynamic drag emerged as the predominant determinant of energy consumption, representing approximately 74.8% of the aggregate energy usage of the vehicle, succeeded by grade resistance at 14.4%, rolling resistance at 10.3%, while acceleration resistance exerted the least influence at 0.5%. This underscores the assertion that the maintenance of a consistent driving velocity significantly curtails energy consumption.

3- The findings illustrated that auxiliary systems, including heating, cooling, and illumination, exert a considerable influence on energy consumption, with the maximum recorded usage attaining 3.61 kWh during nocturnal winter excursions, contrasted with the minimal consumption observed at 1.86 kWh during diurnal summer journeys. This emphasizes the necessity of formulating energy management strategies, such as enhancing the efficiency of HVAC systems and deploying intelligent lighting technologies to mitigate energy losses.

4- The results showed that the high-voltage battery size, calculated from operational data, reached 44 kWh (400V), enabling it to provide 110 amperes for one hour, making it the primary power source in the electric vehicle. It directly impacts driving range, performance, and energy consumption efficiency. Additionally, the calculations indicated that the required low-voltage battery size for operating auxiliary systems is estimated at 0.35 kWh (12V), which provides 29.17 amperes for one hour, ensuring efficient operation of auxiliary devices without affecting the performance of the electric motor. This highlights the importance of effective energy distribution between both systems to optimize energy consumption and extend the vehicle's driving range.

Recommendations

1. Given that wind resistance significantly contributes to energy consumption, it is essential to develop electric vehicle designs with a lower drag coefficient to improve energy efficiency, particularly at high speeds.
2. The impact of low temperatures on energy consumption is critical, necessitating improvements in heating and cooling systems by employing more efficient technologies, such as recovering waste heat from internal vehicle operations.
3. To mitigate the effects of energy consumption on long trips, it is recommended to establish a fast-charging network in areas with challenging terrain and extreme climate conditions, ensuring the sustainability of electric vehicle operations.
4. The findings indicate that aggressive acceleration leads to a significant increase in energy consumption. Therefore, drivers should be educated on best practices for economic driving, such as avoiding sudden acceleration and maintaining a stable speed whenever possible.
5. To ensure improved performance of electric vehicles, efforts should focus on developing higher energy-density batteries with longer charging cycles, contributing to extended driving range and reducing reliance on frequent charging.
6. Increasing awareness of electric vehicles as a sustainable transportation option is crucial, along with enhancing government support policies to encourage their adoption. This includes tax exemptions and financial incentives for purchasing electric vehicles.

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