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**BAU 2024**

**T.C.  
BAHCESEHIR UNIVERSITY  
GRADUATE SCHOOL OF EDUCATION  
DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING**

**SUSTAINABILITY AND THERMODYNAMIC ASSESSMENTS OF  
SOLAR ASSISTED ELECTRICAL VEHICLES**

**MASTER'S THESIS**

**YOUNIS ALBAZZAZ**

**ISTANBUL 2024**

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## ABSTRACT

### SUSTAINABILITY AND THERMODYNAMIC ASSESSMENTS OF SOLAR-ASSISTED ELECTRICAL VEHICLES

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The need for renewable energy is driven by the urgent need to address climate change, improve air quality and public health, enhance energy security, create economic opportunities, and promote resource sustainability and technological innovation. Transitioning to renewable energy sources is a critical step toward a more sustainable and resilient future for current and future generations. Solar Assisted Electric vehicles (SAEVs) are a concept that combines Electric Vehicle (EV) technology with solar energy to enhance their efficiency and sustainability. However, it's essential to note that there are challenges and limitations to consider, such as the limited surface area available for solar panels on a vehicle, the variability of solar energy generation depending on weather conditions, and the initial cost of equipping vehicles with solar panels. Nevertheless, SAEVs have the potential to play a significant role in sustainable transportation. The proposed study's major purpose is to examine the sustainability and thermodynamic performances of Internal Combustion Engine Vehicle (ICEV), EV, and SAEV through a series of PVSOL and RetScreen Expert simulations. Also, MATLAB was used to perform the necessary calculations. According to the findings, switching from an ICEV to a SAEV results in up to 83.6% fuel consumption savings, about 62.5% reduction in greenhouse gas emissions, and 9.25 years payback period. In terms of societal impact, a vehicle powered by solar energy is preferable to the other two options discussed.

**Keywords:** Solar Vehicle, Solar Power, Renewable Energy, Partial Shading, Sustainability

## ÖZ

### SUSTAINABILITY AND THERMODYNAMICS ASSESSMENT OF SOLAR-ASSISTED ELECTRICAL VEHICLES

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Yenilenebilir enerjiye olan ihtiyaç, iklim değişikliğini ele alma, hava kalitesini ve halk sağlığını iyileştirme, enerji güvenliğini artırma, ekonomik fırsatlar yaratma ve kaynak sürdürülebilirliğini ve teknolojik yeniliği teşvik etme acil ihtiyacından kaynaklanmaktadır. Yenilenebilir enerji kaynaklarına geçiş, mevcut ve gelecek nesiller için daha sürdürülebilir ve dayanıklı bir geleceğe yönelik kritik bir adımdır. Güneş Destekli Elektrikli Araçlar (SAEV'ler), verimliliklerini ve sürdürülebilirliklerini artırmak için Elektrikli Araç (EV) teknolojisini güneş enerjisiyle birleştiren bir konsepttir. Bununla birlikte, bir araçtaki güneş panelleri için mevcut sınırlı yüzey alanı, hava koşullarına bağlı olarak güneş enerjisi üretiminin değişkenliği ve araçları güneş panelleriyle donatmanın ilk maliyeti gibi dikkate alınması gereken zorluklar ve sınırlamalar olduğunu unutmamak önemlidir. . Bununla birlikte SAEV'ler sürdürülebilir ulaşımda önemli bir rol oynama potansiyeline sahiptir. Önerilen çalışmanın ana amacı, İçten Yanmalı Motorlu Taşıt (ICEV), EV ve SAEV'nin sürdürülebilirliğini ve termodinamik performanslarını bir dizi PVSOL ve RetScreen Expert simülasyonu aracılığıyla incelemektir. Ayrıca gerekli hesaplamaların yapılabilmesi için MATLAB kullanılmıştır. Bulgulara göre ICEV'den SAEV'ye geçiş, yakıt tüketiminde %83,6'ya varan tasarruf, sera gazı emisyonlarında yaklaşık %62,5 azalma ve 9,25 yıllık iyi bir geri ödeme süresi sağlıyor. Toplumsal etki açısından güneş enerjisiyle çalışan bir araç, tartışılan diğer iki seçeneğe göre tercih edilebilir.

**Anahtar Kelimeler:** Güneş Enerjili Araç, Güneş Enerji, Kısmi Gölgeleme, Sürdürülebilirlik



To My Family  
*Thank You*

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## LIST OF ABBREVIATIONS

DC	Direct Current
AC	Alternating Current
EV	Electrical Vehicle
ICE(V)	Internal Combustion Engine (Vehicle)
SAEV	Solar Assisted Electrical Vehicle
PV	Photo Voltaic
EBD	Electric Brake-force Distribution
IPMSM	Interior Permanent Magnet Synchronous Motor
BTM	Battery Thermal Management
PCM	Pulse Code Modulation
ROA	Rider Optimization Algorithm
PID	Proportional Integral Derivative
BEV	Battery Electrical Vehicle
PIHV	Plug-in Hybrid Vehicle
HEV	Hybrid Electrical Vehicle
FCEV	Fuel Cell Electrical Vehicle
EREV	Extended Range Electrical Vehicle
NEV	Non-Electrical Vehicle
AV	Autonomous Vehicle
GHG	Greenhouse Gas
MPPT	Maximum Power Point Tracking
IAD	Incident Angle Distribution
TTW	Tank to Wheel
NEDO	New Energy and Industrial Technology Development Organization

PEC	Power Electronic Converter
SoC	State of Charge
SGTCS	Solar-powered Grid Tied Charging Station
O&M	Operating and Maintenance



## **Chapter 1**

### **Introduction**

#### **1.1 Theoretical Framework**

The three "E's" – Energy, Economy, and Environment – represent a critical and interconnected trio of factors that play a central role in shaping individuals, businesses, and governments' policies, practices, and decisions. Analyzing and balancing these three elements is essential for achieving sustainable development and addressing global challenges such as climate change. Balancing these three "E's" is often called the "triple bottom line" approach, which encourages organizations and policymakers to consider economic profit and social and environmental impacts when making decisions. This approach recognizes that long-term prosperity and well-being depend on the responsible management of energy resources, a sustainable economy, and environmental stewardship. Achieving a harmonious equilibrium among energy, economy, and environment is a complex challenge, but it's essential for a sustainable and prosperous future. Social impact is also an important factor used in an analysis and is considered one of the three main pillars of sustainability. It aims to foster community, equity, and well-being, ultimately contributing to a more sustainable and just world. Often, achieving social sustainability requires collaboration among governments, businesses, civil society, and individuals. In summary, 3E analysis is a holistic approach that considers energy, environment, and economics, intending to find sustainable and balanced solutions in the context of energy systems and policies. Thermodynamics analysis, on the other hand, is a more specialized field that focuses on the physical principles governing energy transformations and the efficiency of those transformations. While there may be some overlap in certain applications, they serve different purposes and address different aspects of energy and related systems. This research uses the 3Es and social analysis for the sustainability and thermodynamics assessments of the proposed cases.

## 1.2 Statement of the Problem

Nearly three-quarters of the direct global CO<sub>2</sub> emissions from fuel combustion are currently credited to the transportation sector, with internal combustion engine (ICE) powered road vehicles accounting for most of these emissions (Sierra Rodriguez, de Santana, MacGill, Ekins-Daukes, & Reinders, 2020). The transportation sector is also considered a sector with the highest amount of greenhouse gases contributing to global warming on a large scale (Fredy et al., 2020). Because of the unsustainable nature of fossil fuels and rising consciousness about environmental pollution, electric vehicles (EVs) have been developed in the transportation sector. Although EVs reduce the amount of CO<sub>2</sub> emission in the transportation sector, it has a limited effect on the zero-emission goals because the electrical energy supplying the vehicle is derived from fossil fuels that cause the atmosphere to be filled with greenhouse gases while burning. So, renewable energy should be used to power EVs directly by supplying the EV or indirectly by providing the EV charging units (NEDO PV-Powered Vehicle Strategy Committee Interim Report, 2018).

Among various renewable energy sources, more people are turning to solar energy because it is abundant in nature, accessible, environmentally friendly, and supports environmental sustainability (Padwad & Naidu, 2022). One of the primitive methods to harness solar energy for the EV is simply mounting the solar PV panels on the roof of the EV. The drawback of this method is the lack of the required area for placing sufficient solar panels to run the EV or even to power some small specified additional loads (Vu, Pham, & Shin, 2019). Those PV systems, on the other hand, have their own set of issues that might cause losses and lower power output (Pandey, Dung, Mishra, & Kumar, 2022). Integrating an EV and solar energy through curved solar panels or cells can thrive. Still, the main concern is the effect of the non-flat solar panels attached to the EV on the panels' energy capture capability, which is not the same case with flat solar panels (Tayagaki, Araki, Yamaguchi, & Sugaya, 2019). Therefore, a scientifically accurate model is required to predict the amount of captured solar irradiance by the solar cells integrated into the EV's curved surfaces and calculate the additional mileage that can be achieved (Ota, Masuda, Araki, & Yamaguchi, 2019). That meaningful model should also consider the

shading occurrence probability since the driver's convenience can affect the capturing efficiency by inadvertently subjecting the SAEV to obstacles.

### **1.3 Purpose of the Study**

This research will conduct sustainability (economy, environment, and social) and thermodynamic (energy) analyses for the SAEVs concerning traditional EVs and ICEVs using the key performance indicators after comprehensive research. The study will simulate and compare different scenarios with two cases each: the base case and the proposed one. Each scenario will consider the transition from the base case to the proposed case, noting that each case represents one type of the three suggested vehicle types: ICEV, EV, and SAEV. The research will show which scenario is more sustainable among the three and give an adequate idea about the output of a PV module attached to an EV by simulating a SAEV considering partial shading and curved roof issues. It will also show the parameters that affect the partial shading the most and reduce the efficiency of the harvested energy.

### **1.4 Hypotheses/Research Questions**

At the end of this research, the following questions will be discussed and answered:

1. Can the SAEV be modeled considering the curved surface of the vehicle roof and the partial shading issues?
2. Are SAEVs more sustainable than ICEVs and EVs when considering sustainability and thermodynamics?
3. Is it worth implementing solar technology into EVs to decrease power consumption from the utility grid?
4. Do the curved nature of the vehicle's roof and the partial shading issues significantly affect the vehicle-integrated solar cells' energy harvesting?

## 1.5 Significance of the Study

The Solar Impulse airplane successfully flew around the globe using only solar electricity in 2016, while a NEDO research and development effort achieved a conversion efficiency of 31% at the PV module level. These innovations showed that PV has a lot of promise to be a significant energy source in mobility applications with a small installation footprint (NEDO PV-Powered Vehicle Strategy Committee Interim Report, 2018). When designing Photovoltaic (PV) systems, partial shading is considered a severe problem and is avoided by considering all potential shadows cast by neighboring objects. However, partial shading happens often and unexpectedly, reducing the quantity of solar irradiation the solar module can gather. Even for efficient PV projects, partial shading cannot be totally avoided (Y. J. Wang & Sheu, 2015). For estimating the total amount of absorbed irradiance into a particular PV system, the shading impact should also be considered and predicted for the chosen geographical area using some roughness indicators, as the panels mounted on the EV won't have a fixed position or orientation (Araki, Ota, & Yamaguchi, 2020).

In this research, the simulated SAEV topology will consider the effect of fully and partially shading cases on generated energy considering highly efficient solar cells installed on the vehicle. The full-shading case is estimated using weather data, as the car will be simulated at different times of the year. Partial shading will also be considered using the PVSOL program to simulate a one-year scenario with varying obstacles around the vehicle. Also, the effect of the curved nature of the car roof on the solar cells integrated into the vehicle roof will be investigated using curved surface factors. After completing the modeling stages, the proposed case will be compared with other created cases in terms of sustainability and thermodynamic performance.

## 1.6 Definitions

1. **Partial shading:** In the context of solar panels or photovoltaic (PV) systems, partial shading refers to a condition where some sections of a solar panel or an array of panels are exposed to less sunlight or are partially blocked from direct sunlight. This partial shading can occur for various reasons, such as nearby buildings, trees, clouds, or even dirt or debris on the surface of the solar panels.
2. **RETScreen software:** a comprehensive and user-friendly software tool developed by Natural Resources Canada (NRCAN) to help individuals and organizations evaluate various projects' energy efficiency, renewable energy, and sustainability potential. The name "RETScreen" stands for "Renewable Energy Technology Screen."
3. **PVSOL:** a software tool used in solar energy and photovoltaics (PV). Valentin Software, a company specializing in renewable energy software solutions, developed and distributed it. PVSOL is primarily designed to design, simulate, and analyze solar photovoltaic systems.

## **Chapter 2**

### **Literature Review**

Investment in renewable energy has been greatly boosted by the rebound from the Covid-19 pandemic-related downturn and the response to the global energy crisis. When comparing the predictions for 2023 with the figures for 2021, it is clear that annual investment in clean energy has increased far more quickly than that of fossil fuels over this time (24% vs. 15%). In 2023, it is expected that around USD 2.8 trillion will be invested in the energy sector. Clean energy, which includes nuclear power, storage, grids, low-emission fuels, renewable energy, efficiency upgrades, end-use renewables, and electrification, will cost more than USD 1.7 trillion. The remaining sum, a little over 1 trillion USD, will be used to power and provide fossil fuels without interruption; of this, 15% will come from coal, and the remaining amounts from oil and gas. Today, 1.7 dollars are spent on clean energy for every 1 dollar spent on fossil fuels. This ratio stood at 1:1 five years ago (IEA, 2023).

The literature study is categorized into three distinct areas: the improvement of electric vehicles (EVs) and the modeling of EVs. In the meantime, the sustainability (economy, environment, and social) and thermodynamic (energy) analyses used in the literature are also studied. The subsequent chapters provide comprehensive information.

#### **2.1 Enhancement of EVs**

Electric vehicles (EVs) are typically powered by electricity instead of traditional ICEVs that run on gasoline or diesel. Their popularity is rising due to their potential to reduce greenhouse gas emissions, dependence on fossil fuels, and air pollution. Continuous research is being done to enhance the vehicles' efficiency by minimizing vehicle losses or adding range extenders to decrease the dependency on electricity while maintaining the same efficiency. The ongoing enhancement of EVs is crucial for

accelerating their adoption and realizing their many benefits, including reduced emissions of greenhouse gases, increased air quality, and energy efficiency. Enhancing the energy efficiency of EVs can expand their range and reduce operating costs by optimizing the drivetrain, regenerative braking, and reducing vehicle weight (Sanguesa, Torres-Sanz, Garrido, Martinez, & Marquez-Barja, 2021).

**2.1.1 Efficiency enhancements.** The ability of an electric car to brake is one of its most crucial functional features. An automobile's three essential performance safety indications are vehicle stability during braking, braking stopping distance, and braking acceleration. The kinetic energy of the vehicle must be diminished while braking. The main goal of electric vehicles is to regenerate as much kinetic energy as possible during braking and store it in the battery. Implementing the best braking strategy requires understanding the highest feasible brake acceleration, the ideal battery charge working range, and the maximum potential battery charging rate. As a result, it's essential to choose a suitable model while creating a solid approach (Hosseini Salari, Mirzaeinejad, & Fooladi Mahani, 2023).

The vehicle's five degrees of freedom and electrical energy cycle model were initially presented to design a braking strategy for an electric car within wheel motor technology by Hosseini Salari et al. (2023). The state space equations for creating a brake torque controller were then provided. The ability of the Electric-Brake-force Distribution (EBD) performance of the braking system to compensate was used in a novel way to assign more brake torque to the regenerative brake. The performance index for the front and rear wheels was introduced concerning the restrictions impacting regenerative braking to construct nonlinear model predictive controllers. The performance index assigned the EBD's possibly compensable capacity to the regenerative brake to create a fail-safe solution. The performance index was adjusted using the weight adjustment approach to consider the current situation. Utilizing the plan and creating a control system during a complicated braking maneuver and a routine driving cycle improved the vehicle's safety and energy usage. The application of this technique in electric vehicles with in-wheel motors is made more accessible by optimizing the problem solution, which provides a straightforward algebraic function relating to the restrictions. The outcomes of the

proposed model revealed a reduction in stopping distance under hard braking of roughly one meter and an increase in vehicle mileage of 24%.

Another strategy for increasing and enhancing electric vehicle efficiency was proposed by Ding et al. (2017). Unlike Hosseini Salari et al. (2023), who focused on regenerative braking, (Ding et al.) focused on increasing the inverter-motor's total efficiency since the primary source of propulsion for electric vehicles is the inverter-motor drive system. For an interior permanent magnet synchronous motor (IPMSM) traction system in electric vehicles, a novel efficiency improvement control has been put forth based on loss models and gold section search. In loss model control, the loss models of the IPMSM and the inverter are considered, meaning that the traction system's total efficiency may be improved. The system's efficiency is increased by adopting a gold section search, which searches the ideal variable in tiny steps. To verify the suggested procedure, experiments are carried out. The experimental results demonstrated that the proposed methodology increases the efficiency of both the motor and the inverter, resulting in more efficient operation of the entire traction system. The overall efficiency can increase by a maximum of 2.7%. The experiments also showed that the traction system can run at all times with high efficiency, which makes it ideal for electric cars with varied speeds and loads. Further research was done on how the proposed efficiency increase methodology would affect fuel economy, battery capacity, and cruise time. The cruising time may be increased at the same battery capacity condition if fuel and battery capacity are similar. The suggested approach might also easily be expanded into other industrial applications.

On the other hand, Mohammed, Elfeky, and Wang (2022) focused on the battery charging and discharging losses that are affected by temperature because the performance of a power battery, particularly the temperature-sensitive lithium-ion (Li-ion) battery, is what determines how well EVs work. A summary of active and passive battery thermal management (BTM) performance is provided. Additionally developed and studied is the thermal performance of large-format prismatic Li-ion batteries operating in harsh environments. In the created model, passive thermal management is considered. The

traditional BTMs (natural/forced air and liquid) add complexity and costs while being insufficient in temperature consistency, especially at high discharge rates. Thermal management based on heat pipes is easier and more effective than active BTMs. The pulse code modulation (PCM) based BTMs reduce the need for additional power-consuming components while offering a quick temperature response. Another complementary cooling system is needed to get the battery to work as desired. Compared to passive or active thermal management, hybrid BTMs displayed superior thermal performance. However, the hybrid BTMs should be given more excellent thought regarding weight, power use, and economic evaluation. The work presented by (Mohammed et al.) showed that the battery module's use of an aluminum sheet improved temperature uniformity and reduced the maximum temperature rise. The temperature drops as the aluminum sheet's thickness increases. Production guidelines and standards should be appropriately adhered to avoid overburdening the system. Their future study will concentrate on the aspects currently absent from the cost analysis and evaluation of the EVs' BTM.

Away from regenerative braking, inverter-motor, and charging-discharging losses, Ali Faris, Ibrahim, Mohamad wasel, Abdulwahid, and Mosleh (2021) focused on the controlling algorithm of the electric vehicle charging system and how to enhance its efficiency by providing better response time. They used MATLAB-SIMULINK simulation to test their proposed algorithm. The Rider Optimization Algorithm (ROA) has improved the control of the steering control system for the electric golf cart system. Additionally, the traditional proportional–integral–derivative (PID) controller has been used, where the data acquired through ROA are used to estimate the PID parameters. The findings of this study demonstrated an improvement in the transient response with the charge control system, with parameter values for the Maximum overshooting, increasing time, peak time, and settling time of 0%, 0.0341, 0.7, and 0.1188 seconds, respectively. When compared to similar data obtained in the same way, these results revealed a significant improvement.

For plug-in electric vehicles (PEVs) that use both grid and solar PV sources, a novel power electronic converter (PEC) has been created by Singh, Badoni, and Tatte (2020).

The proposed PEC can function for all vehicle propulsion, regenerative braking, and charging modes. The grid and solar PV system are used to accomplish the vehicle charging. When charged, the planned PEC is used as both isolated and non-isolated single-ended primary-inductor converter depending on the vehicle charging status, whether it is charging from the grid or the solar PV system. While doing so, it functions as a typical boost converter and buck converter, respectively, in the propulsion and regenerative braking modes. With an 800 W charging power and 48 V battery, computer simulation and prototype models were used by (Singh et al.) to validate the modes of the proposed system. The total system offered a dependable and effective solution for the battery charging system for electric vehicles and may be a potential option for later-generation electric cars.

**2.1.2 Range extenders.** EV range extenders are auxiliary power sources or technologies designed to increase the driving range of electric vehicles beyond the capacity of their main battery pack. Range extenders can be a practical solution for addressing "range anxiety" in electric vehicles, as they provide a safety net for longer journeys or when charging infrastructure is limited. However, they also add complexity, cost, and weight to the vehicle. The choice of a range extender depends on factors like the vehicle's intended use, driving habits, and environmental considerations.

As one of the range extenders, a novel trailer-based intelligent fuel cell range extender has been suggested by Wu, Ren, Davies, Shang, and Haas (2019). Based on a review of the present problems and solutions relating to the range constraints experienced by Battery Electric vehicles (BEVs), the solution's applicability, efficacy, and efficiency have been supported. For attaining ranges between 250 and 350 km, the proposed 1.8 kg fuel cell tank can increase the capacity of small and big BEVs by more than 50% and 25%, respectively. The trailer-based demountable design presented by (Wu et al.) boosts refueling station use effectively by centralizing refueling and decreasing reliance on charging infrastructure. Battery pack sizes for BEVs can be reduced thanks to the flexibility to add range extension as needed, which eases the burden on raw materials and eliminates the need for recycling. Unlike building for the highest predicted range, constructing a BEV for the most frequent trips lowers overall costs and improves BEV

efficiency. Due to the option to hire this range extender for sporadic long-distance trips, it expands usability. It can be beneficial to maintain battery health and reduce the harmful effects of adverse external environmental conditions to recharge or keep the battery charge within cautious State of Charge (SoC) limits. The suggested strategy by (Wu et al.) can assist Fuel Cell Electric Vehicles (FCEVs) in addition to the advantages described for BEVs. It can simplify infrastructure construction, hydrogen production, distribution, and cost reduction in the short term. This ingenious fuel cell range extender could aid in the development of BEVs and FCEVs to close the gap between current and future automotive industry demands for zero Tank-To-Wheel (TTW) emissions.

As an idea for another range extender, Friedl et al. (2018) proposed that the use of a range extender powered by an ICE could be one of these alternatives. (Friedl et al.) discussed adding an ICE to the EV as a range extender and compared it among single-piston, 2-piston, and rotary-type engine range extenders. Regarding single-piston engines, (Friedl et al.) showed that it is feasible to combine pre-existing engine parts from other applications, such as motorcycles, to enhance the component volumes and create a plan that is as cost-effective as possible. This plan lowers the quantity of necessary research work and the expense of purchasing new production facilities. Therefore, using the most basic ICE layout, which is still a single-cylinder engine, would be one of the more appealing options for range extenders. The goal is to use motorcycle or power-product parts in the community to a large extent to use automotive range extenders. For the 2-piston engine configuration as a range extender, it was shown that it has more advantages like the possibility of straightforward and adequate mass balancing, Access to donor engine parts (mainly from bikes), Proven technology, established production options for critical components, and good size/power ratio. Lastly, (Friedl et al.) showed that the automated auxiliary power supply unit provides the most significant combustion engine and generator integration for electric vehicles. This is why the rotary engine type was selected for research, and it was possible to increase the potential power from 15 kW (electric) at 5000 rpm to 25 kW at 7000 rpm.

The market penetration of EVs is constrained by several factors, including the scarcity of charging infrastructure, the lengthy charging time, the high cost of long-range EVs, and the constrained range of more economical EVs. Consumers frequently put these problems under the umbrella term "range anxiety." Range extenders, gadgets that supply the car with additional energy to supplement the primary battery, are one remedy for the range anxiety problem. The ICE, free-piston linear generator, fuel cell, micro gas turbine, and zinc-air battery were five significant range extenders described and discussed in a study by Tran et al. (2021). The exhaustive review included each technology's fundamental definitions, functioning principles, benefits, and drawbacks and briefly compared them. Additionally, each range extender's most recent research discoveries and developments were addressed. (Tran et al.) concluded that each of the mentioned five range extenders has advantages and disadvantages. Each range-extending technique has a distinct benefit, but more research and development are still needed to solve the drawbacks. The efficiency of the ICE range extender needs to be increased, and the emissions decreased. Priority one for fuel cell range extenders is their high price and shortage of fuel infrastructure. Microgas turbines must speed up startup and boost efficiency. Before becoming commercialized, Zn-air battery range extenders need more development.

Puma-Benavides, Izquierdo-Reyes, Calderon-Najera, and Ramirez-Mendoza (2021) analyzed the most recent innovations in design, control, optimization, and methodologies for Extended Range Electric Vehicles (EREVs), including the architecture, significant components and their interactions, component sizing, and ways to determine the best system-level design. They showed that although there appear to be many layouts at first glance, the most widely used one has an electric motor in the middle. However, an in-wheel engine is customary if the vehicle has excellent performance. The critical factor to consider is the cost of deploying the technology to recover energy and improve autonomy. Some technologies are less expensive and simpler to manage. Every technology discussed by (Puma-Benavides et al.) benefits electric automobiles. Each researcher or research facility can implement and conduct tests to confirm and optimize the application of the chosen technologies based on the financial resources at their

disposal. The combustion engine is now the most popular technology for enhancing autonomy. Because of this, most researchers work to lower the amount of fuel ICEs use to boost energy effectiveness and recover energy. Optimization methods will depend on the extent of the research but often entail determining the most effective configuration of all components, thereby resolving various design optimization layers, according to (Puma-Benavides et al.) literature analysis. These could also be utilized in more thorough coordination techniques considering technology and topology selection. Depending on the technologies used, (Puma-Benavides et al.) have provided a roadmap for identifying key elements and how they interact to develop a new architecture and optimize every level. The insertion of approximations of the original problem should abbreviate the driving cycle utilized for design, or one should use parallel computing to minimize the computational burden significantly. Short, realistic, and representative driving cycles should be used as input for the control (energy management technique) or any simulation. In some circumstances, a customized driving cycle is required to examine the extended-range electric vehicle's behavior concerning energy consumption, range, and emissions. How to deal with numerous topologies with a wide range in terms of component kinds and amounts in a more natural way is a topic that still needs to be solved. Additionally, optimization issues and dynamically generated topologies encourage the creation of control algorithms that can automatically manage different topologies. To tackle the design issue at the system level and identify a competitive EREV configuration for the market, optimization objectives can be defined to incorporate fuel, cost, emissions, and performance elements.

Focusing on extending an EV range by using solar energy, Abdelhamid, Pilla, Singh, Haque, and Filipi (2016) discussed the financial and energy effects of using a solar PV system as an on-board auxiliary power source for plug-in electric vehicles (EVs) intended for propulsion. The suggested solution can boost EV energy efficiency while lessening its environmental effect by offering a variable energy source for charging that doesn't require additional energy storage or infrastructure. For plug-in EV applications, a thorough on-board PV system model was created and optimized for a solar energy-to-DC electrical power ratio. The PV device, the location of the sun, thermal and electrical

performances, the maximum power point track (MPPT) algorithm, energy storage, tilt option, angling on the vehicle surface, and mounting configuration options were among the many design elements that were examined in this model. When not in usage, this suggested system converts into a flexible energy-producing system that can be fed into the grid and used to power electrical appliances in residences and workplaces. The outcomes of this dynamic model may be used to calculate the on-board PV contribution for any size vehicle and can take into account different PV module kinds, areas, efficiency, installation sites, timings, and weather. The findings of their study have great potential for the global application of on-board photovoltaics in electric vehicles (EVs) to increase daily driving range and improve economic value, as no additional infrastructure is required. However, this system's potential is greater in areas with high electricity prices and sunshine. To establish the commercial viability of this proposed system, more work is needed to broaden its implementation for a particular vehicle under a particular situation. (Abdelhamid et al.) applied their model to 5 different EVs but didn't focus on comparing them with traditional ICEVs. Also, they didn't simulate a partial shading model with different obstacle probabilities. To fill this gap, this research makes a comparison among the simulated SAEV, ICEV, and EV. Also, a simulated model for partial shading was made and imported to the SAEV.

## **2.2 Modeling of SAEVs**

An inventive strategy for using renewable energy to power electric vehicles (EVs) is to model a solar-assisted electric vehicle (SAEV). This idea combines conventional electric vehicle technology with solar panels to lessen reliance on electrical power and boost transportation sustainability. Considering technical, environmental, economic, and user-centric factors requires a multidisciplinary approach when modeling a solar-assisted electric vehicle. As technology develops, SAEVs present a viable path to cleaner, more sustainable transportation solutions. Accurate modeling is crucial for optimizing these cutting-edge vehicles' design and performance.

**2.2.1 Modeling and construction.** Studies and research have been conducted to find the most efficient sun energy harvesting in the transportation sector, specifically passenger automobiles. This can be accomplished by designing brand-new solar-powered vehicles or improving existing electric cars to use solar power as an additional energy source. First, engineers and scientists need a precise model to determine how much solar irradiance the vehicle surfaces can absorb and how to increase capturing efficiency. The next step is to study the factors that influence and deplete the energy captured and work to reduce them while preserving the vehicle's efficiency. From there, plans can be developed for a practical electric vehicle that uses solar energy the most.

A simple solar vehicle was modeled by Oosthuizen, van Wyk, and Hamam (2017) and was named Sun Chaser 2, considered an upgrade to Sun Chaser 1, developed earlier. Sun Chaser 2 was constructed based on a mathematical model that considers the parameters, or forces, that might impact the vehicle's performance. The built car had a mass of only 330 kg and an area of 6 m<sup>2</sup> having 24% solar cell efficiency. The battery, from which the motor and auxiliary devices drew their power, was directly charged by the solar energy captured by the solar cells. The vehicle's performance was monitored in different driving patterns and across various terrains for eight days. The car had almost 702 W rated solar cells as input power and achieved an average distance of 246 km using 80% of the charged battery with an average speed of up to 50 km/h. The PV cells area was large and flat because the vehicle had a unique design that accommodates just one passenger and differs significantly from typical passenger automobiles available in the transportation sector. This is why (Oosthuizen et al.) did not raise the surface's curvature. Additionally, no shading patterns were considered, and mostly sunny days were used for the case study.

Another solar vehicle was modeled by Cabrane, Ouassaid, and Maaroufi (2017) without being constructed. In this vehicle, the solar cells can directly supply the DC voltage bus, providing the motor and the auxiliaries to run the vehicle. As Oosthuizen et al. (2017) did, the car was designed based on mathematical equations that consider the forces influencing the vehicle's performance. The primary goal of (Cabrane et al.) was to improve the vehicle's performance by using two supercapacitors in the design. These

capacitors, parallelly connected to the DC voltage bus, will enhance the system's stability by mitigating the impact of peak battery currents and extending battery life. The complete vehicle was simulated, and the findings showed that the power efficiency was higher than it would have been without supercapacitors.

Another study area focused on enhancing the current generation of electric vehicles used in transportation by adding solar cells. Before such an enhancement can be made, a comprehensive analysis should be conducted to understand how much energy would be generated or how many extra kilometers would be added by the installed solar cells. Masuda et al. (2016) investigated the possibility and advantages of utilizing a plug-in hybrid vehicle (PIHV) with solar panels. (Masuda et al.) relied in their model on adding solar modules to a test passenger car (test Prius) and monitoring its performance for 100 days, in contrast to Oosthuizen et al. (2017), who constructed their one-passenger unique vehicle. This time, the car weighed 1410 kg and was a typical passenger car. 800W solar panels were installed horizontally on the vehicle's roof, hatch, and engine hood, and vertically on the side doors. Also, a small mobile pyranometer was mounted on the vehicle to measure solar irradiance. An average power of 1.8 kWh/day was obtained, corresponding to 18.4 km of extra distance from the attached solar cells at an 8.8 km/kWh rate. (Masuda et al.) didn't emphasize the significance of the vehicle's curved construction. They didn't suggest or employ shading models with the outcomes as with (Oosthuizen et al.).

**2.2.2 Curved surface correction factor for solar energy harvesting.** The curved correction factor for PV panels is crucial in solar energy systems, especially when dealing with curved or nonplanar surfaces. Unlike traditional flat PV panels, curved surfaces can capture sunlight from multiple angles throughout the day, enhancing energy production. However, determining the precise correction factor is essential to calculate the energy yield. This correction factor accounts for variations in incident angles, reflection, and shading effects due to the curved design, ensuring that the estimated energy output aligns with real-world performance. By accounting for these factors, solar energy system designers can optimize the efficiency of curved PV panels and make informed decisions about their deployment in various applications, including solar-powered vehicles, building-integrated photovoltaics, and other innovative solar installations.

Ota, Masuda, Araki, and Yamaguchi (2018) investigated the impact of the curved surface of the electric vehicle when the solar cells are integrated into the vehicle and not just mounted horizontally or vertically on it, in contrast to Cabrane et al. (2017), Masuda et al. (2016), and Oosthuizen et al. (2017) that either presented and analyzed unique designs of solar vehicles or just analyzed attaching solar panels to electric cars. (Ota et al.) introduced a new unitless correction factor that can model the power generation of a curved solar cell module concerning typical flat solar panels. That correction factor can help analyze and model the 3-dimensional curved surface as 2-dimensional. The factor can be calculated using ray tracing simulation based on each surface's parameters. The ray tracing simulation generates a ratio of the absorbed to the projected flux that can help compute the correction factor for that specifically chosen surface. Also, the annual solar irradiance projected to a vehicle was measured using an array system of mobile pyranometers attached to the vehicle for 1 year. Over a year, various vehicle irradiance levels were recorded under different weather conditions. As a result, it was demonstrated that the curve correction factor of vehicles roofs could often vary between 0.70 and 0.90 by utilizing various surface parameters. The 1-year case study of solar irradiance using the pyranometer array showed that most solar-assisted vehicles could have a solar irradiance range from 2.53 to 3.52 kWh·m<sup>-2</sup>/day. The curve correction factor provided an estimate of the solar irradiance capture of any curved surface that is a simple convex while

ignoring any light being absorbed in the backside of the cells. Based on that factor, Tayagaki et al. (2019) showed the impacts of nonplanar panels on solar power generation for solar-assisted electric vehicles. They investigated the effect of the curved structure of the roof on the power generation of solar cells integrated into the vehicle compared to conventional flat solar panels. (Tayagaki et al.) calculated the irradiance being captured for the roof and sides of a vehicle. They tilted the vehicle's surfaces using a model that depends on the solar radiation's Incident Angle Distribution (IAD) and the estimated absorbed irradiance to the curved surface. The flux absorbance ratio into the vehicle's different surfaces was calculated using the geometrical model instead of ray tracing simulations. Their results showed that the curve correction factor, presented by Ota et al. (2018), can be an excellent tool to model and estimate the solar power generation of solar-assisted electric vehicles with solar-cells-incorporated surfaces and tilt angles less than  $40^\circ$ . Although it has been demonstrated that the curve correction factor is a valuable tool, there are other ways to determine how much a given surface absorbs solar irradiance. Mobarak, Kleiman, and Bauman (2021) presented a mathematical model for estimating energy capture of the tilted solar cells carved into the vehicle's metal. The generated energy will be supplied to the DC voltage bus of the electric vehicle through a voltage booster. Their method was based on calculating the projection cosine loss of the inclined surfaces by using spherical coordinates for the related angles. Then, the cosine loss was averaged over all panel rotation angles since the panel rotation angle couldn't be predicted for a vehicle. (Mobarak et al.) didn't use any curve correction factor as many other researchers did; instead, they used an energy capture mathematical model, which depends on the projection cosine, the latitude, and the air mass by taking Chevrolet Bolt's inclined surfaces as an example. Their model was based only on the direct irradiance component of the sun.

**2.2.3 Partial shading issue for SAEVs.** Partial shading in PV panels refers to a situation where some portions of a solar panel array are exposed to less sunlight or are partially shaded by objects such as trees, buildings, or debris. This phenomenon can significantly impact the efficiency and performance of the solar panel system. When a PV panel is partially shaded, it creates what is known as "hotspots" on the shaded cells. These hotspots can lead to voltage and current imbalances within the panel, potentially causing damage to the cells and reducing the overall energy production of the system. Modern PV systems often incorporate bypass diodes MPPT technology to mitigate the effects of partial shading. These solutions help optimize power output by allowing unaffected panels to continue generating electricity efficiently, ensuring that even under less-than-ideal conditions, solar energy production remains as reliable as possible.

A partial shading model was also developed by Mobarak et al. (2021), assuming the obstacles would interrupt the energy capture for some time each day. By taking a certain obstacle height and using zenith angle values, the model calculated the zenith angles during which the vehicle would not face any shading during the day. They simulated the impact of panel tilt and partial shade on the solar energy collection of 150 drivers in Los Angeles and Detroit over a year to examine grid, driver, and environmental advantages. A partial shading pattern was used that in each 60-minute hour, 40 minutes are considered an interval of partial shading divided into two 20-minute periods and 20 minutes of no-obstacles during the day. Also, cell temperature and configuration effect on the captured energy were discussed, and some models were presented. Based on meteorological data of Los Angeles and Detroit and the proposed partial shading pattern, (Mobarak et al.) showed that the energy capture decreased the worst in January, which was 33%, and decreased the least in July, which was only 13.7 %.

Integrating a technique for calculating captured solar irradiance with a stable shading model will give a better analysis of the solar-assisted electric vehicle solar energy acquisition. So, Araki et al. (2020) presented a mathematical model that can calculate the received irradiance into the surface of the electrical vehicle supported with solar cells while considering the effect of partial shading. The model depends on meteorological data

and the probability of partial shading occurrence using uniformly distributed objects and random driving orientation. In this model, (Araki et al.) should have paid attention to the diffused and scattered components of the solar irradiance as Mobarak et al. (2021) did. (Araki et al.) also presented the partial shading model used in the mathematical equations, developed using Monte Carlo simulations that depended on grazing angle. The Monte Carlo simulation turned on the random values of several variables like the number of days in a year, the time of the day, the number of cells partially shaded, the number of cells fully shaded, the shading ratio of each partially shaded cell, car orientation, short circuit current of each cell, open circuit voltage of each cell, and diode ideality. The grazing angle shows the density of the obstacles around the vehicle assuming the obstacles are randomly distributed and have random heights. The generated power from the solar cells was calculated using the curve correction factor presented by Ota et al. (2018) using ray tracing simulation to find the flux absorbance ratio. The total absorbed irradiance into the roof and sides of the vehicle for many cases as well as the proposed model was validated by the one-year case study made by (Ota et al.) that used an array of attached pyranometers to a vehicle during a year.

To assess the PV performance of PV-integrated buildings under various partial shading conditions, different modeling approaches of a PV system integrated into a shading device, including detailed models and a model introducing some simplification, have been developed by Piccoli, Dama, Dolara, and Leva (2019). I-V curve and cell temperature are both modeled. The detailed electrical model solves the equations resulting from their connections to determine the module's I-V characteristic after analytically describing each cell's I-V characteristic using a five-parameter approach and of the bypass diodes. The simplified model uses the same methodology as the detailed model for a single cell but simplifies the computations involved in determining the PV generator's I-V characteristic and Maximum Power Point (MPP). Along with the electrical model, a specific dynamic thermal model has been developed for predicting the temperature of the cells under partial shading conditions, including cell dissipation due to severe mismatch conditions. Between March and October 2018, a measurement campaign was conducted by (Piccoli et al.) to compare and validate the detailed and simplified models. The

proposed detailed optical-thermal-electrical PV model has been proven to be an effective tool for examining the effects of PV system integration in buildings. It enables designers to assess the system regarding both electrical and thermal effects (such as power losses and hot spots). The evaluation of simplified models can also be done using the detailed model. The simplified model produced results comparable to the detailed model while requiring less computational work, making it a valuable tool to be included in long-term simulations (i.e., creating simulations for early performance evaluation).

### **2.3 Sustainability and Thermodynamic Analyses**

Regarding energy and environment analysis of EVs and SAEVs, Michaelides (2020) made a study that showed that EVs' well-to-wheel efficiency is on par with those of cars with ICEs. The study revealed that the efficiency of EVs, from the production of energy to its use in the vehicle, is comparable to that of automobiles with ICEs. Their research also demonstrated that transitioning from ICEV to EV results in a net decrease in carbon dioxide emissions, particularly when a significant proportion of the electricity is generated from noncarbon sources. Conversely, transitioning to EVs might lead to increased carbon dioxide emissions in countries where a substantial amount of electricity is generated from coal combustion. The current circumstances have demonstrated a global average of 16.24% in terms of carbon dioxide avoidance. Furthermore, major cities with limited land lack the necessary high PV panel regions for solar-powered EV charging. Charging a large number of EVs during the day might potentially disrupt the power grid and lead to blackouts, given the current electricity demand patterns. However, several countries already possess sufficient surplus electricity producing capacity during nighttime to accommodate the charging of many EVs. In order to shift a substantial proportion of the existing vehicle fleet to EVs, it would be imperative to implement additional regulations, incentives to encourage charging during non-peak periods, and optimization measures.

In China, the economic performance of distributed solar PV with EV-reused batteries as energy storage devices is being examined at the provincial level. Bai, Xiong, Song, and Xiaoming (2019) had a thorough grasp of the present financial performance

of distributed solar PV in China before they could look into the viability and prospective applications of recycled EV batteries as energy storage systems for PV. The primary metric used to assess the province-level economy's success is net present value (NPV). The findings demonstrated that, given the existing circumstances, each province's or municipality's PV economic performance is quite appealing, with the commercial and industrial sectors outperforming the residential sector. The commercial and industrial sectors can continue to be lucrative even in the absence of subsidies, although the majority of residential areas can only achieve positive NPV after self-consumption reaches 60%. Additionally, a study is done on the economic feasibility of using recycled batteries as a source of energy storage. Reused batteries play a more significant role as an energy storage device in locations where solar energy is limited, and their financial advantages are readily apparent. In addition, Bai et al. propose certain policy recommendations derived from their findings. Initially, the government can distinguish between the subsidies. Additional reductions in subsidies for the commercial and industrial sectors are feasible since distributed solar PV projects can remain financially viable even in the absence of such support. Furthermore, it is imperative to promote the utilization of repurposed batteries as means of storing energy. The utilization of reused batteries as energy storage devices is already viable in certain areas, therefore indicating the potential for widespread implementation that may subsequently lead to a reduction in the cost of reused batteries. Furthermore, the province-level study acts as a directive for provincial governments in formulating local PV subsidy programs. Additional municipal subsidies are necessary to support development in areas where the economic viability of PV installations is less attractive.

Shrivastava, Alam, and Asghar (2019) in India have successfully developed a cost-effective and reliable method for charging an EV using a solar panel. This advancement has resulted in improved driving range and overall system dependability. A prototype of a vehicle-integrated PV charging system was developed to verify its performance, and the test results were presented. The annual mean solar irradiance profile in Aligarh, India, is utilized for economic research purposes. In addition, Shrivastava et al. (2019) conducted a study comparing the carbon dioxide emissions of EVs charged using

different charging methods with those of ICEVs, specifically for a driving range of 100 km. The cumulative energy conservation achieved by the VIPV charging system throughout its operational lifespan was determined to be 5475 kWh. Consequently, the strain on the electrical generation system is diminished. The VIPV charging system achieves a reduction of 0.92 kg of carbon dioxide emissions per 100 km driven by a PEV, in comparison to a PV-grid charging station. When considering solely the incremental daily earnings resulting from the implementation of the prototype VIPV charging system, the payback period is 108 days. The solar carport and rooftop charging station have a carbon-neutral operation, emitting zero carbon dioxide, and achieve a total energy savings of 48,180 kWh throughout their entire lifespan.

Ullah et al. (2023) offer a solar-powered grid-tied charging station (SGTCS) that optimizes EV charging by permitting the scheduling technique that results in maximum PV power consumption. The suggested model also identifies and takes into account the seasonal variations in power generation and EV charging connectivity. The SGTCS is implemented using HOMER Grid software, and a case study of a practical locality in Islamabad was explored; the full analysis performed includes annual cost estimation, energy prices, EV scheduling, main grid power demand reduction, and the impact of environmental changes. A brief scheduling approach of 250 sessions per day is explored when examining the integration of small and large EVs in the grid-tied solar-integrated charging system. For the energy analysis, they found out that the planned grid-connected PV-based highway charging station offers electricity for 0.05161 \$/kWh, which is significantly less than the grid's cost. To meet the load requirement, just 34.5% of the electricity is pulled from the grid. Regarding environmental analysis, it has been demonstrated that the planned EV charging infrastructure saves carbon emissions by 1,752,305 kWh per year.

## Chapter 3

### Methodology

Fossil fuels provided 80.3% of the world's primary energy supply as of 2019. These sources, however, are unsustainable due to their significant greenhouse gas emissions (REN21, 2021). Based on current confirmed reserves and production rates, fossil fuel's lifespan is limited (BP, 2021a, 2021b). In light of this complicated situation, there is hope for the future thanks to the rise of a new clean energy economy driven by solar PV and EVs. Since 2020, investments in clean energy have increased by 40%. One of the main, though not exclusive, causes is the drive to reduce emissions. Well-developed sustainable energy technologies have a compelling economic case. Along with industrial plans and the goal of creating jobs in clean energy, energy security is also a crucial consideration, especially for nations that import fuel. There are clear signs of an accelerated rate of change, even if not all clean technologies are prospering and some supply chains—most notably those for wind—are under strain. In 2020, one in every 25 cars sold was an electric vehicle; by 2023, only one in five was. In 2023, a record-breaking 500 gigawatts (GW) of new renewable energy-producing capacity are expected to be added. Every day, more than \$1 billion is spent on solar energy deployment. The ability to manufacture essential parts of a clean energy system, such as solar PV modules and EV batteries, is growing quickly. Because of this momentum, the IEA recently decided in its updated Net Zero Roadmap that there is still hope for reducing global warming to 1.5 °C, even though it is extremely challenging (IEA, 2023). EVs have the potential to significantly reduce society's reliance on fossil fuels, as well as greenhouse gas emissions and regulated emissions that cause local air pollution and adverse health effects compared to conventional ICEVs (Mobarak et al., 2021). The EV's energy storage unit can supply the electricity needed to power the vehicle loads, but It doesn't have enough energy to give the intended operating range' As a result, the range extenders in use are meant to deliver the extra energy needed to give the loads more endurance (Aharon & Kuperman, 2011). Solar arrays are, by far, the most practical range extender equipped with road vehicles, vehicles without pilots, and rickshaws. As mentioned earlier in the problem statement in

chapter 1, any modeling of an SAEV should cover two main issues: the curved structure of the roof's effect on the energy harvesting of the vehicle and the partial shading of the vehicle roof due to the surrounding obstacles. Each of these two issues should have its simulation, chosen parameters, and variables. The vehicle types in each scenario were selected to show the main advantages of transitioning from the normal ICEV to the EV and from the EV to solar-energy-integrated EV. This chapter will include the vehicle selection procedures, in which it is shown how and why each vehicle type is selected, the partial shading and curved roof modeling, the final amount of harvested energy calculation for the modeled SAEV, and the indicators used to compare the three vehicle types in the sustainability (economy, environment and social) and thermodynamic (energy) analyses.

### **3.1 Research Design**

**3.1.1 Vehicle selection procedures.** Greenhouse gas (GHG) emissions and global warming harm the environment and economy and significantly impact human health. Carbon emissions are anticipated to rise considerably unless viable mitigating measures are implemented (IEA, 2021; Ramli, Muis, Ho, Idris, & Mohtar, 2019). Transportation is the most reliant on fossil fuels, accounting for 37% of total end-use carbon dioxide emissions (Energy Agency, 2021). In 2016, gasoline and diesel cars comprised 97% of the EU's current fleet and 91% of new vehicles in the Netherlands in 2018 (Hulshof & Mulder, 2020). The ICEV is one example of a car that uses fossil fuels and harms the environment and human health. Figure 1 depicts the simple ICEV structure, which includes a fuel tank from which the engine receives the necessary energy for combustion. The essential power for vehicle movement is created due to the combustion process in the engine. This power is delivered from the engine to the wheels via mechanical transmission, with energy flowing in just one way (Jain & Kumar, 2017). For the previously noted concerns regarding the environmental implications of ICEVs and the crucial role ICEVs play in the transportation sector, the first vehicle category considered in this study is regular ICEVs that utilize gasoline as the vehicle's only energy source. The vehicle type chosen is a Toyota Corolla 1.8 autonomous vehicle (AV).

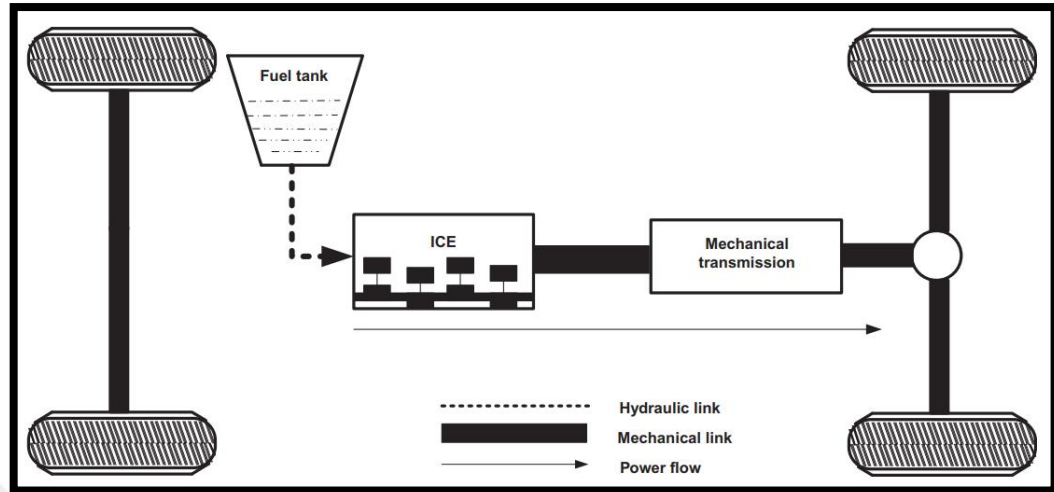


Figure 1. ICEV topology (Jain and Kumar, 2017))

The transition from ICE to alternative drivetrain technologies, such as EVs, is expected to reduce fossil fuel use and environmental implications (Hulshof & Mulder, 2020). The designations made by automakers have led to the mass production of electric vehicles. Due to the depletion of non-renewable resources, many nations, including the U.S., Germany, and France, have committed to reducing the use of gasoline and diesel cars and increasing the use of electric vehicles (Mohammadi, 2018). EVs are becoming more popular because of various causes, including lower prices and growing climate and environmental concerns. Most developed nations' governments support using EVs to reduce the concentration of air pollutants, carbon dioxide, and other GHGs. Based on engine technology, EVs are classified into five types: BEV, Plug-In Hybrid Electric Vehicle (PIHEV), Hybrid Electric Vehicle (HEV), FCEV, and EREV. Most EVs may have several batteries. The primary battery supplies power to the motor and transmission system, while the secondary battery supplies power to other low-voltage loads (Dolganova, Rödl, Bach, Kaltschmitt, & Finkbeiner, 2020). The BEV is a viable alternative to the ICEV because of its numerous advantages, including zero emissions, high efficiency, independence from petroleum fuels, decreased noise, and safe and smooth operation. Figure 2 depicts the simplified structure of the BEV. An electric motor is employed in this vehicle to provide the necessary moving power. The motor is powered

by a battery, which may be charged externally through an electrical source or internally via regenerative braking. In the latter situation, the electric motor is a generator for charging the battery. A mechanical transmission system is utilized to convey mechanical energy generated by the motor to the wheels. The power flow is bidirectional, depending on whether the vehicle consumes or charges the battery via regenerative braking (Jain & Kumar, 2017). To demonstrate the benefits of transitioning from ICE technology cars to EVs and the percentage decrease in environmental negative impacts due to this move, the second vehicle category studied in this research is EVs, especially the Chevrolet Bolt BEV.

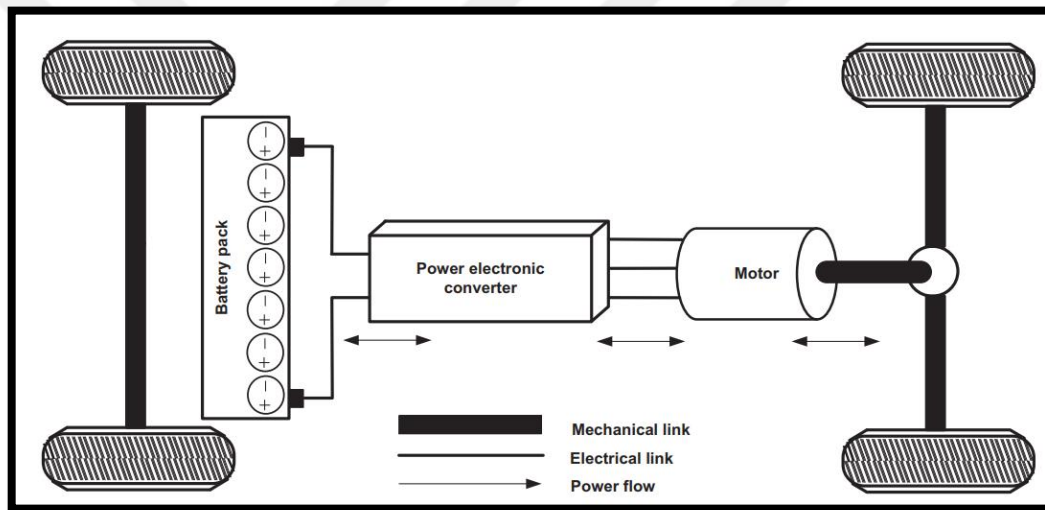


Figure 2. BEV topology (Jain and Kumar, 2017)

Solar PV technology has been commercially deployed in EVs in recent years. The limited space in the EV, the lower efficiency of curved PV panels compared to conventional ones, and the variable radiation value due to the vehicle's continual motion appear to be the key areas of difficulty (Araki et al., 2020; Ota et al., 2018; Tayagaki et al., 2019). If the PV module is used to directly power the vehicle motor by charging the BEV's primary battery, a DC/DC voltage amplifier is necessary to raise the PV module output voltage (Sanguesa et al., 2021). The electricity produced by solar panels attached to a vehicle is inadequate to directly power the motors of BEVs and HEVs (Schuss, Fabritius, Eichberger, & Rahkonen, 2020). Fewer loads are linked to a BEV's secondary

battery than the primary battery, which powers the motor and transmission system. As a result, an installed PV module can supply the extra electrical power required to charge the secondary battery and power these secondary loads. Also, the cell construction would be simple for this architecture because the needed voltage is just 12 V, as opposed to almost 800 V for the main battery (Aharon & Kuperman, 2011). Because PV technology is being incorporated into EVs to provide a portion of the needed electricity for vehicle operation and movement at nearly no cost, the third investigated and chosen example in this study will be an SAEV that takes power from the grid and the PV module. This SAEV comprises two parts: a BEV and a portable PV system. The BEV is a Chevrolet Bolt, much like this study's second car.

In the SAEV system depicted in Figure 3 and simulated in this research, the Battery Management System (BMS) charges the primary battery using grid-supplied power. The primary battery powers a DC/DC booster, which raises the input voltage to a higher level to maintain the voltage on the high-voltage bus, typically 800-900 V. DC energy is stored in the primary battery. After being supplied through the inverter, it is transformed into an alternating current (AC). A DC/AC converter is employed because the vehicle engine provides the required torque for the gear system, and the wheels move using AC energy. On the other hand, the gathered solar energy powers the low-voltage bus and the secondary loads attached to it. The alternator charges the secondary battery while driving and powers the low-voltage bus. This SAEV topology utilizes an architecture where the mounted PV module charges a BEV's secondary 12 V battery.

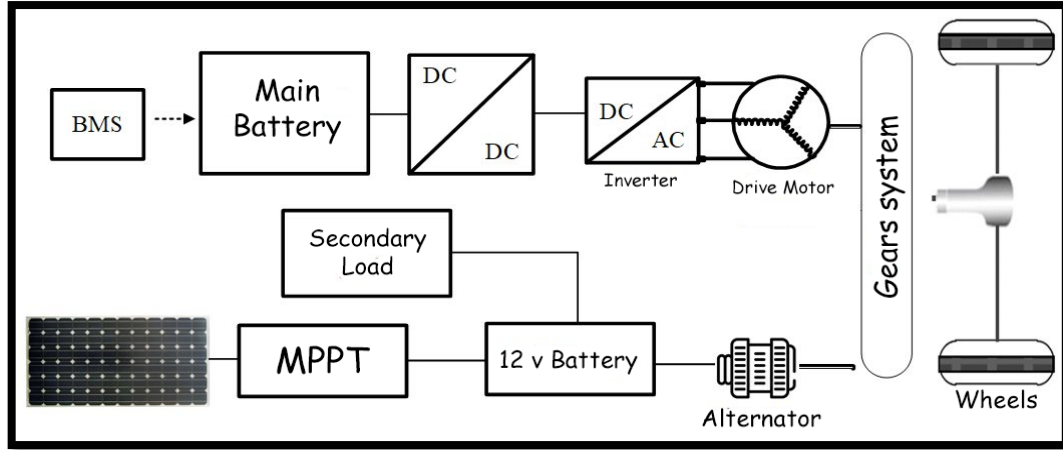


Figure 3. Solar charging through secondary battery SAEV topology

**3.1.2 Partial shading and curved surface modeling.** This research modeled two issues related to collecting solar energy by the SAEV. The first is the well-known partial shading issue in PV panels, which was already discussed in the previous chapters, and the second is the vehicle's curved roof structure and its effect on the SAEV's gathered energy. This model is based on the SAEV architecture discussed earlier, shown in Figure 3. The partial shading effect issue, the first modeled issue, is modeled using different PVSOL simulation scenarios. The distance between the obstacles, the distance between the vehicle and the obstacles, and the obstacles' height are changed continuously in the simulation. PV panels must operate at their maximum power point (MPP) for each solar irradiance level to guarantee optimal overall system efficiency. Powerful MPPT algorithms ensure optimal utilization of incident solar irradiation in urban situations where typical EVs operate (Sarigiannidis, Stathis, & Kladas, 2015). In this simulation, an intelligent MPPT is considered that can handle the effects of partial shading as efficiently as possible while keeping the losses low, and it is considered that the obstacles always avoid the sun.

Regarding the second issue, the curve correction factor is calculated by MATLAB based on the assumed EV roof measurements ( $A_{rp}$ : roof projected area,  $A_{rc}$ : roof curved area,  $\phi_{a/p}$ : projected to absorbed flux ratio) in this research. The results of the PVSOL simulations and meteorological data from Meteonorm (Direct and Reflected Irradiance) are imported to MATLAB to calculate the total harvested solar energy by the PV cells

integrated curved roof. The selected geographical location for the meteorological data, like sun irradiation, was Ataturk Airport in Türkiye -Istanbul. MATLAB's final output is the total amount of energy harvested from the sun while considering the partial shading, the curved structure of the vehicle roof, and the battery charging/discharging losses. The SAEV, EV, and ICEV are then evaluated for sustainability (economic, environmental) and thermodynamics (energy), and the cars are compared using the RETScreen Expert tool. RETScreen Expert is used to do energy, environmental, and economic analyses depending on the scenarios and vehicle types specified. Figure 4 illustrates the programs' co-simulation to give the 3Es (Energy, Environment, and Economic) outcomes.

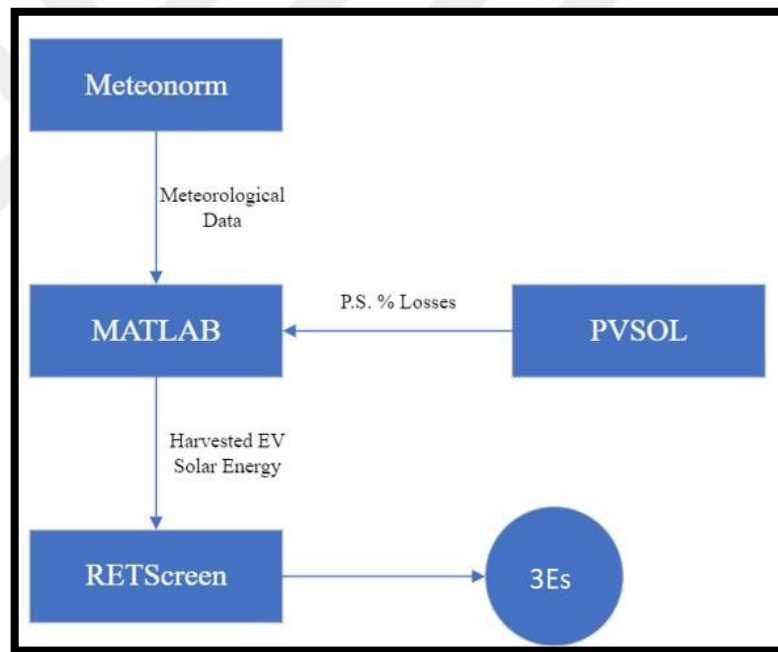


Figure 4. The programs' co-simulation for conducting the 3 Es

When a portion of a solar panel receives less light or shadow than others, it is said to be partly shaded. When the irradiance is changed equally, the output power decreases. Still, when partial shadow occurs, the I-V curve has several peaks, making it difficult for the charge controller to monitor the highest point (Arun & Mohanrajan, 2019). As a result,

its frequent occurrence is one of the critical drawbacks of solar panels, which can result in irreversible damage to the PV system (Geetha & Usha, 2022). To make the partial shading scenario simulated in PVSOL as accurate as possible, the simulation parameters were changed continuously to check for an average case, and this change can be seen in Table 1. The simulation was also conducted to find the most influential parameter on the partial shading efficiency.

Table 1  
*Parameters Used in the PVSOL Simulation*

Parameters	Minimum Value (m)	Maximum Value (m)	Step (m)	Average Case (m)
Distance between obstacles	1	5	1	1
Distance between the vehicle and obstacles	4	8	1	4
Obstacles' height	6	46	10	16

In each scenario, one parameter was changed while keeping the other two constant to calculate the annual irradiance of that scenario ( $G_{ann}$ ). The  $G_{ann}$  of each design is compared with a design that has no obstacles at all ( $G_{ann, ref}$ ), and the average one is selected. Figure 5 depicts one of the created PVSOL scenarios.

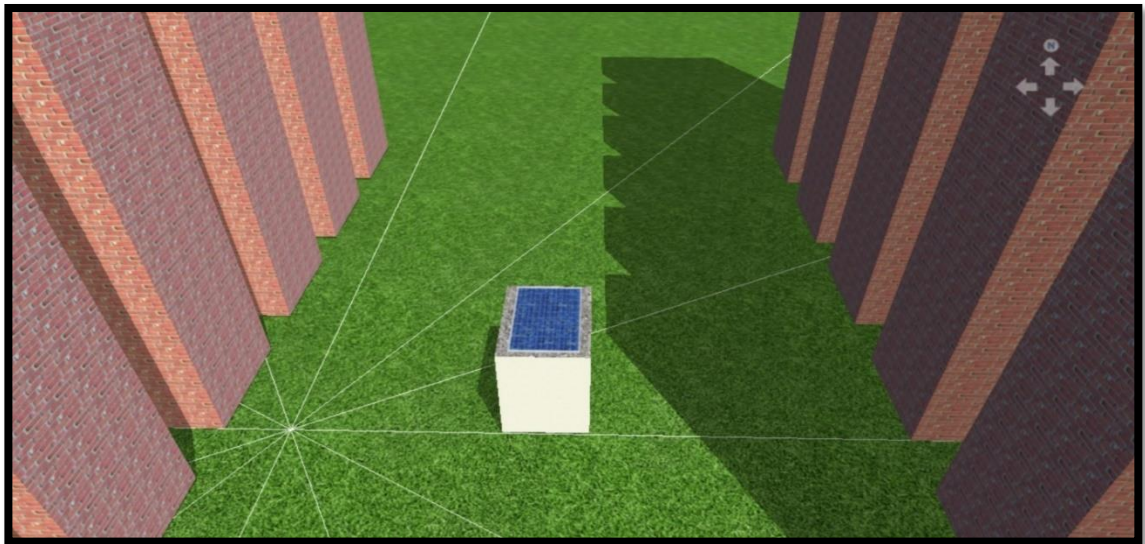


Figure 5. A created case in PVSOL simulation

The partial shading losses ( $L_{p.s.}$ ) are calculated approximately by MATLAB using Equation 1.

$$L_{p.s.} = \frac{G_{ann}}{G_{ann,ref}} \quad (1)$$

The curve correction factor ( $f$ ), which has a specific value depending on the three-dimensional bent structure of the PV module, converts the study of a conventional PV panel's two-dimensional calculations into a three-dimensional model (Ota et al., 2018). It helps calculate the amount of power nonplanar PV panels can generate while considering taking the flat PV panels used in the market as a reference (Tayagaki et al., 2019). When installed on curved surfaces, such as a vehicle's roof, each PV cell receives a different quantity of sun radiation and operates at a different temperature. So, the curve correction factor may be used to average the total irradiance obtained by all PV cells integrated into a curved surface (Schuss et al., 2020). Figure 6 shows instances of that factor, which ranges from 0 to 1, with the coving factor noting that the coving factor represents the ratio of the projected area to the curved one. The higher the angle of curvature of the surface, the lower the  $f$  value. The  $f$  may be estimated via Equation 2 provided by Ota et al. (2018) based on the assumptions and estimations of Araki et al. (2020); Motor Corporation (2019); Ota et al. (2018) and the actual SAEV roof specifications shown in Table 2.

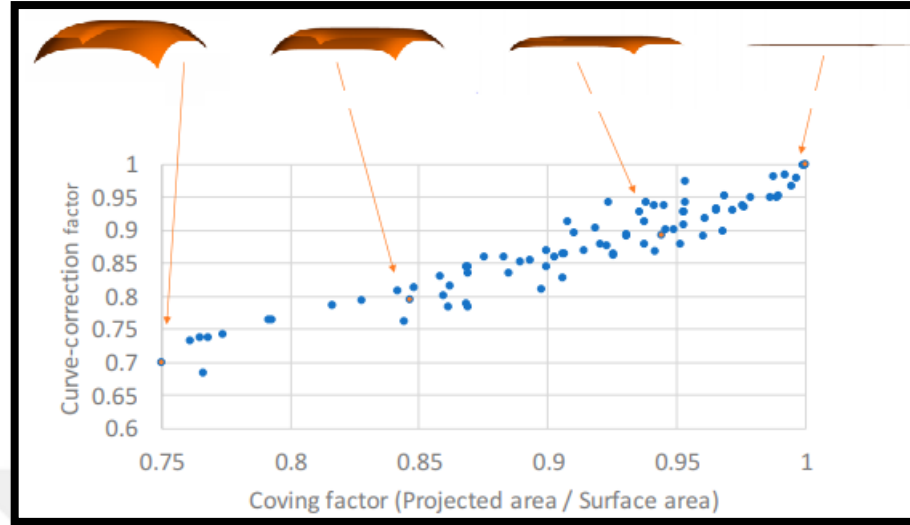


Figure 6. Curve correction factor of different curved surfaces based on the coving factor (Araki et al., 2020)

$$f = \frac{A_{rp}}{A_{rc}} \cdot \Phi_{a/p} \quad (2)$$

Where  $A_{rp}$ ,  $A_{rc}$ , and  $\Phi_{a/p}$  are the roof projected area, the roof curved area, and the ratio of the absorbed irradiance by the curved roof to the projected one, respectively.  $A_{rp}$  and  $A_{rc}$  can be measured manually and easily from the concerned curved roof. At the same time,  $\Phi_{a/p}$ , which was calculated based on equations presented and validated by Ota et al. (2018), is estimated using repeated Ray-Tracing simulations for different values of sun irradiance inclination angles and other roof measurements.

Table 2  
*Calculated and Assumed Parameters Used in the MATLAB Calculations*

Parameter	Assumed/measured Value	Computed Value
$f$	-----	0.8577 (Ota et al., 2018)
$A_{rc}$	2.096 m	-----
$A_{rp}$	2 m	-----
$\Phi_{a/p}$	-----	0.8991 (Ota et al., 2018)
$L_B$	0.05 (Araki et al., 2020)	-----
$L_{p.s.}$	-----	0.18 [PVSOL]
$\eta_{PV}$	34% (Motor Corporation, 2019)	-----

**3.1.3 Harvested energy calculation.** After dealing with the partial shading, curved surface, and battery charging/discharging loss issues, the final energy harvested by the assumed SAEV model will be calculated. Equation 3, which was also demonstrated by Ota et al. (2018), is implemented in MATLAB to calculate the total harvested solar energy ( $E_{SE}$ ) from the PV module installed on the curved roof of the vehicle while taking into consideration the partial shading losses, the curve correction factor, and the battery charging and discharging losses.

$$E_{SE} = A_{rc} \cdot G \cdot f \cdot \eta_{PV} \cdot (1 - L_{p.s.}) \cdot (1 - L_B) \quad (3)$$

Where  $E_{SE}$  is the total harvested energy calculated using the solar irradiance  $G$  imported from Meteonorm software for the chosen geographical location,  $\eta_{PV}$  is the total efficiency of the PV solar module, and  $L_B$  is the battery charging and discharging loss. The remaining terms were illustrated earlier. The solar cell structure assumed by Motor Corporation (2019) and used in this research is a triple-junction compound that consists of joining gallium phosphide (InGaP), gallium arsenide (GaAs), and indium gallium arsenide (InGaAs).

### 3.2 Selected indicators for the sustainability and thermodynamic analyses

The RETScreen program evaluates three scenarios for 3E (energy, economic, environmental) analysis: a transition from ICEV to EV, a shift from ICEV to SAEV, and a change from EV to SAEV. Table 3 shows the vehicle types chosen for each scenario's base and proposed cases. This analysis estimates that vehicles travel 18,250 kilometers per year, or 50 kilometers daily. The social analyses are also done based on the literature review. The indicators used for the comparison are divided into sustainability (economic, environmental, social) indicators and thermodynamics (energy) ones.

Table 3  
*Vehicles Selected for the RETScreen Simulation Different Scenarios*

	1 <sup>st</sup> Scenario	2 <sup>nd</sup> scenario	3 <sup>rd</sup> scenario
Base Case	Toyota Corolla 1.8 AV (ICEV)	Chevrolet Bolt (EV)	Toyota Corolla 1.8 AV (ICEV)
Proposed Case	Chevrolet Bolt (EV)	SAEV(Chevrolet Bolt + portable PV module)	SAEV (Chevrolet Bolt + portable PV module)

**3.2.1 Thermodynamic analysis.** In terms of energy analysis, the yearly fuel consumption savings based on each vehicle's fuel efficiency are used as an indication for the comparison. Fuel efficiency assesses how much energy a vehicle converts into momentum to drive (Laos). The liters of gasoline utilized by ICE cars are converted to kilowatt-hours using a factor of conversion that states that one liter of gasoline equals 8.9 kilowatt-hours of electricity (Canada, 2023). This conversion will allow comparing cars that use different energy consumption units. There are two charging sources for SAEVs: the grid and the PV module mounted to the vehicle's roof.

The daily quantity of harvested energy from the PV module, calculated earlier using MATLAB, is deducted from the vehicle fuel use efficiency, provided by RETScreen databases in kWh per 100 km traveling distance. Because the SAEV's daily journey range is 50 km, this 100 km will be completed in two days. As a result, the subtraction operation will be repeated twice.

**3.2.2 Sustainability analysis.** In terms of environmental analysis, the indicator used in this analysis is the yearly decrease in GHG emissions in tons of carbon dioxide between the base and proposed cases in each scenario. This statistic is based on the quantity of kWh used by each vehicle, considering **Türkiye's** energy transmission and distribution losses, which are considered to be 14.8% (CEIC, 2018).

In terms of economic analysis, the simple payback period computed by the RETScreen software, which is based on the initial additional cost and yearly cash revenue, is used as an indicator. It represents the time it takes for the proposed case to get back its initial extra cost through annual cost savings after switching from the base case. These savings include annual O&M cost reduction and saved fuel consumption. The cost difference between each vehicle is calculated and applied as an initial cost increase in each scenario. The average cost of the ICE and EV vehicles reported in Table 3 is \$19,704 and \$34,963, respectively, according to the RETScreen database. According to BuyaCar (2022), the average EV cost is increased by \$1,500 to account for the extra expense of the portable PV system. Also, the expense of the smart MPPT controller of 80\$ (Amazon, n.d), was added to the initial transition cost resulting in an SAEV cost of \$36,543. Meanwhile, petrol and power rates in Türkiye are 1.11 dollars per gasoline liter and 0.07 dollars per kilowatt-hour, respectively (GlobalPetrolPrices, 2022). Regarding operating and maintenance (O&M) expenditures, an approximate cost of 1152, and 695.8 dollars is spent annually for the maintenance and operation of the ICEV and EV, respectively (Tennessee, 2022). Regarding SAEV, as it is a combination of an EV and solar panels, the O&M cost reduction resulting from the transition from an EV to SAEV is assumed to be zero since solar panels only require cleaning and no maintenance.

Regarding the social aspect, public acceptance is used as an indicator to show the people's acceptance of the transition from ICEVs to EVs and the introduction of PV technology into their daily lives by reviewing the literature without including any numerical values.

## Chapter 4

### Findings and Discussion

#### 4.1 Findings

This study examines the sustainability (economic, environmental, and social) and thermodynamic (energy) characteristics of SAEV, EV, and ICEV using a series of PVSOL and RETScreen Expert simulations. Also, MATLAB is used for calculations. Based on PVSOL simulations, partial shadowing losses due to obstacles are calculated to be (18%). MATLAB uses this number and meteorological data from the Meteonorm program to calculate solar energy received by the SAEV's PV module. Also, it is found that the factor affecting the partial shading losses the most among the three proposed factors is the height of the obstacles, as seen in Figure 7. Figure 8 illustrates the MATLAB calculations' hourly output for the gathered energy during one day based on meteorological data for a sunny day.

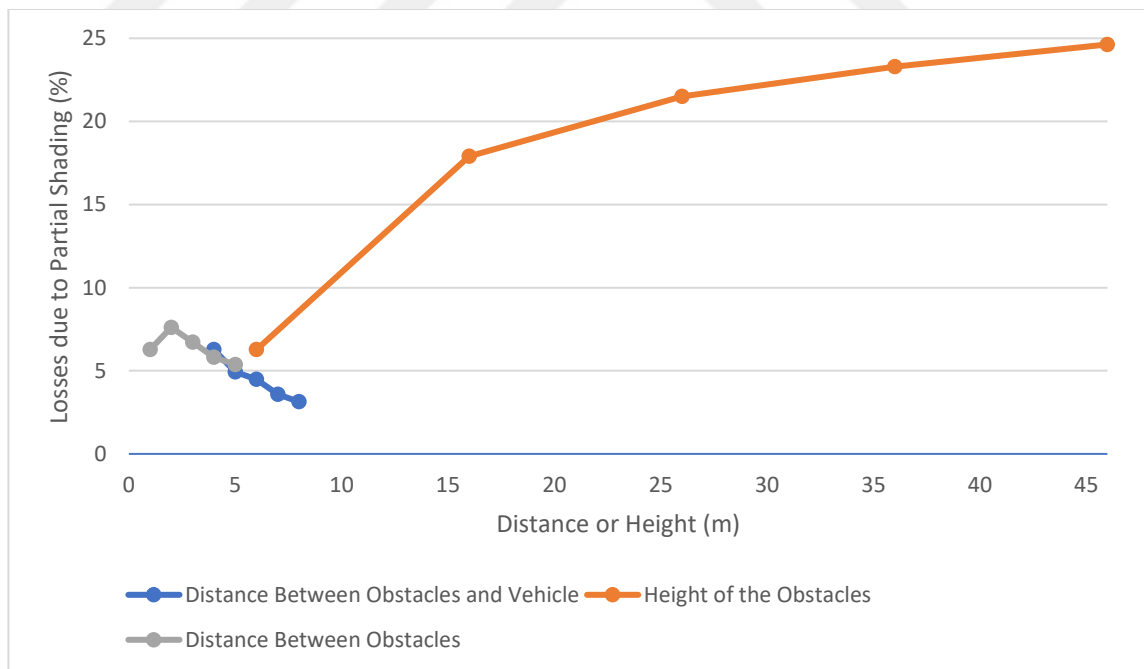


Figure 7. The partial shading percentage loss versus all the three selected PVSOL simulation parameters

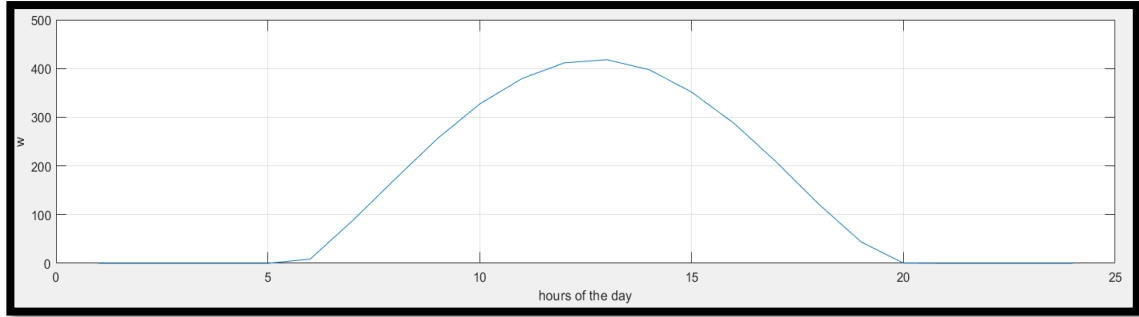


Figure 8. Hourly gathered energy from the SAEV PV calculation for one day

As seen in Figure 8, the captured energy from PV modules increases as the sun rises. Its greatest value corresponds to the available solar irradiation during the midday hours. The total energy captured daily is around 3,472 Wh/day, with a maximum strength of 418 W at midday.

Regarding RETScreen results, tables 4, 5, and 6 show the obtained outputs for energy, economic, and environmental analyses based on RETScreen simulations. Energy, economic, and environmental analysis results in plots can be seen in Figures 9, 10, and 11, respectively. Two situations are compared in each scenario: the base and the proposed one. According to the data, the metrics used for energy, economic, and environmental analyses include yearly fuel consumption saving, simple payback period, and yearly decrease in GHG emissions.

Table 4  
*RETScreen Findings for the Energy Calculations*

Scenarios	Cases	Fuel	Annual fuel consumption (kWh)	Fuel	Fuel
		Consumption Efficiency (kWh/km)		Savings (kWh)	Consumption Savings (%)
1 <sup>st</sup>	ICEV	0.6645	12,127	8,933	73.7
	EV	0.175	3,194		
2 <sup>nd</sup>	EV	0.175	3,194	1,205	37.7
	SAEV	0.109	1,989		
3 <sup>rd</sup>	ICEV	0.6645	12,127	10,138	83.6
	SAEV	0.109	1,989		

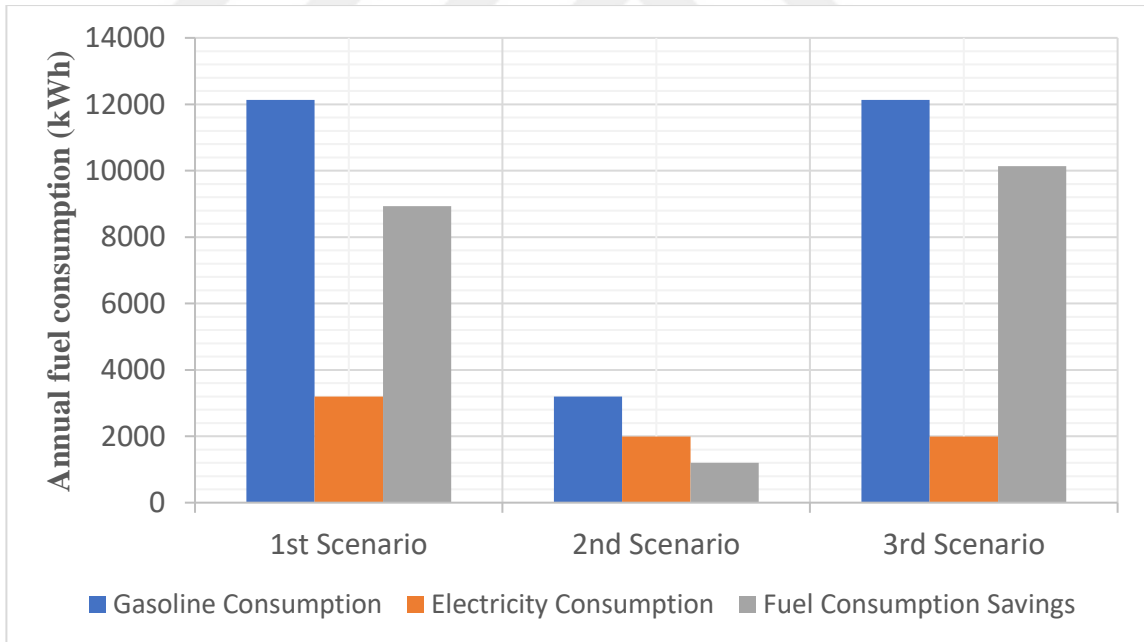


Figure 9. Fuel Consumption and savings of the three scenarios

Table 5  
*RETScreen Findings for the Economic Calculations*

Scenarios	Cases	Initial transition cost (\$)	Annual O&M reduction (\$)	Annual fuel consumption savings (\$)	Total Annual savings (\$)	Payback period (years)
1 <sup>st</sup>	ICEV EV	15,259	456.2	1,192	1,648.2	9.25
2 <sup>nd</sup>	EV SAEV	1,580	0	93	93	16.98
3 <sup>rd</sup>	ICEV SAEV	16,759	456.2	1,285	1,741.2	9.62

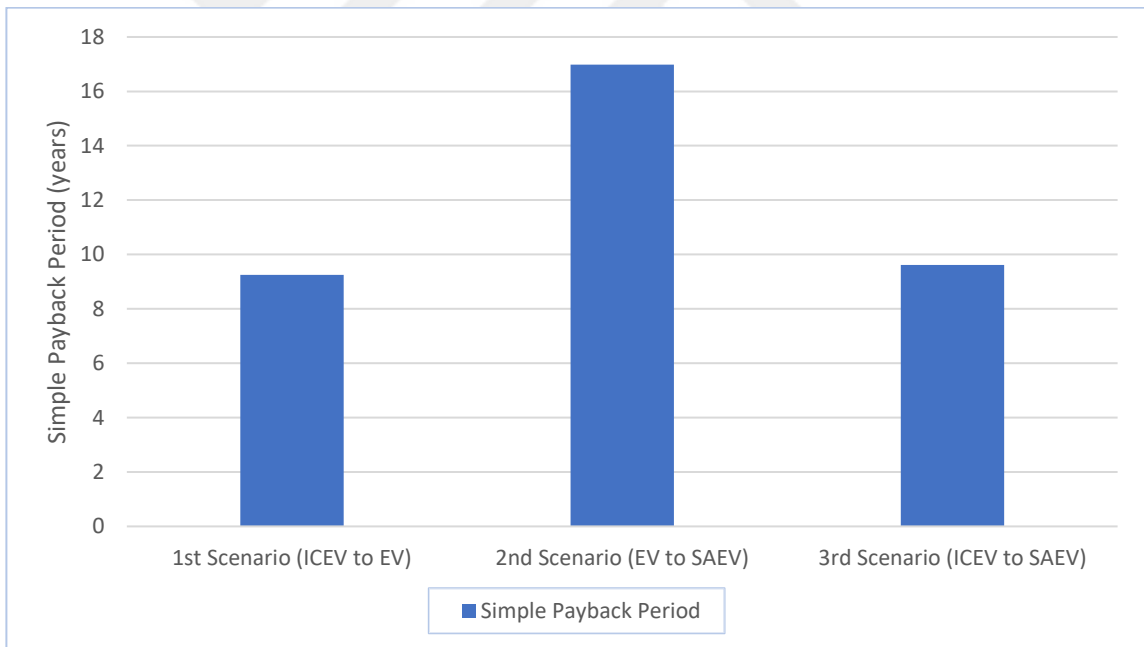


Figure 10. The simple payback period for each scenario

Table 6  
*RETScreen Findings for the Environmental Calculations*

Scenarios	Cases	GHG emission (tCO <sub>2</sub> )	Reduction (tCO <sub>2</sub> )	Reduction (%)
1 <sup>st</sup>	ICEV	2.9	1.1	39.8
	EV	1.7		
2 <sup>nd</sup>	EV	1.7	0.6	37.7
	SAEV	1.1		
3 <sup>rd</sup>	ICEV	2.9	1.8	62.5
	SAEV	1.1		

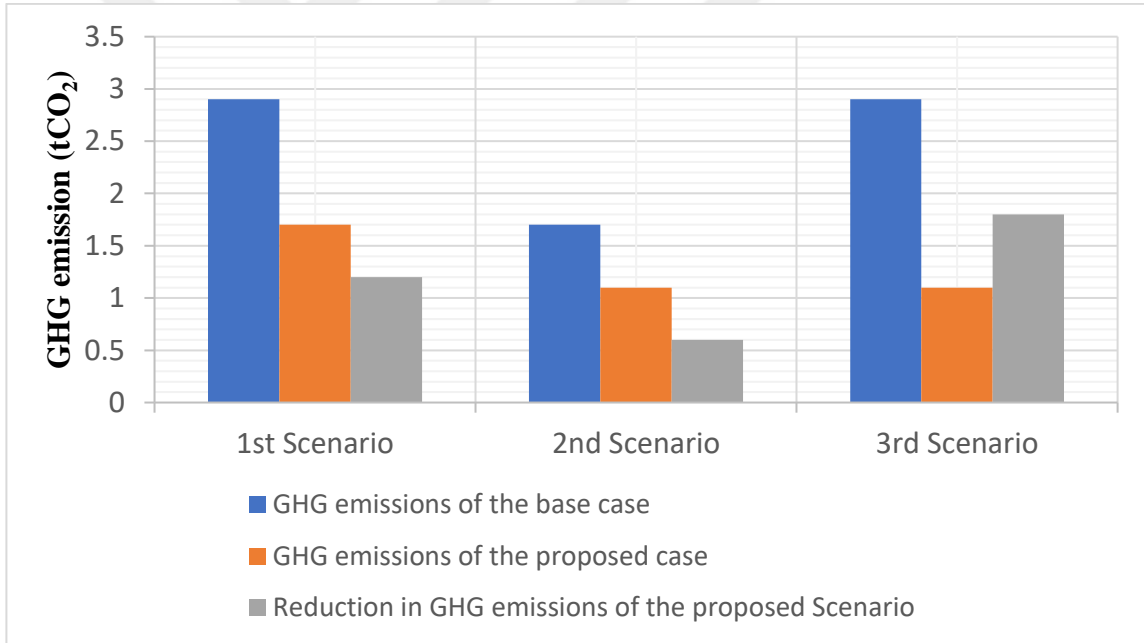


Figure 11. GHG emissions reduction of the three proposed scenarios

Regarding the social aspect of the analysis, the literature review for the public acceptance of electric vehicles and solar energy usage in their life showed that promoting Non-Electric Vehicles (NEV) is a crucial step in ensuring the sustainability of the automotive and transportation industries and an effective way to reduce car emission

levels and save energy. The current development of new energy vehicles is facing a significant issue in encouraging public acceptance of them. In less developed areas, public acceptability of NEVs is greatly influenced by perceptions of risk, cost, subjective norm, and quality. Perceived risk and perceived expense significantly negatively affect public acceptability of NEVs in developing countries, whereas personal standard and NEV quality have substantial favorable effects. The government should vigorously develop new energy vehicle technology, particularly battery utilization technology, raise the technical bar for the industry, lower the price of batteries, establish a collaborative innovation system among the government, universities, and businesses, and enhance the performance of new energy vehicles to hasten the development of such cars in less developed regions. To mitigate public anxiety over potential risks associated with new energy vehicles, it is also necessary to increase the dependability of batteries and car range, to judiciously increase the number of charging pile points, to enhance the convenience of new energy vehicles, to foster a favorable environment for their use, and to create an ideal after-sales service system for cars (R. Wang, Zhao, Wang, & Jiang, 2021). To encourage the use of EVs in the transportation sector, it is essential to consider public perceptions about and willingness to utilize EVs. For increasing economically practical distributions, it is necessary to look into both the technical constraints of EVs, such as battery size and weight, and drivers' personal and social concerns. According to earlier studies, users' adoption and preferences are crucial for effective maintenance in the transportation sector. Well-designed strategies could persuade potential drivers to think about using EVs for transportation in light of the rising environmental concerns in our society. In other words, plans should consider EVs' economic and user experience. For instance, the UK government runs integrated supporting programs and offers incentives for low-emission vehicles based on seven categories, with a purchase price reduction of 35% (up to £4500). The supporting plan in Norway focuses primarily on tax benefits, such as no purchase/import taxes, no toll fees, half-company automobile tax, and so on. However, the national and local governments run two independent EV support programs in South Korea, respectively (Park, Lim, & Cho, 2018). A new trend known as the "solar revolution in design" emerged during the previous 70 years due to silicon PV cell cost reductions

brought about by rising manufacturing volumes, improved solar cell efficiencies, and increasing social acceptance of photovoltaic technology. Since solar energy is substantially less expensive than it formerly was, there is now a chance to consider the aesthetic qualities of PV modules and PV systems and creative methods to incorporate them into urban or rural cars, buildings, and landscapes (Sierra & Reinders, 2020).

## **4.2 Discussion of Findings**

In the context of the energy study, a scenario is considered more sustainable if its results significantly reduce the amount of fuel consumed compared to the other two scenarios. The average annual fuel consumption in kWh is calculated by taking the yearly traveled distance, 18,250 kilometers, and multiplying it by the fuel consumption efficiency for one kilometer derived from the RETScreen database for each car. In the first scenario, because the ICEV, which is the base case, consumes 12,127 kWh annually with a consumption efficiency of 0.6645 kWh/km, and the EV, which is the proposed case, consumes only 3,194 kWh with a consumption efficiency of 0.175 kWh/km, the first scenario has a high percentage fuel consumption saving value of 73.7%, as seen in Table 4. In the second scenario, as a result of the reduction in the efficiency of the base case fuel consumption efficiency to 0.175 kWh/km, the second scenario results in a saving percentage of 37.7%. In the third scenario, because of the significant gap between the base case's fuel consumption efficiency of 0.6645 kWh/km and the proposed one's fuel consumption efficiency of only 0.109 kWh/km, the third scenario has the most significant percentage of savings out of the three scenarios, at 83.6%. This is the highest of the three possibilities. This significant difference is because most of the fuel used in the presented third scenario (ICEV to SAEV) originates from renewable sources, which are more energy-efficient than fossil fuels. That is to say, the transition from ICEVs to SAEVs is the most In terms of economic analysis, the shorter the simple payback period in years, the more sustainable the scenario. The transition cost is defined as the difference between the initial purchase costs of the base and proposed vehicles, as shown in the preceding section. In each scenario, the transition cost is used as the initial cost, while the annual

O&M costs and fuel usage savings are used as the annual cashflow. According to Table 5, the first scenario has a transition cost of 15259 \$, a yearly fuel savings of 1192 \$, and a reduction in O&M expenditures of 456.2 \$. Because of the significant reduction in fuel use when switching from ICEV to EV, a payback period of 9.25 years was reached. As a result, significant cash flow will be generated from fuel savings. The second scenario has the longest payback period of 16.98 years due to the lowest amount of fuel consumption savings and, as a result, the lowest yearly revenue from fuel savings. Furthermore, there is no reduction in O&M costs in this scenario, i.e., when switching from EV to SAEV. The third scenario yielded a simple payback period of 9.62 years, which is very close to the first scenario because only the cost of the portable PV module was added to the initial transition cost, resulting in a payback period of only 0.37 years.

For environmental analysis, a scenario is considered more sustainable if there is a more significant reduction in GHG emissions between cases in that scenario because the scenario's potentially harmful environmental effects will be mitigated more. The total amount of greenhouse gas emissions produced by each vehicle was determined by obtaining the GHG emission factor for each kWh from the RETScreen database for Türkiye. Next, the GHG emission factor for each kWh was multiplied by the annual consumed kWh to determine the total amount of greenhouse gas emissions produced by each vehicle in terms of tCO<sub>2</sub>, taking into account the 14.8% losses that were caused by the transportation and distribution of electric power in Türkiye. According to Table 6, the first scenario has a reduction percentage of GHG emissions of 39.8% because the base case (ICEV) has the most significant fuel consumption and the proposed case (EV) reduces this consumption by 73.7%. Because the difference in fuel usage between the two cases (EV and SAEV) is relatively tiny and both cases use electricity as their sole or a significant portion of their energy source, the second scenario achieves a 37.7% reduction in GHG emissions. The third scenario, which has the highest percentage reduction in GHG emissions, has a decrease of 62.5% because the majority of the fuel consumed by the suggested case (SAEV) originates from clean energy sources. This scenario has the

highest percentage reduction in GHG emissions. This also indicates that shifting directly from ICEV to SAEV is more sustainable in terms of the analysis of the environment.

Regarding social analysis, the literature review showed that the popularity of EVs has rapidly increased over the past ten years. Due to several factors, including increased government backing, cost reductions, technology developments, and better charging infrastructure, the public is becoming more accepting of EVs. Acceptance of electric vehicles is anticipated to increase as the market for them develops a future of electrified and more environmentally friendly transportation. Regarding the transition to the use of solar energy in their life, the review showed that solar energy is becoming increasingly popular due to its advantages for the environment, cost savings, energy independence, and technological improvements. Public support for solar power is projected to increase as the technology develops and becomes more widely available, further promoting the use of solar energy as a clean and sustainable energy source. So, the public acceptance of the people is inclined towards cost-effective and emission-free energy. The use of EVs is more preferred than the ICEVs, and the SAEVs are more favored than EVs and ICEVs because more cost-effective and emission-free energy is used in the SAEVs than in the other two vehicle types.

#### **4.3 Discussion of Findings as per the Research Questions**

Based on the findings of this study, The previously mentioned research questions in Chapter 1 can be discussed and answered clearly.

1. Can the SAEV be modeled considering the curved surface of the vehicle roof and the partial shading issues?

Yes, it can be modeled, and both mentioned issues can be solved using the curve correction factor and a reasonable partial shading scheme. As seen in the calculations conducted in this research in Chapter 3, the curve correction factor was

easily calculated based on an equation relating the factor to the vehicle roof measurements. So, the curved surface issue can be solved efficiently using only that factor and roof measurements. Regarding partial shading, a model can't be 100% accurate in predicting the shading because the shading depends on the driver's convention of driving. The driver can drive the vehicle in an obstacle-filled or clear environment. So, an average case of a road filled with average-height obstacles on both sides can help approximate, as accurately as possible, the partial shading loss of a SAEV and solve the second issue in modeling the vehicle.

2. Are SAEVs more sustainable than ICEVs and EVs when considering sustainability and thermodynamics?

Yes. Based on the findings, the SAEV is more efficient considering the energy efficiency, the environmental impacts, and the long-term costs. Even when talking about public acceptance in the social aspect, people are more inclined to have an electric vehicle instead of an ordinary gasoline one and to depend on clean and free solar energy in their daily lives.

3. Is it worth implementing solar technology into EVs to decrease power consumption from the utility grid?

Yes. Based on the created module in this study, the addition of solar technology to the EV reduces the amount of yearly electricity consumption from the grid to about 37.7% of its previous value.

4. Do the curved nature of the vehicle's roof and the partial shading issues significantly affect the vehicle-integrated solar cells energy harvesting?

Yes, the curved structure of the vehicle roof reduces the amount of harvested energy to 67% of its standard flat value, depending on the curvature of the surface. So, a flat PV panel with an area of  $x$  will have solar energy harvested of  $y$ . It will have the same curved area when curving that panel to the exact measurements applied in this study. However, the total solar energy harvested can decrease up to to 67% of  $y$ ,

depending on the amount of curvature. Also, the partial shading model used in this study showed that the energy harvested could be affected and reduced to approximately 75%, with an average of 82%, of the energy harvested without partial shading considered.

#### **4.4 Limitations**

Due to the complex nature of the system and the many variables that affect its performance, modeling a SAEV presents several difficulties and restrictions.

The ability of solar panels to convert sunlight into electricity is constrained. Commercial solar panels typically have an efficiency of 15% to 20%. This limits the amount of energy that can be harvested because only a portion of the available sunlight can be converted into electricity. Also, solar panel surface area is constrained on SAEVs. The vehicle's roof and hood may not have enough room to generate significant energy, especially if it is small. In the meantime, curved nature causes more complex scenarios. On the other hand, sunlight conditions, which can change throughout the day and in different climates, are a significant factor in solar energy generation. The solar panels are less functional on cloudy days, in the shade, or at night.

A car's solar panels might only extend the range by a small amount, especially for long-distance driving. The energy produced may be used primarily to power auxiliary systems or make up a negligible portion of the total driving range.

Despite these drawbacks, SAEVs can still provide advantages in terms of lower emissions, reduced fuel consumption, and increased energy resilience, particularly for short commutes and urban driving where solar energy generation is more practical.

## **Chapter 5**

### **Conclusion**

#### **5.1 Conclusions**

Through a series of PVSOL, RetScreen Expert simulations, and MATLAB calculations, the proposed study assessed the sustainability and thermodynamic performances of ICEV, EV, and SAEV by calculating the annual fuel saving, simple payback period, and decrease in GHG emissions. According to the results, the third scenario gives the most considerable fuel consumption reduction. So, when transferring from an ICE car to a SAEV, the difference in fuel consumption efficiency is the largest. In other words, based on an energy study, the third scenario is the most viable one. In terms of economic analysis, this is distinct. The first scenario is the most cost-effective one because it has high total annual savings and, eventually, the lowest simple payback period (9.25 years). However, the third scenario's payback term only differs by 0.37 years, or about four and half months, from the first scenario's payback. So, an extra negligible cost should be paid to obtain an SAEV, saving more annual energy consumption. Regarding environmental analyses, the third scenario reduces greenhouse gas emissions the most since some energy consumed originates from the sun, a renewable resource. In order to assess how much more sustainable the SAEV is than the other two vehicle types, it is utilized as a reference case. For the social aspect, a vehicle incorporated with solar energy is preferred to the other two discussed types.

Table 7  
*RETScreen Findings for the 3Es Analysis*

Scenarios	Cases	Energy (percentage fuel consumption saving)	Economy (simple payback period in years)	Environment (percentage GHG reduction)
1 <sup>st</sup>	ICEV EV	73.7	<b>9.25</b>	39.8
2 <sup>nd</sup>	EV SAEV	37.7	16.98	37.7
3 <sup>rd</sup>	ICEV SAEV	<b>83.6</b>	9.62	<b>62.5</b>

## 5.2 Recommendations for future work

Future SAEV models should consider various technological developments, sustainability, and user experience. For example, improvements should be made to the technology used in the solar panels to increase the solar panels' efficiency. When the efficiency is increased, more energy can be harvested from the same solar-energy-harvesting system that is integrated into the EV. This means that the energy efficiency of the system will be increased, and, consequently, more cost-free & emission-free driving distances will be provided. Also, energy management optimization should be implemented in the SAEV control system that can divide energy between the battery, the solar panels, and the vehicle's propulsion system in an effective manner. In this way, the losses occurring during the energy harvesting and dissipation process can be minimized. The energy optimization process is done using predictive algorithms and machine learning based on driving conditions and user behavior. Another aspect that must be focused on as future work for the SAEV is the solar panels' integration method. New strategies for incorporating solar panels into the vehicle's design, such as embedding them into the body, windows, or other surfaces should be implemented. This might increase the area that can be used for solar panels without sacrificing design or aerodynamics. Increasing the area of the solar panels has the same effect of increasing their efficiency.

As an extension to work proposed in this study in the future, fusing these energy, economic, and environmental assessment approaches with the exergetic and sustainability

evaluation of different EV topologies for future research. Incorporating social and risk factors would also improve the sustainability of the suggested review. Multi-criteria decision-making techniques can be applied to this challenging issue. Additionally, simulation results can be verified by observing SAEVs or electric vehicles (EVs) fitted with portable PV modules over extended periods and in various weather situations.



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