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Demand Side Management Strategies for Electric Vehicles Charging/Discharging and to Support the Intermittent and Variable Nature of RES

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Demand Side Management Strategies for Electric Vehicles Charging/Discharging and to Support the Intermittent and Variable Nature of RES

by

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Preface

The research work is partially funded by Programma Operativo Nazionale Ricerca e Innovazione 2014-2020 (CCI 2014IT16M2OP005), risorse Fondo Sociale Europeo REACT-EU, Azione I.1 “Dottorati Innovativi con caratterizzazione industriale”, Azione IV.4 “Dottorati e contratti di ricerca su tematiche dell’innovazione” e Azione IV.5 “Dottorati su tematiche Green”.

This research was primarily conducted at the University of Palermo, Italy, within its dynamic and multidisciplinary research environment. The academic guidance and collaborative spirit of the university have been instrumental in shaping the direction and depth of this work. I am sincerely grateful for the valuable support and resources provided throughout this journey.

A significant portion of this research was carried out at the Fraunhofer Institute for Factory Operation and Automation (IFF) in Magdeburg, Germany, during my period abroad as a visiting researcher. I deeply appreciate the opportunity to work alongside world-class researchers in such a stimulating environment.

A part of this work was also developed during an industrial training period at Prysmian Group, Palermo, Italy. The experience of working within a leading global company in energy and telecom cable systems provided valuable practical insights. This collaboration bridged the gap between academic research and real-world industrial applications, greatly enhancing the impact and relevance of the study.

Abstract

The rapid electrification of the transport sector, driven by the global push for sustainability, presents both opportunities and challenges. While Electric Vehicles (EVs) offer a promising solution to reducing greenhouse gas emissions, their large-scale adoption places unprecedented demands on power grids, potentially exacerbating energy sustainability concerns. This thesis investigates the dual impact of EVs on the environment and power systems while exploring innovative solutions to mitigate the associated challenges.

This thesis presents a comprehensive investigation into the integration of EVs and Fuel Cell Electric Vehicles (FCEVs) within evolving power systems, emphasizing the importance of Demand Side Management (DSM), digital technologies, and Renewable Energy Sources (RES) in achieving decarbonization targets. It is structured around six interrelated studies, each contributing to a unified methodology that addresses environmental impact, grid stress, and energy optimization.

The first study quantifies the environmental benefits of EVs under varying carbon emission coefficient factors in four European countries and highlights the importance of clean electricity for achieving meaningful reductions in greenhouse gas emissions. The second study focuses on Italy and shows how regional differences in energy mix affect EV-driven decarbonization. The third study examines urban and insular power networks in Palermo and Favignana, respectively, revealing significant challenges such as load peaking, line congestion, and voltage instability under rising EV penetration.

To mitigate these grid-level impacts, the fourth study explores DSM strategies using Time-of-Use (TOU) pricing and residential battery storage, showing a 67% reduction in EV charging cost and a two-year payback period. The fifth study introduces digital twins for real-time EV load management in microgrids with high-RES penetration, demonstrating enhanced load shifting, peak clipping, and valley filling. Finally, the sixth study evaluates the techno-economic feasibility of onsite hydrogen production from RES to support FCEV-based public transport on Favignana Island. The proposed hybrid microgrid system achieved a 90% reduction in GHG emissions and a 31% cost saving compared to diesel systems.

Collectively, the findings illustrate that integrating smart DSM strategies, digital twins, and RES can transform EVs and FCEVs from grid stressors into active energy assets. This thesis provides a scalable framework for policy makers, utility operators, and researchers seeking to align transport electrification with energy sustainability and grid resilience goals.

Acknowledgements

This PhD journey has been a rollercoaster of challenges, perseverance, and growth. There were moments of exhaustion, frustration, and self-doubt, but also times of discovery, excitement, and fulfillment. This thesis would not have been possible without the unwavering support and encouragement of many incredible individuals, to whom I am deeply grateful.

First and foremost, I extend my deepest gratitude to my supervisor, **Prof. Maria Luisa Di Silvestre**, for her invaluable guidance, patience, and belief in my potential. Her expertise and constant encouragement have played a pivotal role in shaping this research. I am also profoundly thankful to my co-supervisor, **Prof. Gaetano Zizzo**, whose insightful advice, constructive feedback, and technical guidance have been invaluable throughout this journey. A special thanks to my PhD coordinator, **Prof. Eleonora Riva Sanseverino**, for her support and leadership, ensuring a smooth and enriching academic experience. I would also like to express my sincere gratitude to **Prof. Pio Lombardi** for his invaluable guidance and supervision during my research stay at Fraunhofer IFF, Magdeburg, Germany.

This journey would not have been possible without my family, who have been my greatest source of strength and motivation. To my **Father** and **Mother**, whose endless sacrifices, prayers, and encouragement have fueled my determination. To my brother, **Barkat Ali**, and my sister, **Sony Ahmad Zeb**, for always believing in me and cheering me on, even from afar. And to my wife, **Hafsa**, who has been my anchor through the most challenging days, offering her love, patience, and unwavering support in every step of this demanding journey.

I am also immensely grateful to my **Friends**, who have been my escape from the stresses of academia. They provide laughter, motivation, and companionship when I need it the most. Their encouragement has helped me push through the long nights, endless simulations, and countless revisions.

This PhD has tested my limits in ways I never imagined, but it has also been a journey of immense learning and personal growth. Completing this thesis is not just an academic achievement—it is a testament to the support, love, and encouragement of all those who have stood by me. To each and every one of you, from the bottom of my heart—**Thank you!**.

Contribution statement

This thesis is the original work of the author. The research presented herein was conducted under the supervision of Maria Luisa Di Silvestre and co-supervision of Gaetano Zizzo, and all sources of information have been duly acknowledged. The key contributions of this thesis are:

- An in-depth evaluation of the environmental and energy system effects resulting from the integration of Electric Vehicles (EVs), especially in urban and island grid networks.
- The development and execution of Demand Side Management (DSM) strategies for electric vehicle charging focus on improving the integration and adaptability of Renewable Energy Sources (RES).
- The development of a digital twin framework for simulating and optimizing EV-based DSM within a renewable energy microgrid environment.
- Evaluation of time-of-use-based EV charging models as a strategy to align EV demand with periods of high renewable generation.
- The exploration and deployment of onsite hydrogen production from renewable energy sources will aid Fuel Cell EVs, increasing the use and value of renewable energy in transportation.

Declaration by author

I, Qais Ali, declare that this thesis and the work presented in it are my own and have been generated by me as the result of my original research. Where information has been derived from other sources, I confirm that this has been indicated and acknowledged appropriately.

This thesis has not been submitted, either in whole or in part, for a degree or other qualification at this or any other institution.

Sign.......................... Date:

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List of publications

1. Ali Q, Di Silvestre ML, Lombardi PA, Riva Sanseverino E, Zizzo G. Electrifying the Road to Net-Zero: Implications of Electric Vehicles and Carbon Emission Coefficient Factors in European Power Systems. Sustainability. 2024; 16(12):5084.
https://doi.org/10.3390/su16125084"
2. Q. Ali, M. L. Di Silvestre, P. Lombardi, E. R. Sanseverino and G. Zizzo, "The Role of Renewable Energy Generation in Electric Vehicles Transition and Decarbonization of Transportation Sector," 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Madrid, Spain, 2023, pp. 1-6,
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3. Q. Ali et al., "A Simulation Study for Assessing the Minimum Number of V2G Recharge Points in Favignana," 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Prague, Czech Republic, 2022, pp. 1-6,
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8. Muhammad Farooq Azam, Qais Ali, Guido Ala, Eleonora Riva Sanseverino. "Techno-Economic Assessment of Renewable Energy-Driven Desalination Systems for Remote Islands". This paper is completed but has not yet been submitted.

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List of Abbreviations

BMS Battery Management System

CC Capital Cost

CO_2 Carbon Dioxide

COECF Carbon Emission Coefficient Factor

CRF Capital Recovery Factor

DG Distributed Generation

DR Demand Response

DSM Demand Side Management

DT Digital Twin

EMS Energy Management System

EU European Union

EVs Electric Vehicles

FCEVs Fuel Cell Electric Vehicles

GHG Greenhouse Gas

GHI Global Horizontol Radiation

HIL hardware in Loop

ICEPCs Internal Combustion Engine Passenger Cars

ICEVs Internal Combustion Engine Vehicles

IEA International Energy Agency

IPCC Intergovernmental Pannel on Climate Change

IRENA International Renewable Energy Agency

LCOE Levelized Cost of Energy

LCOH Levelized Cost of Hydrogen

MG Micro Grid

NPC Net Present Cost

NZE2050 Net Zero Emission 2050

O&M Operation and Maintenance
PEVs Plug-in Electric Vehicles
POWER Prediction of Worldwide Energy Resources
PT Physical Twin/Physical System
PV Photovoltaics
RC Replacement Cost
RES Renewable Energy Sources
SDS Sustainable Development Scenario
SG Smart Grid
SMR Steam Methane Reforming
SoC State of Charge
TC Total Cost
TOU Time of Use
TPVs Traditiona Passenger Vehicles
USD US Dollars
V2G Vehicle to Grid
WE Wind Energy
WMO World Meteorological organization
WT Wind Turbine

Chapter 1

Introduction

The widespread adoption of electric vehicles (EVs) speeds up the shift to cleaner transportation by reducing Greenhouse Gas (GHG) emissions and reducing reliance on fossil fuels. However, as EV adoption increases, new challenges arise, especially regarding grid stability, peak demand management, and environmental issues related to electricity generation from fossil fuels and renewable energy sources. This thesis first examines the potential negative impacts of large-scale EV adoption on both power systems and the environment. Then, it investigates strategies and solutions to alleviate these challenges, ensuring EVs' sustainable and resilient integration into the energy landscape.

1.1 Background and Motivation

1.1.1 Global Warming

Extreme weather events, like severe heatwaves, heavy rainfall, wildfires, catastrophic floods, and powerful storms, are becoming more frequent and concerning global realities. We are on the verge of irreversible climate change, which is undoubtedly a global emergency. According to the World Meteorological Organization (WMO), the climate change impact and rate increased dramatically from 2011 to 2020, and it was the warmest decade on record [1]. In this decade, the Antarctic Continental ice sheet was reduced by approximately 75% more than the previous decade's ice reduction. WMO report further highlighted that since the 1990s, each following decade has been warmer than the previous one, and no reverse of this trend has been seen. In 2021, the most extreme heatwaves were featured in June in North America. Four mega-weather disasters each cost over 20 billion US dollars (USD) in damage [2]. In Canada, on June 29, the temperature rose to 121 Fahrenheit at Lytton, British Columbia. In Quillayute, Washington, USA, the temperature rose to a record high of 110 Fahrenheit on the same day. The study [2] further highlighted the costliest disaster in Louisiana, which happened on 29 August 2021, with almost 65 billion USD in damage. In the same year, in July, the deadliest flood struck the eastern part of Belgium and the Western part of Germany, killing 240 people with damage of 43 billion USD. The flood in Zhengzhou, China, in June 2021, killed more than 300 people with 30 billion USD in damage. The cold waves in the central USA caused 23 billion US dollars in damage and led to 246 fatalities in February 2021.

Intense heat is deadly and destroys societies and economies. The study [3] shows that in two decades, from 2000 to 2019, almost 489000 deaths occurred yearly due to extreme heat. Among these, 45% were in Asia and 36% in Europe. In 2022, labor capacity losses due to heat exposure led to a potential income reduction of 836 billion USD [4]. Table 1.1 illustrates the economic damage, fatalities, and affected people from droughts, floods, heat waves, storms, and wildfires in 2022 [5].

Table 1.1: Damage caused by extreme weather in 2022.

Hazard	Fatalities	Affected People in million	Economic loss in billion US dollars
Drought	2601	107.35	35.65
Flood	8050	57.55	46.78
Heat Wave	61782	0.029	0
Storm	1605	16.98	137.43
Wildfire	76	0.245	1.12

In 2023, severe droughts, rising ocean temperatures, and scorching wildfires occurred. Severe droughts hit different regions of Europe in the spring due to low winter snowfall and rainfall [6]. In some areas of Spain, scarcity forced residents to limit their water use. Along with Spain, the heatwaves and droughts affected crops in the UK, Germany, Scandinavia, the Baltic Sea, and Ireland. The water level was also reduced in one of Europe's major rivers, the Rhine, affecting shipping across Germany. Other than Europe, the USA, China, Brazil, and many Asian countries were affected by droughts and heat waves, causing billions of USD in damage. In the summer of 2023, severe wildfires pushed Canada, Mexico, Greece, Hawaii, and many other countries to the brink of environmental and economic collapse. This year was no different than the previous, where extreme climate events caused both losses of human lives and damaged the economies.

In 2024, extreme weather escalated to alarming levels. According to a study [7], 24 extreme weather events contributed to at least 3700 deaths, and millions were displaced. These 24 events are just a tiny fraction of the 219 that happened in 2024. In April 2024, heavy rainfall hit the United Arab Emirates and Oman and caused severe disruption of public life and infrastructure, with more than 20 fatalities [8]. In October 2024, Spain experienced a severe flood in Valencia [9]. This event caused thousands of USD in damage and displaced thousands of people. The number of events that occurred in Italy in 2024 is shown in Table 1.2 [10].

Table 1.2: Extreme weather events occurred in Italy in 2024.

Category	Number of Events
Flood from intense rainfall	134
Wind damage	62
River Flooding	46
Damage from prolonged drought	34
Hail damage	30
Others	39

Extreme climate events increase with each year. Globally, January 2025 recorded the highest temperatures ever, making it the second-warmest January in Europe [11]. In my hometown, Swat, Pakistan, there was only one rainfall in January. This area is in the north of Pakistan and is famous for snowfalls and rainfalls [12]. This indicates that global warming is a critical emergency requiring immediate action.

1.1.2 Causes of Global Warming

Climate change is caused by increasing carbon emissions from various sectors. Globally, GHG emissions continue to rise when they should decline rapidly. We must identify the main contributing sectors to reduce GHG emissions effectively and quickly. This knowledge can create effective solutions for reducing GHG emissions in each sector. The global GHG emissions by sector are detailed in Figure 1 for 2015 to 2021 [13].

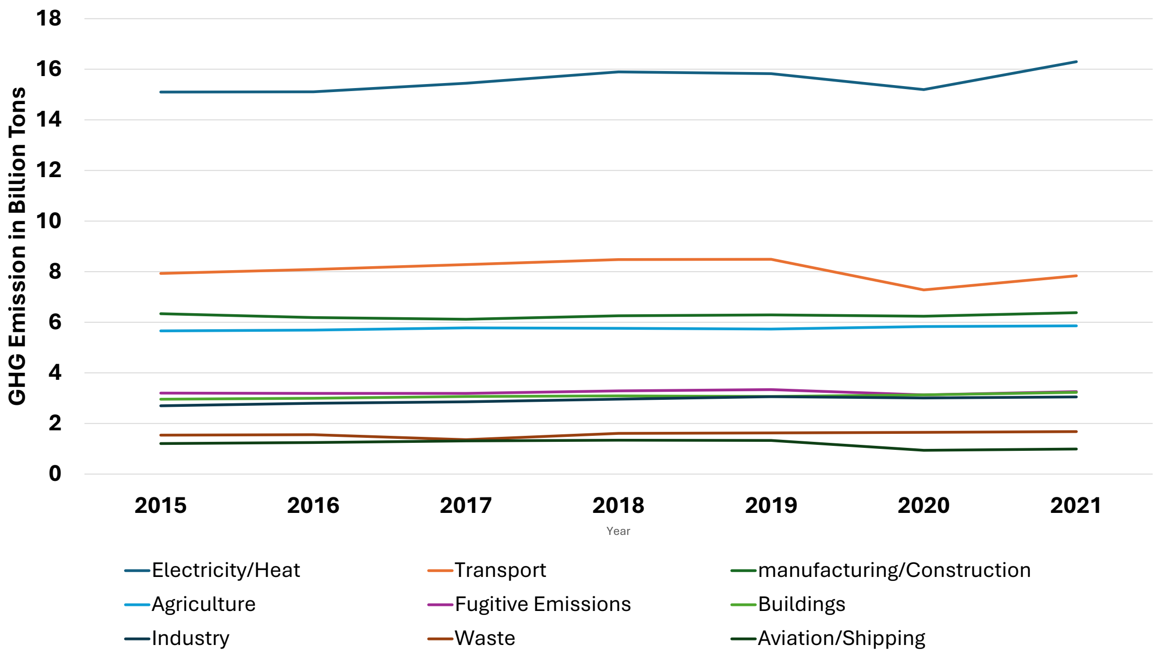


Figure 1.1: Greenhouse Gas Emission by Sector.

Figure 1.1 shows that the transport sector is the second major source of GHG emissions. In 2021, this sector contributed 7.8 billion tons of CO2 to GHG emissions. Light-duty vehicles contribute 48% of emissions from the transport sector. Figure 1.2 shows GHG emissions of the transport sector by vehicle type [14]. Cars are the most significant cause of transportation emissions. Hence, different strategies and policies have been introduced to mitigate GHG emissions in this sector.

1.1.3 Electrifying The Transport Sector

Electrification of the transport sector can play a vital role in addressing the problem of high GHG emissions from this sector. Many countries worldwide have taken the initiative to replace fossil-dependent cars with EVs. In 2023, every fifth car sold was an EV [15]. EV sales reached almost 14 million, of which 95% were in the USA, Europe, and China in 2023. Figure 1.3 shows the global EV stock in 2023.

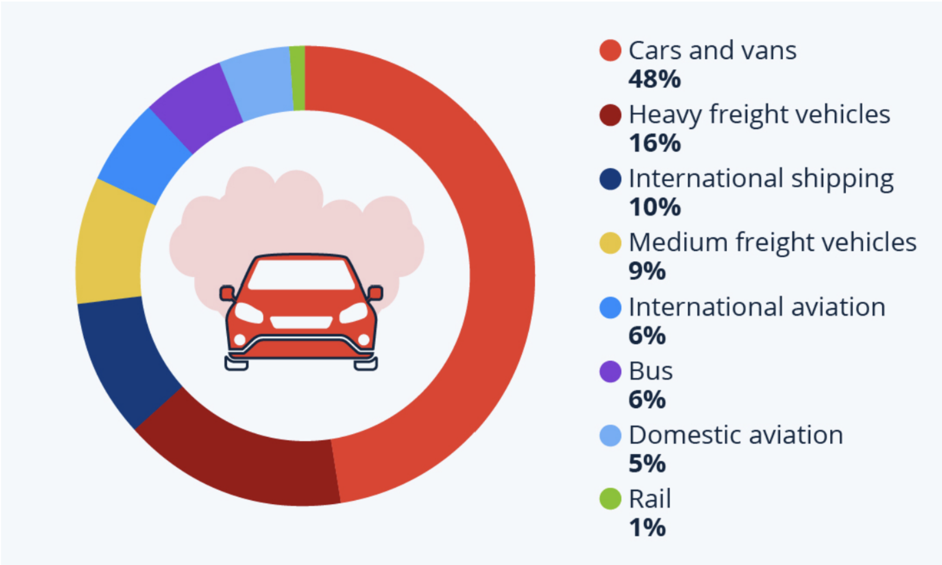


Figure 1.2: Greenhouse Gas Emission by Vehicle Type in Percent.

Manufacturer competition, decreased in EV prices, and ongoing supportive policies have driven EVs' market share. By the end of 2024, the EV market is expected to reach 11% in the USA, 25% in Europe, and 45% in China [16]. Furthermore, the global volume of EVs has been forecasted to increase from 14.2 million in 2023 to more than 71 million units in 2035 [17].

Moreover, fuel cell technology is well-developed and on its way to widespread commercialization in the automotive industry. With less refueling time, satisfying driving ranges, and fuel efficiency, Fuel Cell Electric Vehicles (FCEVs) will soon attract more users [18]. Figure 1.4 shows the current number of FCEVs and future targets for some selected countries on top [19]. Furthermore, by the end of 2023, in Europe, France had 914, the Netherlands had 615, Germany had 2317, Poland had 165, Austria had 67, and Italy had 71 FCEVs [20]. This number tends to increase, and it is predicted that there will be 13 million FCEVs in operation worldwide by 2030 [21]. Both EVs and FCEVs depend on electricity for their operation. There will be millions of EVs on roads soon, which will put a huge burden on the electric power systems.

1.2 Research problem Statement

The rapid growth of EVs and FCEVs transforms the transport sector, presenting a feasible approach to reducing GHG emissions. Yet, this transition brings notable challenges for electric power systems, specifically in managing the rising and unpredictable electricity demand from EV charging. The situation is further complicated by the integration of RES, such as solar and wind energy, which are naturally variable and intermittent. If not adequately managed, EV charging could result in grid overload, voltage instability, frequency issues, and greater dependence on fossil-fuel-based plants. Traditional grid management approaches are inadequate for addressing the dynamic nature of EV loads coupled with variable RES generation. Conventional demand response programs and static pricing mechanisms do not

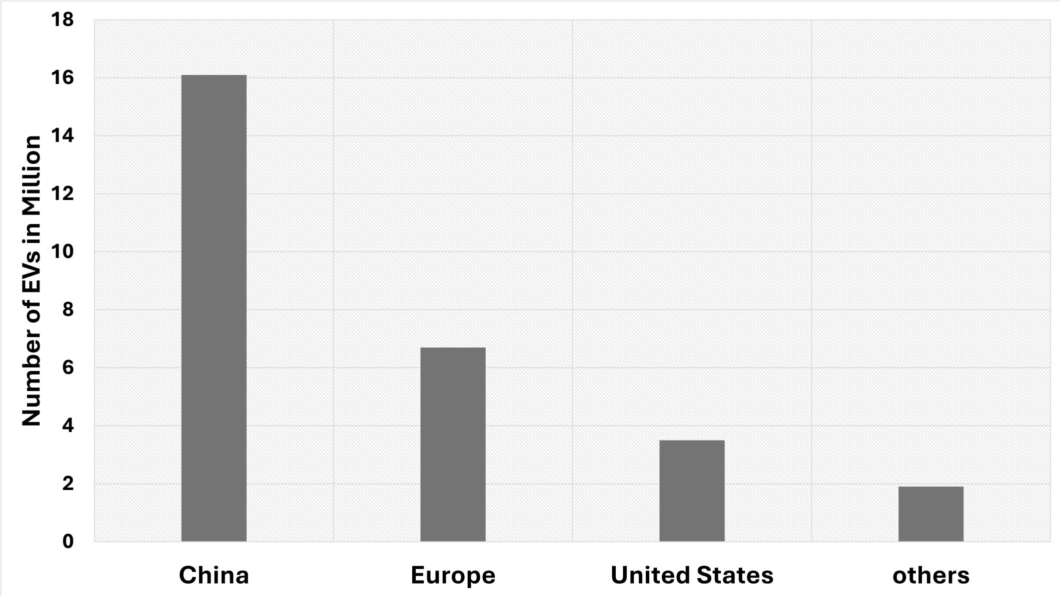


Figure 1.3: EV stock globally in 2023.

consider real-time electricity supply and demand variations. This raises essential questions: How can EV charging be optimized to support the grid rather than burden it? How can Demand Side management (DSM) strategies balance grid demand while maximizing the use of RES? Another critical challenge is the electricity source for EV charging. EVs are considered a sustainable alternative to internal combustion Engine vehicles (ICEVs), but their environmental advantages depend on the carbon footprint of their electricity. If fossil fuels primarily meet the energy demand for EVs, net carbon emissions could stay high or increase. This emphasizes the need for strategies that enhance EV charging efficiency and incorporate more renewable energy to satisfy rising electricity demand. Without a unified effort to align EV growth with renewable energy expansion, the environmental benefits of EV adoption could be undermined.

To gain insight into these challenges, this research begins by analyzing the effects of EVs on the power grid, mainly how widespread EV use boosts electricity demand, results in peak load problems, and may lead to grid instability. The second study investigates the environmental consequences of EVs, highlighting that their advantages can be diminished if the energy for charging is sourced from fossil fuel power plants. The third study broadens this analysis to urban and isolated networks, evaluating how localized grids—like those in cities or island microgrids—confront distinct challenges with high EV adoption. These studies underscore the urgent need for effective DSM strategies to optimize EV charging, balance grid demand, and successfully integrate RES.

This research addresses these challenges by examining advanced DSM EV charging and discharging strategies. It explores the potential of Time-of-Use (TOU) pricing, onsite hydrogen production from RES for FCEVs, and implementing digital twin-based control in microgrids to strengthen grid stability, enhance energy efficiency, and lessen dependence on fossil fuels. By incorporating intelligent DSM methods, EVs can evolve from mere consumers to proactive contributors to the grid, utilizing approaches like Vehicle-to-Grid (V2G) and adaptive charging strategies. This research aims to bridge the existing knowledge gap by develop-

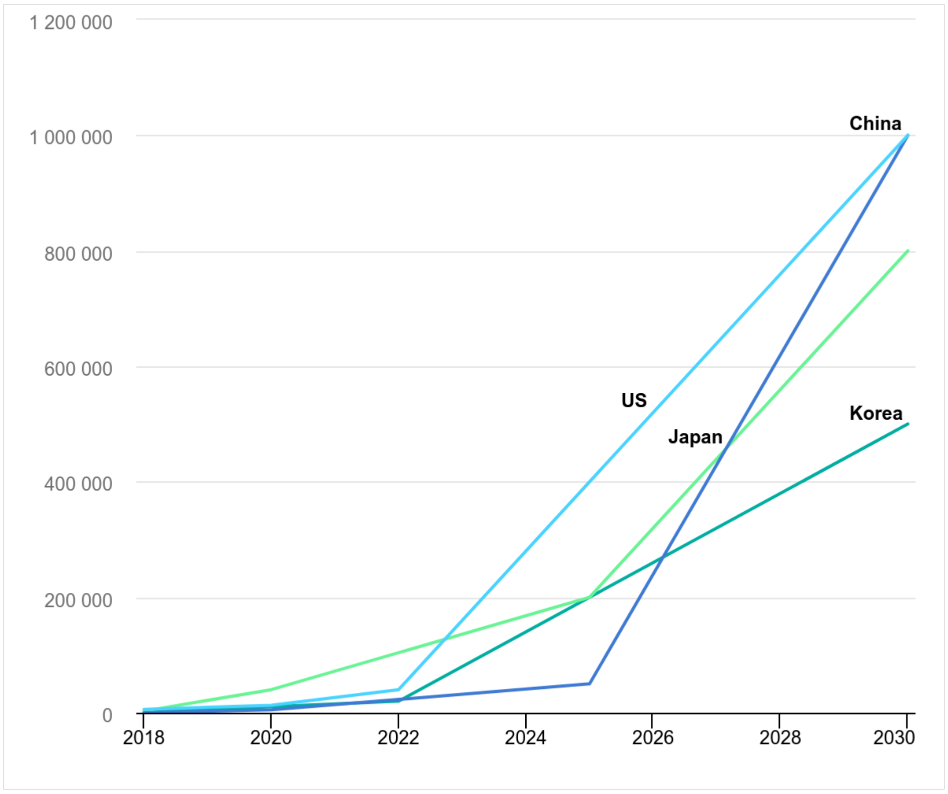


Figure 1.4: Future targets for FCEVs.

ing and assessing DSM frameworks that optimize the interaction between EVs and the grid, promote the effective use of renewable energy, and support a sustainable energy transition.

1.3 Research Question

The primary research question of the thesis is, "How can DSM strategies play a significant role in a grid with high EV adoption and high RES penetration? " Further research questions are given below:

1.3.1 Impact Assessment

- What are the main challenges posed by a significant number of EV transitions on the electricity grid regarding grid stability and load demand?
- How can GHG emissions be affected by the energy source used for charging EVs?
- How can the number of EVs impact the congestion of the transmission and distribution lines of the power grid?
- What are the effects of EVs on urban and insular power systems?

1.3.2 DSM Strategies

- How can TOU electricity prices be used to reduce the stress on the grid?

- How can DSM improve the Coordination between EV charging and RES generation?
- How can V2G technology improve the stability and reliability of RES-based microgrids?

1.3.3 Advanced Techniques

- How can innovative technologies like digital twins be used to implement DSM strategies to support EV demands?
- Can onsite hydrogen production from RES effectively support public transport's electrification and reduce grid and fossil fuel dependence?

1.4 Scope of the Study

This study examines the effects of widespread EVs adoption on power grids, environmental sustainability, and urban as well as remote networks. It focuses on DSM strategies aimed at optimizing EV charging, minimizing peak demand, and improving grid stability, especially in systems integrating renewable energy. The research delves into TOU pricing, V2G technology, and the use of digital twin control in microgrids to boost energy efficiency and lessen dependence on fossil fuels. The study also explores onsite hydrogen production from RES, specifically for public transport, which encourages clean mobility options and lowers emissions. Its goal is to create and assess DSM frameworks and hydrogen strategies that support the sustainable incorporation of EVs and FCEVs into the changing energy landscape.

1.5 Structure of the Thesis

The short details of the thesis' chapters are given below:

Chapter-2: In this chapter, the literature of each study is explained.

Chapter-3: This chapter provides an overview of the impact of the energy sources used to charge EVs. It also discusses the effect of EVs on the distribution grids. The study is conducted in detail for four European countries.

Chapter-4: This chapter further emphasizes the impact of EVs on the environment. The study was conducted in detail for three Italian regions and focused significantly on the role of RES in the transition to EVs.

Chapter-5: This study is conducted to analyze the impact of EVs on urban and insular power networks. The study primarily demonstrates how EV loads can affect different power networks.

Chapter-6: This chapter focuses on the solutions to mitigate the challenges caused by the demand for EVs. The detailed study of TOU electricity prices for charging EVs is highlighted. The last section of this chapter further shows how DSM and V2G support RES.

Chapter-7: This chapter discusses innovative technologies. The use of digital twins for DSM in RES-based microgrids with the penetration of EVs has been discussed in detail.

Chapter-8: The chapter focused on onsite hydrogen generation for FCEVs to support public transportation. Furthermore, the comparison between FCEVs and ICEVs has been highlighted to demonstrate the significance of FCEVs.

Chapter-9: This chapter contains the conclusion of the study, discussing future works and limitations.

Chapter 2

Literature Review

2.1 State-of-art Methodology: Integrating EVs into a Renewable and Flexible Power Ecosystem

The transition to electrified transport represents a cornerstone in the global strategy for carbon neutrality, but its success hinges on more than just the deployment of electric vehicles (EVs). It requires a holistic transformation of the energy ecosystem. The six studies presented in this thesis collectively form a layered methodological approach that integrates policy, energy modeling, grid impacts, and advanced control strategies to achieve a resilient and low-carbon transport future.

At the foundational level, Study 1 assesses the climate benefits of transport electrification in different global regions and under varying Carbon Emission Coefficient Factors (COECFs). By comparing the environmental impact of charging EVs using renewable energy sources (RES) versus fossil-based grids, the study establishes a critical boundary condition: electrification without clean electricity has limited climate benefit. This sets the stage for further investigation into the systemic requirements of EV integration.

Building on this, Study 2 and Study 3 explore the operational impacts of large-scale EV deployment on both continental (urban) and isolated (insular) grids. These studies analyze technical issues such as voltage stability and peak load increase, emphasizing the spatial dependency of EV impacts. The comparative analysis between a major city (Palermo) and an isolated island (Favignana) demonstrates the need for customized solutions, highlighting how grid constraints and demand profiles shape the feasibility and risk of EV integration.

To mitigate these operational challenges, Study 4 and Study 5 introduce Demand Side Management (DSM) as a technological and economic solution. Study 4 examines the use of Time-of-Use (TOU) pricing and residential battery storage to shift EV charging to off-peak periods, while Study 5 elevates this strategy through the application of digital twins. By modeling real-time system dynamics, digital twins allow predictive and adaptive control over EV charging, enabling load balancing in grids with high renewable penetration. Together, these studies transition the methodology from passive forecasting to proactive grid optimization.

Finally, Study 6 broadens the scope by including Fuel Cell Electric Vehicles (FCEVs) and the onsite production of green hydrogen using RES in microgrids. This provides an alternative zero-emission pathway for sectors where EVs may be less feasible (e.g., heavy transport), and connects the decarbonization of transport to hydrogen economies. The study demonstrates that microgrids with RES and hydrogen infrastructure can provide both local energy resilience and sustainable transport fuel, especially in remote or space-constrained environments.

The first three investigate the impact of EVs on the environment as an emissions source and the power grid as a load. These studies also examine the effect of EVs on insular and urban power systems networks. The last three studies propose solutions to mitigate the negative impact of EVs on the power grid. Further, these studies illustrate EVs' coordination with RES in grid-connected systems and smart microgrids. The six studies are shown in Figure 2.1 and each study's literature and key novelty are discussed in detail below. In sum, this thesis offers a cohesive methodology that:

- **Quantifies** the environmental merit of EV adoption under varying grid scenarios.
- **Diagnoses** grid-level challenges from high EV penetration in different network topologies.
- **Implements** DSM techniques, enhanced with digital technologies, for operational resilience.
- **Extends** the decarbonization potential through green hydrogen and FCEVs in RES-based microgrids.

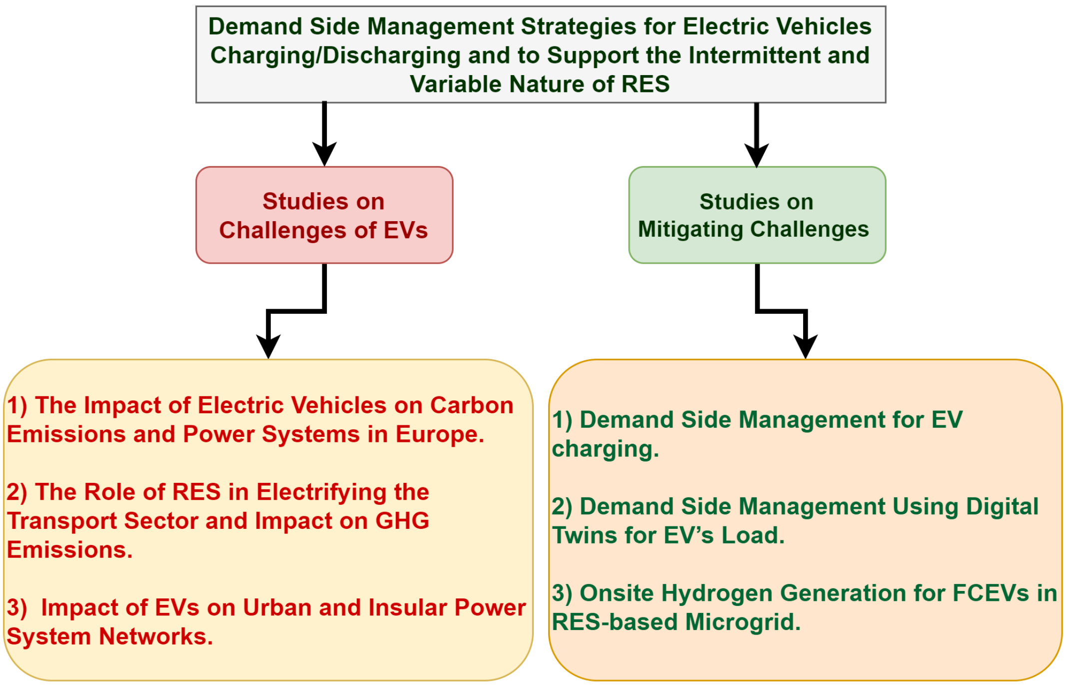


Figure 2.1: List of Studies Done.

2.2 Study 1: The Impact of Electric Vehicles on Carbon Emissions and Power Systems in Europe

The global climate is increasingly erratic and unpredictable, with a 1.1°C rise in temperature already yielding widespread disasters. Events like the devastating flood in Pakistan, which affected over 33 million people, the unforeseen bushfires in Australia, and frequent wildfires in Italy and the United States underscore the significant impact of climate change. Moreover, occurrences like the Himalayan glacier burst in India and urban floods in Europe further highlight this trend. These events, along with extreme droughts and high temperatures, pose severe threats to the livelihoods and food security of millions globally [22, 23, 24]. The Intergovernmental Panel on Climate Change (IPCC) report shows that these extreme weather conditions will be more severe and more frequent, resulting in the sea level rising and forcing the mass migration of people [25]. The change will impact the ecosystem since crops will likely fail and human life will be at high risk. Climate change will soon have far-reaching effects on human life. To address global warming, many European Union (EU) countries have established both short-term and long-term goals for reducing GHG emissions in alignment with commitments made under the Paris Agreement. These goals include a Net-Zero Pledge, aiming to decrease Carbon Dioxide (CO_2) emissions to 21.1 Gt by 2030 from 33.9 Gt in 2022, with a further reduction target to 6.3 Gt by 2040, ultimately aiming for zero CO_2 emissions by 2050 (NZE2050) [26]. The Sustainable Development Scenario (SDS) shows different goals and projections for reducing GHG emissions in various sectors by 2030 [27]. A goal of 5.9, 1.2, 1.1, and 0.7 Gt reductions in emission from the power, industry, transport, and buildings sectors has been set, shown in Figure 2.2. Compared to SDS goals, there will be an additional reduction in GHG emissions for each sector for the NZE2050 scenario by 2030.

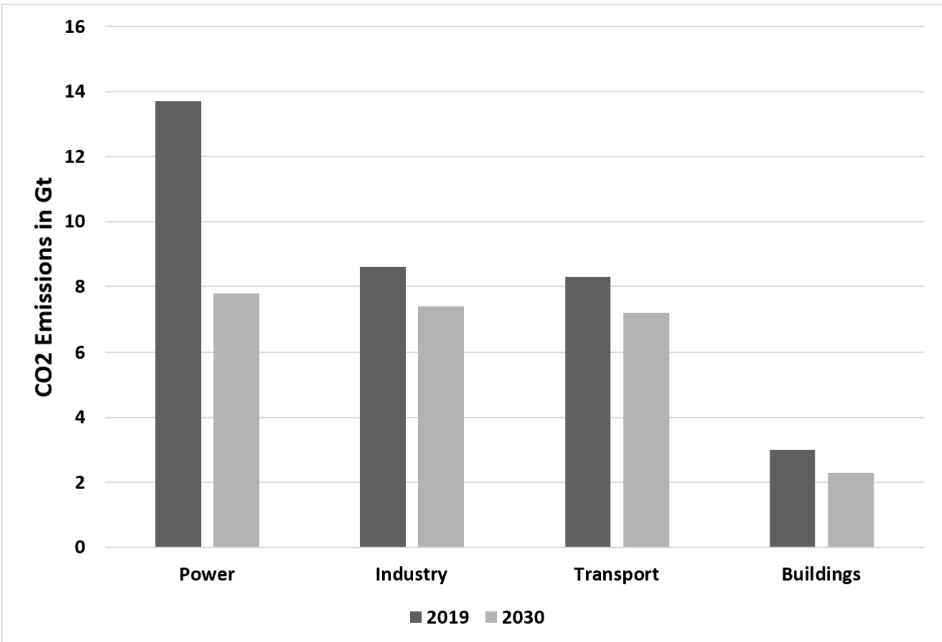


Figure 2.2: Share of each sector in GHG emissions from the energy sector .

The transport sector is one of the highest contributors to CO_2 emissions globally. The energy sector contributes approximately 73.2% of global emissions, of which 16.2% is from the transport sector [28]. Road transport, mainly passenger cars, stands as the most significant contributor to GHG emissions in the transport sector. In 2019, cars alone contributed approximately 500 thousand kt of CO_2 emissions in the EU, surpassing emissions from other vehicle types. This underscores the significant role of passenger cars in climate change and the pursuit of NZE2050 goals. Without appropriate measures, road transport is projected to contribute over 70% of GHG emissions from the entire transport sector by 2050 [28].

Also, the energy demand for the transport sector is growing much faster as compared to any other sector; thus, this sector needs to be cleaner and more environmentally friendly, as it accounts for 29% of the final energy consumption, and only 3.7% is from Renewable Energy Sources (RES) [29]. Many governments worldwide are working on electrifying the transportation sector and moving toward EVs [30]. Global EV market shares have increased exponentially, as governments and consumers spent double on EVs in 2021, which led to a significant increase in the EU and China [31]. The rising global EV sales and market shares are shown in Figure 2.3. In 2021, there were approximately 2.3 million EV registrations in the EU, and in China, 3.4 million EV registrations were recorded [32].

It has been estimated that there are approximately 16 million EVs on the roads, consuming around 30 TWh of electric energy annually. The market for EVs tends to increase more and more quickly. For example, the United States set a goal to achieve 50% electrification of new cars by 2050 and also to install 500,000 charging stations. EU countries and automakers have announced a target 30% of EVs by 2035 [32]. The prediction shows there will be around 70 million EVs by 2025, and nearly 230 million EVs by 2030, and the stock shares of EVs will rise to 12% [33].

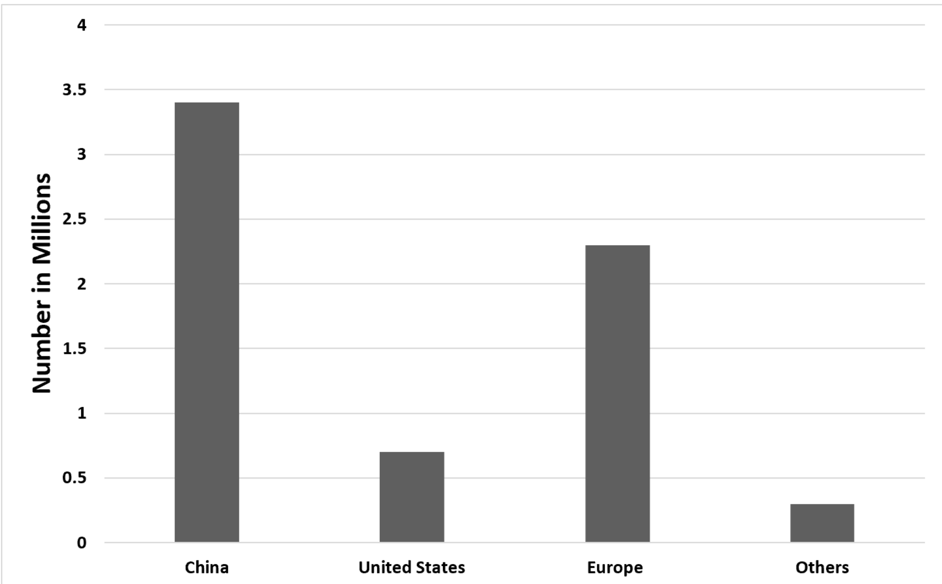


Figure 2.3: Electric cars global sales 2021.

The shift from Traditional Passenger Vehicles (TPVs) to EVs is significant and could strain the power system without prompt implementation of proper strategies. EVs with fast onboard charging of 350 kW per charge could increase building power demand by over 250% By 2030, in China, the EU, and the United States alone, the energy needed to charge EVs will exceed 270 billion kilowatt hours [34]. The substantial energy demand for charging EVs challenges achieving clean and carbon-free transportation systems. Figure 2.4 illustrates the electric energy required by EVs in 2025 and 2030. By 2030, 271 billion kWh of energy from RES will be needed to achieve a net-zero-emission transport sector [35]. RES is crucial in decarbonizing transportation and is closely linked [35]. Shifting the energy mix towards RES is essential to reduce indirect emissions from EVs and make them emission-free. Currently, coal constitutes about 38% of global electricity generation, exceeding 60% in some growing economies like India and China [36]. Timely solutions to these challenges are imperative to ensure a clean and environmentally friendly transport sector.

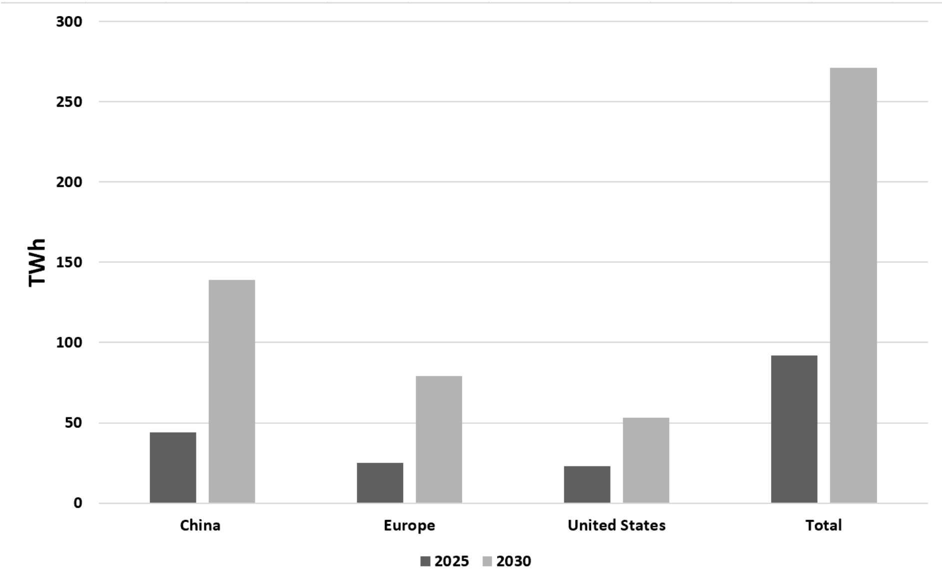


Figure 2.4: Energy demand to charge EVs.

Many studies have already been carried out to study the impact of EVs on power systems and climate change. One of the studies examined 30 provinces of China and focused on the role of EV charging infrastructure in mitigating climate change [37]. Similar studies on how EVs can contribute to reducing GHG emissions and improving air quality have been carried out [38, 39, 40, 41, 42, 43, 44]. Many researchers have examined the carbon footprint of the EV lifecycle, including the production, use, and recycling phases. However, most of these studies are generic and do not consider different levels of EV market penetration [45, 46, 47, 48]. Many of these analyses have concentrated on the emissions associated with EV battery production and have compared the entire lifecycle emissions of EVs to those of TPVs. Previous research has predominantly addressed indirect emissions from EVs across their entire lifecycle. This study focused on the use phase of EVs with three different penetration levels of 10%, 30%, and 60% of EVs with consideration of the short-term, medium-term, and long-term goals, respectively, and for Switzerland, Italy, Germany, and Poland with low, medium, medium-high, and high Carbon Emission Coefficient Factors (COECFs), respectively. These four countries were selected due to their varying COECF levels: Switzerland has the lowest COECF, Poland has the highest, and Italy and Germany fall in between. Therefore, this choice enables the study results to be extrapolated across the entire European region by incorporating data from other countries that exhibit similar energy profiles to the one analyzed in the study. In addition to this, the study also focuses on the impact of fast charging demand requirements on the power transmission and distribution systems. In concluding this study, the capital cities of the four examined countries are taken into account. The study investigates the power demand in each city as well as the projected requirements for the fast charging of electric vehicles, employing the IEEE-14 bus system with modifications made using PSS®E software. The key contributions of this study are given below.

2.2.1 Novelty and Key Contribution of the Study

This research brings several novel contributions to the field:

- Use Phase of EVs: Unlike previous studies that look at the entire lifecycle, this work specifically examines the use phase of EVs at different market penetration levels.
- Comparative Analysis: The study compares the environmental impact of EVs in Switzerland, Italy, Germany, and Poland, chosen for their varying COECFs.
- Impact of Fast Charging on Power Grids: This research explores the effects of fast charging requirements on power distribution lines, a less studied area.
- Scenario Analysis with Extreme Energy Mixes: It examines two extreme scenarios—100% renewable energy and 100% coal-powered plants for charging EVs to understand the range of impacts on greenhouse gas emissions.
- Use of Simulation Software: The study uses the IEEE-14 bus system with modifications in PSS®E software to simulate and evaluate the EVs' impact on power system.
- Derivation of Maximum COECF Limit: Additionally, the study derives the maximum COECF limit for EU countries for which an EV can reduce CO_2 emissions compared to TPVs.

This study is aimed at engineers, scholars, policymakers, and industry experts in energy, transportation, and environmental sustainability. It thoroughly examines the ramifications of EV adoption on energy consumption, focusing on four EU nations. This study underscores the significance of regional energy compositions by analyzing scenarios aligned with NZE2050 goals and exploring various energy mix configurations for EV charging. Leveraging simulation software, this study assesses the impact of EV load on transmission and distribution infrastructure, highlighting the imperative of infrastructure upgrades. Moreover, this study offers actionable insights for policymakers, emphasizing the urgency of renewable energy objectives and integrated strategies to alleviate grid pressure. This research contributes valuable insights to the discourse surrounding the shift toward sustainable transportation and energy systems, outlining challenges and suggesting solutions for a resilient and environmentally conscious future.

2.3 Study 2: The Role of RES in Electrifying the Transport Sector and Impact on GHG Emissions

This study comprehensively discusses the impact of EVs on GHG emissions, emphasizing the role of RES. Different studies show that light-duty vehicles significantly affect climate decarbonization goals, making electrification in this sector a crucial global opportunity [49]. Although there are specific pathways set to achieve the goals of electrification of the transport sector, according to the International Energy Agency (IEA) report, Global EV Outlook 2021, there will be 145 million EVs excluding two/three-wheelers by 2030, and can be reached to 230 million EVs in 2030, if the governments speed up the efforts to achieve the climate goals [50]. However, the main problem will be the source from which electricity will be generated to charge the EVs. If the electricity used for charging EVs is not from RES, then there will be no significant effect of electrification of the transport sector on climate change goals.

Numerous studies have demonstrated the effects of EVs and FCEVs on various power systems, with the impact of RES. The cost of the refueling station and charging stations from RES for EVs and FCEVs has been analyzed in [51]. The proposed model is then applied to a case study on passenger cars for German highways. A case study for the Beijing-Tianjin-Hebei region indicates that without increasing RES power capacity and with 100% EV penetration, it could generate energy savings and will reduce GHG emissions by at least 11% by 2050 [52]. A study for the Italian transport and heating sector has been conducted [53]. This study focuses on how the increasing electricity demand of the transport and heating sectors supports RES penetration. The study further illustrates that the electrification of both these sectors can reduce GHG emissions by up to 25%. The study [54] examines the feasibility and costs of climate objectives across energy scenarios, stating that low-carbon transportation relies on biofuels and synthetic fuels. At the same time, electrification better integrates nuclear and RES, affecting easing costs. Another study for Nepal using the MARKAL model examined the benefits of transport sector electrification [55]. The study finds that 35% EV penetration will require 495 MW hydropower and 7.86 additional TWh electricity generation by 2050. This transition reduces the GHG emissions by 12.9%. A study [56] utilizes the TIMES-Canada model to evaluate the transport sector electrification, assessing baseline, energy policy, and climate policy scenarios. Results showed that EV adoption speeds up post-2040 under the standard scenario and after 2030 with aimed policies. In contrast, climate policies prompt a more significant transition, leading to the elimination of ICEVs.

Moreover, many other studies have been done on regions moving toward zero emissions transport systems, but no such research has been done in detail for the Italian transport sector. Like in [57], a study has been done on China's transport sector decarbonization, and long-term pathways and strategies have been discussed. Also, in [58], policies and strategies have been discussed for decarbonizing China's roads, and emissions reduction targets have been set. In [59], different pathways have been proposed for the Danish transport sector for zero carbon transport and concluded that electro-fuels will play a vital role in achieving these goals. In this study, the decarbonization impact of EVs combined with the COECF of power plants has been studied and discussed in detail for three different regions of Italy: the Tuscany region, Sicily region, and Sardinia region. All three areas have different COECF levels for electricity grids. Along these three regions, two scenarios: the ideal scenario with 100 % RES in the power grids for charging the EVs with the lowest COECF of the grid, and the extreme scenario with all the generation from coal power plants in the power grid for charging the EVs have been studied and compared the results with the CO_2 emissions from traditional passenger vehicles.

2.4 Study 3: Impact of EVs on Urban and Insular Power System Networks

This study considers the insular power network of Favignana Island and the urban power network of Palermo city. The effects of EVs on both these networks have been thoroughly examined in comparison to one another. The increased number of EVs and FCEVs will significantly impact grid stability, Voltage stability, and load balancing. Numerous studies have been conducted on the effect of EVs on voltage stability. In [60], the EVs' impact on voltage instability, power quality, power supply and demand imbalance, and the environment has been discussed. A study illustrates the power grid issues caused by EV penetration, like demand and supply mismatch and voltage fluctuations [61]. EV chargers are power converters serving nonlinear loads. This nonlinear behavior of EV chargers causes voltage instability in the power grids [62]. The study [63] showed the issue related to power quality. The study conducted on the power grid in Bangladesh revealed problems with the voltage profile and highlighted the impact of integrating EVs on the transformers within the distribution system. The effect of EVs on the medium voltage distribution system has been shown in [64]. The study discusses the overvoltage and undervoltage issues associated with RES and EVs. A sudden increase in EV load can cause instability in the power grid voltages. Hence, the voltage stability of the power grid is highly distorted with the integration of EVs into the grid [65, 66]. A large number of EVs can put a great deal of stress on the distribution network's components, especially on power transformers. A study [67] showed that a sudden increase in load with the integration of EVs increases the transformer temperatures to notable limits at distribution ends. In addition, the life and performance of the transformer have been studied with various types of EV charging in [68, 69, 70].

Most problems can occur due to an increase in load demand. Hence, many studies have been done to examine the impact of high EV penetration on grid demand. A study [71] showed 53% increase in load demand with 30% penetration level of EVs. The residential distribution network demand significantly increased with just 10% of EVs [72]. Additionally, a study [73] examines the impact of a 100% penetration level of light-duty EVs on peak demand. This whole penetration level significantly increased peak demand and affected grid stability. A study [74] showed that even a small number of EVs could exceed the demand limits when charging during peak hours. Many other studies investigate the impact of EVs on increasing demand for power grids [75, 76, 76].

The literature indicates that most grid problems can arise from a sudden increase in load demand. This study has developed a case study for two regions of Italy: the city of Palermo and Favignana Island, which were chosen as the urban and insular power networks, respectively. Both regions represent entirely different power system networks. This research investigates the impact of 10%, 20%, and 50% EV penetration on the load of both power grids. The complete study, results, comparisons, and discussions are presented in detail in Chapter 5.

2.5 Study 4: Demand Side Management for EV charging

Electricity demand can vary significantly due to abrupt changes in weather, fluctuations in economic activity, infrastructure damage, increased usage of EVs in large quantities, and other reasons. At times, these variations can result in power failures. Shifting to RES can also cause these variations, as power consumption may increase while the supply of renewable energy is uncertain. This evolving energy landscape emphasizes the need for a more flexible electricity grid. Fortunately, we possess practical tools to manage these peak-demand situations, ensuring reliable service and increasing reliability and cost savings for utilities and consumers. Demand Side Management (DSM) stands out as a key strategy employed to regulate demand, encouraging consumers to adjust the level and timing of their electricity usage [77]. In the present smart grid context, there is an opportunity to further leverage this aspect of EVs by integrating them into DSM strategies within the grid. DSM can be crucial in charging EVs to mitigate peak load and reduce charging costs [64, 78, 79, 80, 81]. Different DSM strategies are shown in Figure 2.5 [82].

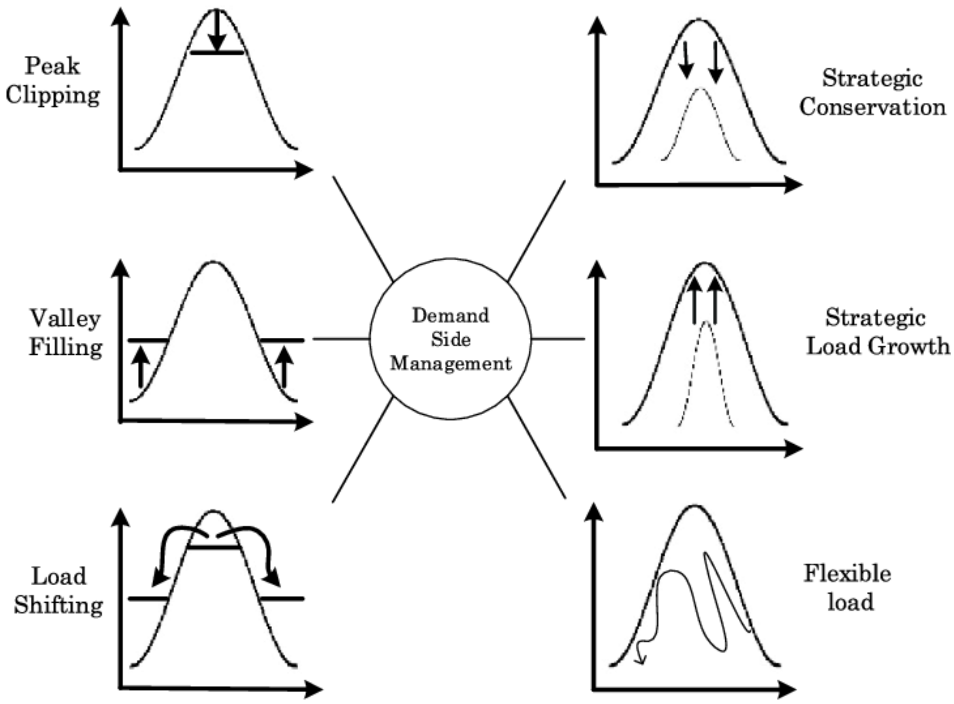


Figure 2.5: Demand Side management Strategies.

The main goal of the DSM strategies is to manage the load of the power system efficiently and effectively and to minimize the overall cost of the power system. Thus, these strategies can be applied to manage EVs' load effectively and smooth the load profile of the power system. One of the main DSM tools is to use the Time-of-Use (TOU) of electricity prices to manage the users' energy consumption. TOU prices strategy can be used to achieve peak clipping, Valley filling, and load shifting, as shown in Figure 2.5. Different researchers have used TOU strategies to charge EVs in various ways. In [83], accurate data has been utilized for distribution systems and driving distances for the Republic of Korea with TOU prices to design an intelligent charging system for leveling loads in aggregated moods. In [84], they used data from 45 charging stations in Tianjin, a significant city in North China comprising over 47,000 charging instances, to model the charging behavior and power demand, and they proposed a charging strategy to reduce the cost and GHG emissions. Like the previous two papers, most worked on charging the EV fleet and have not considered additional battery storage [85, 86, 87, 88]. In other research, batteries have been used only in photovoltaic generations [89]. However, this research has considered a single residential charging system with additional battery storage for power storage during off-peak hours for later use in charging the EV in peak hours. Also, this research is done for the areas where the consumer has only access to the grid, and no photovoltaic energy is available due to space, weather, or other reasons. The complete study has been presented in Chapter 6.

2.6 Study 5: Demand Side Management Using Digital Twins for EV's Load

DSM plays a vital role in the stability, reliability, and security of modern grids and microgrids [90]. Soon, the number of EVs on the roads will reach millions, placing a significant burden on the grids due to increased electric loads [91]. This high electricity demand can be managed by introducing new technologies to implement DSM strategies, such as load shifting and peak shaving [92, 93, 94]. RES are intermittent and variable and can cause load-balancing issues if not adequately managed. Many studies have been done to support the variability of RES using DSM [95, 96, 97]. Other studies focused on EV management using different DSM techniques. In [98], deep learning techniques were used for the EV charging station utilizing DSM. In [99], a grid-connected PV, Wind, and battery system was studied with EVs as a load. TRANSYS software has utilized DSM for EVs charging to minimize the burden on the grid and maximize the profit. Another study showed a 10-12 percent reduction in electricity consumption when DSM is used with EV [100]. DSm strategies have been used for EVs with different types of chargers using fuzzy logic [101]. The DSM impact on the integration of RES and EVs has been studied in [102]. Further, a study has been conducted for ROME, Italy [103], with a demand-side approach for the optimal charging of EVs.

Advanced technologies like digital twins can significantly improve power systems' stability. Various studies have used digital twins for EV or its battery analysis [104, 105, 106, 107]. The research study in this thesis is different. It illustrates using digital twins for load shifting, valley filling, and peak shaving of EV loads. The study explains the concept, benefits, tools required, and implementation methodology in detail. Further, the digital twin concept is utilized for the DSM of EV loads. The results and details of the study are given in the chapter.

2.7 Study 6: Onsite Hydrogen Generation for FCEVs in RES-based Microgrid

The FCEV market is growing exponentially. Different countries have implemented policies and are working to mitigate the challenges faced in transitioning to FCEVs. Researchers are also contributing, so many studies have been conducted on onsite hydrogen generation using RES, emphasizing its potential as a sustainable energy solution. A study in Queensland, Australia, investigated the influence of increasing the capacity of solar photovoltaic (PV) systems, wind turbines, and electrolyzers. The study concluded that the target hydrogen price of 2 USD/kg could be achieved by 2040, considering scaling effects [108]. Researchers in Chile studied how local renewable energy sources, hydrogen delivery times, and generation curtailment impact the Levelized Cost of Hydrogen (LCOH). Based on these factors, the LCOH varied from $2.67 to $12.74 per kilogram [109]. A cost-effective stochastic model was developed for the optimal placement of hydrogen fueling stations on an island in Turkey. This model considers a high penetration of RES and includes a demand response program. The findings suggest that system operators can utilize hydrogen storage systems and responsive electricity demands to improve sales and profitability in the local hydrogen market [110]. Integrating green hydrogen into various sectors, such as heating, lighting, transportation, industry, and power generation, has been explored as a strategy to mitigate GHG emissions. A comprehensive discussion on the challenges, impacts, and future policies of green hydrogen integration for regions including Japan, the EU, the USA, Australia, and Canada has also been provided [111]. Focusing on Canada, a study investigated green hydrogen potential across 13 provinces and territories using offshore and onshore PV systems. The green hydrogen production potential was quantified as 0.34, 1.6, 2.13, 9.16, 11.07, 12.61, 17.81, 19.01, 19.75, 20.11, 25.62, 29.94, and 39.54 Mt for Prince Edward Island, Nova Scotia, New Brunswick, Newfoundland and Labrador, Yukon, Northwest Territories, Manitoba, Saskatchewan, Alberta, Nunavut, British Columbia, Ontario, and Quebec, respectively [112]. In Queensland, Australia, another study analyzed three scenarios for green hydrogen production from multiple RES: PV only, wind only, and a combination of both. Results revealed that the LCOH was lowest for wind-only systems at 4.26 USD/kg and highest for PV-only systems at 14.378 USD/kg [113]. A dataset of over 4,500 hydrogen refueling events across multiple years was also analyzed in [114]. The findings highlighted that stable and consistent hydrogen production improved the energy efficiency of the refueling stations. Seven RES-based designs for EV charging and hydrogen refueling stations in Karachi, Pakistan, were evaluated. Among these, PV and biogas-powered stations were identified as the most cost-effective, achieving an LCOH of 4.28 USD/kg [115]. Further research in Egypt developed an atlas for green hydrogen production using wind and solar energies. The study concluded that the LCOH varied between 1.07 USD/kg and 3.27 USD/kg across different regions and scenarios [116].

Multiple studies have focused on techno-economic analyses. In Northern Germany and California, optimally sized PV-wind systems achieved LCOH between 4.5 and 5.3 USD/kg, driven by local energy potentials and scaling benefits [117]. South Africa's combined solar-wind system demonstrated hydrogen production with an LCOH ranging from 4.45 USD/kg to 5.97 USD/kg. The proposed system also enabled the export of power to the grid, emphasizing its efficiency in the mitigation of GHG emissions in the power sector [118]. In rural India, a hybrid RES system produced 1,838 kg of hydrogen yearly for 330 INR/kg, indicating its feasibility for rural electrification and transportation needs [119]. In a study, decentralized hybrid solar-wind systems in Fiji have achieved LCOH values ranging from $8.73 to $13.00 per kilogram while significantly lowering CO2 emissions [120]. In Sub-Saharan Africa, green hydrogen offers a potential solution for easy access to energy and net-zero emissions. However, economic feasibility is a concern. Increasing the efficiency of the electrolyzer and scaling production could minimize the costs, estimated at 9.49 USD/kg [121]. A techno-economic analysis of hydrogen transportation and storage also examined cost optimization strategies for delivering hydrogen from production sites to refueling stations across various scenarios [122]. In Kentucky, a study found that integrating hydrogen production with solar-powered EV charging stations resulted in LCOH values of 10 USD/kg, 6.5 USD/kg, and 4.3 USD/kg, showcasing the economic potential of these systems [123].
Numerous studies have examined various types and numbers of hydrogen vehicles in the con-

text of hydrogen refueling stations. For instance, A techno-economic analysis conducted in Gokceada, Turkey, evaluated 25 hydrogen vehicles, each with a small storage capacity of 5 kg. The study assessed wind-solar-battery and wind-battery systems, resulting in LCOH values of 8.92 USD/kg and 11.08 USD/kg, respectively [124]. Similarly, another study examined seven African cities, focusing on wind energy as the exclusive source for hydrogen production. This scenario's LCOH varied between 6.34 and 8.97 USD/kg [125]. A separate analysis evaluated 24 hydrogen vehicles with 5 kg storage capacities in Niğde, Turkey, and Zaragoza, Spain. The study found that the LCOH for a solar PV system in Niğde was 6.15 USD/kg, while the LCOH for a combined Wind-PV system in Zaragoza was 5.83 USD/kg [126]. An analysis proposed an off-grid solar refueling station for small aerial vehicles weighing less than 25 kg, focusing on hydrogen storage capacity. This study was conducted by Boeing Research and Technology Europe [127]. Furthermore, a study in the Fielding area of New Zealand examined hydrogen refueling stations for fuel cell tractors and trucks. This research focused on optimization using the moth-flame algorithm, resulting in LCOH of 4.61 USD/kg [128].

Limited research has been conducted on hydrogen production and refueling infrastructure in Italy. A study examined the feasibility of hydrogen production and refueling stations, highlighting the need to develop hydrogen infrastructure [129]. A CNR-ITAE survey reviewed the development of fuel cell microcars for 14 Sicilian islands, assisting advances in clean transportation [130]. Subsequent research examined the challenges and opportunities of green hydrogen within the geopolitical context of the region [131]. One of the studies analyzed hydrogen fuel buses in four European cities, comparing their emissions to diesel buses and highlighting the environmental benefits of adopting hydrogen [132]. Another study examined hydrogen refueling stations for heavy-duty vehicles involved in long-distance freight transport, considering a penetration rate of 5-7%. The results highlighted substantial reductions in GHG emissions and calculated the hydrogen requirements for the specified penetration rates [133]. A comprehensive analysis was conducted on hydrogen infrastructure for sustainable mobility in three Italian cities: Milan (in the north), Rome (in the center), and Catania (in the south). The study evaluated two energy supply options: connecting to the grid using green energy through Power Purchase Agreements and direct connection to solar PV systems. The LCOH is €7.4/kg to €67.8/kg for the first option, though for the other option, it varied from €5.5/kg to €27.5/kg [134].

The novelty of the proposed study lies in its comprehensive and location-specific approach to onsite hydrogen-based public transportation. Which differentiates this study from existing studies in the area. Unlike the aforementioned research, which frequently focuses on hypothetical assumptions or generic scenarios. This study is precisely modeled from the perspective of Favignana Island and presents several key distinct features:

- This study focused entirely on Favignana Island and examined the feasibility of public transportation powered by green hydrogen. Until now, there has been no such study available for this region.
- This study relies on actual data from the island. This data includes the bus routes, schedules of the buses' arrivals and departures, and the daily operation of buses to get the actual demand for hydrogen required. While most of the studies assume the generic number of vehicles or penetration levels of vehicles.
- The study also covers the seasonal variations in demand for the fuel requirement of

public transport. Hydrogen demand for both peak (Summer) and off-peak (Winter) has been analyzed to provide insight into variation in hydrogen demand

- A comprehensive cost analysis has been performed to assess the economic feasibility and cost affordability of diesel and hydrogen fuel cell buses on a per-kilometer basis. This analysis specifies a significant understanding of the financial implications of each fuel type. In addition, the reduction in GHG emissions for both fuel types of buses has been discussed in detail.
- The study identifies Favignana Island as an optimal location for solar PV-generated hydrogen stations for refueling. The summer demand increases by three times, which the high potential of solar PV energy in summer on Fvignana Island can cover.

This study uniquely links theoretical analyses with practical applications and showcases an economical, sustainable, and feasible model for hydrogen-powered public transportation on Favignana Island.

Chapter 3

The Impact of Electric Vehicles on Carbon Emissions and Power Systems in Europe

The global trend is shifting toward adopting low-carbon transportation solutions, with electrification emerging as a prominent approach. The effectiveness of this transition in mitigating climate change hinges significantly on the source of electricity used for charging Electric Vehicles (EVs). This chapter focuses on four European Union (EU) countries: Switzerland, Italy, Germany, and Poland, each characterized by varying levels of carbon emissions from their power systems. Assumptions are made for the short-term (10%), medium-term (30%), and long-term (60%) penetration of EVs, aligning with the 2050 net zero emissions targets. The study investigates the impact of these penetration levels on energy demand, exploring scenarios ranging from 100% renewable source-generated electricity to 100% coal-generated electricity for EV charging. Finally, utilizing PSS®E, simulation software, the study assesses the implications of the EVs' load on medium-voltage transmission lines. The findings highlight the substantial influence of electrifying the transport sector on environmental sustainability and the power system infrastructure, underscoring the critical role of regional energy mixes and the power system Carbon Emission Cofficient Factor (COECF). Even with a modest transition to EVs, regions with lower COECF witness significant benefits. In contrast, regions with high COECF experience minimal impact despite large-scale EV adoption. Additionally, densely populated urban areas may encounter challenges related to transmission line congestion in meeting the growing demand for EVs charging.

3.1 Methodology

Four EU countries were selected for this study, Switzerland with low COECF, Italy with medium COECF, Germany with medium-high COECF, and Poland with high COECF of the power grid. The flow chart in Figure 3.1 shows the step-by-step methodology of this research. This research focused on two areas:

(i) The Environmental Impact of EVs, which is an analytical study aimed at analyzing the impact on greenhouse gas emissions if traditional vehicles are replaced by a certain percentage of EVs, taking into account the share of Renewable Energy Sources (RES) in electricity production.

(ii) The impact of EVs on the grid infrastructure, which is a simulation-based study, performed in the PSS®E environment and aimed at assessing whether the replacement of conventional vehicles with EVs, even if it has a potentially positive environmental impact, may lead to the establishment of excessive power flows in electricity distribution networks.

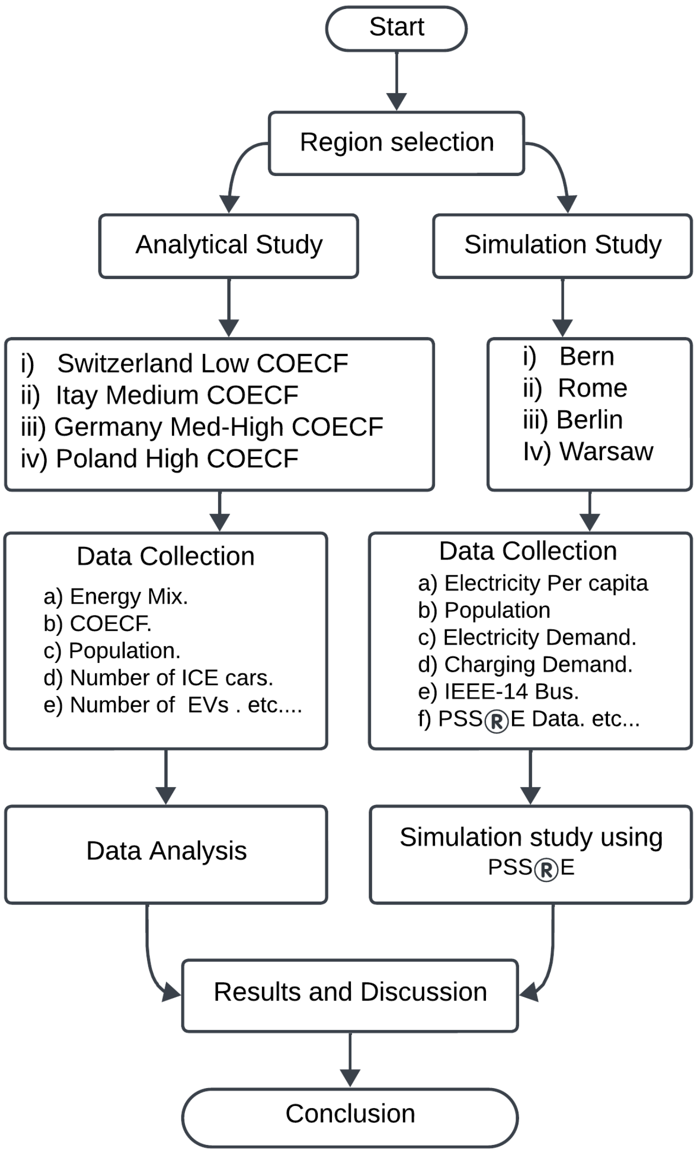


Figure 3.1: Flow chart of the methodology.

For the simulation study, the capital cities of the four selected countries were considered. After choosing the regions for both studies, the data were collected for the analytical research and the simulations. The analytical study gathered necessary data for the energy mix, COECF, population, Number of Internal Combustion Engine Passenger Cars (ICEPCs) per person, number of EVs, EVs' efficiencies, and average traveling distances for all the regions. After the data collection, the study was extended to the NZE2050 scenario for all four countries with different penetration levels of EVs. Two scenarios, the ideal scenario of 100% of wind energy available for charging the EVs and the extreme scenario of 100% power available from coal power plants to charge the EVs were also discussed to study the role of RES in the electrification of the transport sector in more detail. After collecting the data, they were transformed into helpful charts and graphs for better understanding. The data were then analyzed, and results were obtained. For the simulation study, the necessary data of the capital city of each country were collected, as shown in Figure 3.2. Then, the IEEE-14 bus system was used as a test case power system using PSS®E simulation software. The details of this study are given in the following in-depth sections.

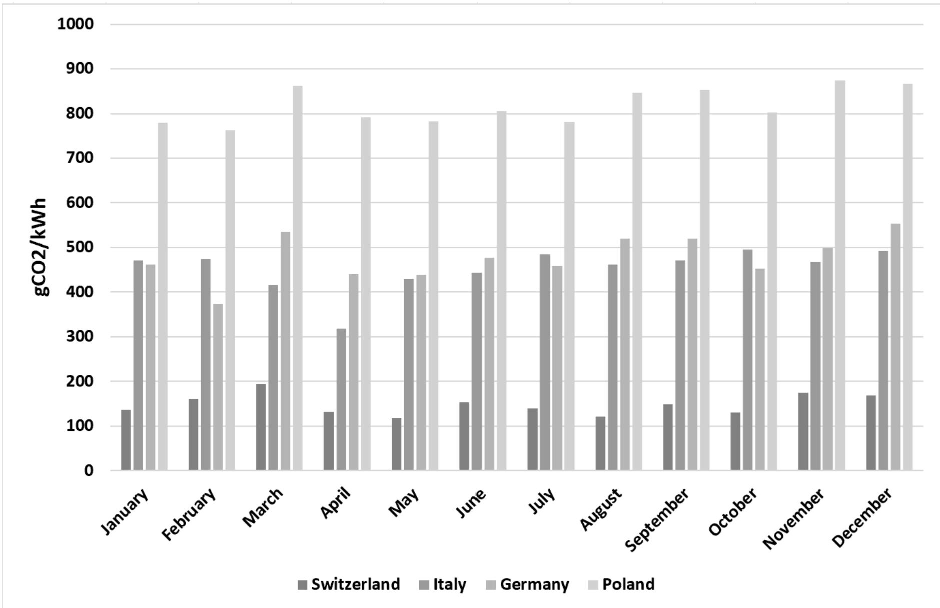


Figure 3.2: COECF for Switzerland, Italy, Germany, and Poland for the year 2022.

3.1.1 Sources Used for Data Collection

This research collected data from various sources, including online websites, reports from reputable organizations, journal papers, and books. Notably, about 70% of the data came from online sources and reports from international organizations, such as the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), the International Automobile Federation Foundation (FIA), the World Food Program (WFP), the International Renewable Energy Agency (IRENA), and European Commission energy reports. Specifically, for 57% of data from online websites, 37% of the online data was sourced from prestigious European industry websites, 18% from reputable international organizations, 18% from government agency websites, 12% from EU project websites, and the remaining 18% from small company websites, blogs, and researcher websites as shown in Figure 3.3.

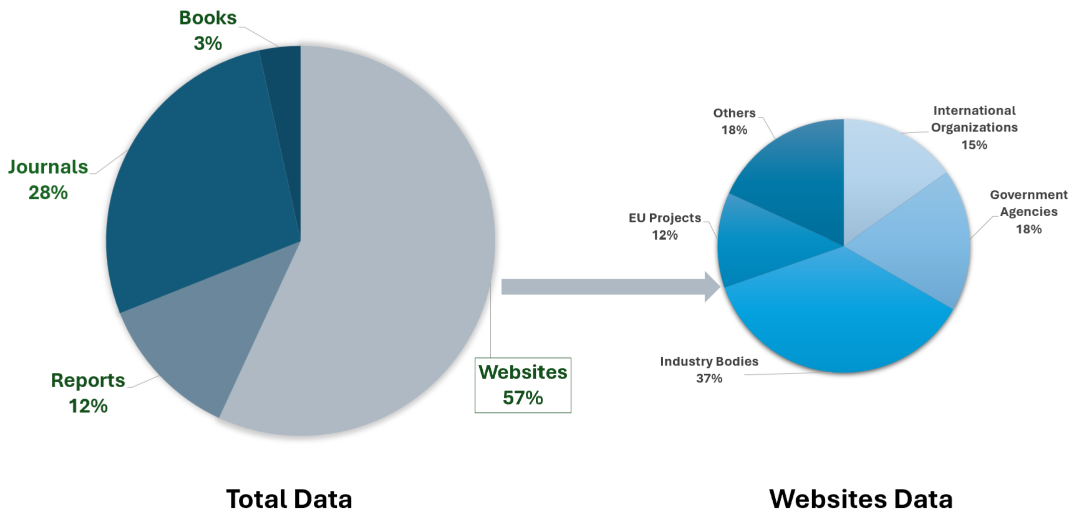


Figure 3.3: Sources used for data collection.

To ensure robustness, the data were cross-checked from multiple sources. The collected data were then analyzed and are discussed in detail in the following sections.

3.1.2 Data for the Four European Countries

In this section, the data which were used for the four countries are discussed briefly. For the EU, a CO_2 emission goal of 110 g CO_2/km for new ICEPCs has been set [135, 136], and we used this value for our study. The average distances covered by each car per year are 13,602 km, 13,505 km, 7700 km, and 8607 km for Germany, Switzerland, Italy, and Poland, respectively [137, 138]. To make the calculation and comparison simple and easy to understand, each car's traveled distance value of 11,300 km/year was used for the study, which is an average value for the EU [137, 138].

3.1.3 Carbon Emission Coefficient Factor of Selected Regions

The four countries selected for this study have different COECFs, which are shown in Figure 3.2 for each month of 2022. For this study, the average COECF of the year 2022 was used for the selected regions. Switzerland has the lowest COECF with 152 g CO_2/kWh, Italy with 452 CO_2/kWh, followed by Germany with an average COECF of 507.5 g CO_2/kWh, and Poland has the highest COECF of 823 g CO_2/kWh [139].

3.1.4 Internal Combustion Engine Passenger Cars Data

The number of passenger cars per 1000 inhabitants is highest in Poland, 664, followed by Italy and Germany with 663 and 580 cars per 1000 inhabitants, respectively. For Switzerland, it is 550 cars per 1000 persons [140, 141, 142, 143]. The total number of passenger cars for each country was calculated using Equation 3.1:

$$T_{ICE} = N_p * A_{vc} \tag{3.1}$$

where T_{ICE} is the total number of ICEPCs, N_p is the population of each country, and A_{vc} is the average number of cars per person. The average number of cars per person is 0.58, 0.55, 0.663, and 0.664 for Germany, Switzerland, Italy, and Poland, respectively [140, 141, 142, 143]. Thus, the total number of ICEPCs can be calculated for each country and also their emissions using Equation 3.2:

$$CE_{ICE} = D_t * E_m * T_{ICE} \tag{3.2}$$

D_t is the average distance traveled by car per year in kilometers, E_m is the emissions from each car in g CO_2/km, and T_{ICE} is the total number of ICEPCs.

3.1.5 Electric Vehicles Data

Many EVs are available in the market with different efficiencies, ranges, and battery capacities from other companies. This study analyzed and used the most recent data on EVs. Based on the data of the most recent 10 models of EVs [144] shown in Figure 3.4, the average efficiency was calculated and used for the study, which is 0.164 kWh/km. The study was performed for 10, 30, and 60% penetration levels of EVs for the four countries, and the total number of EVs for each penetration level was calculated using Equation 3.3:

$$N_{EV} = N_p * A_{vc} * P_{ev} \tag{3.3}$$

where N_{EV} is the total number of EVs for each penetration level, N_p is the total population for each country, A_{vc} is the average number of cars per person, and P_{ev} is the penetration level of EVs. The CO_2 emissions related to EVs were calculated using Equation 3.4:

$$CE_{EVs} = E_c * N_{EV} * COECF \tag{3.4}$$

where CE_{EVs} are the total annual emissions of EVs, E_c is the electricity consumed by each EV annually for charging, N_{EV} is the total number of EVs for each penetration level, and COECF is the carbon emission coefficient factor of each region. The total number of ICEPCs and EVs for each penetration level is shown in Table 3.1.

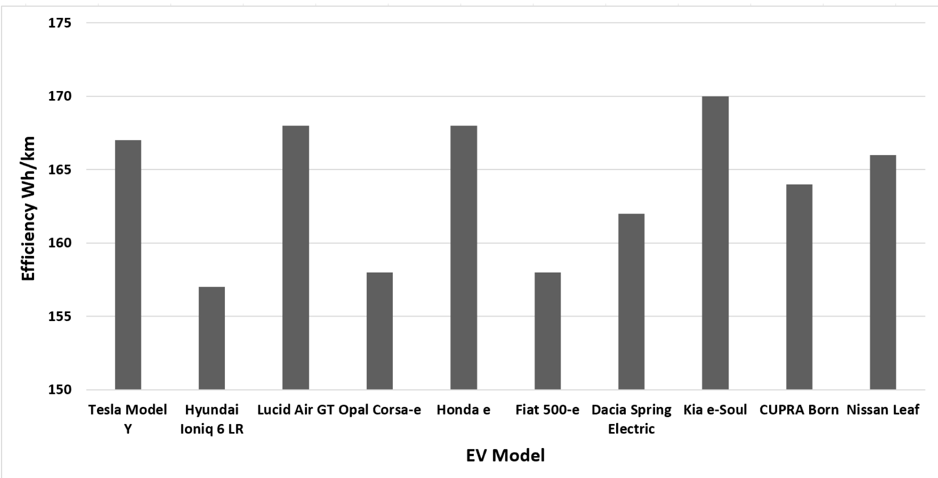


Figure 3.4: Different EV models and their efficiencies.

Table 3.1: Total number of ICEPCs and EVs of each country.

Country	Total ICEPCs	10% of EVs	30% of EVs	60% of EVs
Switzerland	4841650	484165	1452495	2904990
Italy	39918272	3991827	11975481	23950963
Germany	48955300	4895530	14686590	29373180
Poland	25066937	2506694	7520081	15040162

3.1.6 Net Zero Emission 2050 (NZE2050) Goals

The electricity generated in Germany, Switzerland, Italy, and Poland in 2021 was 552, 64.2, 278, and 176.52 TWh, respectively [145, 146, 147, 148, 149, 150]. According to NZE2050 goals, the demand will increase by 2% each year for the EU [151, 152]. To meet the demand, each country has to increase its electricity generation by 2% each year. It has been estimated that the electricity generation will be approximately 980, 114, 493, and 317 TWh for Germany, Switzerland, Italy, and Poland by 2050 as shown in Figure 3.5.

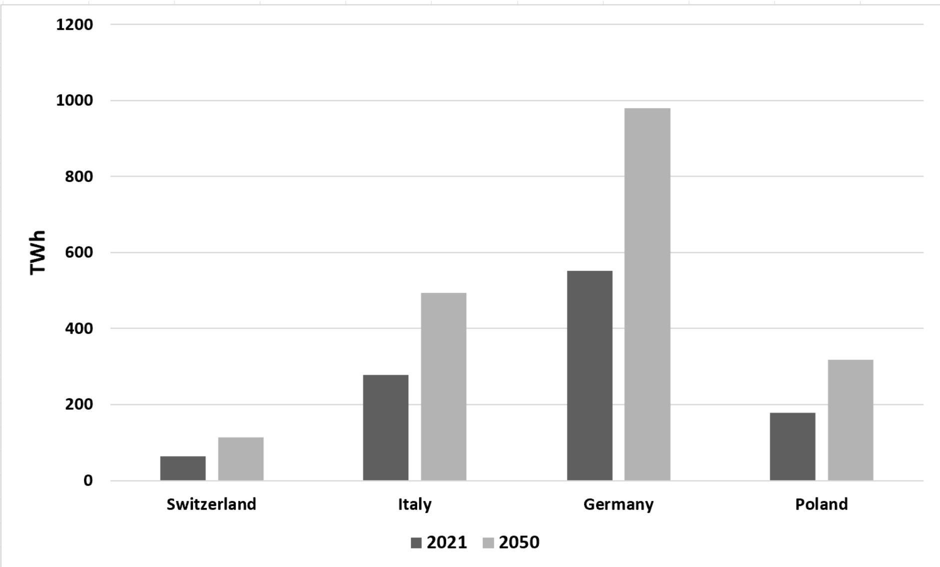


Figure 3.5: Estimated generation of NZE2050 scenario by 2050.

Different goals have been set to achieve a 33% electricity share from solar generation, 35% electricity share from wind, 12% share from hydro, 5% share from biomass, 8% share from nuclear energy, 3% from geothermal, and only 4% electricity production from fossil fuels by NZE2050 scenario for EU by 2050 [151, 152]. In this study, the goals of NZE2050 were assumed for the selected countries, and the new COECF for each country was calculated using Equation 3.5:

$$COECF_n = \frac{\sum E_{gi} * COECF_{ei}}{T_g} \tag{3.5}$$

where E_g is the share of electricity generated from each source, $COECF_e$ is the carbon emission coefficient factor for each source of generation, and T_g is the total generation of each country. From Figure 3.6, it can be seen that if the four countries achieve the NZE2050 goals, the new COECF will be reduced to 57.55 gCO_2/kWh for all four countries because high shares of electricity generation will be from solar and wind.

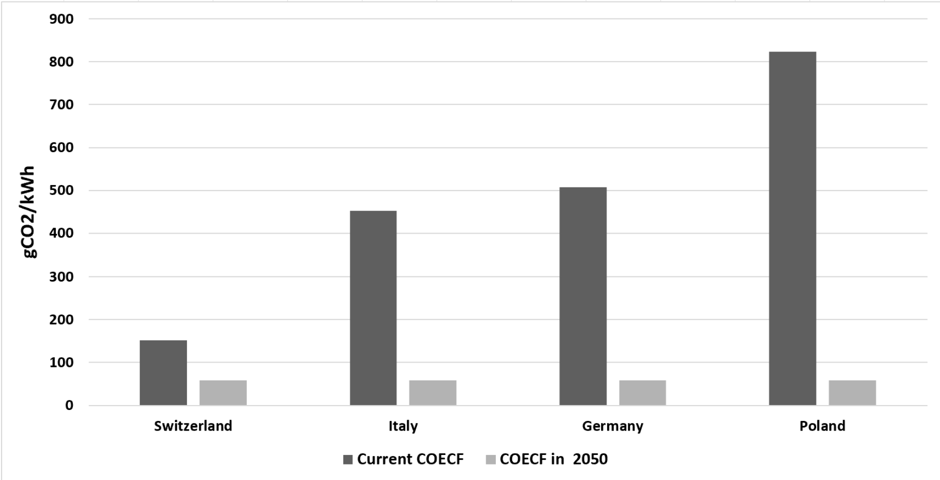


Figure 3.6: COECF for the four countries for 2022 and 2050.

3.1.7 Maximum COECF Limits

In this section, the maximum limit of COECF for which an EV will have a positive impact in terms of CO_2 emissions reduction in comparison to ICEPCs is derived by comparing Equations 3.2 and 3.4. Hence, the comparison is performed for a single EV and a single ICEPC. Hence, we will obtain Equation 3.6 to calculate the maximum required value of COECF:

$$COECF_m = \frac{D_t * E_m}{E_c} \tag{3.6}$$

As previously outlined in this study, D_t is the distance traveled by car annually, and the average distance traveled by each car for the EU is 11,300 km/year E_m is the new CO_2 emissions standard set by the EU for ICEPCs, which is 110 gCO_2/km. E_c is the energy consumed by each EV annually, which is 1853.2 kWh. Thus, the value for the maximum COECF limit estimated is 670 gCO_2/kWh. This means that the power generation system with COECF less than 670 gCO_2/kWh will experience a reduction in CO_2 emissions for each EV added to the transport system.

3.1.8 Simulation Data

Data on the four countries' capital cities were gathered for the simulation. The electricity consumption per capita in 2022 was 6.395, 5.270, 4.435, and 7.302 MWh for Berlin, Rome, Warsaw, and Bern, respectively [153]. The total consumption of the city was calculated by multiplying the electricity consumption per capita of the city by the population of the city, which is 3.677 million for Berlin, 4.332 million for Rome, 1.799 million for Warsaw, and 0.445 million for Bern [154, 155, 156, 157]. The Tesla Model Y electric vehicle has emerged as the best-selling car in Europe in recent years. For this study, the standard fast-charging rate of 100 kW was taken into account [158, 159].

Simulation studies have focused solely on the long-term objective of achieving 60% EVs adoption. Globally, there is around 1 public charger for every 10 EVs [160], and only 1 out of 9 chargers in Europe is a fast-charging station [161], so approximately only 1% of EVs will have fast-charging station availability according to the current fact and figures. Hence, a case study was formulated under the assumption that only 1% of the total 60% of EVs in each city are simultaneously connected to the power network for fast charging. The outcome was generated utilizing PSS®E software, with the power network modeled using the IEEE-14 bus test system for this study. Figure 3.7 illustrates the modified single-line diagram of the IEEE-14 bus system [162]. The power network comprises a Slack bus designated as Bus 1, housing generator Gen1, and four generator buses identified as Gen2, Gen3, Gen4, and Gen5. Also, the loads are labeled as L1, L2, L3, etc. In Figure 3.7, the green side indicates the 33 kV system, and the red lines indicate a low-voltage system of 11 kV. The results and the impact of this section are discussed in depth in the Results and Discussion of Simulation Study section and the Impact Assessment section below.

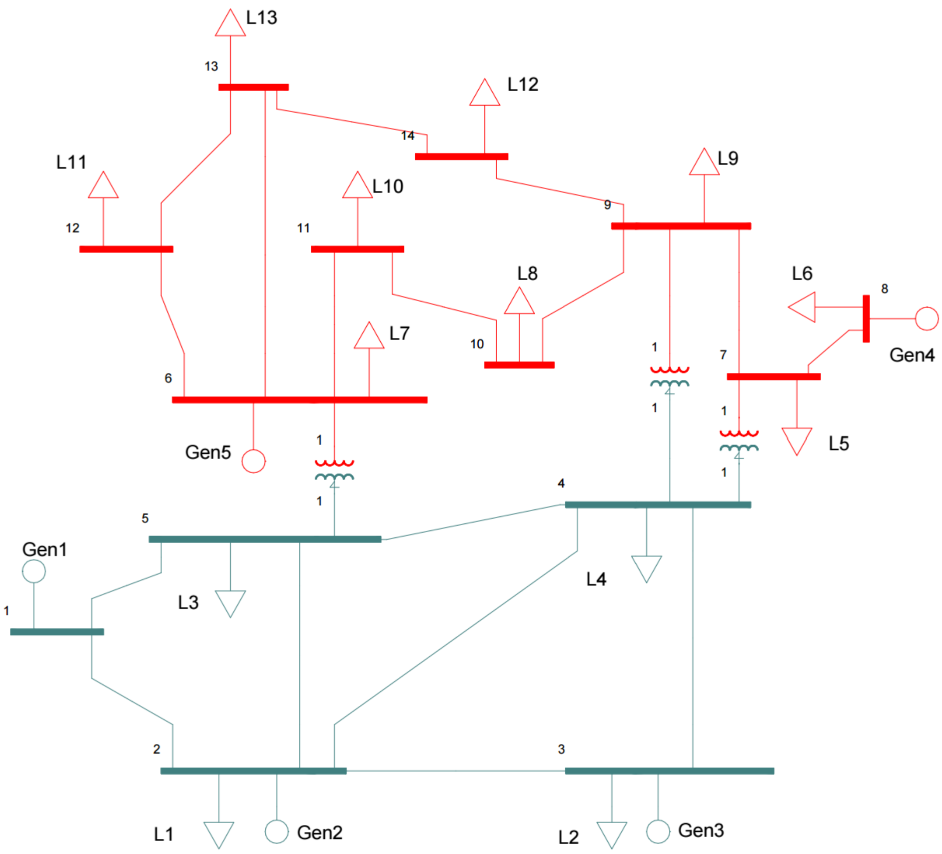


Figure 3.7: Single line diagram of IEEE-14 bus system.

3.2 Results and Discussion

Three scenarios, with 10% EVs considered as a short-term goal, 30% EVs considered as a medium-term goal, and 60% EVs considered as a long-term goal, were studied for each of the four countries. Similarly, these scenarios were also studied for NZE2050 goals, and lastly, ideal and extreme scenarios were also discussed. The data for each scenario were studied and analyzed, the calculation was performed, and the results were obtained and briefly discussed in the following subsections.

3.2.1 Short-Term Goal, 10% EVs

In the first scenario, only 10% of ICEPCs are replaced by EVs for each region and the results are obtained as shown in Table 3.2. When there are no ICEPCs replaced by EVs, the CO_2 emissions are 6.018 Mt for Switzerland, 49.62 Mt for Italy, 60.85 Mt for Germany, and 31.16 Mt for Poland. When 10% of the ICEPCs are replaced by EVs and the combined CO_2 emissions of remaining ICEPCs and 10% EVs are calculated, it is observed that the only significant emissions reduction occurs for Switzerland because of the low COECF. The total CO_2 emissions are reduced by almost 8% for Switzerland. For Italy, 1.62 Mt CO_2 is reduced with 10% EVs. The CO_2 emissions for Germany with 10% EVs is reduced by 1.479 Mt, from 60.85 Mt to 59.37 Mt, which shows only a 2.3% reduction. This is due to the relatively high COECF of the power generation system. However, the impact of EVs is negative for Poland; instead of reducing the CO_2 emissions, it adds up emissions as shown by the negative sign in the table. With very high COECF, CO_2 emissions for Poland will increase by 0.705 Mt per year from 31.16 Mt to 31.865 Mt.

If all four countries achieve NZE2050 goals, there will be a significant reduction in CO_2 emissions as can be seen in the table. The CO_2 emissions are reduced by 0.55 Mt, 4.54 Mt, 5.56 Mt, and 2.85 Mt per year for Switzerland, Italy, Germany, and Poland, respectively, with 10% EVs. In an ideal scenario, if all these 10% EVs are charged from wind energy, which has the lowest COECF, then there will be approximately a 9.9% reduction in CO_2 emissions for all four countries as compared to the emissions from ICEPCs. For an extreme scenario, if all the EVs are charged from electricity generated from coal power plants which have the highest COECF of 980 gCO_2/kWh [163], then there will be 4.77% higher CO_2 emissions than the emissions of ICEPCs without EVs.

Table 3.2: CO_2 emissions with 10% EVs.

Country	CO_2 Emissions from ICE Cars in Mt/Year	CO_2 Emissions with 10% EVs in Mt/Year	The Difference in Mt/Year	CO_2 Emissions in NZE2050 Scenario in Mt/Year	The Difference in Mt/Year
Switzerland	6.018	5.552	0.46	5.468	0.55
Italy	49.62	48	1.62	45.1	4.54
Germany	60.85	59.75	1.478	55.29	5.562
Poland	31.16	31.865	−0.705	28.31	2.85

3.2.2 Medium-Term Goal, 30% EVs

In this scenario, 30% of the ICEPCs are replaced by EVs, and the results obtained are shown in Table 3.3. With 30% EVs, the CO_2 emissions are reduced by 1.406 Mt, from 6.018 Mt to 4.612 Mt, for Switzerland; for Italy, the CO_2 emissions are reduced by 4.856 Mt; for Germany, the decrease in CO_2 emissions is low in percentage as compared to the total emissions, being reduced by only 4.44 Mt per year. The negative impact of EVs is increased due to an increase in indirect emissions from charging EVs for Poland due to there being fewer renewable energy sources and high CO_2 emission resources being used to produce the electricity. The CO_2 emissions are increased by 2.121 Mt, from 31.16 Mt to 33.281 Mt per year, with a 30% penetration of EVs. By achieving the goals of NZE2050, all four countries will reduce the CO_2 emissions to a high extent as can be seen from Table 3.3; there are reductions of 1.65 Mt, 13.61 Mt, 16.69 Mt, and 8.547 Mt for Switzerland, Italy, Germany, and Poland, respectively. The impact of EVs will be much higher if the ideal scenario is used for charging the EVs; there will be a 29.5% reduction in CO_2 emissions for all four countries, and for the extreme scenario, the CO_2 emissions will be increased by approximately 14.5% per year for each country.

Table 3.3: CO_2 emissions with 30% EVs.

Country	CO_2 Emissions from ICE Cars in Mt/Year	CO_2 Emissions with 30% EVs in Mt/Year	The Difference in Mt/Year	CO_2 Emissions in NZE2050 Scenario in Mt/Year	The Difference in Mt/Year
Switzerland	6.018	4.612	1.406	4.367	1.65
Italy	49.62	44.764	4.856	36.01	13.61
Germany	60.85	56.408	4.441	44.162	16.69
Poland	31.16	33.281	−2.212	22.613	8.547

3.2.3 Long-Term Goal, 60% EVs

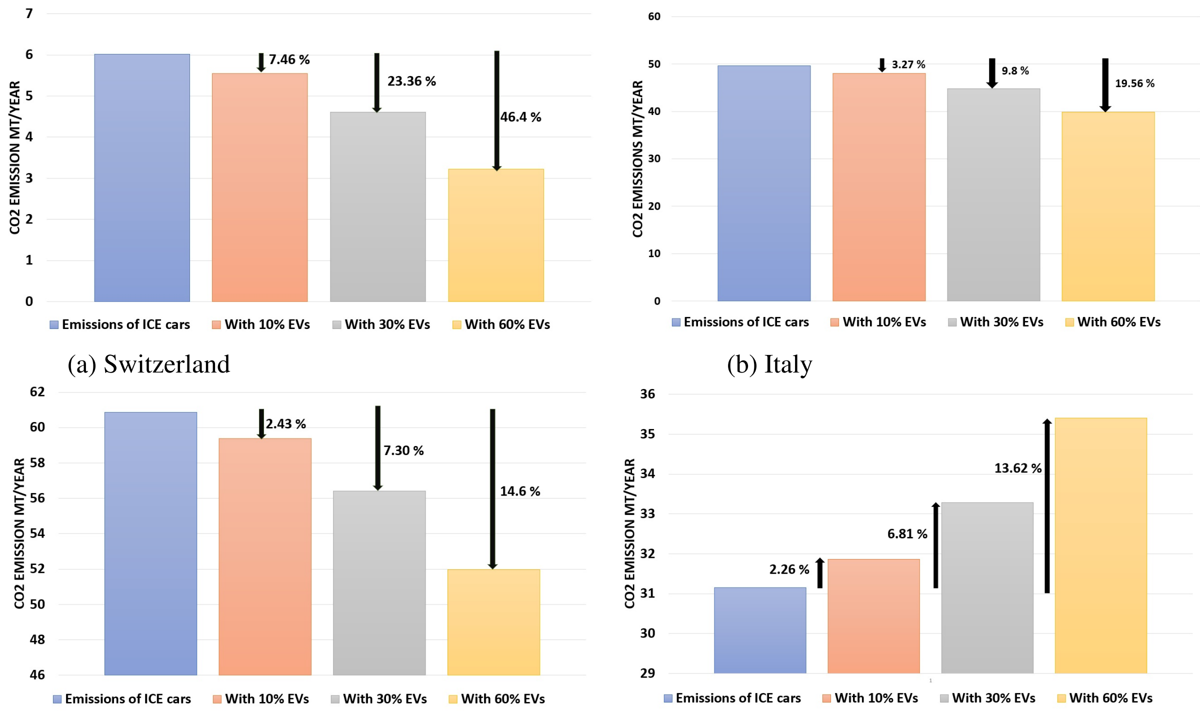
In the last scenario, 60% of ICEPCs are replaced by EVs, and the results are obtained as given in Table 3.4. The CO_2 emissions for Switzerland are reduced significantly, as for the first two scenarios, with no EVs, the emissions are 6.018 Mt, and are reduced by 2.792 Mt per year with 60% EVs in the system. For Italy, the reduction in CO_2 emissions is higher than for Poland and Germany because of medium COECF, and the CO_2 emissions are reduced by 9.71 Mt/year for 60% EVs. For Germany, the CO_2 emissions are declined by a small percentage even with such a high penetration level of EVs, with only 8.88 Mt per year. As Poland's electricity generation system is highly dependent on coal generation, the impact of EVs is increased negatively with the increase in the EV penetration level. With 60% EVs, the CO_2 emissions are increased by 4.243 Mt per year. The NZE2050 goals show a promising reduction in CO_2 emissions of 3.301 Mt, 27.22 Mt, 33.377 Mt, and 17.09 Mt per year for Switzerland, Italy, Germany, and Poland, respectively, with 60% EVs. In the ideal scenario charging, if all the EVs get charged with electricity generated from wind turbines, there will be almost a 59% reduction in CO_2 emissions for all four countries, and for the extreme scenario, the emissions will increase by 28.2%.

Table 3.4: CO_2 emissions with 60% EVs

Country	CO_2 Emissions from ICE Cars in Mt/Year	CO_2 Emissions with 60% EVs in Mt/Year	The Difference in Mt/Year	CO_2 Emissions in NZE2050 Scenario in Mt/Year	The Difference in Mt/Year
Switzerland	6.018	3.225	2.792	2.717	3.301
Italy	49.62	39.91	9.71	22.402	27.22
Germany	60.85	51.965	8.884	27.473	33.377
Poland	31.16	35.403	−4.243	14.07	17.09

3.3 Impact Assessment of Current COECF on Each Country

To evaluate the impact of COECF of current power generation on CO_2 emissions of the transport sector for 10, 30, and 60% EVs, the results are graphically represented in Figures 3.8 and 3.9 for better understanding and assessment. The result shows that the only significant reduction in CO_2 emissions for a 10% penetration level of EVs is for Switzerland, which is almost 7.46% per year, this is due to very low COECF and high dependency on RES for electricity generation. For Italy, the reduction is noticeable, and the CO_2 emissions are reduced by 3.25% shown in Figure 3.8b. The 10% penetration of EVs has not much impact on the CO_2 emissions reduction for Germany due to the relatively high COECF with a considerable share of electricity generation from coal, and the emissions are reduced by only 2.4% per year. On the other hand, due to the high dependency on coal power plants for electricity generation and with COECF higher than 670 gCO_2/kWh, Poland will experience a negative impact with each replacement of ICEPC with EV, and with 10% EVs, the CO_2 emissions are increased by 2.26% shown in Figure 3.8d.



(a) Switzerland (b) Italy

(c) Germany (d) Poland

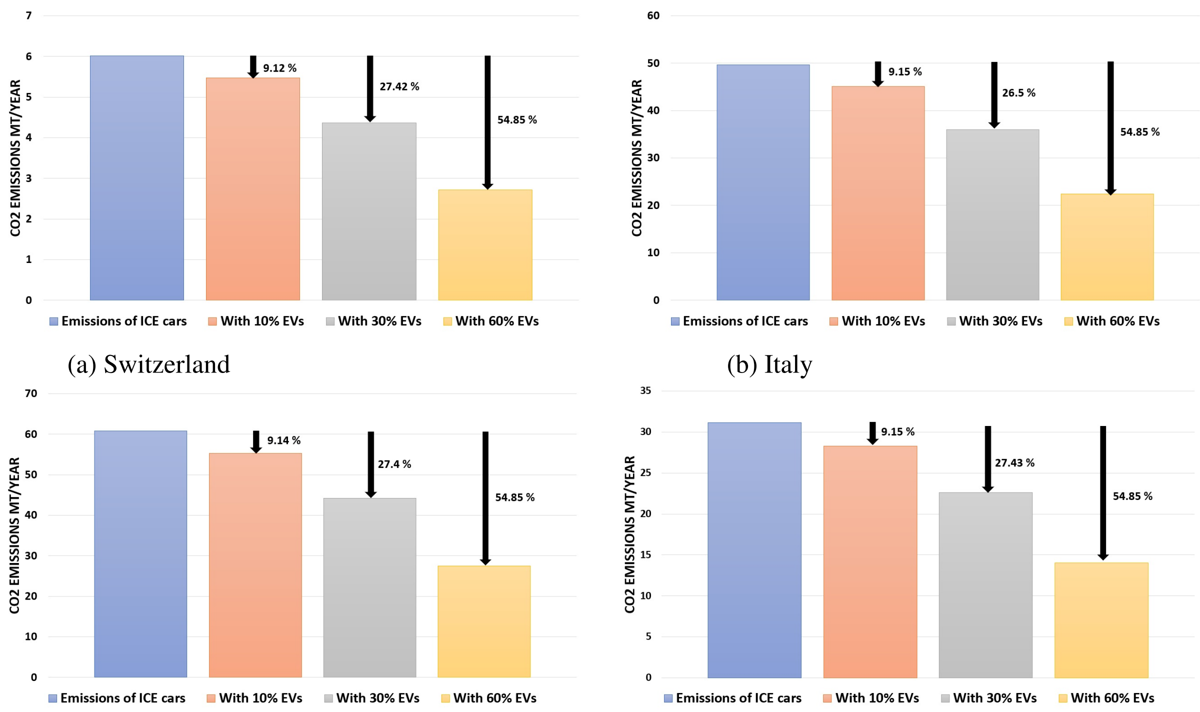
Figure 3.8: Emissions with no EVs and with 10, 30, and 60% EVs for each country with current COECF.

When the ICEPCs are replaced with 30, and 60% EVs, a noticeable decline of 23.36% and 46.40% per year, respectively, in the CO_2 emissions is seen for Switzerland, shown in Figure 3.8a. For Italy, the CO_2 emissions are reduced by 9.8% for 30% EVs and 19.56% for 60% EVs, respectively, shown in Figure 3.8b. The impact with 30% and 60% EVs is positive but not very promising for Germany; with 30% EVs, the CO_2 emissions are only reduced by 7.3%, and even with a 60% penetration level of EVs, only a 14.6% reduction per year is noticed, shown in Figure 3.8c. However, as mentioned before, because of the high COECF of the electricity generation sources, the negative impact is increased with an increase in the EV penetration level, and it is noticed that for a 30% penetration level, the CO_2 emissions are increased by 6.81% per year, and for 60% EVs, the rise in CO_2 emissions is 13.6% per year shown in Figure 3.8d.

3.4 Impact Assessment of COECF With NZE2050 Goals

The goals for NZE2050 have already been discussed in this chapter. If all three countries achieve the NZE2050 goals, the COECF will be reduced to approximately 57 gCO_2/kWh for all four countries. The CO_2 emissions calculated for NZE2050 with 10, 30, and 60% penetration levels of EVs are graphically represented in Figure 3.9. Because of the low COECF for all four countries, the impact of EVs on CO_2 emissions is positive, as even with 10% EVs, a significant fall in the emissions is noticed, and CO_2 emissions for all four countries are reduced by approximately by 9% as shown in Figure 3.9. For 30% and 60% EV penetration, the reduction in CO_2 emissions is significant; for 30% EVs, the CO_2 emissions reduction is

27%, and for 60% EVs, the CO_2 emission reduction is approximately 54% annually for all four countries shown in Figure 3.9.



(a) Switzerland

(b) Italy

(c) Germany

(d) Poland

Figure 3.9: Emissions with no EVs and 10, 30, and 60% EVs for each country with new COECF.

3.5 Impact on Demand Increase

The rise in electricity demand due to the replacement of ICEPCs by 10, 30, and 60% EVs for all four countries was calculated and is presented in Table 3.5.

Table 3.5: Electricity demand of each penetration level of EVs for the four countries.

EV Penetration Level	Switzerland Demand (TWh)	Italy Demand (TWh)	Germany Demand (TWh)	Poland Demand (TWh)
10% EVs	0.897	7.4	9.072	4.645
30% EVs	2.692	22.19	27.217	13.937
60% EVs	5.384	44.38	54.434	27.872

This increase in electricity demand for each country was obtained with the assumption made, and has already been discussed previously in the chapter. The energy demand for all the countries will increase to a high extent, as EVs will replace more and more ICEPCs; and for 60% of EVs, approximately 5.384, 44.38, 54.434, and 27.872 tera-watt-hours energy will be required by Switzerland, Italy, Germany, and Poland, respectively, to charge these EVs annually. This energy demand needs to be generated from RES to make the impact of EVs more positive and significant. For 60% EVs, Figure 3.10 shows how CO_2 emissions can be increased or decreased depending on the RES penetration level in the power generation system. As the COECF of Switzerland is too low and the generation grid has a high percentage of RES, it is close to ideal, but if all the EVs charge in the extreme scenarios, we can see that the emissions will be more than double as compared to the current COECF. The current COECF for Poland is too high and almost matches the extreme scenario, but if we reach the ideal scenario, the emissions will be cut by almost 2/3. For Italy and Germany, both the ideal and extreme scenarios will decrease and increase the CO_2 emissions by 50% respectively as compared to the current COECF of the power generation system shown in Figure 3.10. Figure 3.10 illustrates that what impact each country will experience in reducing CO_2 emissions is dependent on the shares of RES in the power generation system to fulfill the electricity demand of charging huge fleets of EVs shortly.

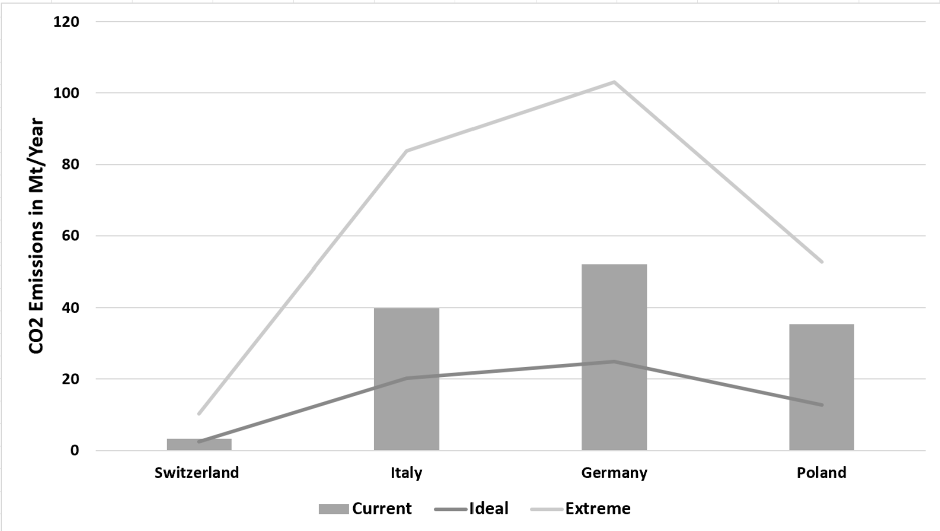


Figure 3.10: CO_2 Emissions in ideal, current, and extreme scenarios' COECF.

3.6 Results and Discussion of the Grid Impact Study

This study assumes the rapid charging capability of 100 kW for the Tesla Model Y [159]. It poses the question of, in the future, if 1% EVs out of the 60% of EVs in each region are simultaneously connected for fast charging for a brief period, what will be the resulting impact on power transmission lines? The consumption load for every city was derived from each city's per capita consumption data. This load was evenly distributed among the 13-load buses within the IEEE-14 bus system. With the existing load, all the power lines were made 50% loaded using Equation 3.7 [164, 165]:

$$P = \frac{E_s.E_r Sin\theta}{L.x} \tag{3.7}$$

where P is power in MW, E_s is the sending end voltages, E_r is the receiving end voltages in kV line to line, and θ is the phase difference between the receiving and sending end voltages,

L is the line length in km, and x is the reactance per km. Using the data in [164, 165], the lines were made 50% loaded for each city with the current electricity consumption of the city, adjusting the lines' lengths using Equation 3.7. Thus, uniform initial conditions were established for all cities, with each city's simulation lines being loaded at 50% capacity based on their current electricity consumption. It was assumed that the transmission lines in each city still had 50% of their power-carrying capacity available to meet the future demand. The anticipated impact of integrating just 1% of the projected 60% EVs was examined to determine the extent to which line loading would increase. In Figure 3.11, the color code illustrates the varying percentage loading of transmission lines in PSS®E software. Blue regions indicate that the power lines are under minimal load, greenish regions indicate approximately 50% loading, red regions signify that the lines have reached maximum capacity, and dark red regions indicate congested areas of the power lines. Given the present consumption demand of the four capital cities, the power transmission lines are made 50% loaded concerning each city's electricity consumption as depicted in Figure 3.12. All four cities will exhibit identical outcomes as illustrated in Figure 3.12, with transmission lines loaded to 50% capacity. Also, the percentage of the loaded capacity is mentioned on each power line.

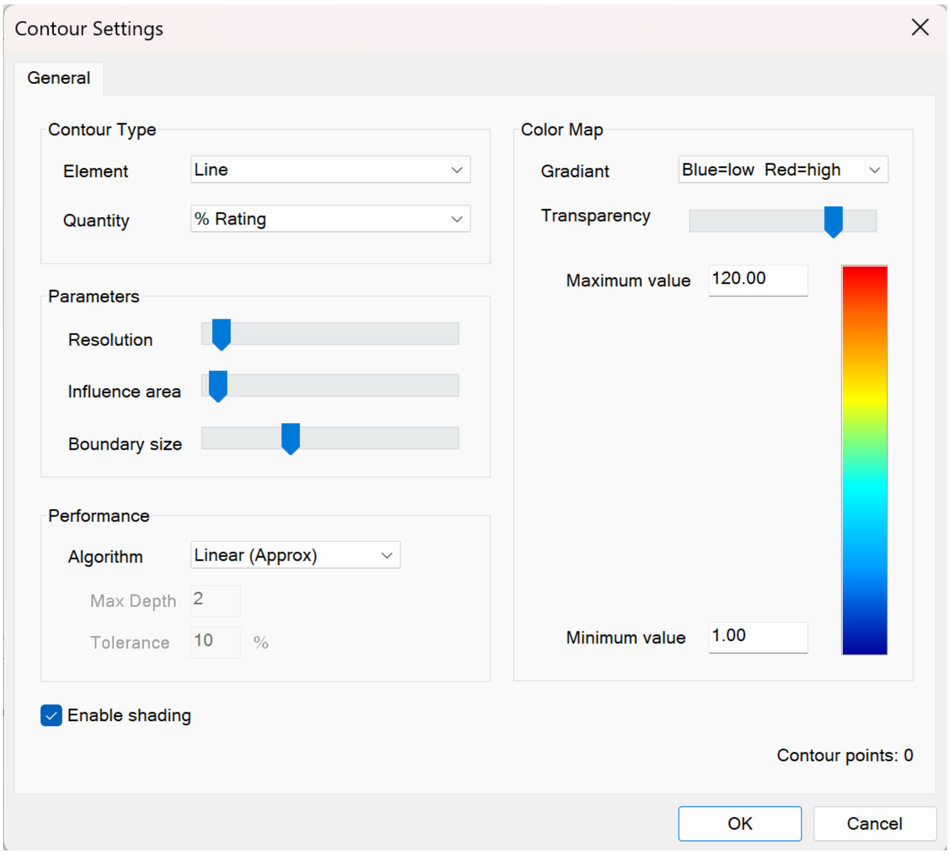


Figure 3.11: The color codes for percentage loading of transmission lines.

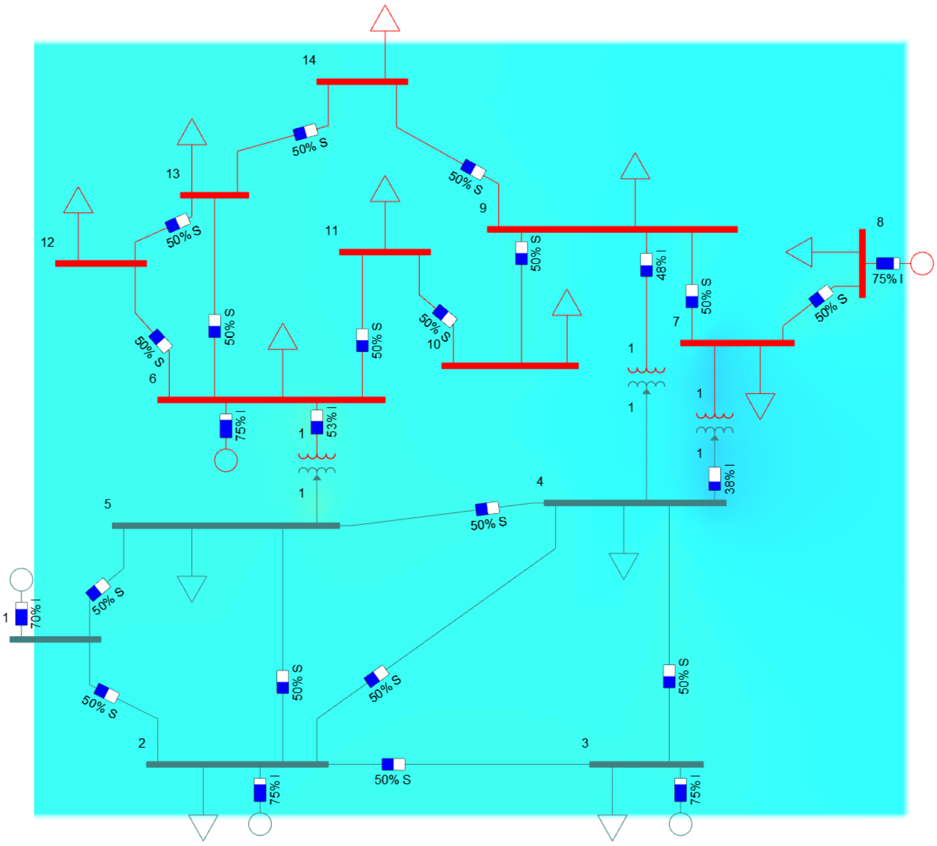


Figure 3.12: Simulation Results with 50% loaded power lines.

3.6.1 Results for Rome, Italy

Rome has a population of 4.332 million and an electricity consumption of 5.27 MWh per capita. For the long-term goal, there will be 1,723,269 EVs in Rome. The assumed 1% of EVs of long-term goal EVs for Rome are connected to the existing network with power lines loaded at 50% capacity; many lines surpass the 100% loading threshold as depicted by the dark red lines in Figure 3.13. Given Rome's sizable population and the anticipated rise in EV numbers, even a tiny fraction of EVs will strain the transmission and distribution lines significantly, leading to substantial congestion issues. The percentage loading of each transmission line is indicated in Figure 3.13.

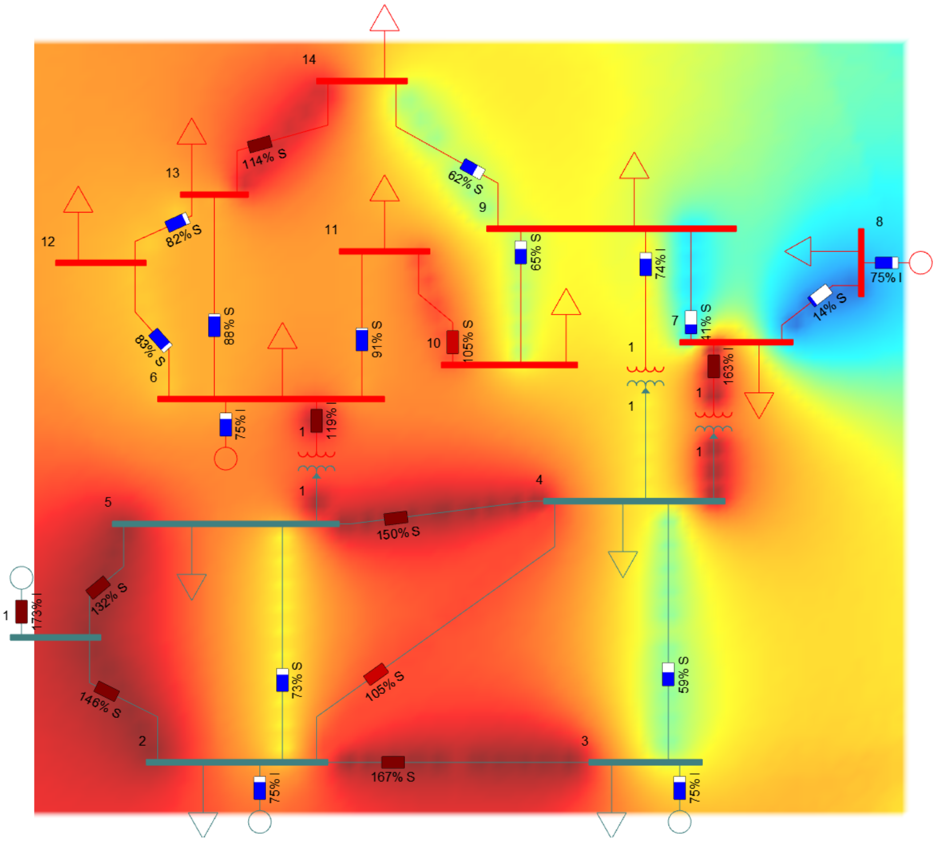


Figure 3.13: Results with 1% EVs fast charging for Rome.

3.6.2 Results for Berlin, Germany

Berlin's electricity consumption stands at 6.4 MWh per capita, with a population of approximately 3.677 million. Based on calculations, it is projected that there will be 1,279,865 EVs if 60%t of the ICEPCs are replaced by EVs. The simulation results for Berlin, Germany depicted in Figure 3.14, include an added load from a fast-charging system serving 1% of the 1,279,865 EVs, connected simultaneously for a short charging period. These results emphasize the significant impact of EVs on power transmission lines, resulting in congestion. Figure 3.14 indicates the percentage loading of each line, revealing that most of the 33 kV lines exceed their maximum capacity due to the additional burden of EV charging. Compared to the 50% loading of the lines, this overload stems from the influx of EVs charging on the system.

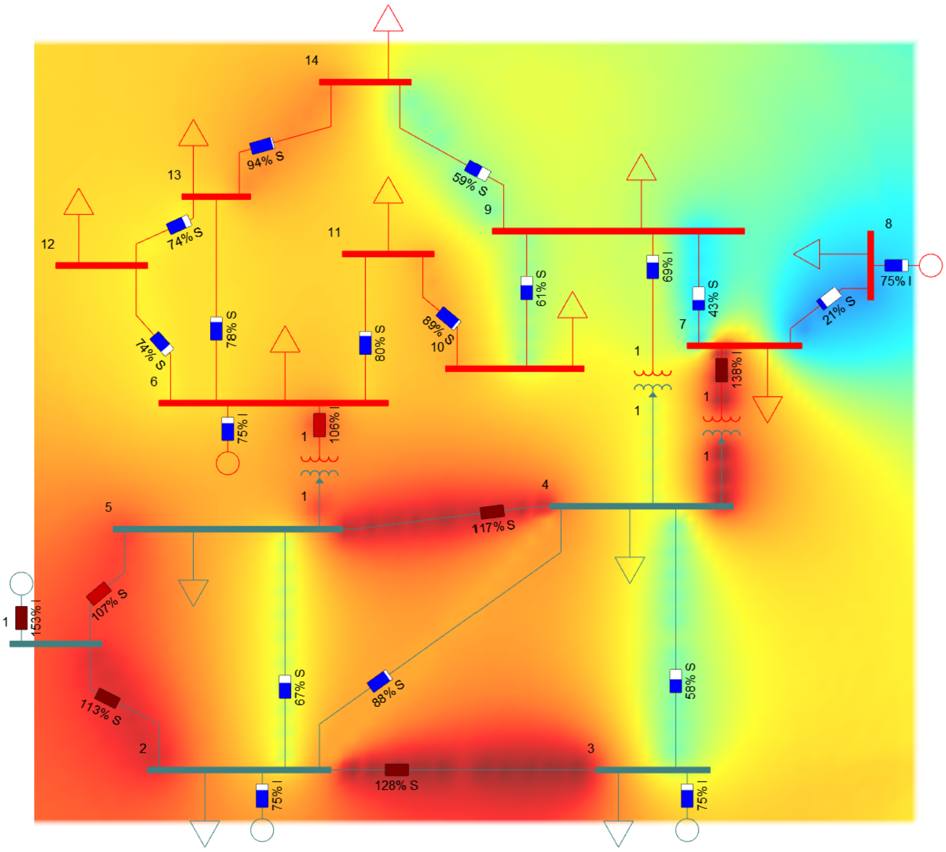


Figure 3.14: Results with 1% EVs fast charging for Berlin.

3.6.3 Results for Warsaw, Poland

Warsaw, the capital of Poland, boasts a population of 1.799 million, with an electricity consumption rate of 4.435 MWh per capita. Projections indicate that 716,721 EVs would be on the roads if EVs replaced 60% of ICEPCs. If only 1% of these EVs simultaneously utilize fast charging at 100 kW for a brief period, the load would surge by 716 MW. Figure 3.15 illustrates the consequential impact of this heightened load, showcasing the percentage increase in power line loading beyond the standard 100% operational threshold. Each line's increased percentage is detailed in Figure 3.15, highlighting the strain imposed by the additional EV charging load on the system.

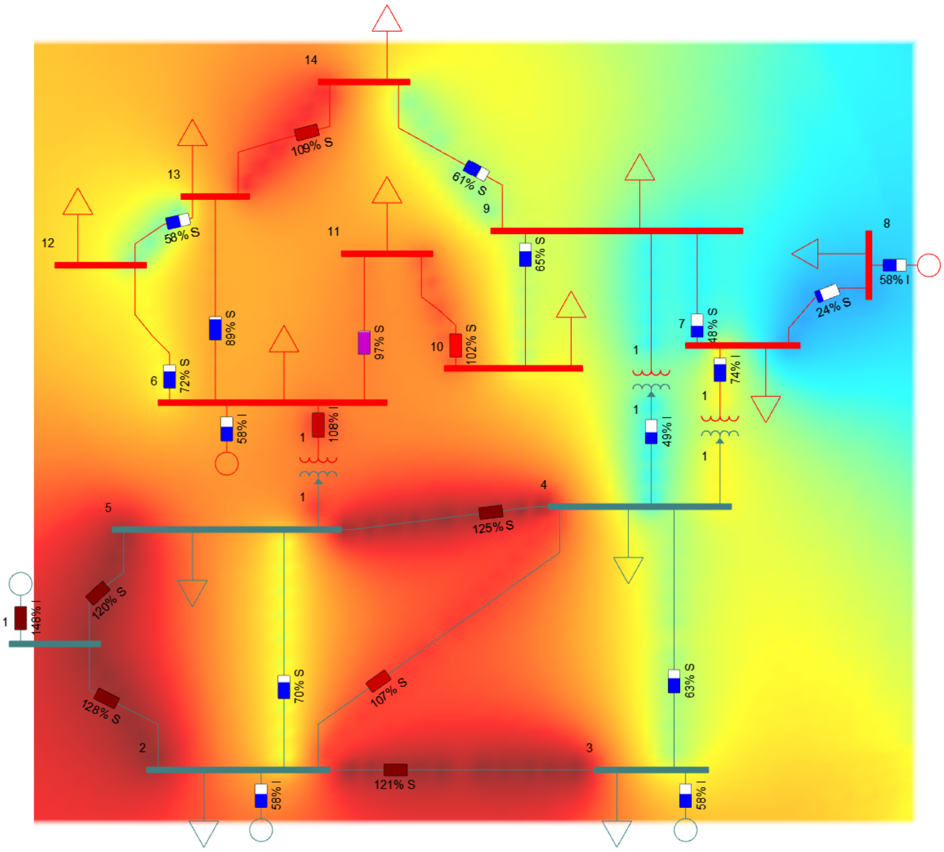


Figure 3.15: Results with 1% EVs fast charging for Warsaw.

3.6.4 Results for Bern, Switzerland

Bern, the capital of Switzerland, is home to a population of 0.445 million, with a per capita electricity consumption of 7.302 MWh. Upon replacing 60% of ICEPCs with EVs (EVs), Bern is projected to host 146,850 EVs on its roads as a long-term goal. Introducing a mere 1% load from fast charging for these EVs would escalate the demand by 146 MW. Figure 3.16 illustrates the repercussions of this heightened load. Although no power line exceeds its maximum capacity, the loading percentage of each line experiences a significant increase. The collective impact of these results is discussed in the impact assessment section, where the outcomes for all four cities are compared.

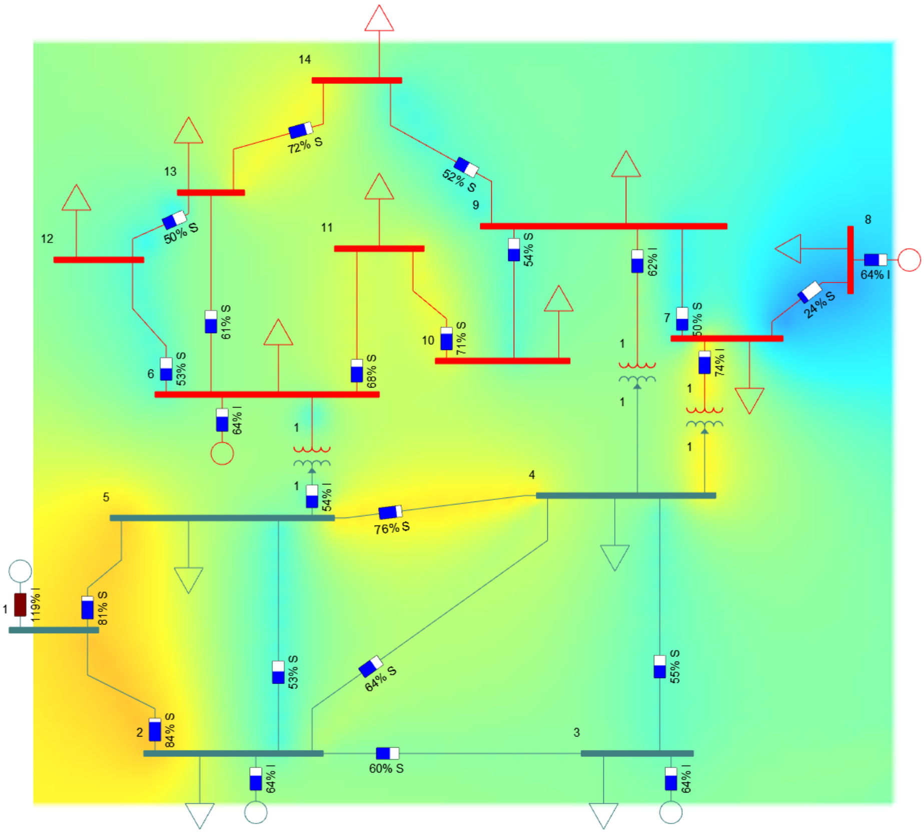


Figure 3.16: Results with 1% EVs fast charging for Bern.

3.7 Impact Assessment on Power System Lines

The simulation study has revealed that various factors, including city population, EV numbers, current electricity consumption, and the existing power-carrying capacity of transmission and distribution lines, significantly influence the power grid. This simulation assumes that all power lines are initially loaded at 50% when no EVs are integrated. However, incorporating just one percent of the long-term goal of EVs into each city has resulted in substantial congestion on the power transmission lines. Fast charging stations draw a considerable amount of power in a short period, especially during peak periods, exacerbating the strain on the system.

This congestion in the distribution and transmission networks compromises grid reliability, leading to equipment failures, overheating, and potential outages. The simulation results highlight that cities with larger populations and higher numbers of EVs, such as Berlin, Rome, and Warsaw, experience more significant impacts on power line loading than cities with lower populations and fewer EVs, such as Switzerland. The simulation depicts the percentage loading of each line for each city, revealing that Rome, being the most densely populated, faces the greatest strain, with one power line exceeding 176% of its capacity. In contrast, Switzerland exhibits less strain with a lower population density, with no line surpassing 84% of its capacity. Moreover, even with power lines initially set at 50% load in the simulation, many lines in Berlin, Rome, and Warsaw exceed 150% loading. This exceeds real-world conditions, where transmission and distribution lines are typically loaded beyond

50%. Consequently, such a system would encounter significant challenges with high EV penetration in the power grid.

3.8 Summary

The journey towards a greener transportation future demands carefully examining EVs and their impact on CO_2 emissions reduction and power systems. The study in this chapter delved into the dynamics across four diverse European nations—Switzerland, Italy, Germany, and Poland—each bearing its own COECF profile. By 2050, the projected surge in electricity demand is staggering: 114 TWh for Switzerland, 493 TWh for Italy, 980 TWh for Germany, and 317 TWh for Poland. A 60% EV adoption rate further amplifies these figures, with demand forecasted to climb by 5.348 TWh, 44.38 TWh, 55.43 TWh, and 27.87 TWh, respectively. Meeting this escalating demand mandates strategic enhancements in grid infrastructure and a robust embrace of RES. Yet, disparities emerge, with Poland's high COECF (823 gCO_2/kWh) casting a shadow on the otherwise positive impact of EVs. Conversely, Switzerland, boasting lower COECF (152 gCO_2/kWh), witnesses remarkable reductions in CO_2 emissions of 7.46%, 23.36%, and 46.40% for 10%, 30%, and 60% EV penetration, respectively. Our findings underscore the pivotal role of RES in steering transportation towards sustainability. As we envision a zero-emission future, it is clear: the time for decisive action on renewable energy goals is now. By intertwining electrification with renewable energy, we chart a course toward a climate-resilient transportation landscape, essential for safeguarding our planet's future.

Efficiently delivering sustainably generated electricity to consumers is crucial for grid reliability, especially with the impending surge in EV charging demand. The case study of four capital cities highlights significant congestion in transmission and distribution lines due to even a small fraction of EVs being simultaneously charged. Loadings exceed 167% for Rome and 128% for Berlin and Warsaw. Upgrading existing power systems is vital to address these challenges. Strategies like increasing grid capacity, integrating distributed energy resources, implementing demand-side management practices, and deploying charging infrastructure strategically are essential for mitigating future challenges in clean transport and smart power systems. Future research could entail conducting economic analyses and assessing policy implications for grid upgrades. This would involve exploring the financial implications of necessary grid enhancements and increased adoption of renewable energy, along with identifying the policy measures required to achieve renewable energy targets.

Chapter 4

The Role of RES in Electrifying the Transport Sector and Impact on GHG Emissions-an Italian Case Study

Electric vehicles (EVs) are the future of the transport sector. The massive transition from traditional passenger vehicles to EVs will play a crucial role in decarbonizing the transportation sector and moving toward zero emissions. The main problem will be the generation source of electricity to charge the massive fleet of future EVs. Hence, clean and renewable energy sources will play a vital role in making EVs carbon-free. In this chapter, the impact of power systems' carbon dioxide emission factors (COECFs) on EVs has been studied in detail. Carbon dioxide emissions have been compared for traditional passenger vehicles and EVs. The study was carried out for three Italian regions, the Tuscany Region, the Sicily Region, and the Sardinia Region, which have low, medium, and high COECFs of power systems, respectively, with different penetration levels of EVs. An ideal scenario with 100 percent renewable energy sources (RES) and an extreme Scenario with 0 percent RES in the power system have also been studied for EVs' role in the decarbonization of the transport sector. The result obtained in this study showed that RES in future power grids will have a significant impact on making EVs zero-emission cars. Many European Union goals of making the transport sector zero carbon cannot be achieved without making the future power system grids renewable.

4.1 Methodology

4.1.1 Flow Chart

Three regions have been selected for this study: the Tuscany region, the Sicily region, and the Sardinia region, with low, medium, and high COECF of the power system. Two scenarios have been made with 100 % RES, very low COECF, and with zero RES, very high COECF for the above three regions shown in Figure 4.1. There was no need for data collection for ideal and extreme scenarios, as these scenarios were made for the selected three areas, and the data collected for these regions will be used. After data collection, all the data were analyzed, and results were obtained. Comparisons and discussions were made based on the results obtained. Each portion has been discussed in the following section of the chapter.

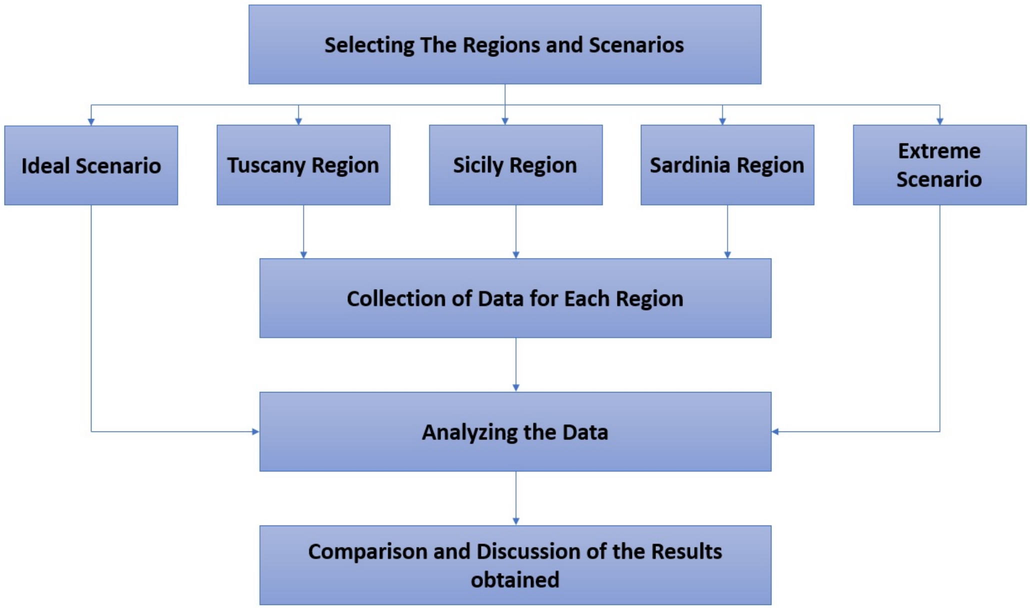


Figure 4.1: Flow chart of methodology used.

subsectionData of the Selected Regions and Scenarios The average CO_2 emission standards for passenger cars have been set to 95 g CO_2/Km in the European Union [166, 167]. The number of passenger cars in Italy per thousand inhabitants is 663, with a ratio of 0.663 cars per person. The average distance traveled by each vehicle in Italy is 7700 km per year [168, 169]. The data for the three considered regions are also obtained and discussed below.

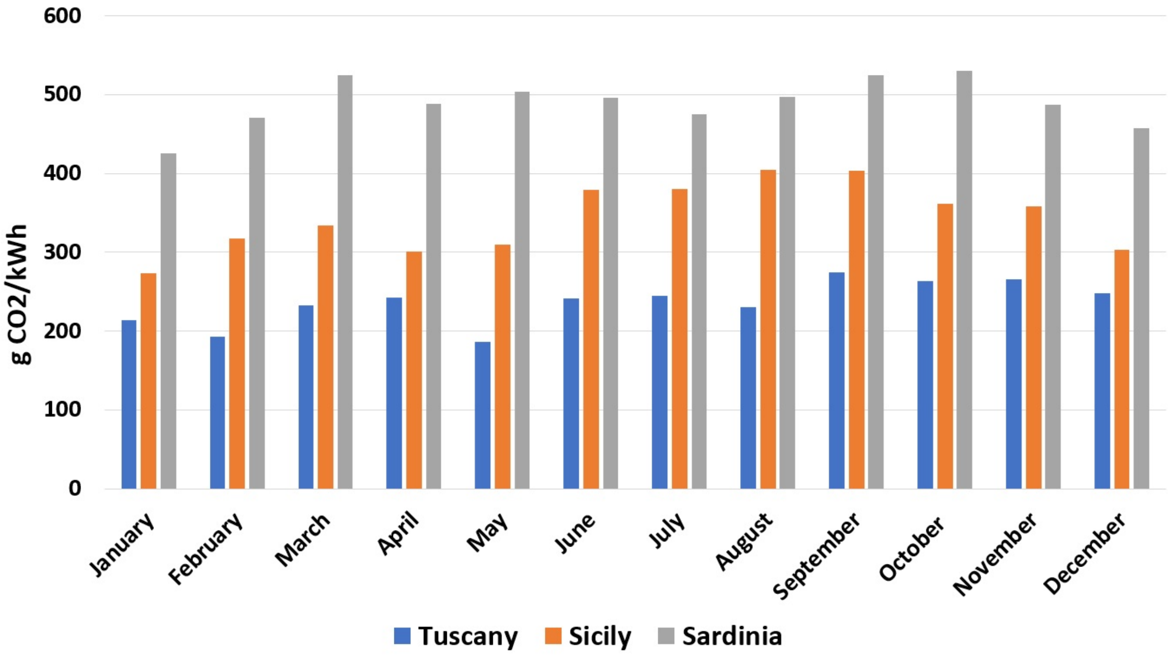


Figure 4.2: CO_2 emissions per kilo-watt-hour for year 2021

Tuscany Region

Tuscany is a region in central-north Italy with an area of 22992 square kilometers and a population of almost 3.7 million. Most of the electricity in this region is generated from solar and geothermal sources and has a low COECF of the power system with an average of 236.5 gCO_2/kWh. Figure 4 shows the monthly COECF of the power system of The Tuscany region in 2021, with a low COECF average of 186.5 gCO_2/kWh in May, and a high COECF average of 275 gCO_2/kWh in September, this is because of different load demand and different generation sources during various times of the year [170].

Sicily Region

Sicily is the largest island in Italy, with an area of 25426 square kilometers and a population of approximately 4875290 inhabitants. Most of the electricity in Sicily is generated by gas and solar energy, and wind turbines generate some of the energy. The average COECF of the Sicily power system was 343.8 gCO_2/kWh in 2021, reaching a high COECF of 404.5 gCO_2/kWh in August and a low COECF of 273.7 gCO_2/kWh in January 2021, due to different load demands and different generation sources during different times of the year[170]. The monthly COECF average of the Sicily region is shown in Figure 4.2.

Sardinia Region

Sardinia is the second-largest island in Italy, with an area of 23813 square kilometers and a population of approximately 1598225 inhabitants. The primary sources of electricity generation in this area are gas and coal, which is why the Sardinia power grid has the highest COECF compared to the other two regions, with an average of 490.2 gCO_2/kWh. The COECF of this region reaches a high of 529.75 gCO_2/kWh in October and a low of 425.86 gCO_2/kWh in January, depending on the load demand and sources of generation at different times of the year, as shown in Figure 4.2.

Ideal and Extreme Scenario

For the ideal scenario, the COECF of the power grid for all three regions is taken as 12 gCO_2/kWh with 100 % electricity generation from wind turbines for charging the estimated number of EVs. And for an extreme scenario, the COECF of the power grid for the three regions is assumed 986 gCO_2/kWh from table 1, with 100 % electricity generation from coal for charging the estimated number of EVs.

4.1.2 Carbon Emissions From Traditional Vehicles

First, the total number of passenger cars can be calculated using equation 4.1.

$$Tv = N_p.A_p \tag{4.1}$$

Here *Tv* is the total number of passenger vehicles estimated. N_p is the number of inhabitants in each region. A_p is the average number of cars per person.

We know the average number of cars per person in Italy, which is 0.663, thus, we can calculate the total number of cars for each region and their emission using the equation 4.2.

$$CET = D.CE \tag{4.2}$$

Here CET is the CO_2 Emissions from each traditional Vehicle. D is the distance traveled by each vehicle in Km. CE is the CO_2 emissions from each vehicle gCO_2/Km.

4.1.3 Data For EVs

Many EVs are in the market from different makers with different ranges and efficiencies. For this study, the most recent passenger EV data has been analyzed, and the average efficiency of the 30 EVs recently introduced in the markets or soon to be launched has been used. The efficiencies of these EVs are shown in Figure 4.3, with an average efficiency of 174.3 Wh/Km or 0.1743 kWh/Km.

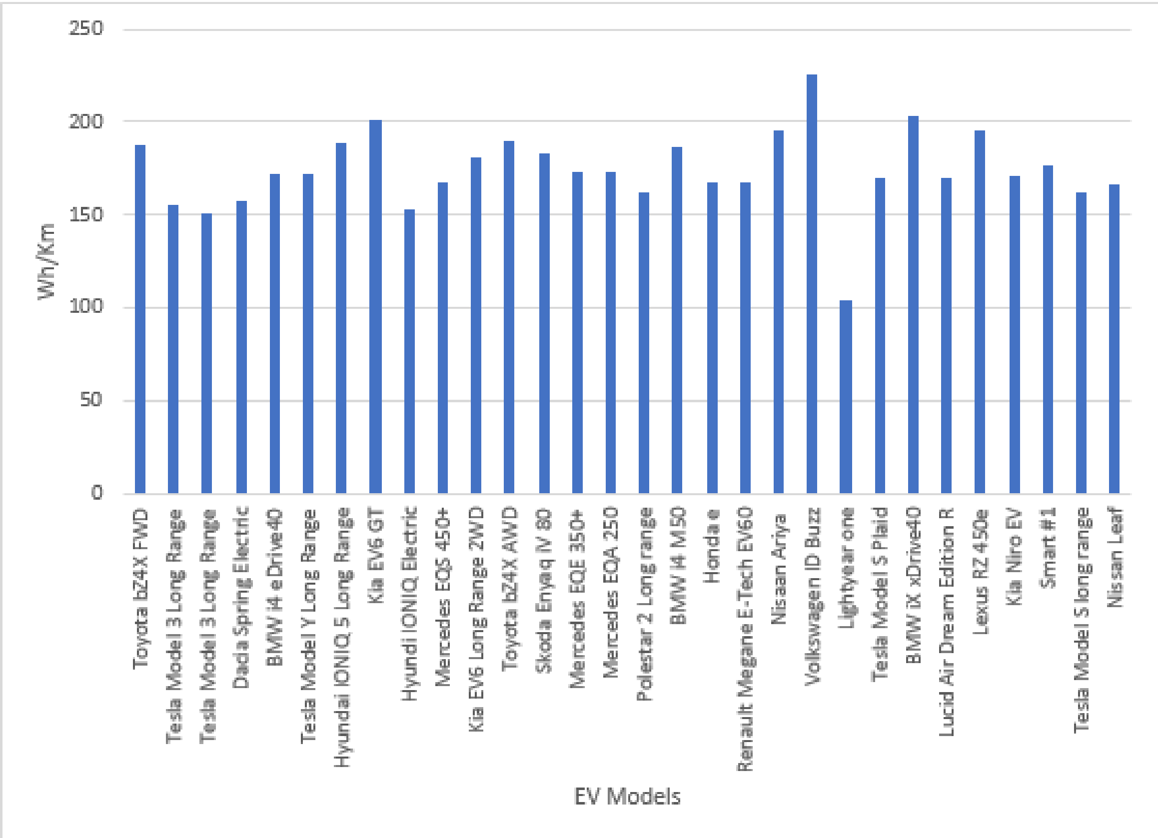


Figure 4.3: List of EVs and their efficiencies

Number of EVs

The number of EVs has been calculated using the following equation 4.3.

$$N_{EVs} = N_p.A_p.P \tag{4.3}$$

Here N_{EVs} is the total number of EVs estimated for our research. N_p is the number of inhabitants in each region. A_p is the average number of vehicles per person. And P is the penetration level of the EVs. For this research, the study has been done for 20 percent, 40 percent, and 60 % penetration levels of EVs.

Carbon Emissions From EVs

The emissions from EVs depend on the COECF of the electricity grid where the EVs will be charged. The following equation 4.4 has been used to calculate the CO_2 emissions of EVs.

$$CEV = EC.COECF \tag{4.4}$$

Here CEV is the CO_2 emissions from each EV. EC is the electricity consumption of an EV (kWh/Km). COECF is the CO_2 emission factor of the grid for each area.

4.2 Results and Discussion

Three scenarios with 20, 40, and 60 % EVs have been studied for each region and the ideal and extreme situation of the RES in the power grid. The data for each scenario has been analyzed and discussed in detail in the following sections

4.2.1 Scenario 1, with 20 % EVs

In this scenario, 20 % of the Traditional Passenger Vehicles (TPVs) have been replaced by EVs for each region, and the results obtained are shown in Table 4.1.

Table 4.1: CO_2 Emissions for each region with 20 % EVs

Region	Emissions from TPVs (CO_2 Mton/Year)	Emissions with 20 % EVs (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)	Ideal Scenario (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)	Extreme Scenario (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)
Tuscany	1.79	1.588	203	1.44	351	2.08	290
Sicily	2.364	2.1898	174.6	1.902	462	2.747	383
Sardinia	0.7752	0.7595	15.7	0.6235	151.7	0.901	125.3

The results show that with only TPVs, the CO_2 emissions for Tuscany, Sicily, and Sardinia regions are 1.791 Mton/year, 2.364 Mton/year, and 0.7735 Mton/year respectively. When 20 % of TPVs were replaced by EVs and taking the current COECF of the power grid, there will be an 11.33 % , 7.4 % , and 2 % decrease in CO_2 emissions per year for Tuscany, Sicily, and Sardinia regions respectively as compared to CO_2 emissions from 100 % TPVs. The results showed that there is a significant decrease in CO_2 emissions for the Tuscany region because this region has low COECF of the power grid. In contrast, for the Sardinia region, there will be no significant change in the CO_2 emissions by replacing 20 % of the TPVs with EVs, because of high COECF of the power grid with most of the generation from the Non-Renewable Energy Sources (NRES). The COECF of the power grid of the Sicily region is intermediate with some generation from NRES and some from RES showing a significant decrease in CO_2 emissions of 194.8 Kton/year. If RES is used for charging 20 % of the EVs, there will be approximately a 19.54 % decrease in CO_2 emissions per year for all three regions, while charging the EVs fleet from 100 % electricity generated from coal power plants, there will be an increase of almost 16.17 % CO_2 emissions per year for all the three regions as compared to the emissions from TPVs.

4.2.2 Scenario 2, with 40 % EVs

In this scenario, 40 % of the TPVs have been replaced by EVs for each region, and the results obtained are shown in Table 4.2. By replacing the TPVs with 40 % of the EVs, there will be a decrease of 22.64 %, 14.76 %, and 4 % of CO_2 emissions per year for Tuscany, Sicily, and Sardinia regions respectively with the current energy mix of each region. Due to the low COECF of the power grid of the Tuscany region, the CO_2 emission reduction is high followed by the Sicily region. There is no noticeable change seen in the CO_2 emission reduction for the Sardinia region even with 40 % penetration of EVs, because of the high COECF of the grid of this region with most of the generation from NRES. If 40 % of the TPVs are replaced with EVs for each region and get charged only from RES a reduction of 39 % in CO_2 emissions can be achieved for all three regions. But the case will be reversed, if these EVs get charged only from NRES like coal power plants, the CO_2 emission will be increased by approximately 31 % per year for each region.

Table 4.2: CO_2 Emissions for each region with 40 % EVs

Region	Emissions from TPVs (CO_2 Mton/Year)	Emissions with 20 % EVs (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)	Ideal Scenario (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)	Extreme Scenario (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)
Tuscany	1.791	1.3855	405.5	1.0903	700.7	2.304	513.6
Sicily	2.364	2.0152	348.8	1.4469	917.11	3.12	754.6
Sardinia	0.775	0.7439	31.28	0.4719	303,3	1.02606	250.86

4.2.3 Scenario 3, with 60 % EVs

In the final scenario, the penetration level of 60 % EVs has been assumed for each region and the result obtained is shown in Table 4.3. With 60 % TPVs replaced by EVs and with the current COECF of the power grid for each region, there will be a 34%, 22.14 %, and 6 % decrease in CO_2 emissions per year for Tuscany, Sicily, and Sardinia regions respectively. Even with such a high penetration level of EVs in the system of the Sardinia region, there is no noticeable change in the CO_2 emissions as compared to emissions from 100 % TPVs due to the high dependency on NRES for electricity generation with high COECF of the power grid.

Table 4.3: CO_2 Emissions for each region with 60 % EVs

Region	Emissions from TPVs (CO_2 Mton/Year)	Emissions with 20 % EVs (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)	Ideal Scenario (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)	Extreme Scenario (CO_2 Mton/Year)	Difference (CO_2 Kton/Year)
Tuscany	1.791	1.827	608.2	0.7399	1050	2.6603	870
Sicily	2.364	1.8406	523.4	0.977	1387	2.5117	1147.7
Sardinia	0.775	0.7283	46.88	0.32224	452.56	1.1513	376.2

A significant decrease in CO_2 emission has been noticed for the Tuscany region and also for the Sicily region, having low and intermediate COECF of the power grid respectively. For the ideal scenario if there is 100 % RES available for charging 60 % of the EVs, more than half, almost 58 % of the CO_2 emission reduction can be achieved than that of TPVs per year. By charging this huge fleet of EVs assumed with electricity from 100 % NRES such as coal power plants, the effect of these EVs will be reversed and the CO_2 emission will be doubled compared to emissions from the 100 % TPVs for all three regions.

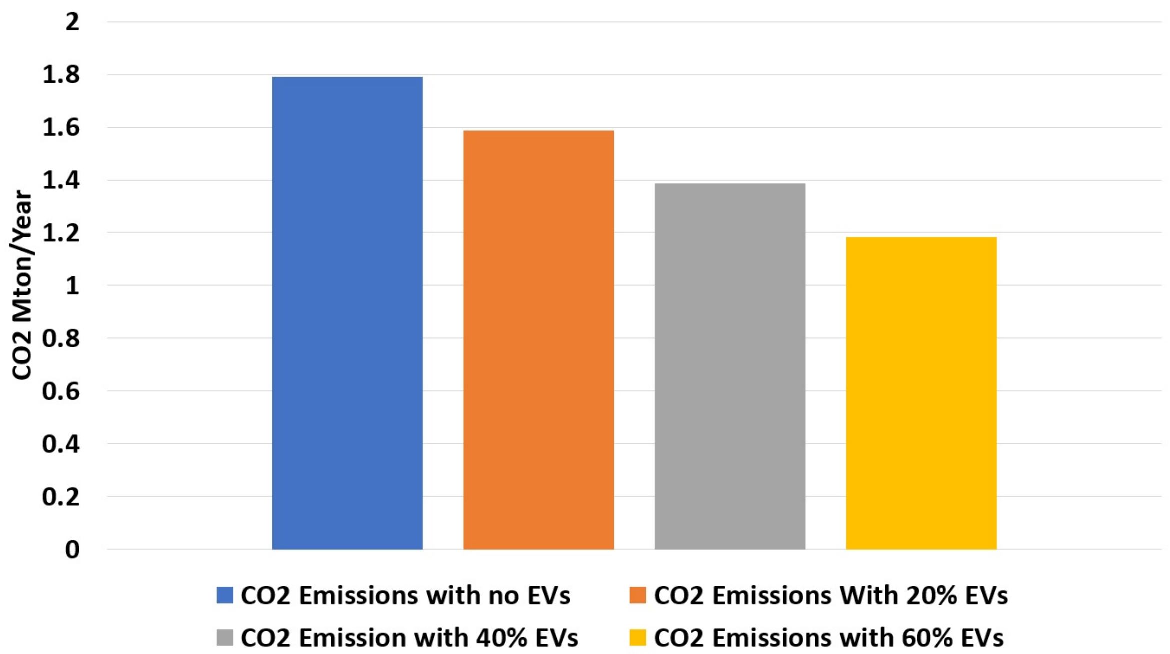


Figure 4.4: CO_2 emissions of Tuscany region per year

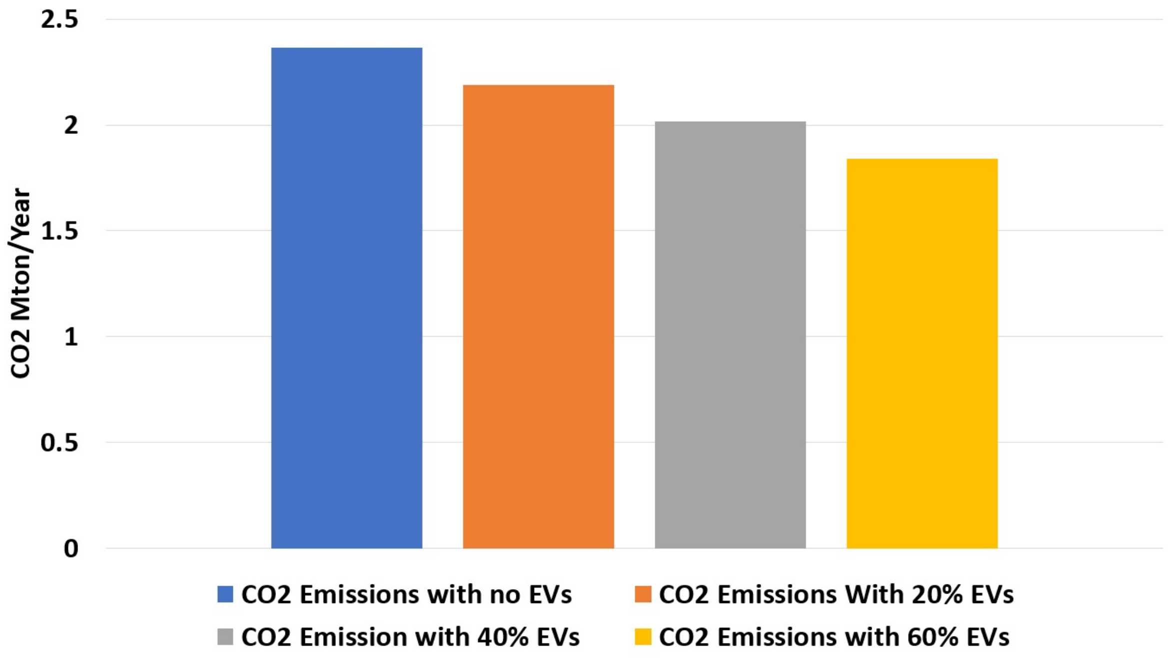


Figure 4.5: CO_2 emissions of Sicily region per year

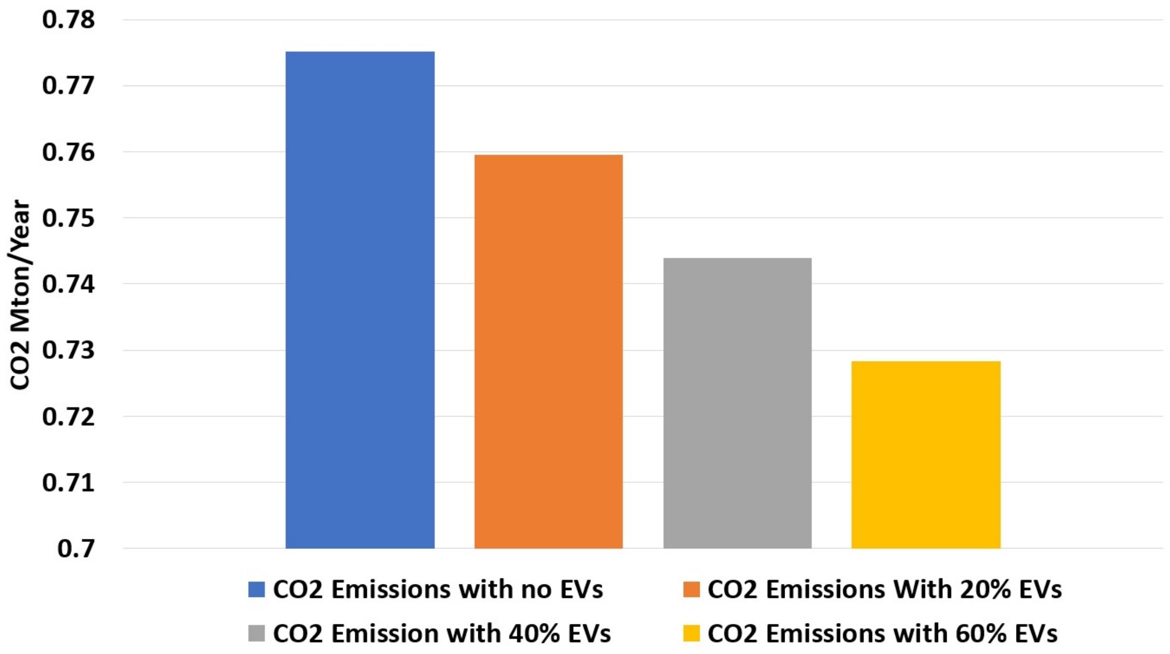


Figure 4.6: CO_2 emissions of Sardinia region per year

The overall results of the penetration level of 20 %, 40 %, and 60 % of the EVs for the Tuscany, Sicily, and Sardinia regions, with low, intermediate, and high COECF of the power grid respectively as shown in Figures 4.4, 4.5 and 4.6. It has been concluded that electrification of the transport sector will have no significant impact on the decarbonization of the transport sector if the power grid is dependent on producing electricity from oil, gas, and coal with high COECF. It can be seen that there has been no noticeable change with such high penetration levels of EVs in the Sardinia region because the major sources of electricity generation in this region are coal and gas. On the other hand, a significant reduction of CO_2 emissions has been observed with each penetration level of EVs for the Tuscany region, due to the factor that electricity generation in this region mostly depends on RES. Thus, there will be no impact of EVs on climate change, if the source of charging these EVs is not clean. So, most of the regions in Poland, Kosovo, Estonia, Bulgaria, and many more will have zero impact on climate change even with a high number of EVs in the transportation sector due to the high dependency on coal for electricity generation in these regions.

4.3 Summary

Many countries worldwide have set goals for the near future to increase the number of EVs. These high EV numbers can move the system toward sustainable and clean transportation only with the availability of RES. The regions with high COECF of the power grid will have no significant impact on the decarbonization of the transport sector and climate change goals. Research results have shown that new policies and frameworks have to be made for the transition towards EVs and to reduce the carbon dioxide emission factor of the grid by moving toward renewable generation. The regions where the power grid systems depend on nonrenewable energy sources for electricity generation will face more problems with a higher percentage of EVs in the future. The transport sector's electrification will not impact reducing the CO_2 emissions. The regions with more clean energy generation and low COECF of the power grid will experience a significant reduction in their CO_2 emissions. Therefore, moving toward clean and green transportation without RES is impossible.

Chapter 5

Impact of EVs on Urban and Insular Power System Networks

The transport sector is moving towards clean and green transportation with the growing market of electric vehicles (EVs) globally. EVs are independent of fossil fuel consumption, but the massive adoption of EVs can soon lead to a significant burden on the power distribution networks. In this chapter, a study on the potential impact of EVs on the power distribution networks of two different regions with totally different realities of population density, an average number of cars per inhabitant, and travel habits has been carried out. The first region is the island of Favignana, having an insular power distribution network, while the other region, the city of Palermo, has a grid-connected power distribution network with eight substations. The load profiles of these two regions have been analyzed in detail with future scenarios of 10, 20, and 50 % penetration levels of EVs. The Monte Carlo method, having the capability of generating data on the behavior of car owners with consideration of different scenarios, has been used, utilizing MATLAB software. The simulation results indicate that the high penetration levels of EVs in the future will lead to high peak load demands and these results will be more severe for the regions having high population densities, a high average of cars per inhabitant, and long driving distances.

5.1 Methodology

This section describes the methodology used to study the impact of an increased load due to EVs on the distribution grids of Palermo anddomestic recharging has been assumed with the EVs penetration level of 10, 20, and 50% the island of Favignana. For the simulations, the domestic recharging has been assumed with the EVs penetration level of 10, 20, and 50% of the total car fleet. The simulation script was created using MATLAB software and the Monte Carlo method. The Monte Carlo method can generate data randomly on drivers' travel behaviors, which can be considered in different scenarios. The study was conducted statistically based on the Italian scenarios and considered two typical days, summer and winter. The script developed in MATLAB software made it possible to extract data of the daily charge profile of the EVs for each scenario considered for the two grids under examination. Figure 5.1 represents the flow chart of the proposed methodology.

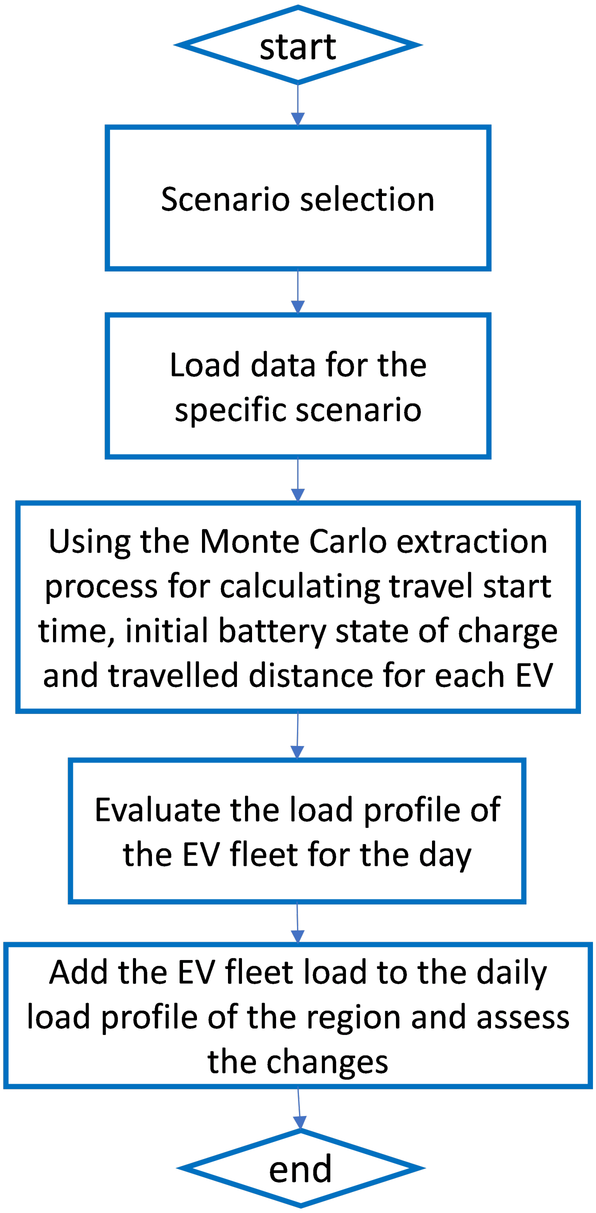


Figure 5.1: Methodology

The data for daily end-time trips typical of the Italian scenario is shown in Figure 5.2, and the probability distribution of daily distance traveled in kilometers is shown in Figure 5.3 and Figure 5.4 for Favignana island and the city of Palermo respectively. The data has been taken from scientific publications [171, 172], and has been modified according to the specific conditions of the two regions. Figures 5.2 and 5.3 conclude that the number of kilometers traveled daily in Palermo is much higher than in Favignana due to the considerable distances to be traveled in the city than on the island. From the probability distribution shown in the previous figures, the respective functions of cumulative probability have been obtained, shown in Figures 5.5, 5.6, and 5.7, and subsequently implemented in the MATLAB script. The cumulative daily load profile due to the EV fleet has been calculated for the two Palermo and Favignana island case studies with penetration levels of 10%, 20%, and 50% EV.

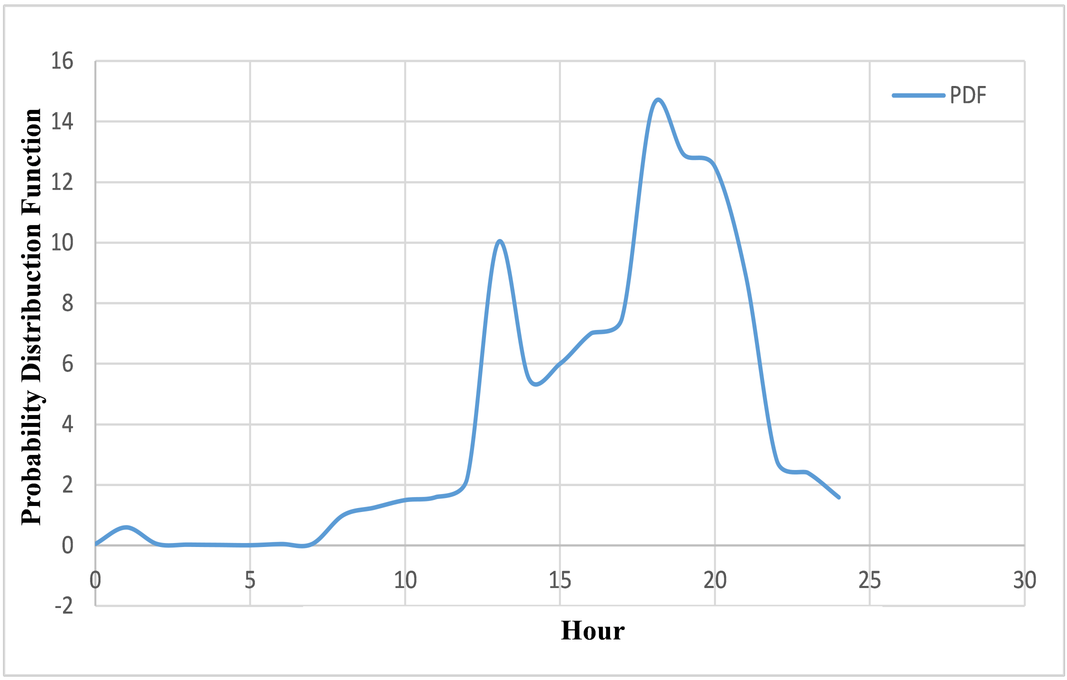


Figure 5.2: Probability distribution of daily trips, typical of the Italian scenario used

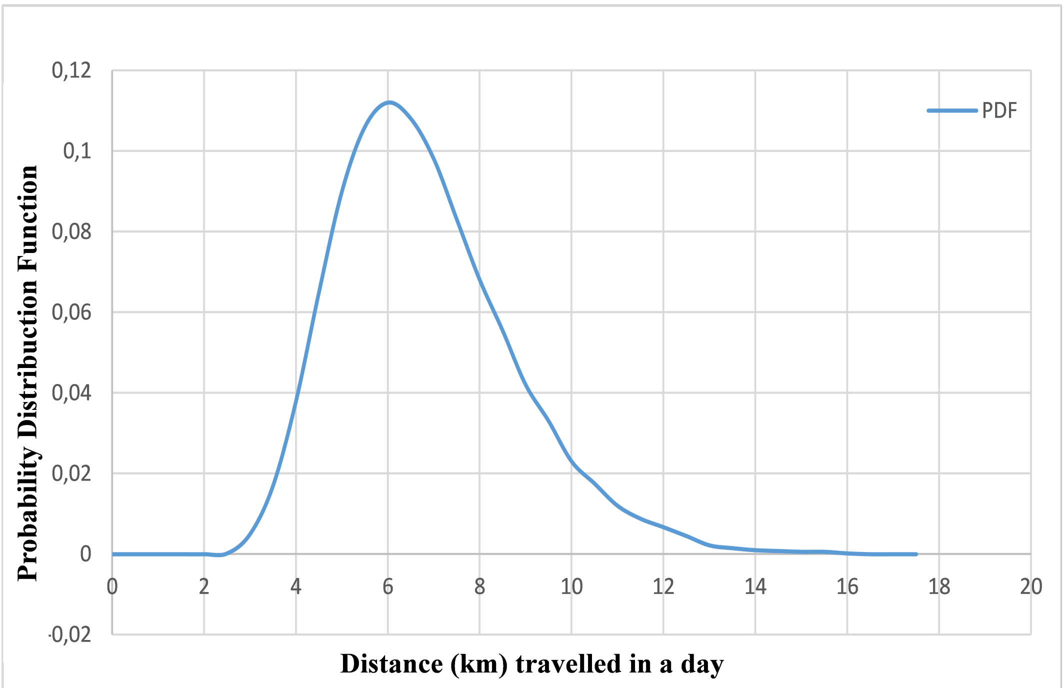


Figure 5.3: Probability distribution of kilometers traveled per day in Favignana

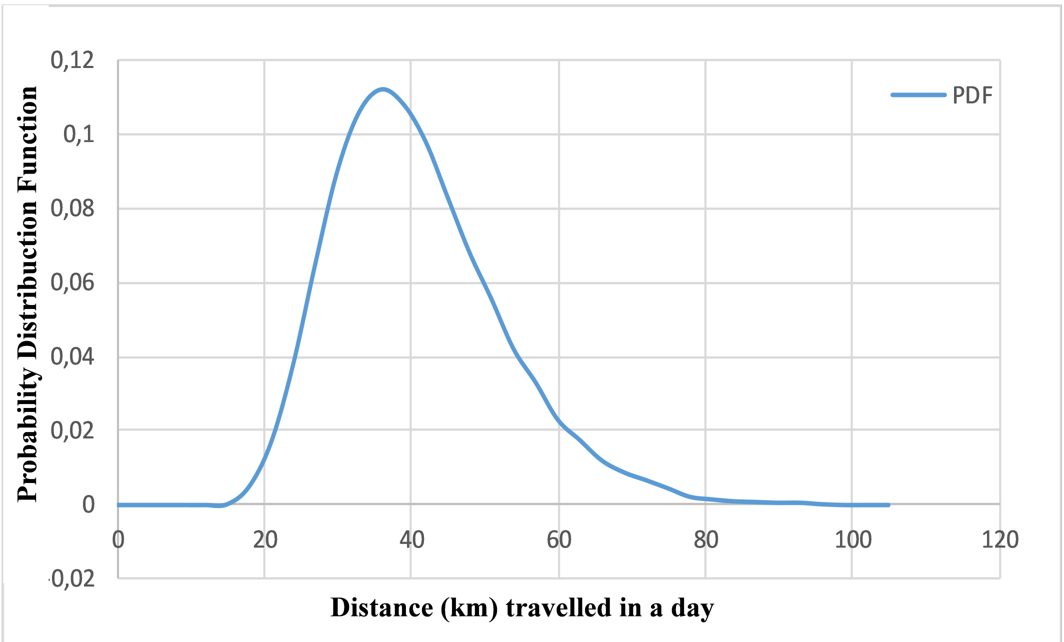


Figure 5.4: Probability distribution of kilometers traveled per day in Palermo

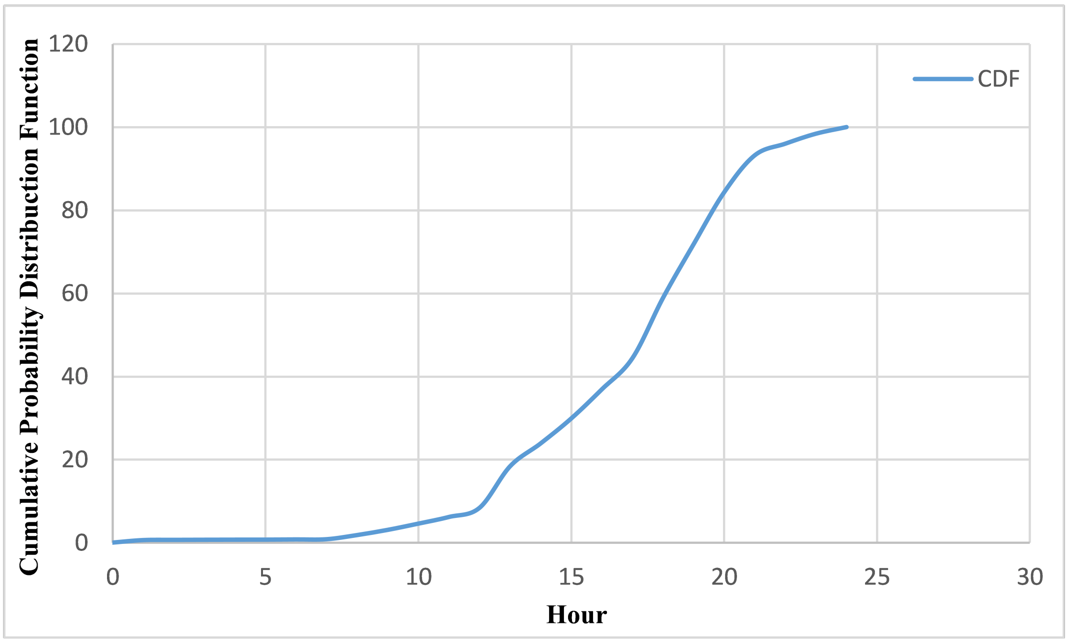


Figure 5.5: The cumulative distribution function of daily trips, typical of the Italian scenario used in the study

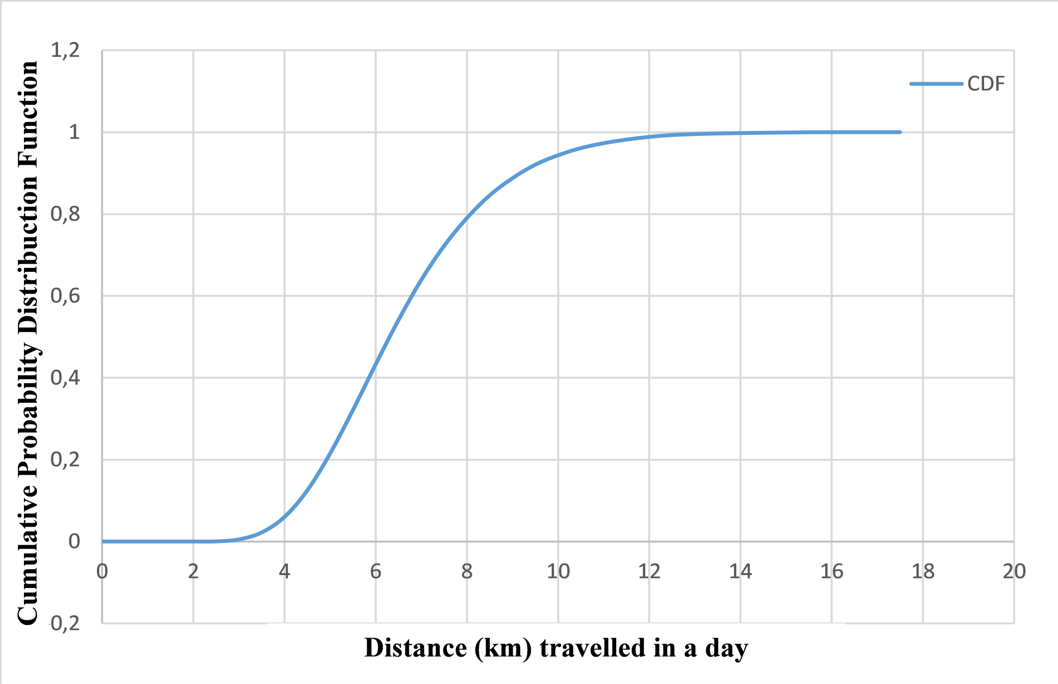


Figure 5.6: The cumulative distribution function of kilometers traveled per day in Favignana

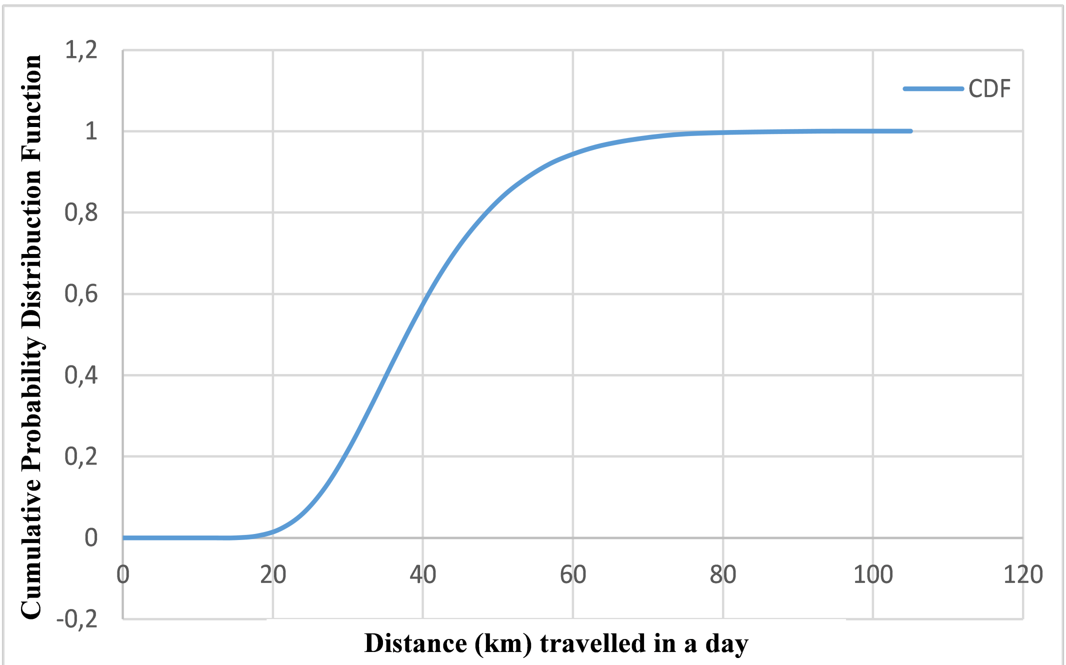


Figure 5.7: The cumulative distribution function of kilometers traveled per day in Palermo city

5.2 SIMULATION RESULTS

This section shows and discusses the simulation results obtained for the city of Palermo and the island of Favignana.

5.2.1 Simulation Results for the City of Palermo

Figures 5.8, 5.9, and 5.10 show the daily load profile of the EV fleet with 10, 20, and 50% penetration levels, respectively, for the city of Palermo. The figures show the total power demand of the EV fleet for each penetration level while considering the recharge duration of the EVs, which has been obtained from the ratio between the EV battery capacity and the average battery consumption during travel. It has been obtained that each car will be recharged every 3 days. The load profile of EVs shown in Figures 5.8, 5.9, and 5.10 has been equally divided among the primary eight substations of Palermo. The overall load profile combining the base load and EV loads is presented in Figures 5.11, 5.12, and 5.13 for February and Figures 5.14, 5.15, and 5.16 for August, respectively.

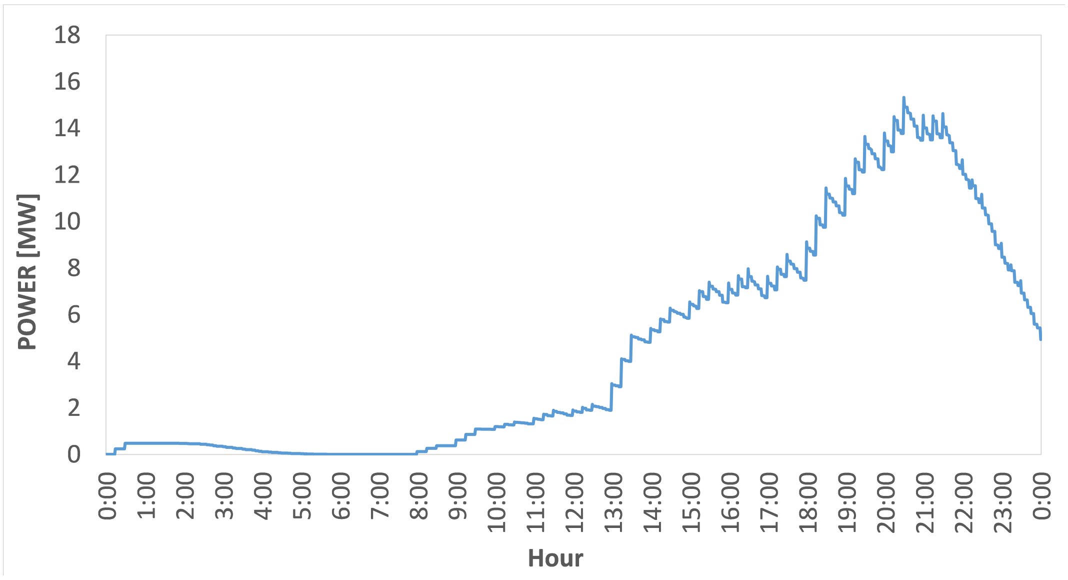


Figure 5.8: Daily load profile due to the EV fleet – Palermo – 10% EV

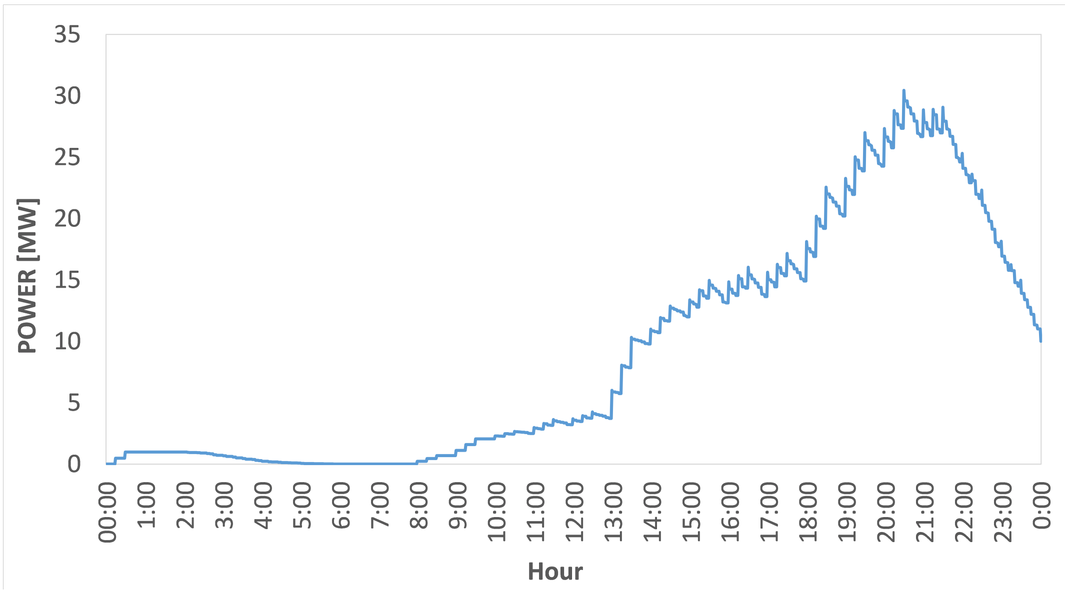


Figure 5.9: Daily load profile due to the EV fleet – Palermo – 20% EV

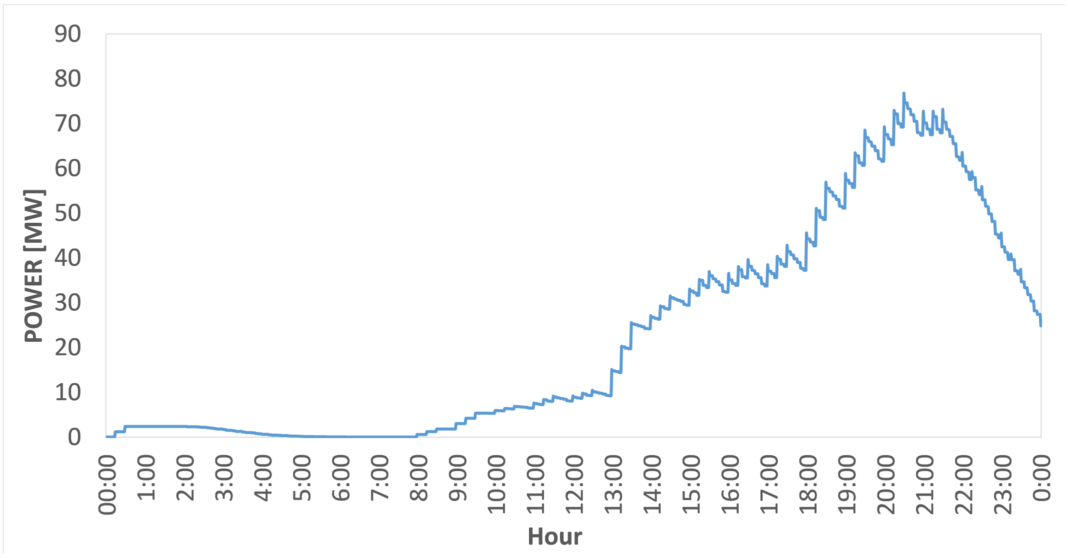


Figure 5.10: Daily load profile due to the EV fleet – Palermo – 50% EV

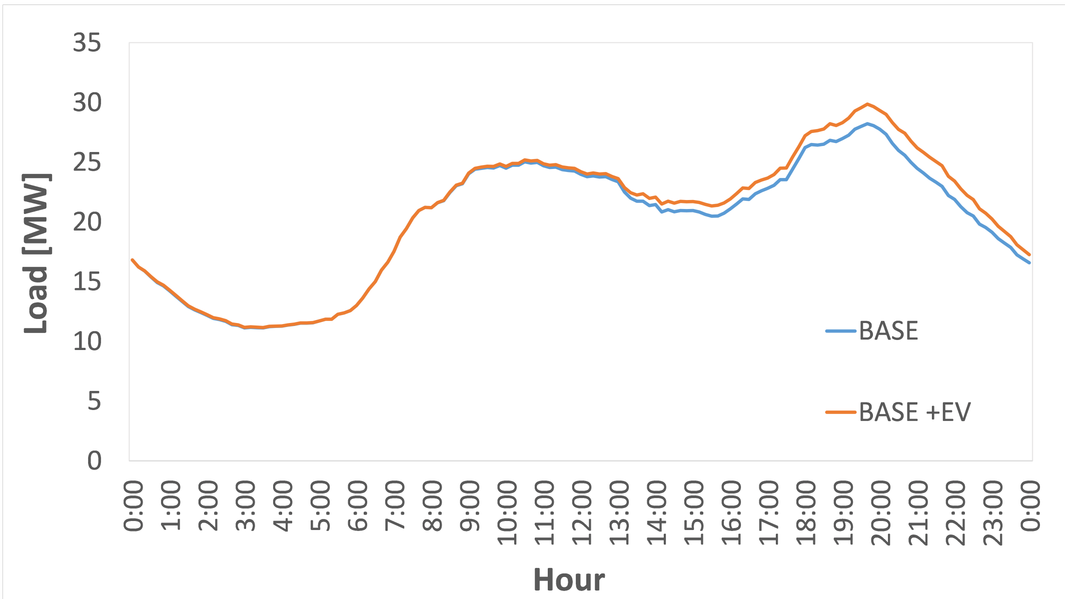


Figure 5.11: Daily load profile in the base case and the presence of EV (BASE+EV) - Palermo - 10% EV- February

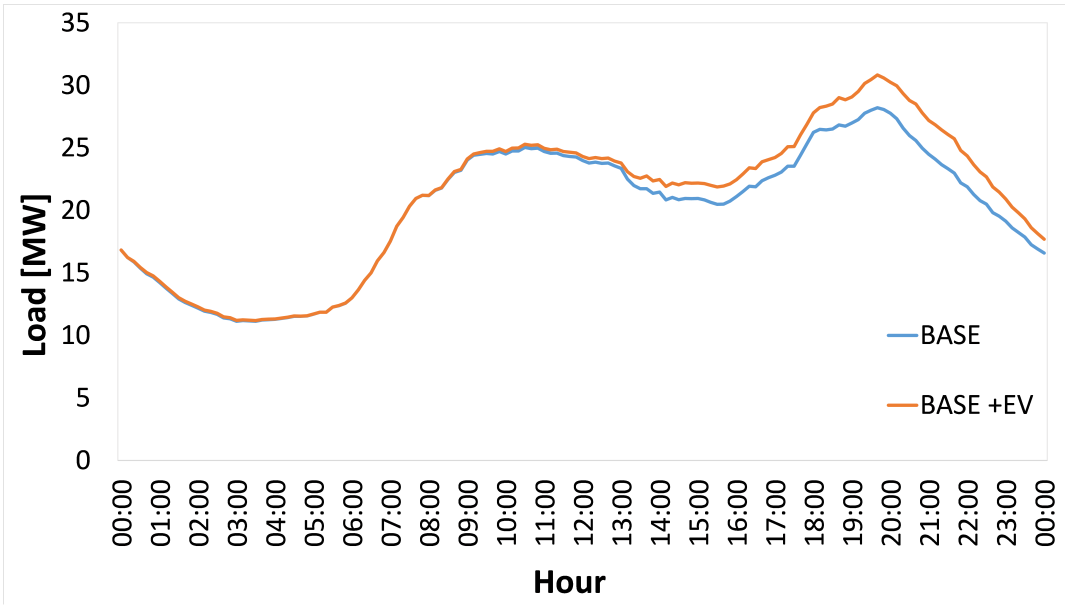


Figure 5.12: Daily load profile in the base case and the presence of EV (BASE+EV) - Palermo - 20% EV- February

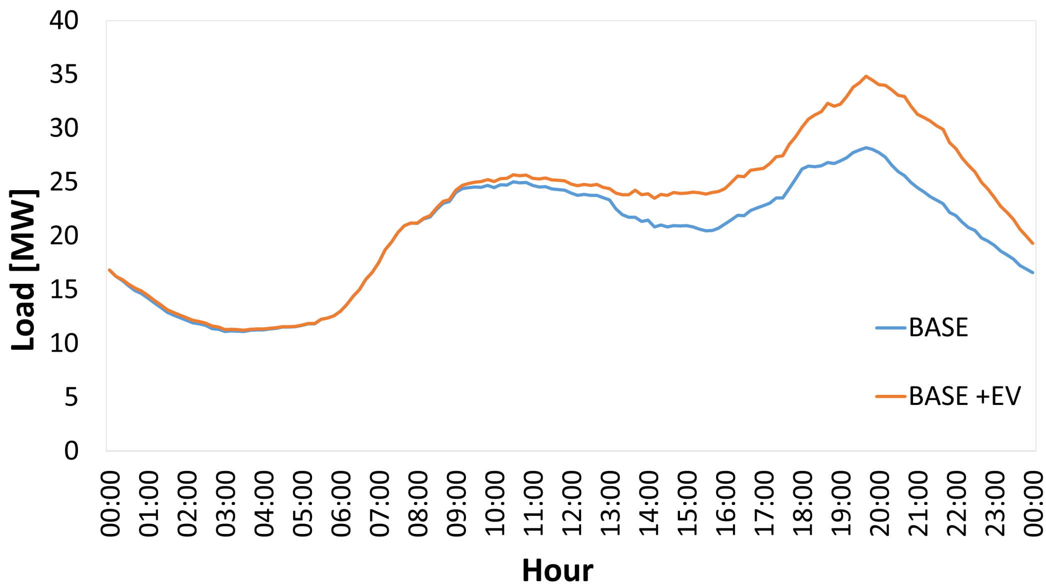


Figure 5.13: Daily load profile in the base case and the presence of EV (BASE+EV) - Palermo - 50% EV- February

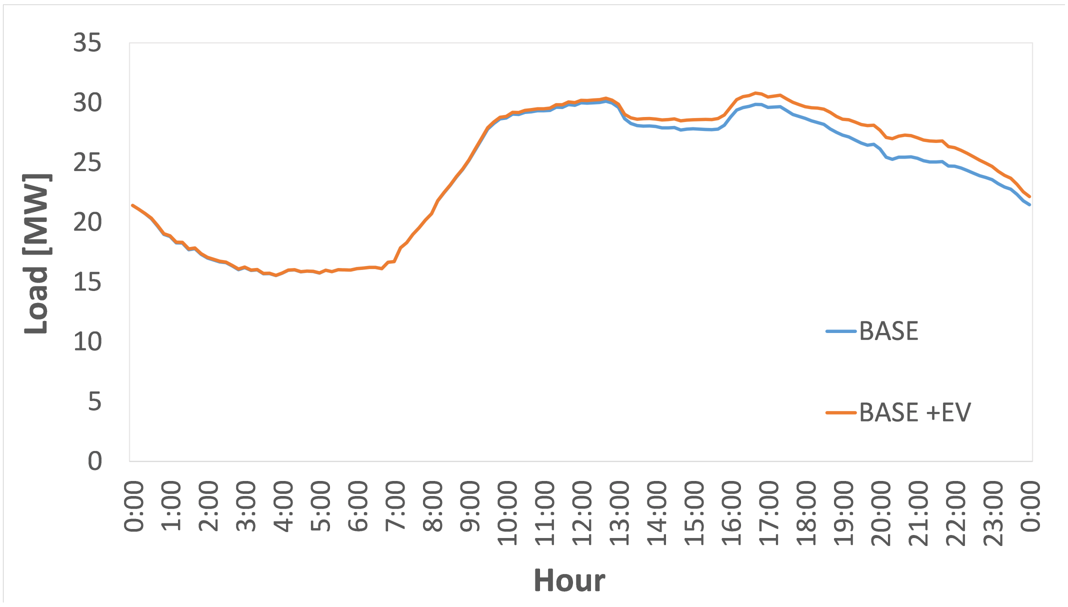


Figure 5.14: Daily load profile in the base case and the presence of EV (BASE+EV) - Palermo - 10% EV- August

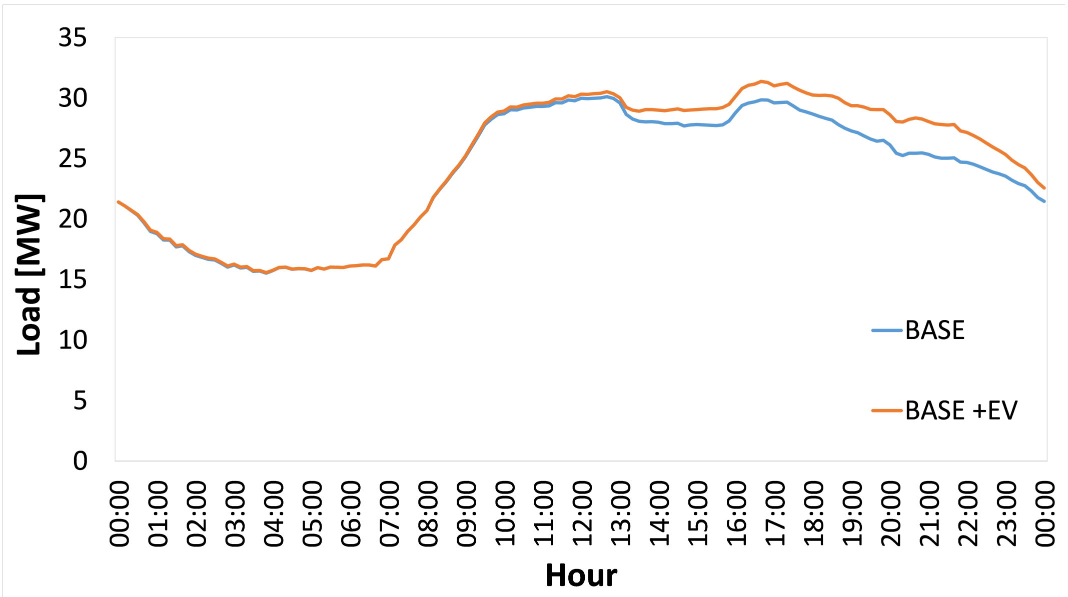


Figure 5.15: Daily load profile in the base case and the presence of EV (BASE+EV) - Palermo - 20% EV- August

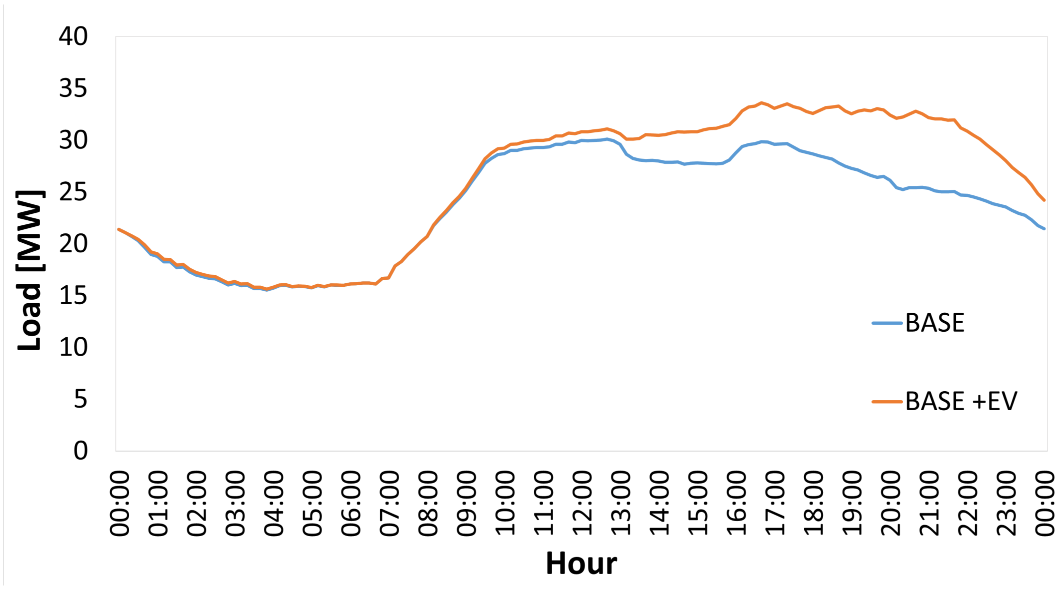


Figure 5.16: Daily load profile in the base case and the presence of EV (BASE+EV) - Palermo - 50% EV- August

5.2.2 Simulation Results for the island of Favignana

As in the previous subsection on Palermo, the same methodology has been employed to obtain the results for Favignana Island, and from these results, we conclude that EVs will be recharged every 18 days. Figures 5.17, 5.18, and 5.19 show the daily load profile of the EV fleet for 10%, 20%, and 50% of EV penetration, respectively.

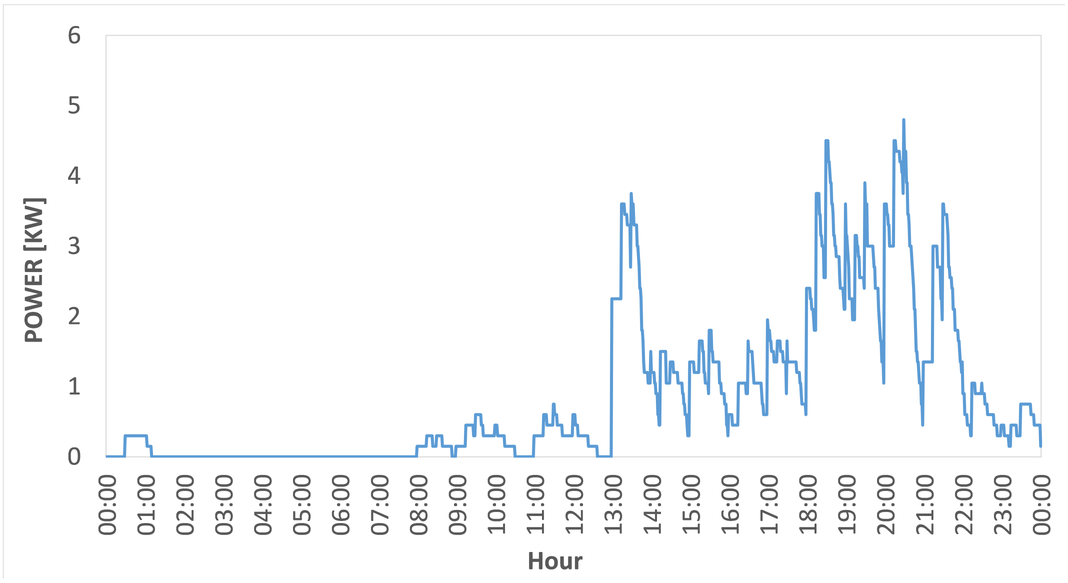


Figure 5.17: Daily load profile due to the EV fleet – Favignana – 10% EV

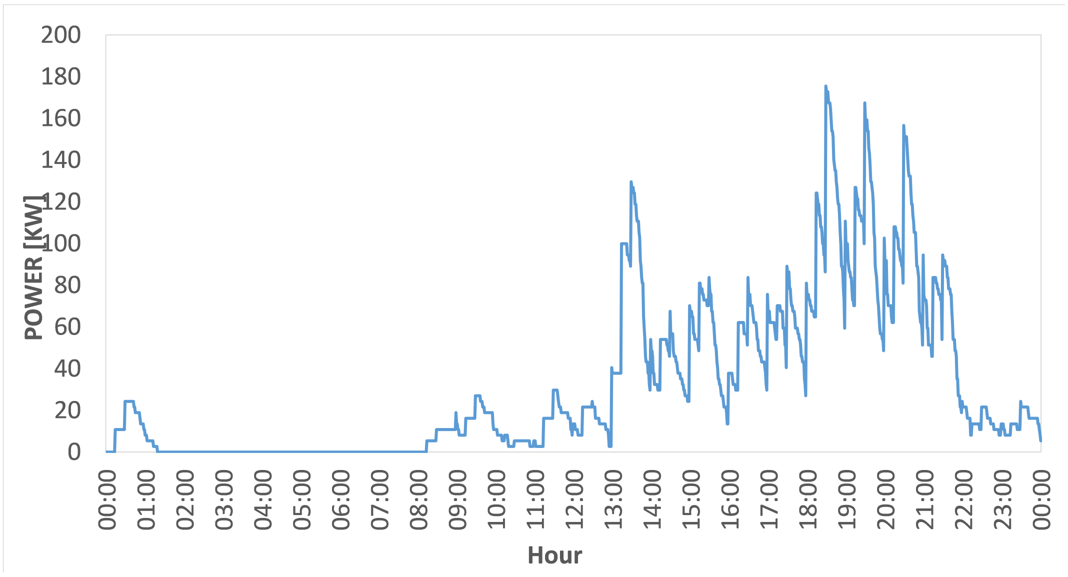


Figure 5.18: Daily load profile due to the EV fleet – Favignana – 20% EV

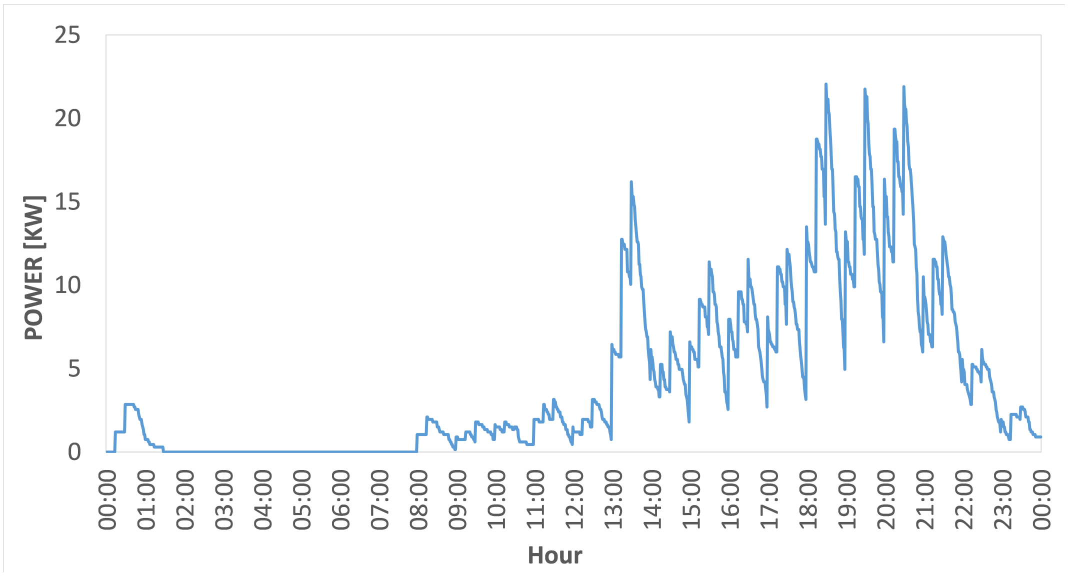


Figure 5.19: Daily load profile due to the EV fleet – Favignana – 50% EV

Figures 5.20, 5.21, and 5.22 for February and Figures 5.23, 5.24, and 5.25 for August show the daily load profile in the base case and the presence of EVs with a 10, 20, and 50% penetration level, respectively.

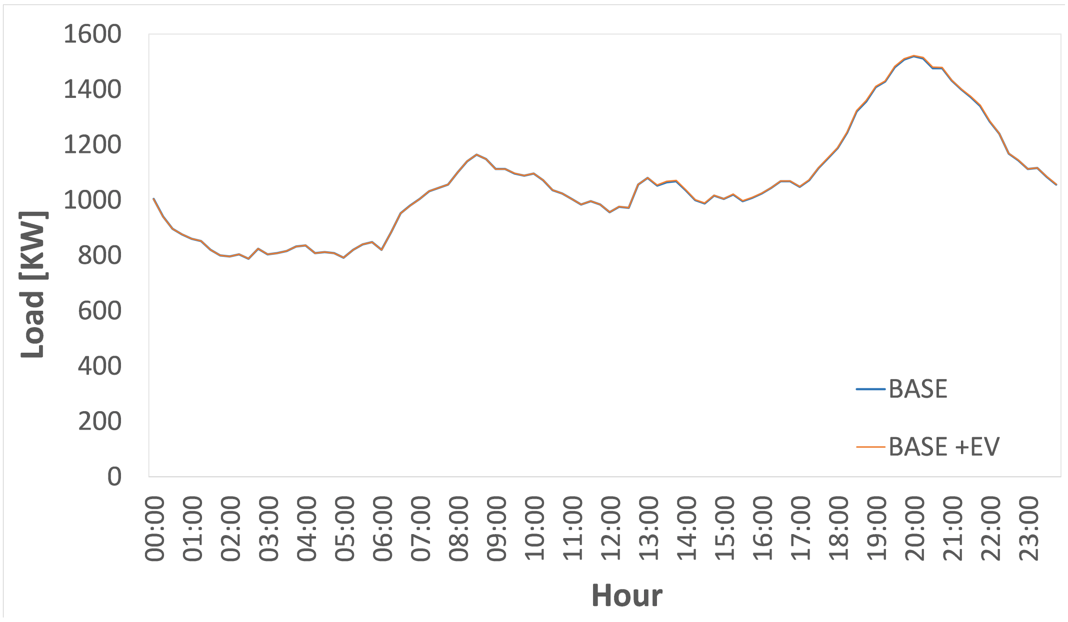


Figure 5.20: Daily load profile in the base case and the presence of EV (BASE+EV) - Favignana- 10% EV- February

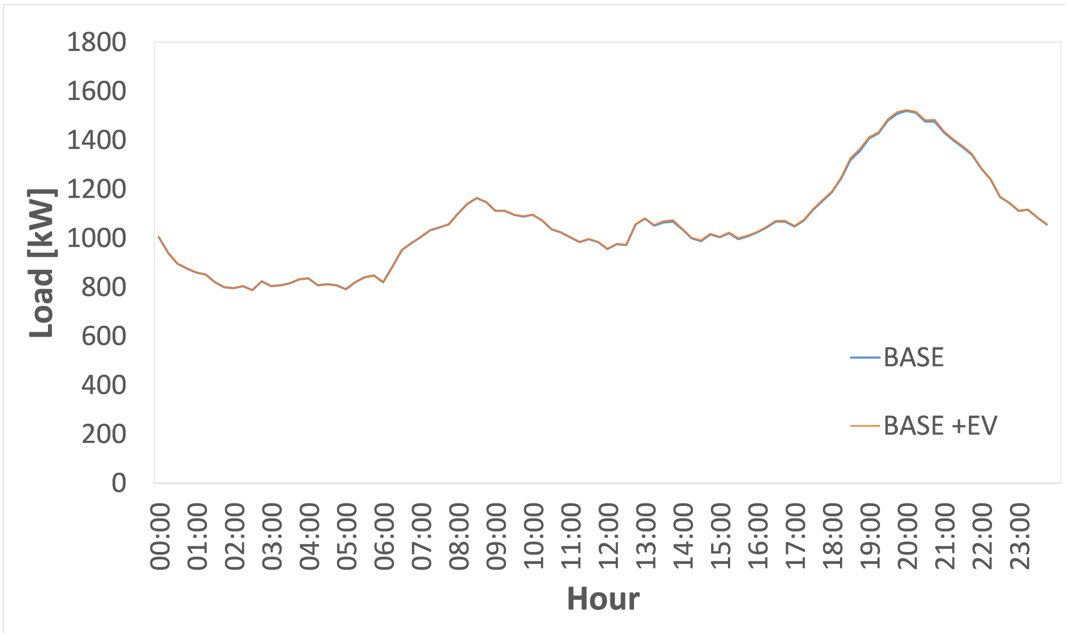


Figure 5.21: Daily load profile in the base case and the presence of EV (BASE+EV) - Favignana- 20% EV- February

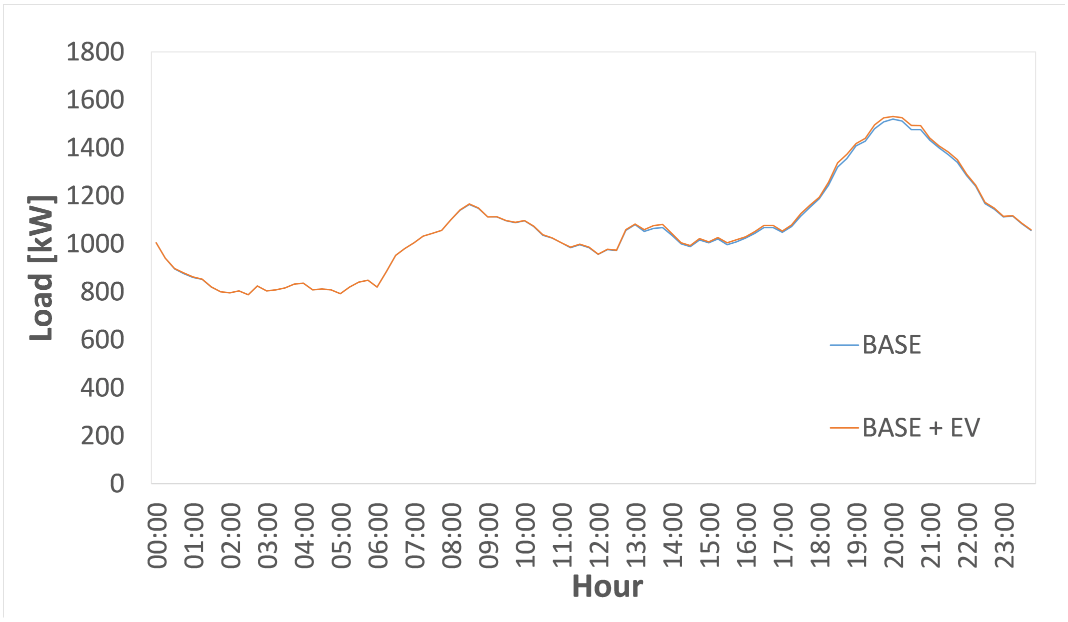


Figure 5.22: Daily load profile in the base case and the presence of EV (BASE+EV) - Favignana- 50% EV- February

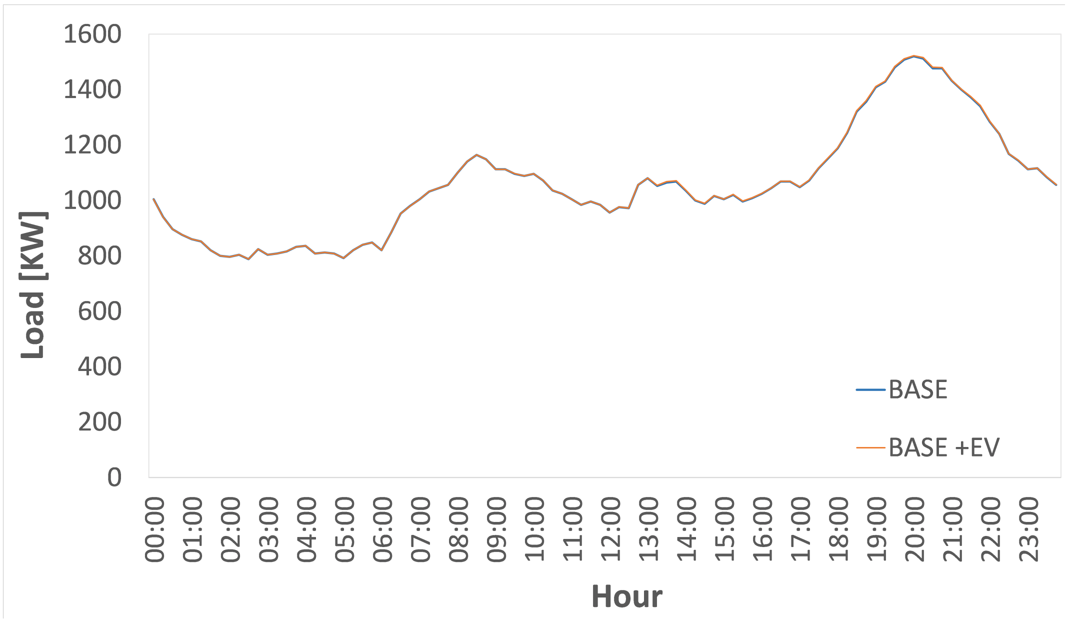


Figure 5.23: Daily load profile in the base case and the presence of EV (BASE+EV) - Favignana- 10% EV- August

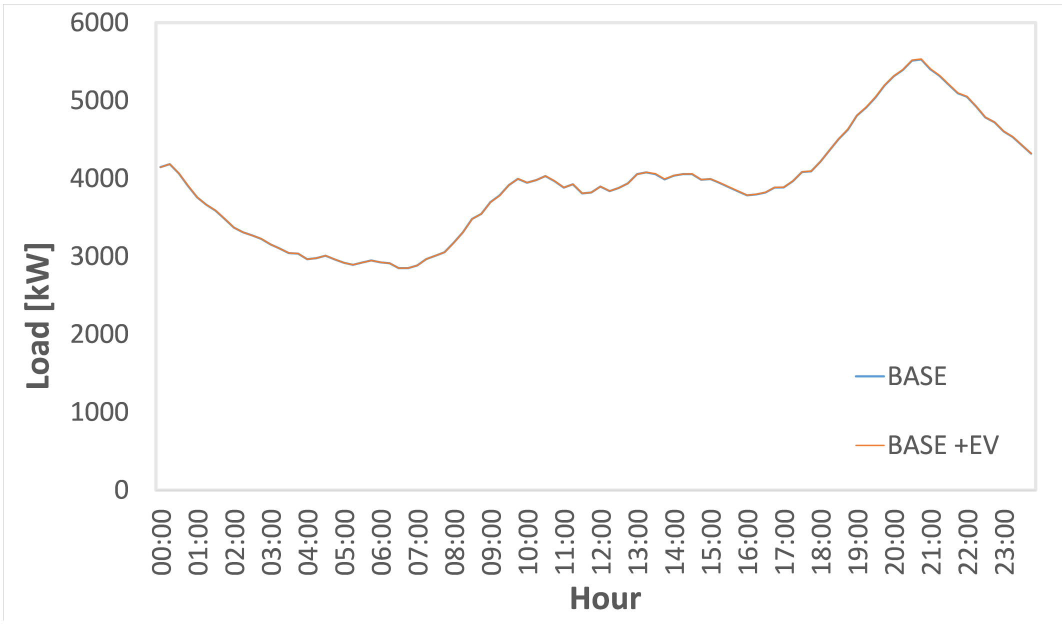


Figure 5.24: Daily load profile in the base case and the presence of EV (BASE+EV) - Favignana- 20% EV- August

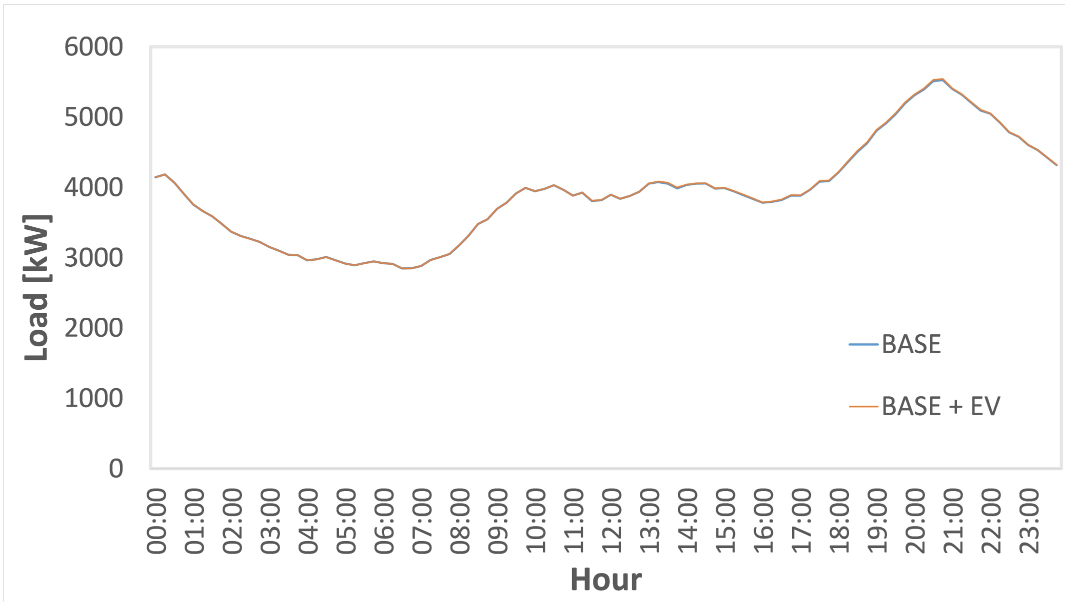


Figure 5.25: Daily load profile in the base case and the presence of EV (BASE+EV) - Favignana- 50% EV- August

5.3 DISCUSSION

5.3.1 Impact Assessment on the City of Palermo

A comparative analysis of the network's load profile with and without EVs was carried out to evaluate the impact of EVs on Palermo's power distribution grid. From figures 5.11 and 5.14, with a 10% penetration level of EVs, there is no noticeable change till 13:00, however, after 13:30 the load profile with EVs tends to increase. A maximum variation of 7.5% around 20:30 on the day of February and 7.2% around 21:40 on the day of August has been observed compared to the load profile without EVs. With a 20% penetration level of EVs, the load profile with and without EVs are identical until 11:30 on both days, but after that, the load profile of the network with EVs significantly increased and a maximum variation of 11.9% around 20:30 on the day of February and maximum variation of 11.5% around 21:30 on the day of August occurred as shown in Figures 5.12 and 5.15. Finally, with a 50% penetration level of EVs, a significant and huge difference has been observed between the load profiles of the network with and without EVs as compared to the previous two scenarios. A maximum variation of 36.7% around 20:00 on February and a maximum variation of 36.2% around 21:00 on August has been observed between two load profiles, shown in Figures 5.13 and 5.16 respectively. With a 50% penetration level of EVs concerning the total car fleet, the base load increased by 37%, which substantially impacted the city electric grid.

5.3.2 Impact Assessment on the Island of Favignana

For the island of Favignana, there was no noticeable change in the load profile of the network for all the scenarios shown in Figures 5.20 to 5.25. It has been observed, even with a 50% penetration level of the EVs, no significant change occurred in the load profile. From the research done on Favignana [173], it has been discussed that even if all the cars on the island are replaced by EVs and recharged every day, it will only increase the load by only 800 kW. This is because of very few numbers of cars on the island with fewer population densities and fewer distances to travel.

5.4 Summary

The study enabled the examination of the impact of a slow recharging system for EVs on the power distribution networks of the island of Favignana and the city of Palermo across various scenarios. The results indicate that EVs do not significantly affect the distribution grid on the island of Favignana, primarily due to the limited number of cars, short travel distances, and reduced need for recharging. Conversely, Palermo has a larger car fleet and greater distances to cover. However, 10% and 20% penetration levels of EVs showed less impact, with 50% penetration of EVs, the load profile increased by approximately 37% as compared to the load profile without EVs. It has been concluded from all the results and discussions that regions with a large number of cars, long travel distances, higher population density, and frequent recharging will experience a more severe impact from the electrification of the transport sector on their power grids than regions with fewer cars and shorter travel distances.

Chapter 6

Demand Side Management for EV charging

Electric vehicles have become increasingly prevalent in recent years, speeding up the peak demand, grid overloading, the need for distribution system modifications, voltage fluctuations, and grid congestion. Efficient, innovative, and ecological charging methods are needed to address these issues. Intelligent charging systems with demand-side management methodologies present a promising chance to tackle these difficulties. This study presents a technique for enhancing the utilization of time-of-use electricity when charging electric vehicles, especially in integrating additional battery storage in smart charging systems. The goal is to reduce both charging costs and the strain on the power grid. An advanced charging system has been developed to charge electric vehicles, considering factors including time-of-use electricity prices, the state of charge of additional battery storage, and the electric vehicle. A detailed model has been developed with MATLAB/Simulink. The study's outcomes offer valuable insights into the advantages and viability of integrating additional battery storage into a smart charging infrastructure. Through the optimization of time-of-use electricity consumption for EV charging, owners can reduce their electricity costs while contributing to a more sustainable and resilient energy environment.

6.1 Methodology

6.1.1 Flow Chart

Figure 6.1 shows the study methodology done in this chapter. The controller will start to check the electricity price, if the electricity price is less than or equal to the off-peak price, then it will move on to check if the EV is connected. If the EV is connected, then it will check the State of Charge (SoC) of the EV's battery and if the SoC of the EV is less than 90 percent. The controller will start charging the EV. If the EV is not connected to the charging system. Then, the system will check the SoC of the battery; if it is less than 90 percent, the battery will be charged. The battery's SoC will be checked if the controller receives higher prices than off-peak prices. If the battery SoC is greater than 20 percent and the EV is connected and has an SoC less than 90 percent, then the vehicle will be charged from the battery.

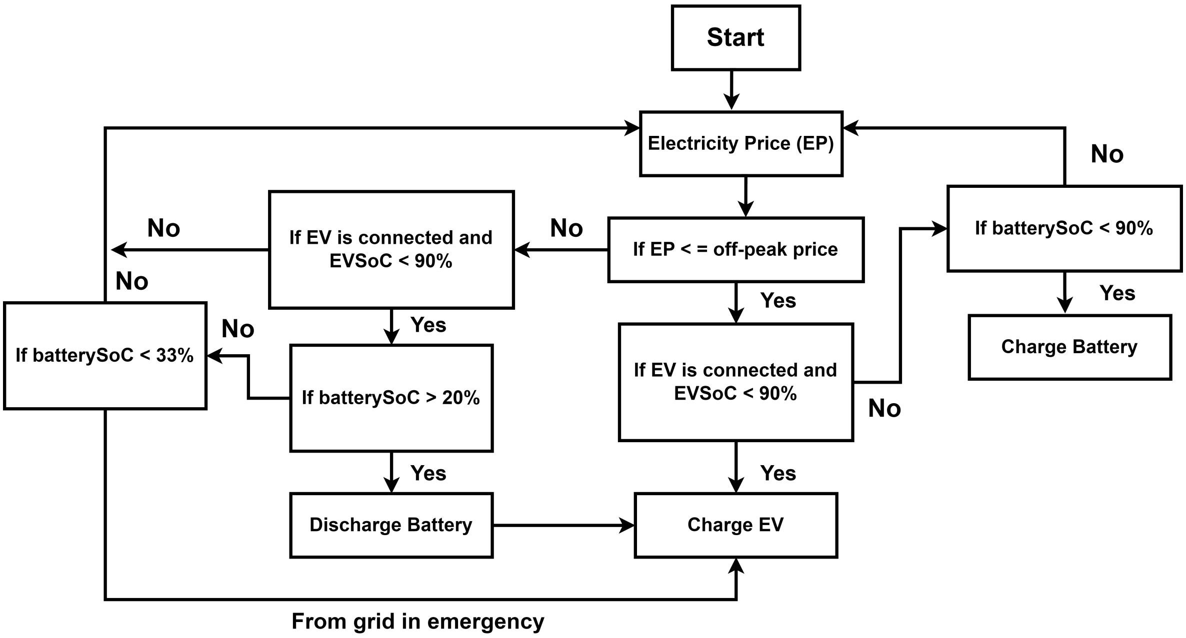


Figure 6.1: Flow chart of the paper methodology.

In an emergency scenario, the electric vehicle can be charged at standard EPr. However, the minimum SoC limit of the EV battery has been calculated. As mentioned in the reports, 5 percent of the vehicles hardly exceed the annual distance of 15000 miles and the average annual distance for the EU is 11300 km [174, 175]. The Fiat e500, the Italian-made EV, data taken for this research is in the top 3 in the best-selling EVs in Europe [176]. Based on the available data, the Fiat e500 requires 13 percent SoC to travel a daily average of 31 km. To preclude irreversible damage, the EV battery should not be discharged below the 20 percent SoC [177]. Hence, the minimum limit for emergency charging at standard rates will be at least 33 percent SOC. The full details of the Fiat e500 have been discussed in the coming section.

6.1.2 The EV model and TOU prices

The Italian-made EV model Fiat e500 Hatchback 42 kWh, third on the most-selling EV cars list in Europe, has been used for this study. The nominal battery capacity and usable battery of the Fiat e500 are 42 kWh and 37.3 kWh respectively. The actual range is 235 km with an efficiency of 159 Wh/km, and in [178], the complete details are given. The battery used within the smart charging system has a capacity of 12 kWh. This can provide a travelling distance of 62 km with a Fiat e500 Hatchback and is sufficient for 2 days considering a person's average traveling distance in Europe. The charger used is a Type-2 residential charger of 11 kW. The single-line diagram of the system is given in Figure 6.2.

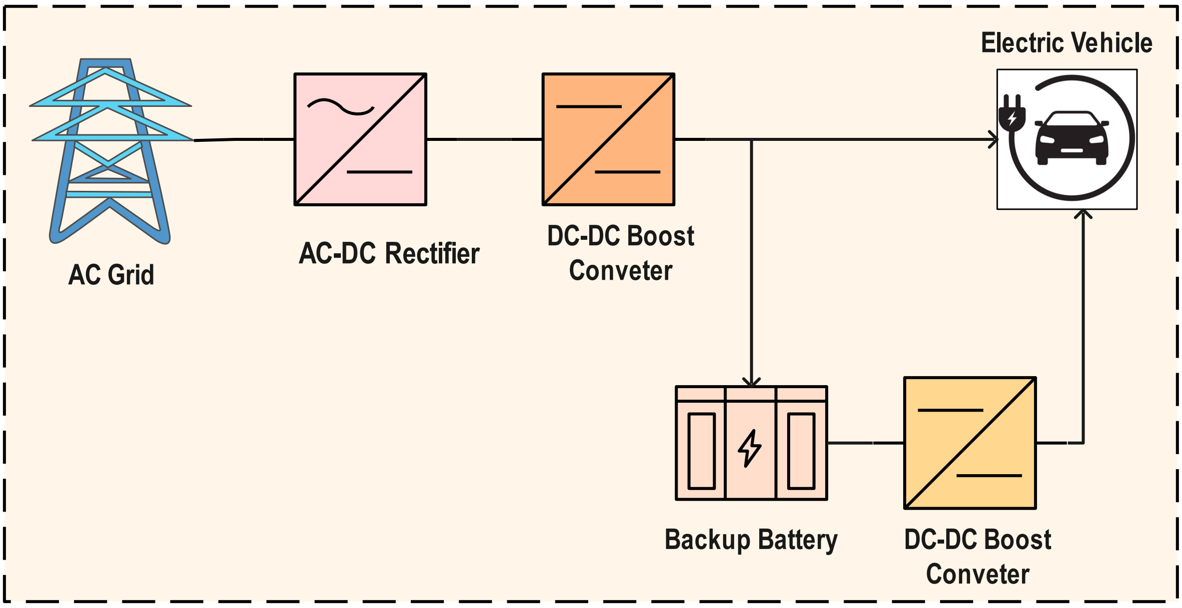


Figure 6.2: System Simple Overview.

The electricity prices for Italy in 2023 were approximately 0.3782 €/kWh [179]. From different studies and literature, we assumed that the off-peak prices would be 0.5 times and the peak prices would be 1.5 times the standard electricity prices [180, 181]. Hence, this study's off-peak and peak electricity prices will be 0.189 €/kWh and 0.57 €/kWh respectively.

6.2 Simulation Results and Discussion

Four scenarios have been developed based on the SoC of the EV and the battery. The simulations are run in MATLAB/Simulink for 30 seconds. The price signals were designed such that for the first 10 seconds, the electricity prices were 0.57 €/kWh, which are the peak prices. The electricity prices for the next 10 seconds were made off-peak, which are 0.189 €/kWh, and for the last 10 seconds, the prices of electricity have been made at standard rates which are 0.33782 €/kWh. Each Scenario has been discussed in detail in the following sections.

6.2.1 Scenario 1

In the first scenario, the SoC of the EV is less than 90 percent while the battery SoC is greater than 20 percent. The simulation results are shown in Figure 6.3. The charging system will take price signals from the grid and check them. As the SoC of the battery is greater than the minimum limit, the EV will be charged only from the battery when the prices per kWh are higher than the off-peak prices. As the electricity prices went low and reached off-peak prices, the battery was disconnected, and the EV battery was charged from the grid, and the current will start flowing from the grid to the charging system. When the prices get high again, the EV will be charged from the battery again and has been disconnected from the grid.

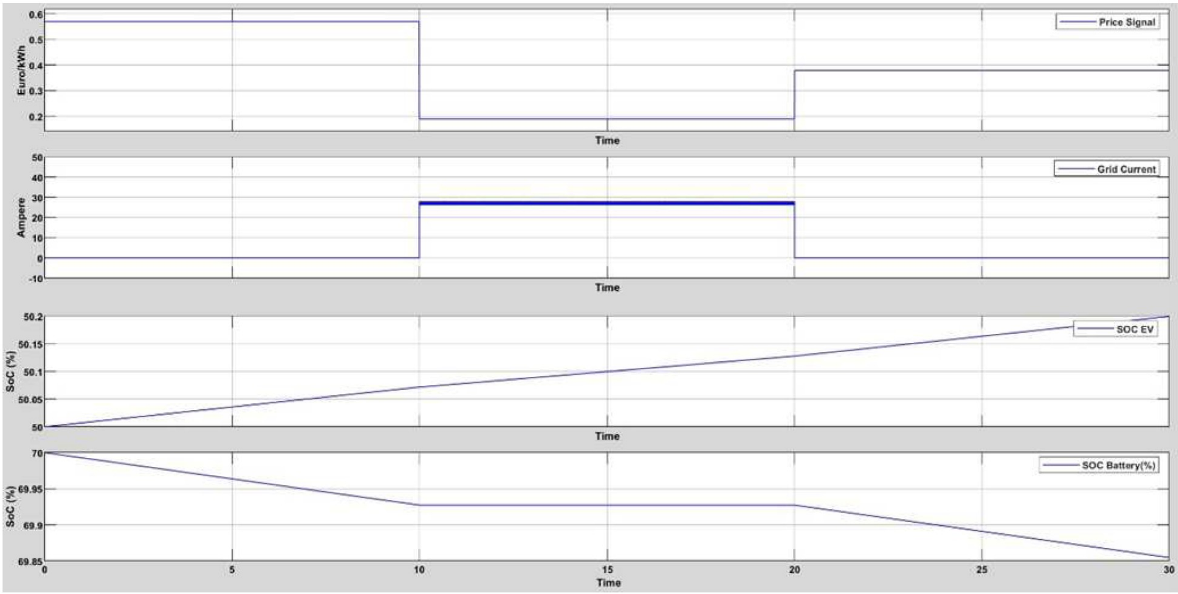


Figure 6.3: Results with EV SoC less than 90 percent and Battery SoC greater than 20 percent.

6.2.2 Scenario 2

In the second scenario, the SoC of the EV is greater than 90 percent, or the EV is not connected for charging, and the battery SoC is less than 90 percent. Shown in the simulation results in Figure 6.4. In this case, the EV charging will not take place because either the SoC of the EV has reached the maximum limit or the EV is not connected for charging. Hence, the battery will charge when the charging system gets off-peak prices. Thus, the system will store the grid's low-price power and use it later to charge the EV in peak periods. For prices greater than off-peak prices, the system will be disconnected from the grid, as can be seen in Figure 6.4, there is no current flowing from the grid to the charging system when the prices exceed the off-peak prices

6.2.3 Scenario 3

This scenario has been made only for emergency cases. When the Battery SoC is less than 20 percent and the EV SoC is less than 33 percent, the minimum charge required to travel a daily average distance is 31 km for EU. In this case, the EV will be charged from the grid until the EV SoC reaches 33 percent. The simulation results are shown in Figure 6.5. This case will not happen often as the battery will always store the off-peak period power from the grid and will always remain connected with the charging system.

6.2.4 Scenario 4

This is the case where the power from the grid will be disconnected. The SoC of the EV and the battery are higher than the maximum limit of 90 percent. The charging system will remain disconnected from the grid and no current will flow from the grid side even when the prices reach off-peak low prices as shown in Figure 6.6.

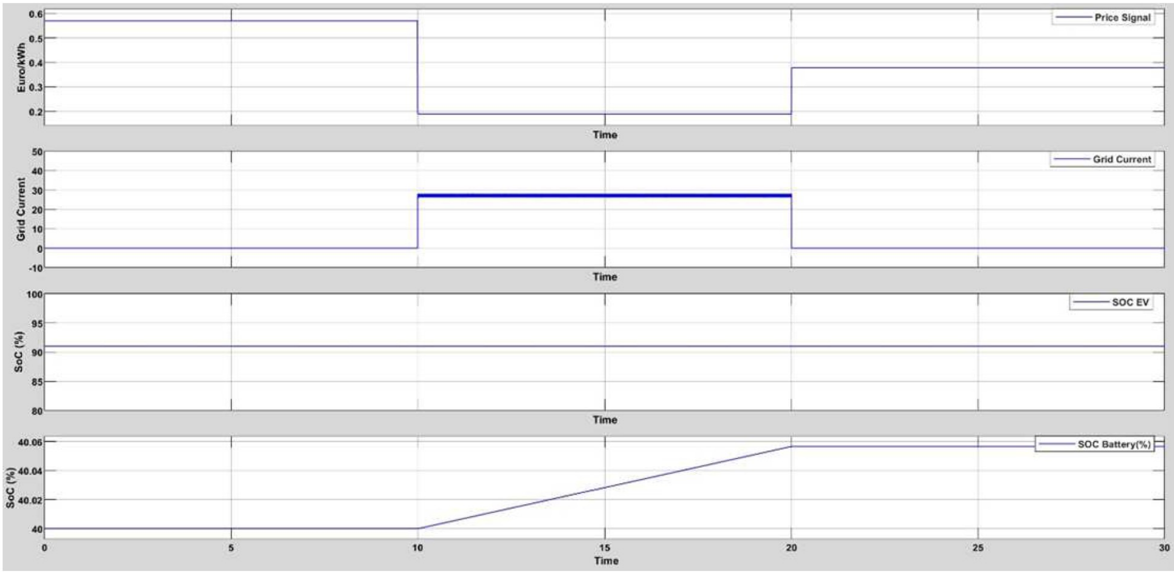


Figure 6.4: Results with EV SoC greater than 90 percent and Battery SoC less than 90 percent.

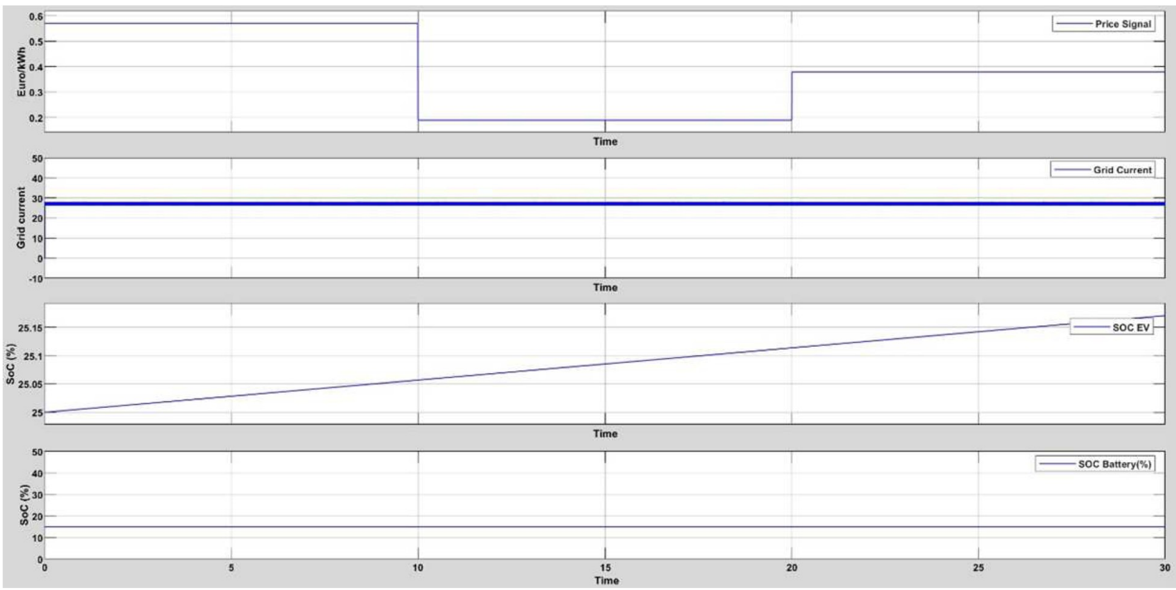


Figure 6.5: Results with EV SoC less than 33 percent and Battery SoC less than 20 percent.

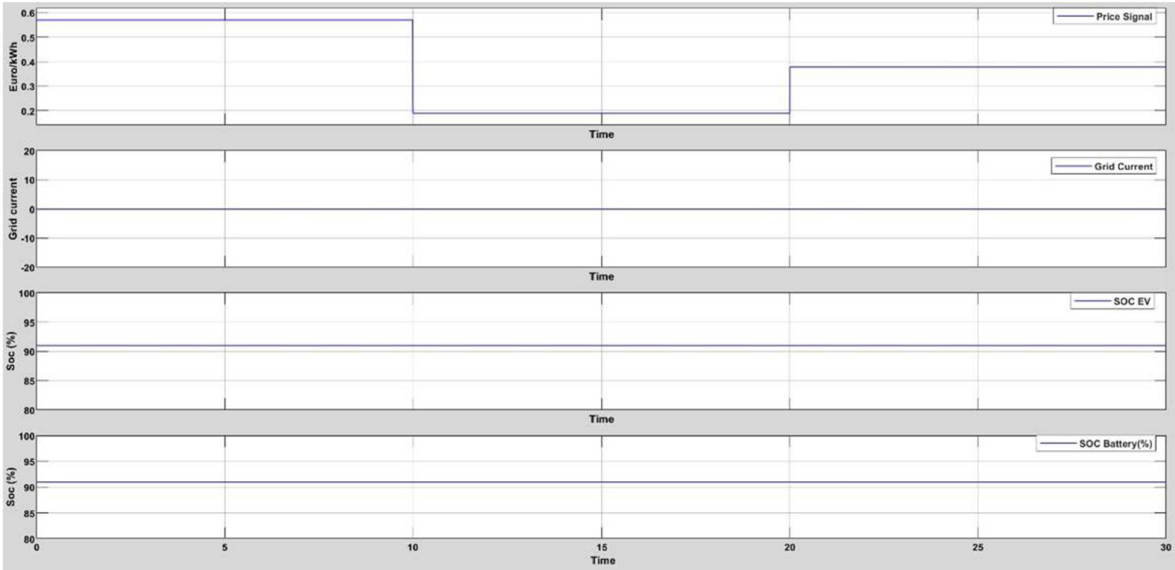


Figure 6.6: Results with SoC of EV and Battery greater than 90 percent.

6.3 Key Results

The summary of the results is given as:
• The EV charging cost will be reduced by approximately 67 percent when charged in peak hours compared to the charging cost in off-peak periods.
• The battery will add cost to the system, a 12-kWh battery has been used. A lithium battery per kWh costs 128 €/kWh [182]. Hence the payback period will be almost 2 years.
• The battery will store the power at lower electricity prices and give it to the EV when the electricity prices are high. Thus, the system will benefit from the off-peak prices even when the vehicle is not at the charging station.
• The EV will only be charged at higher prices when the SoC of both the battery and the EV is below the minimum limit. However, this situation will occur very rarely.
• This system will not only lower the cost of charging for the EV owner but also benefit the grid without adding more strain during peak demand hours.
• This system will be an efficient demand side management tool for peak clipping, valley filling, and load shifting.
• The payback period can be much smaller if this charging system is integrated into the Photovoltaic system and the house loads.

6.4 Summary

Implementing an intelligent charging system with an additional battery storage unit reduces EV charging costs and eases pressure on the electrical grid during peak periods. The system efficiently controls charging and discharging using time-of-use power pricing, considering real-time grid prices, and monitoring the electric vehicle's and the battery's SOC. Despite the initial investment associated with integrating the battery component, the system demonstrates a rapid payback period of just two years, resulting in a 67 Percent reduction in charging costs compared to peak-hour charging periods. In addition to benefiting individual electric vehicle owners, this strategy has the potential to help the overall electrical system by reducing peak load demands. It can contribute to peak clipping, valley filling, and load shifting. In the future, improvements like integrating photovoltaic systems and including home energy demands show potential for boosting system efficiency and further reducing payback periods. This research highlights how innovative charging solutions may reduce EV owners' expenses and enhance energy infrastructure's sustainability and resilience.

Chapter 7

Demand Side Management Using Digital Twins for EV's Load

A Digital Twin (DT) with Demand Side management (DSM) can significantly help reduce the negative impacts of the large number of EVs discussed in the earlier chapters. This chapter uses a DT concept with DSM to EV load and support the RES in the microgrid. *A DT is a set of virtual information constructs that mimics the structure, context, and behavior of the physical system (or system of systems). It is dynamically updated with data from its physical twin (PT), has predictive capability, and informs decisions that realize value. The virtual and physical systems' bidirectional interaction is central to the DT* [183]. DT offers valuable opportunities for enhancing innovative energy systems by enabling real-time monitoring, optimization, and control of microgrids. Their implementation can significantly improve efficiency and reliability in energy management. In this chapter, a residential load is first designed for an off-grid microgrid. Then, the Homer Pro software was utilized to provide the optimal system for fulfilling the load. This optimal system is assumed to be the PT for the study, while the DT was designed using MATLAB/Simulink. In addition, this chapter examines the methodology, conceptual design, necessary tools and technologies, challenges, and applications of the DT.

7.1 Key Components of the Designed Microgrid

The key components of the microgrid discussed in this chapter include residential load, EV load, solar PV system with wind turbines to supply these loads, and battery storage backup. The components are discussed in detail in the following sections.

7.1.1 Residential Load

The residential load was designed using HOMER Pro, as shown in Figure 7.1. It can be seen that the load peaks at 6:00 PM, similar to many residential loads.

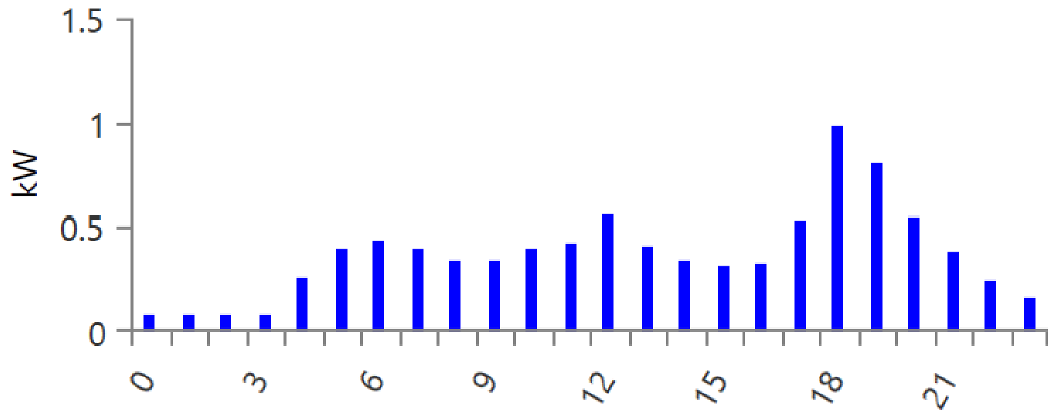


Figure 7.1: Daily residential load profile.

7.1.2 Solar Irradiance and Wind Speed

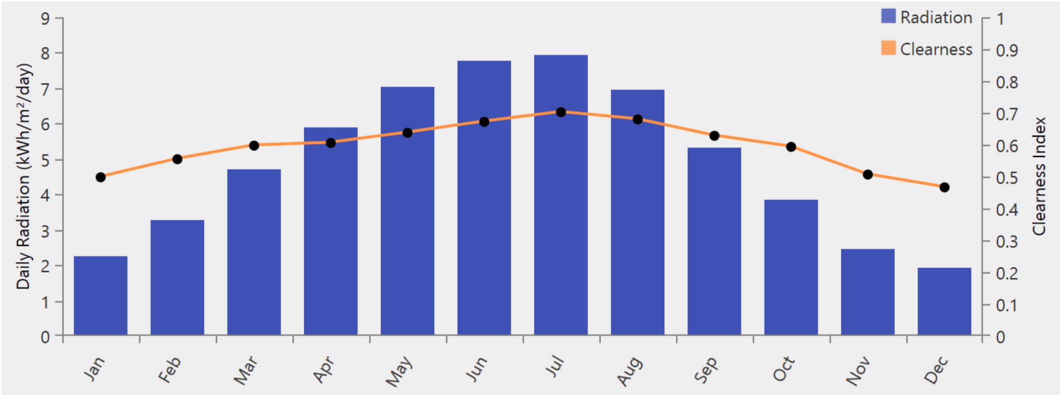
The region chosen for this study is Palermo. Figure 7.2b shows the monthly averages for solar Global Horizontal Radiation (GHI) in Palermo, obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database using HOMER Pro. Figure 7.2 illustrates the average monthly wind speed, sourced from the NASA POWER database at an anemometer height of 10 m using HOMER Pro. The figures indicate that summer has a higher solar PV potential than winter. However, the opposite is true for wind energy, as wind potential is greater in winter than summer. Therefore, both solar PV systems and wind turbines will serve as essential components of the microgrid.

7.1.3 Optimal Systems of HOMER Pro

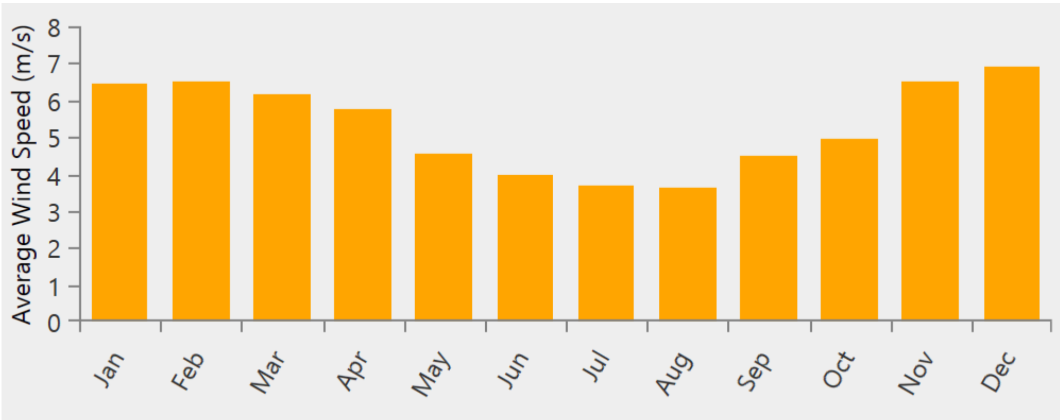
HOMER Pro gives five systems which can be used for the microgrid as shown in Figure 7.3. As previously discussed, the system under study is an off-grid system; therefore, the last two systems are not feasible since both lack storage backup to support the variable RES and have high costs. In Palermo, both solar and wind have high potential; therefore, the optimal system will include both sources in the microgrid. That's why, for the PT, the first system with the lowest cost, that incorporates both a solar PV system and wind turbines, along with a storage system, will be considered for this study. A 1.28 kW PV system and 2 kW wind turbines with 9 kW of battery storage will be required to supply the residential load.

7.1.4 EV Load

The study focuses on residential microgrids, so only level-1 or level-2 EV chargers have been considered. A Level 1 charger (1.2 kW) typically provides 4 miles of range per hour, while a Level 2 charger (6.2 to 19.2 kW) averages 32 miles per hour charge [184, 185]. The effects of level 2 chargers will be examined in detail.



(a) Monthly Average Solar GHI Data.



(b) Monthly Average Wind Speed Data.

Figure 7.2: Renewable Energy Sources for Palermo Region.

	Architecture					Cost		
⚠	PV (kW)	WindTurbine	1kWh LI (#)	Converter (kW)	Dispatch	NPC (€)	LCOE (€/kWh)	Operating cost (€/yr)
	1.28	2	9	1.65	CC	€9,601	€0.147	€163.56
		3	14	1.80	CC	€12,059	€0.184	€232.21
	5.91		27	2.05	CC	€16,382	€0.250	€391.22
⚠	3.46	81		0.500	CC	€175,280	€2.68	€1,655
⚠		138			CC	€291,765	€4.46	€2,760

Figure 7.3: System Suggested by HOMER Pro.

7.2 Conceptual Design

This section illustrates the details and single-line diagram of both the assumed PT and its DT, along with a detailed architecture diagram of the system's workings.

7.2.1 The Assumed PT and its DT

The single line diagrams for both the PT and its DT are presented in Figure 7.4 and Figure 7.5, respectively.

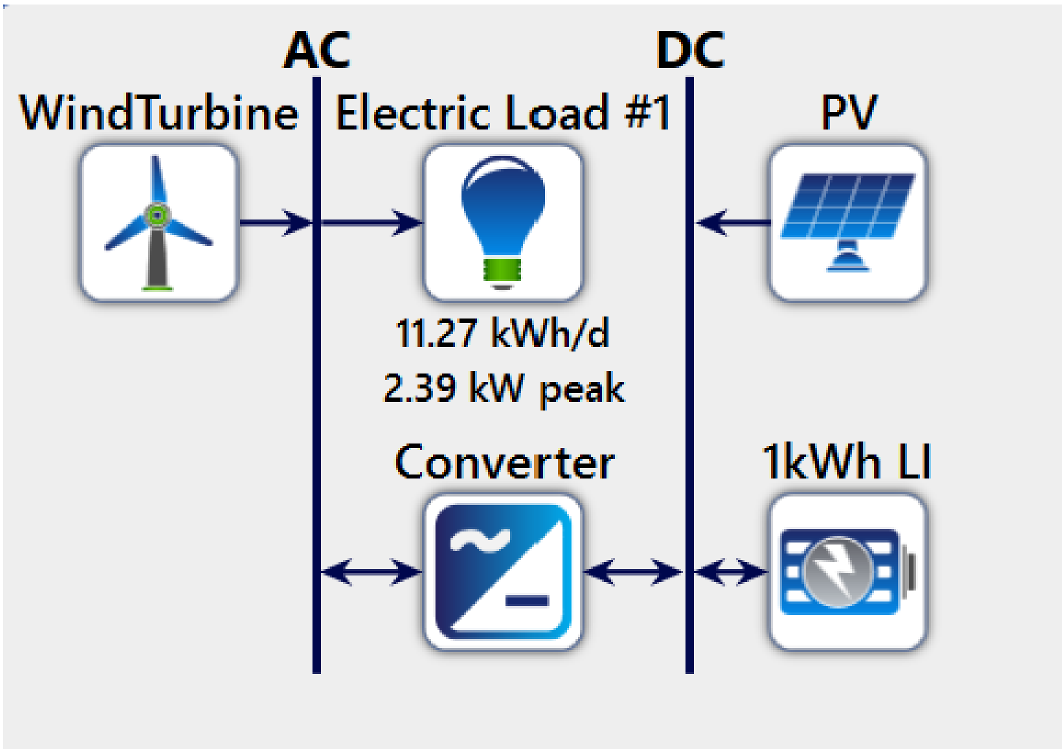


Figure 7.4: The Physical Twin (Assumed).

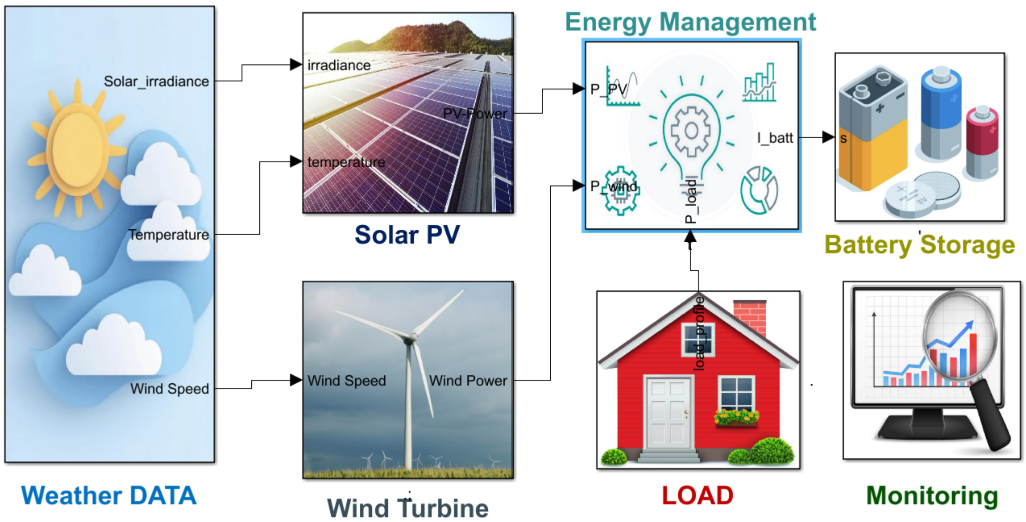


Figure 7.5: The Digital Twin.

The PT has a residential load, wind turbines, a PV system, and a backup storage system. The same system was replicated in MATLAB/Simulink with the same load, energy sources, and weather data, and it was assumed to be its DT. The concept of how these two systems interact has been discussed and explained in detail in the coming sections.

7.2.2 Architecture diagram of Operation Concept

The detailed architecture diagram of the system, which illustrates how PT and Dt work together, is shown in Figure 7.6. The system architecture diagram is a crucial tool for visualizing the overall structure and data flow between the components involved in PT and DT systems. At the core of this architecture, either a person or an intelligent control system continuously monitors the control section that governs the entire system. Within the DT, the control section can conduct prior tests by sending specific queries to the DT. It then analyzes the responses received from the DT to inform subsequent actions. Instructions can be communicated to the PT when the DT receives a positive response. This process allows for implementing prior changes in the PT, which are based on anticipated or future scenarios aimed at optimizing the Microgrid operation. As a result, the DT plays a unique and essential role in the functioning of modern and advanced microgrids.

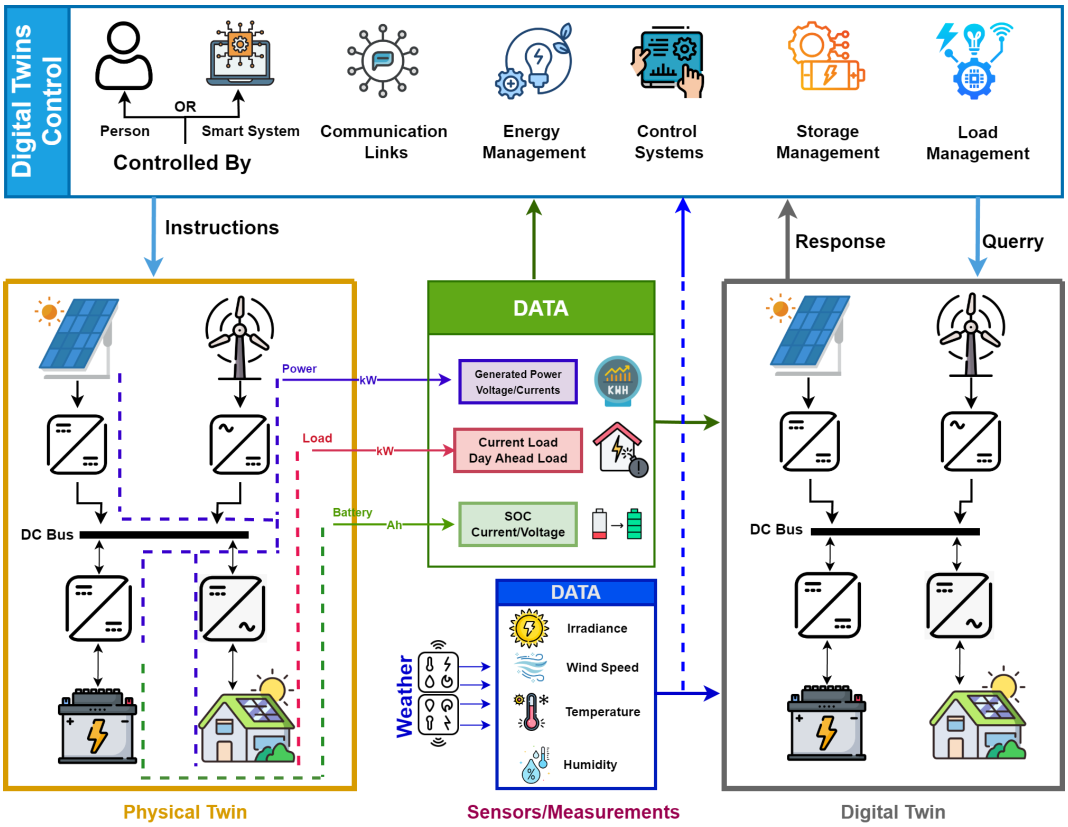


Figure 7.6: Detailed architecture diagram of System Operation.

Furthermore, this system's control and monitoring section is responsible for various crucial operations, including DSM, energy and battery management. These operations collectively enhance the reliability and stability of the microgrids, ensuring efficient energy distribution and utilization. Overall, the integration of DT within MG operations not only improves performance but also supports the transition to smarter energy solutions. The key components of the microgrid and critical data inputs for DT are given in Table 7.1.

Key Components	Data Inputs
Solar Pv and Wind Turbines Battery Storage System Dynamic Residential Load Energy Management Control System Sensors with Communication Infrastructure	Solar Irradiance Wind Speed Ambient Temperature Power from PV and Wind turbines Voltages, Currents and SOC of the Battery

Table 7.1: Key components of the microgrid and critical data inputs for DT.

7.3 Methodology

This section outlines the concept of methodology, which can be utilized to use the DT through real-time simulators. Figure 7.7 shows the idea of implementing DT for real PT.

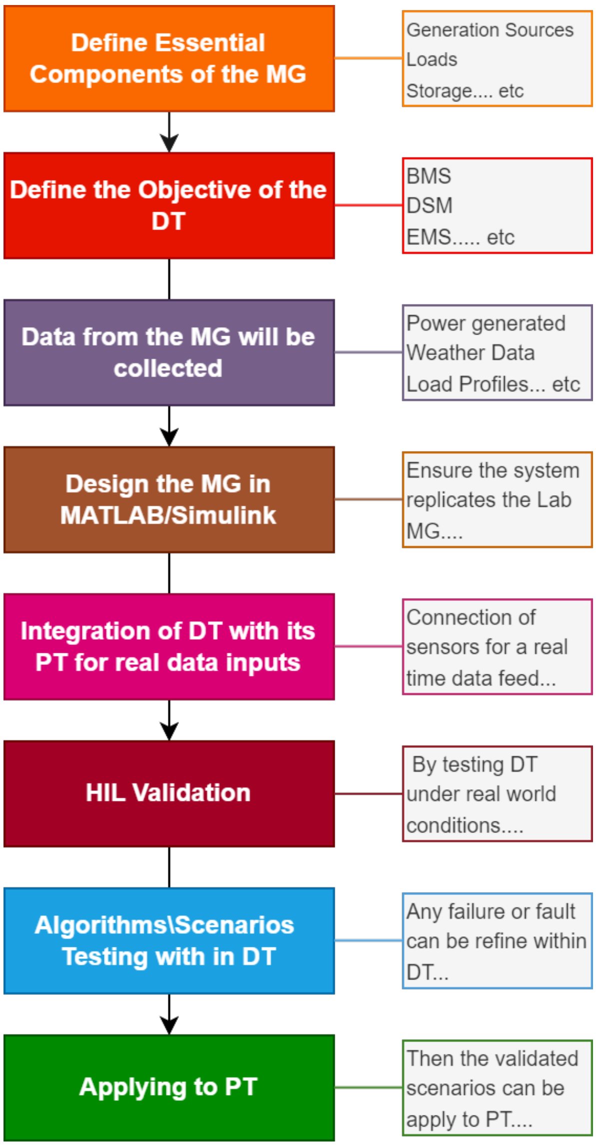


Figure 7.7: Methodology to implement DT.

Figure 7.7 illustrates that first, the essential components of the microgrid, such as generation sources, storage, and load, should be defined. Then, the objective of the Digital Twin (DT) should be determined, such as whether the DT will be used for DSM, battery management, energy management, or merely for monitoring purposes. After that, important data from the PT should be collected, including power generation, weather data, and load profiles. The PT will then be replicated using simulation tools, which can be integrated into the real-time simulator. The data from the PT will be fed to the DT through sensors for real-time monitoring. Following this, hardware-in-the-loop validation will be performed to validate the DT under real-world conditions. Once the DT is validated, it will be ready to assess any forecasted scenarios or algorithms before they actually occur in the PT. If the response of the DT is positive, then it can be applied to the PT, and changes should be made in the actual PT accordingly.

7.3.1 Technologies and Tools

Designing and implementing a DT for a microgrid demands a combination of software, programming languages, data platforms, and testing frameworks to ensure accurate simulations and real-world validation. The following tools can be used during development:

- MATLAB/Simulink represents a superior choice for modeling applications. HOMER Pro can be employed to derive optimal system insights. Additional simulation tools, including PSCAD, Digsilent, PSS/E, and ETAP, may also be utilized for modeling the DT.
- Programming languages such as MATLAB, C/C++, and Python can be used. The appropriate data platforms for DT include ThingSpeak, MySQL, and InfluxDB.
- Many hardware-in-the-loop systems can validate the system. MATLAB/Simulink integrates easily with OPAL-RT, making OPAL-RT a suitable match for MATLAB Simulink. However, other hardware-in-the-loop systems, such as Typhoon, dSPACE, Speedgoat, and National Instruments PXI, are also available.

7.4 Applications and Benefits of DT

DT can have a variety of applications and benefits. Some of them are highlighted below:

- Enhances energy efficiency by dynamically balancing energy supply and demand in real time, ensuring optimal system performance under varying conditions.
- Predictive maintenance uses real-time data and analytics to detect anomalies, facilitating the early identification and resolution of potential equipment failures. This strategy reduces both downtime and repair costs.
- Continuous real-time monitoring offers live updates on system performance, enabling operators to respond swiftly to any issues or deviations. This promotes smooth operations and informed decision-making.
- Lowers energy costs by managing demand and shifting loads during peak pricing hours, leading to significant savings.

- Improves solar and wind energy integration into the microgrid, boosting renewable energy usage while maintaining system stability.
- Conduct simulations of various scenarios to identify and mitigate risks, ensuring stable and reliable microgrid operation even in challenging conditions.

An example of a specific application of DT is thoroughly discussed in the results and discussion section.

7.5 Results and Discussion

First, the PT and DT outputs are compared under the same conditions to ensure that DT accurately replicates PT. Figure 7.8 shows the results of the PT while Figure 7.9 shows the results of DT for the 9th of July. Both results exhibit similarities, indicating that the DT is functioning accurately. The actual case examples are now completed for managing EV load based on the available energy from renewable energy sources and battery storage using DSM with DT technology. Each case will have the same limitations as the previous case, along with a new one to assess the system's reliability and stability. Like in Case-1, EV load is added; in Case-2, the battery storage will have 50% SOC plus the EV load. In case-3, it is assumed that the forecast wind will be half plus the limitation of case-2. The subsequent sections provide an in-depth discussion of each case.

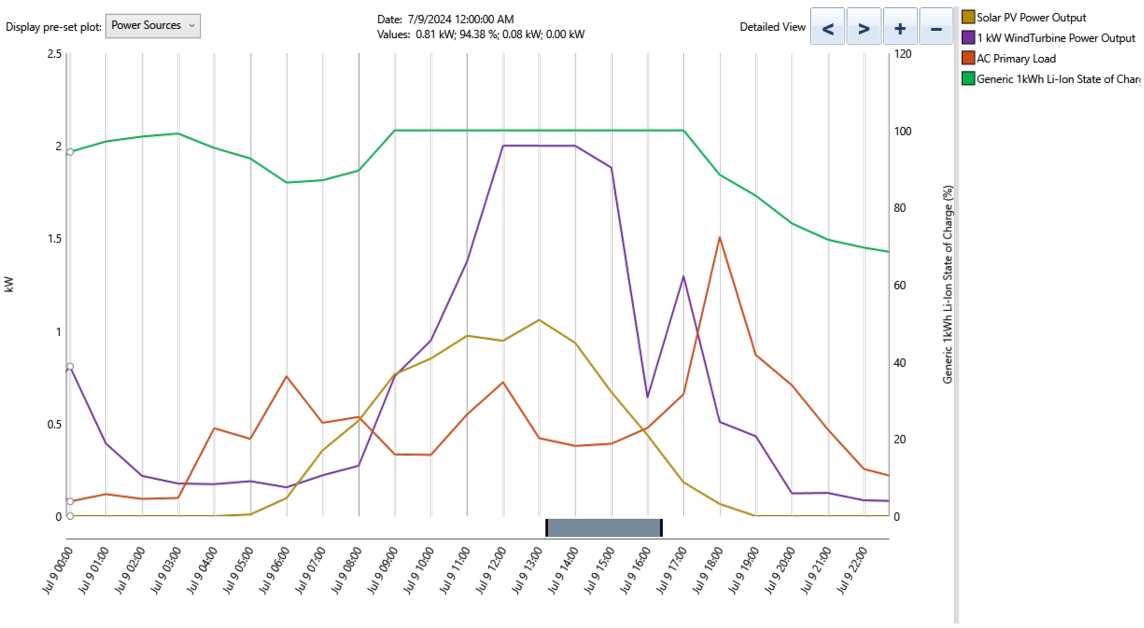


Figure 7.8: Results of PT.

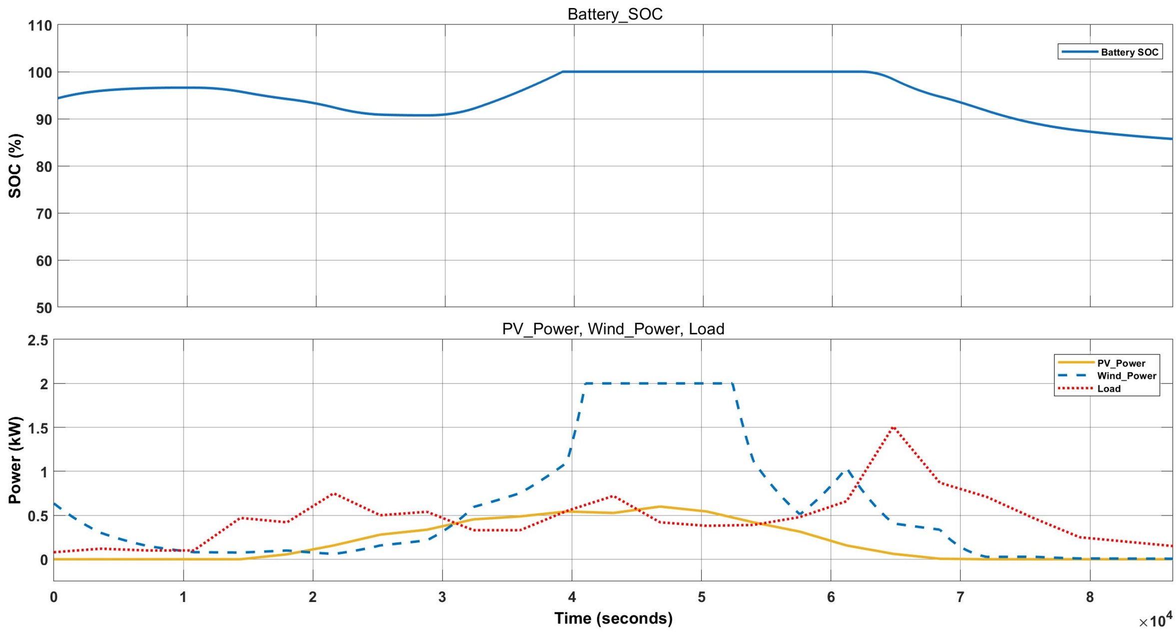


Figure 7.9: Results of DT.

7.5.1 Case-1: Charging EV

In this case, the EV load is added to charge through the level-2 charger rated at 7.2 kW from 16:00 to 19:00.

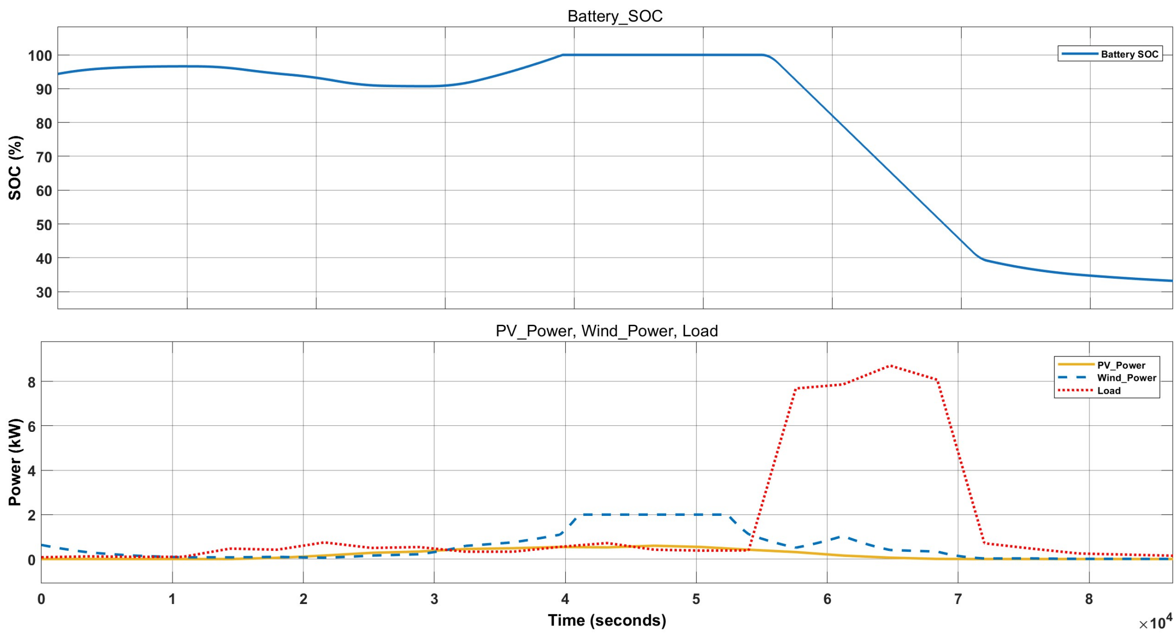


Figure 7.10: Results of DT with EV charging.

Figure 7.10 shows that charging an EV for 4 hours with level-2 chargers does not significantly affect the system. While the battery storage provides most energy to charge the EV, the PT will need no changes.

7.5.2 Case-2: Low Backup Storage

In this case, it is assumed that the battery storage is 50% for a specific day and that the EV will be charged for the same hours as in case-1. The results are shown in Figure 7.11. It can be observed that the system meets the requirements of both the residential load and the EV load without any power shortages. Therefore, the PT will endure this scenario without needing any prior adjustments for this event.

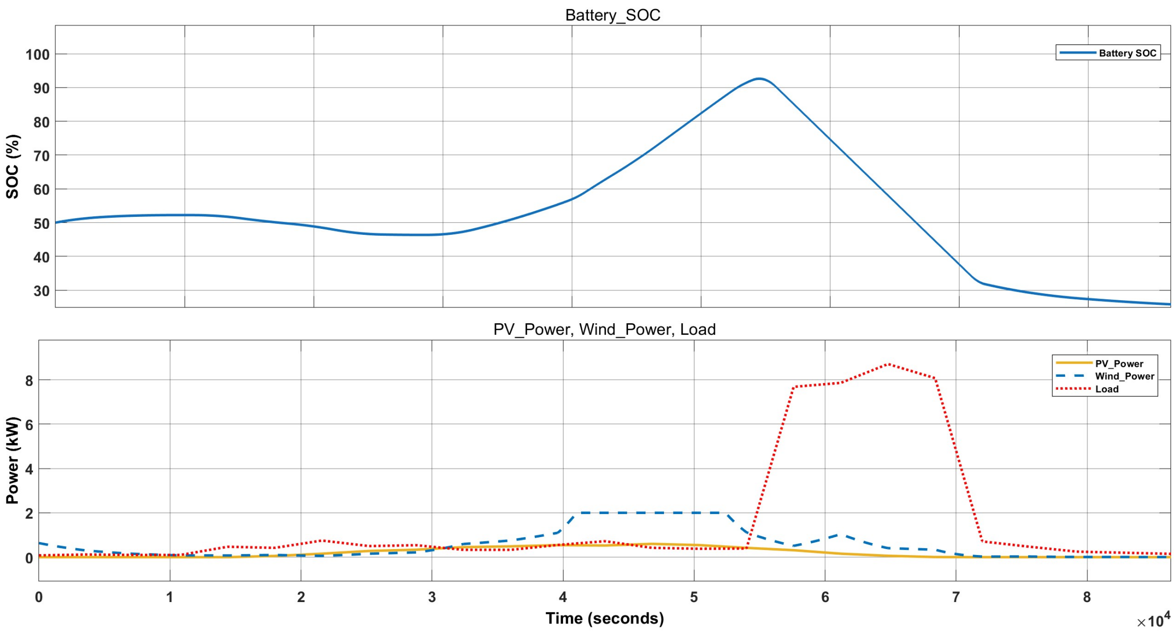


Figure 7.11: Results of DT with Low Backup Storage.

7.5.3 Case-3: Low Wind Forecast

In this case, the wind speed is forecast to be half, and the EV will be charged for the same hours as in Case-2. The results for this case are shown in Figure 7.12. The results indicate that there is no more power to meet the load by the end of the day. The output from the wind turbine is very low, and the PV system also generates no power. At the same time, the battery's SOC reached zero. Therefore, the system will not be able to withstand these scenarios. Thus, the PT must implement changes beforehand to ensure the system's stability and reliability. The following section demonstrates how to use the DMS tool to manage the load, enhance system stability, and accommodate the load.

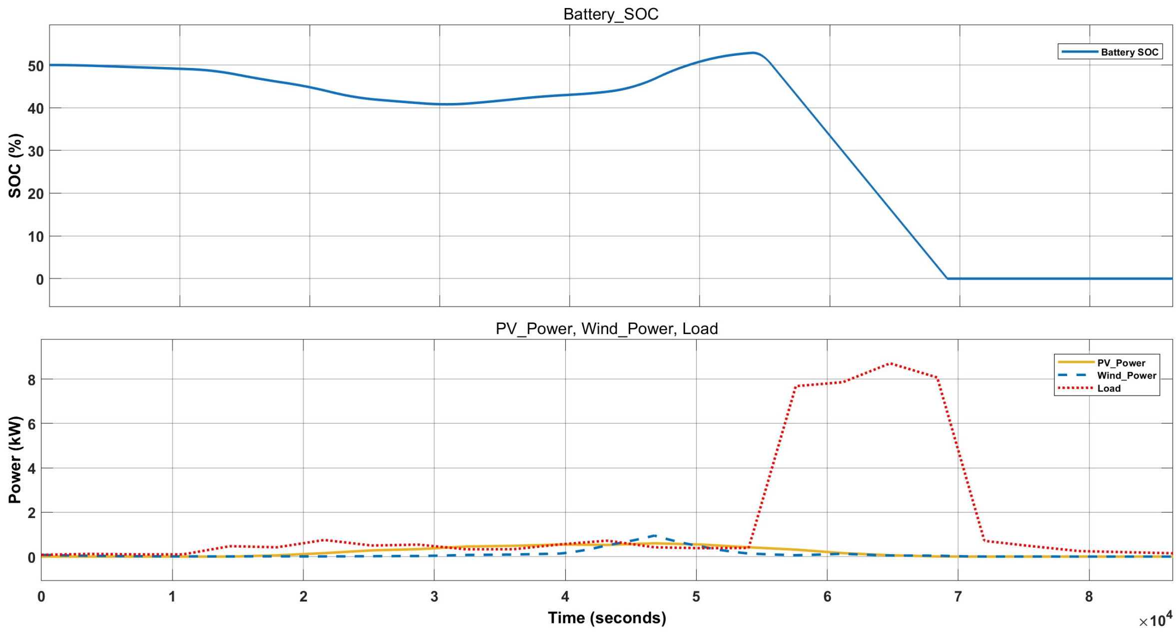


Figure 7.12: Results of DT with Low Wind Forecast.

7.5.4 Load Shifting

In case-3, the system will not support EV charging for 4 hours at 7.2 kW. Therefore, the charging duration is reduced to two hours, and the EV load has been shifted to the lowest load hours to meet the needs of both the EV and residential load. Figure 7.13 shows that the EV load has been shifted to 0:00 and 01:00. Thus, the system is now fulfilling the power needs of the microgrid and ensuring stability.

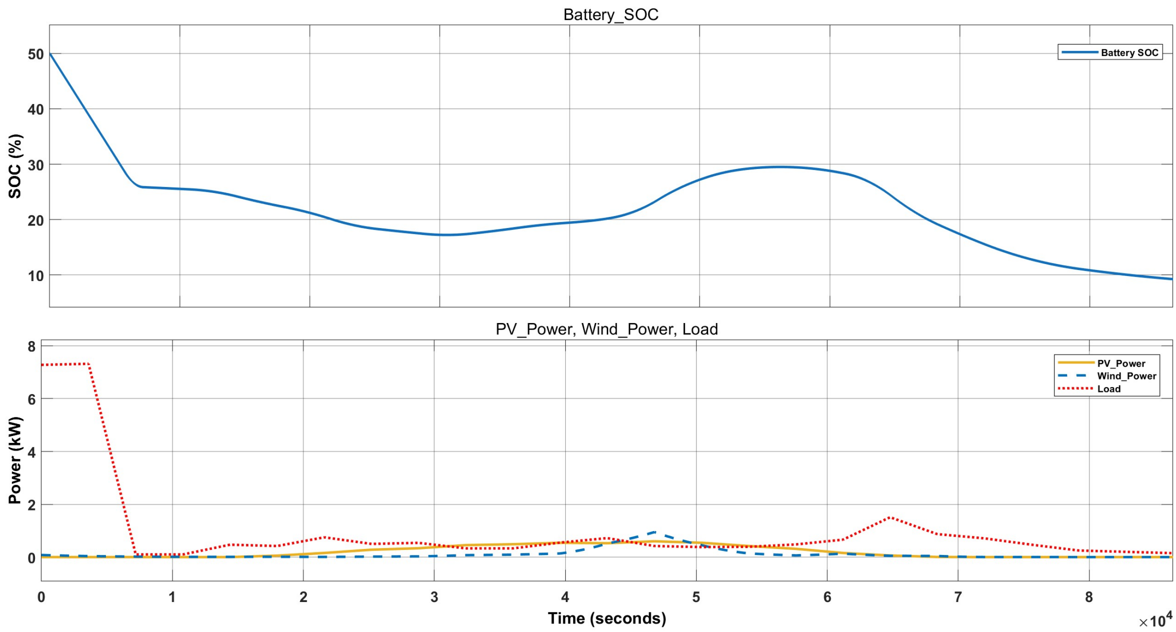


Figure 7.13: Results of DT with Reduced Shifted Load.

7.5.5 Peak Clipping

The issue in Case-3 has an alternative solution: implementing peak clipping to lessen the load peaks. This can be accomplished in the case of EV charging by using a Level-1 charger when there is no complete storage backup and when the output power from RES is very low. Figure 7.14 shows that the EV is charged for the same four-hour duration, and the system can still meet the load demand while using a Level-1 charger. It is concluded that the PT will require both level-1 and level-2 chargers to operate this microgrid efficiently.

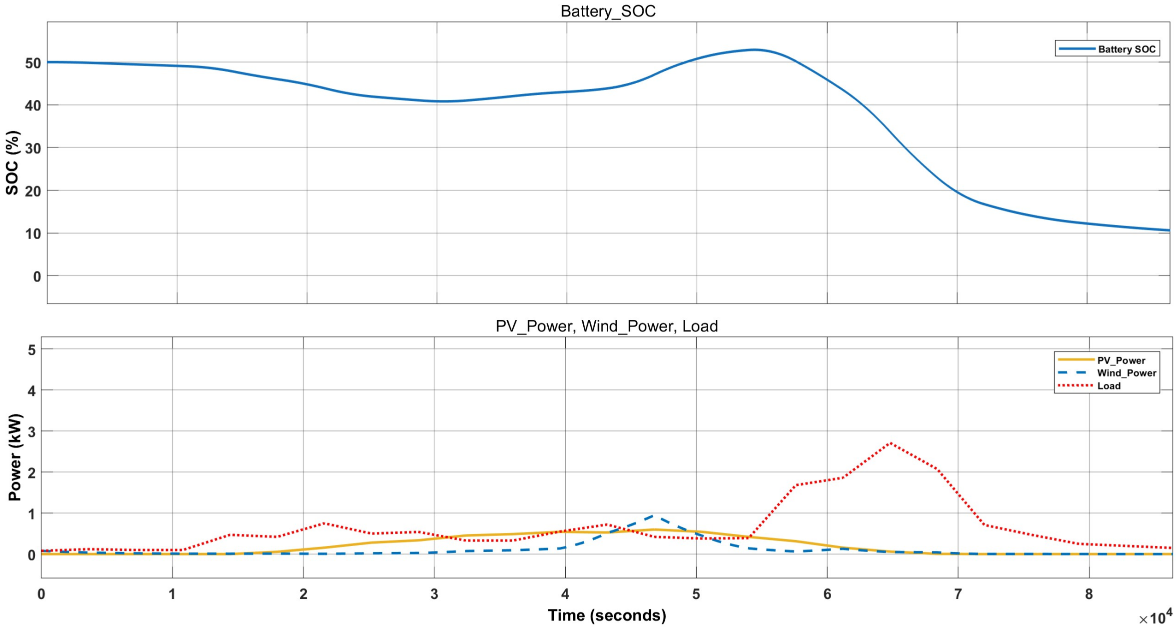


Figure 7.14: Results of DT with Peak Clipping.

7.5.6 Valley Filling

Another important application of sing DT is indicating when the microgrid has surplus power. In Case-1, the EV is charged during the hours when there was no surplus power. In the same case, the system had a surplus power from 12:00 to 15:00. During this period, the battery was fully charged, and the extra power was wasted. By the day's end, the battery storage's SOC was approximately 30% as seen in Figure 7.10. However, the surplus energy was utilized by using valley filling. Figure 7.15 illustrates the outcomes of employing valley filling techniques for EV charging. The results indicate that charging the EV during surplus power hours can save nearly 30% more SOC by the day's end. This will enable the system to handle scenarios like Case-2 and Case-3 effectively. When the EV charges during surplus power or off-peak hours, the battery storage accumulates more energy for peak usage hours. Thus using valley filling techniques will make the microgrid more stable and reliable.

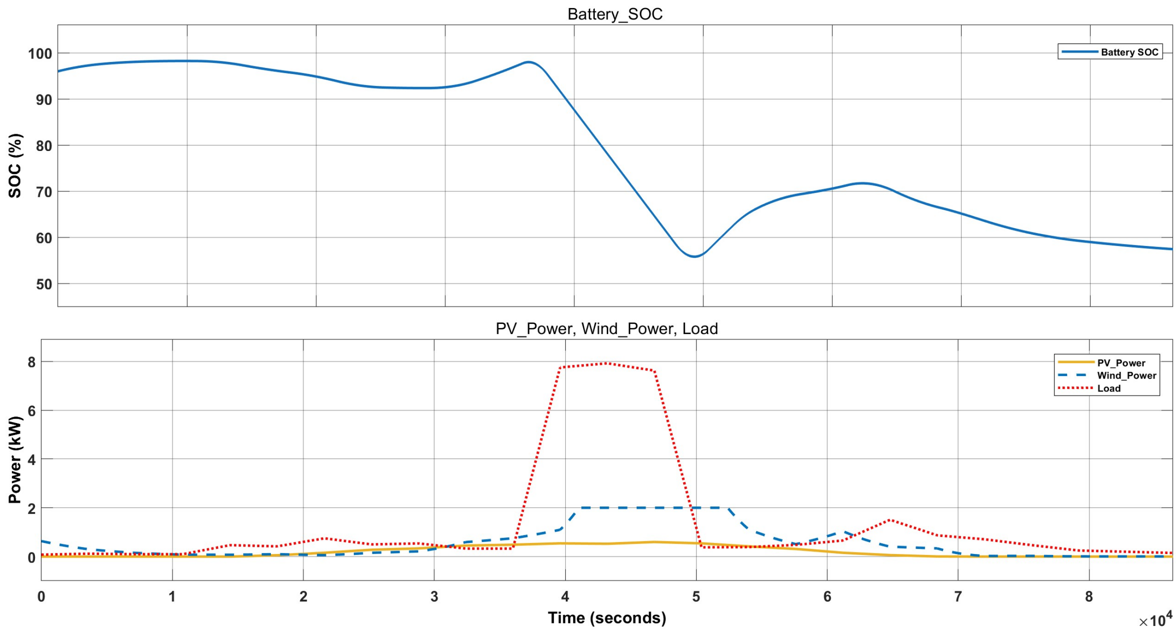


Figure 7.15: Results of DT with Valley Filling.

7.6 Summary

This chapter explores how DT technology can be integrated with DSM to enhance energy management in microgrids, particularly regarding RES and EV penetration. Initially, a microgrid model was created in HOMER Pro to identify the best system setup, which included solar PV, wind turbines, battery storage, and loads from residences and EV. This model was subsequently replicated as a DT in MATLAB/Simulink, allowing for real-time monitoring and predictive control. DT effectively oversees the microgrid system by continuously gathering real-time data from its PT, enabling accurate monitoring of energy generation, usage, and storage capacity. This immediate visibility enables effective energy flow management, load balancing, and optimized use of renewable energy, ultimately improving overall system stability. Different DSM strategies—such as load shifting, peak clipping, and valley filling—were utilized to balance energy supply and demand dynamically. The findings indicate that DT technology significantly boosts microgrid performance by increasing energy efficiency, stabilizing the system, and maximizing the use of renewable energy. Load shifting enabled scheduling EV charging for off-peak times, peak clipping alleviated stress on the storage system by capping power demand, and valley filling ensured the effective use of surplus renewable energy. Through these strategies, the DT offered practical insights to avert power shortages, lower operational costs, and enhance grid resilience. These results underscore the promise of DT-driven DSM as an effective method for regulating EV charging demands within smart microgrids, thus facilitating the development of more sustainable and reliable energy systems.

Chapter 8

Onsite Hydrogen Generation for FCEVs in RES-based Microgrid

The road transportation in the Islands relies heavily on fossil fuels imported from nearby regions. This increases fuel prices. Utilizing these fuels for transportation contributes significantly to greenhouse gas emissions, creating an additional issue. Finding alternatives to fossil fuels that are both environmentally friendly and locally available is the key solution. This chapter uses the HOMER Pro tool to conduct a techno-economic analysis of the public transport system on Favignana Island in southern Italy. This study investigates the feasibility of generating on-site hydrogen from renewable energy sources for fuel cell buses on Favignana Island. A hybrid microgrid system, incorporating solar PV, wind turbines, battery storage, an electrolyzer, and hydrogen storage tanks, has been designed using HOMER Pro. Hydrogen load is designed using actual data from public transport, taking into account both peak and off-peak seasons in the region. HOMER Pro has proposed four optimized systems to address all the requirements and limitations of the system. Case 1 represents the most feasible solution, incorporating solar PV, wind turbines, battery storage, an electrolyzer, and hydrogen storage tanks. This system has a net present cost of 325214 euros and a levelized cost of hydrogen at 5.19 euros per kilogram. This system demonstrated a reduction of about 90% in greenhouse gas emissions and a 30.8% decrease in total costs compared to the diesel bus system. The chapter further analyzes the importance and effectiveness of battery storage systems in reducing system costs alongside renewable energy sources. This study uniquely connects theoretical analyses with practical applications, showcasing an economical, sustainable, and feasible model for hydrogen-powered public transportation on Favignana Island. The upcoming sections will cover the Favignana Energy Sector and Public Transport, Methodology, System Modeling, Results, Impact Assessment, and Summary.

8.1 Favignana's Energy Sector and Public Transport

Favignana is the largest of the three main Egadi islands in southern Italy, covering a land area of 19.8 square kilometers. While part of the island features an uninhabitable mountainous landscape, approximately half consists of an extensive plain home to just under 4,000 residents. Favignana boasts a series of shallow bays with crystal-clear turquoise waters, all within a designated marine protected area. The flat terrain of the island is ideal for exploration by foot or bicycle, and it also has public bus transport, allowing visitors to enjoy a different beach each day [186, 187]. The island's electricity system is not connected to the mainland and is served by a local DSO that supplies power generated from diesel plants [188].

8.1.1 Favignana Public Transport

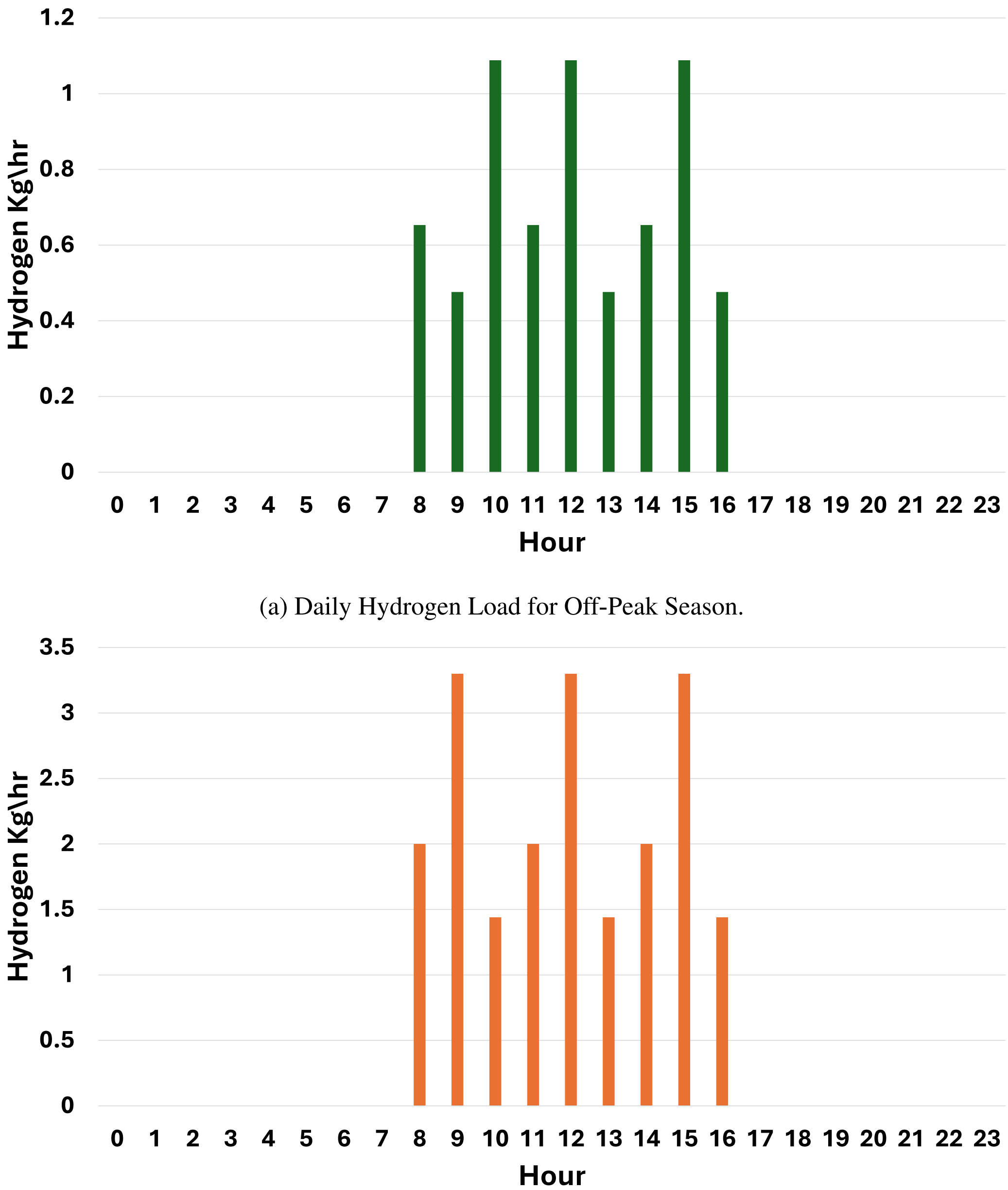
Figure 8.1 illustrates that Favignana's public transport consists of three lines. The blue line represents Line 1, which has a round-trip distance of almost 9.6 km. The red line represents Line 2, with an approximate round-trip distance of 16 km. The green line indicates Line 3, which has a round-trip distance of 7 km [189, 190].

Figure 8.1: Favignana Island's public transport.

During the summer months, from June to September, Favignana Island experiences a high volume of tourists, making it the peak season for tourism. Hence, the peak season increased the number of trips for each line by 3 times [188]. The number of trips for each line during peak season ranges from 8 to 10. We have considered an average of 9 trips per line [189, 190], with three buses allocated for each line during the summer season. During the winter off-peak season, the number of trips was reduced to three per line. The arrival and departure timings for each line and each trip during peak and off-peak seasons are provided in Table 1 and Table 2. Buses 1, 2, and 3 serve Line 1; Bus 4, 5, and 6 serve Line 2; and Bus 7, 8, and 9 serve Line 3.

8.1.2 Hydrogen Load

Hydrogen load has been modeled based on each line's round-trip distances. The bus model used for this study is Universal Fuel Cell, which is Hyundai-made, with a 500 km range, 34 kg storage capacity, and efficiency of 14 km/kg [191]. Each bus has different distances to cover, which results in varying hydrogen requirements. Buses 1, 2, and 3 will need 2 kg of hydrogen daily in the summer. Buses 4, 5, and 6 will require 3.3 kg per day, while Buses 7, 8, and 9 will need 1.44 kg per day. During winter, the hydrogen load will decrease three times as the number of trips was reduced by the same factor. Based on these data, the modeled daily hydrogen load for peak and off-peak months are presented in Figure 8.2.



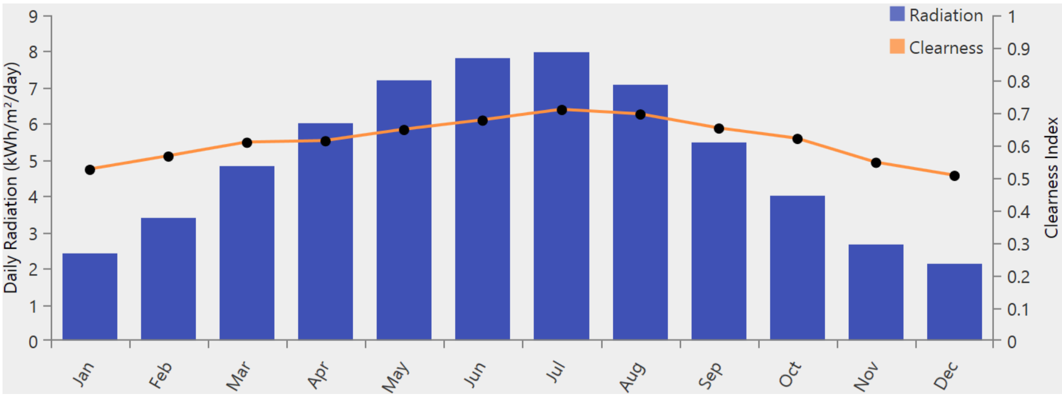
(a) Daily Hydrogen Load for Off-Peak Season.

(b) Daily Hydrogen Load for Peak Season.

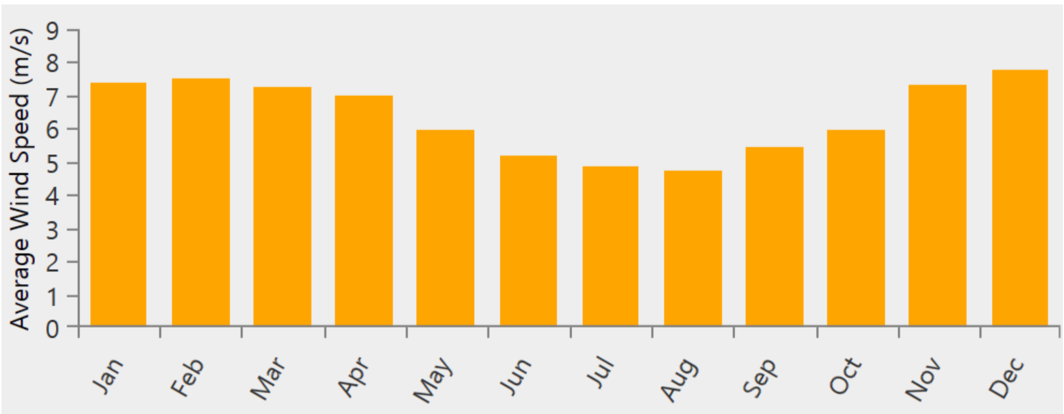
Figure 8.2: Designed Hydrogen Loads Based on Actual Trips.

8.1.3 Favignana Solar and Wind Resources

Figure 8.3a shows the monthly averages for solar Global Horizontal Radiation (GHI) on Favignana Island, obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database using HOMER Pro. Figure 8.3b shows the average monthly wind speed, obtained from the NASA POWER database at an anemometer height of 10 m using HOMER Pro. From the figures, it can be observed that in summer, the solar PV potential is high compared to winter. However, the case is the opposite for wind, as the wind potential is higher in winter than in summer.



(a) Monthly Average Solar GHI Data.



(b) Monthly Average Wind Speed Data.

Figure 8.3: Renewable Energy Sources for Favignana Island.

8.2 Methodology

Hybrid Optimization of Multiple Energy Resources (HOMER) software is used to optimize the system design for the onsite hydrogen generation from RES for public transport on Favignana Island. HOMER Pro microgrid software by UL Solutions is designed by the US National Renewable Energy Laboratory (NREL). It is the global standard for optimizing designs in sectors like urban and rural power systems, off-grid utilities, grid-connected campuses, and military bases [192]. HOMER Pro simulates hybrid RES microgrids for the entire year with timesteps ranging from a minute to an hour. HOMER Pro performs three main tasks: simulation, optimization, and sensitivity analysis. The simulation process assesses the feasibility

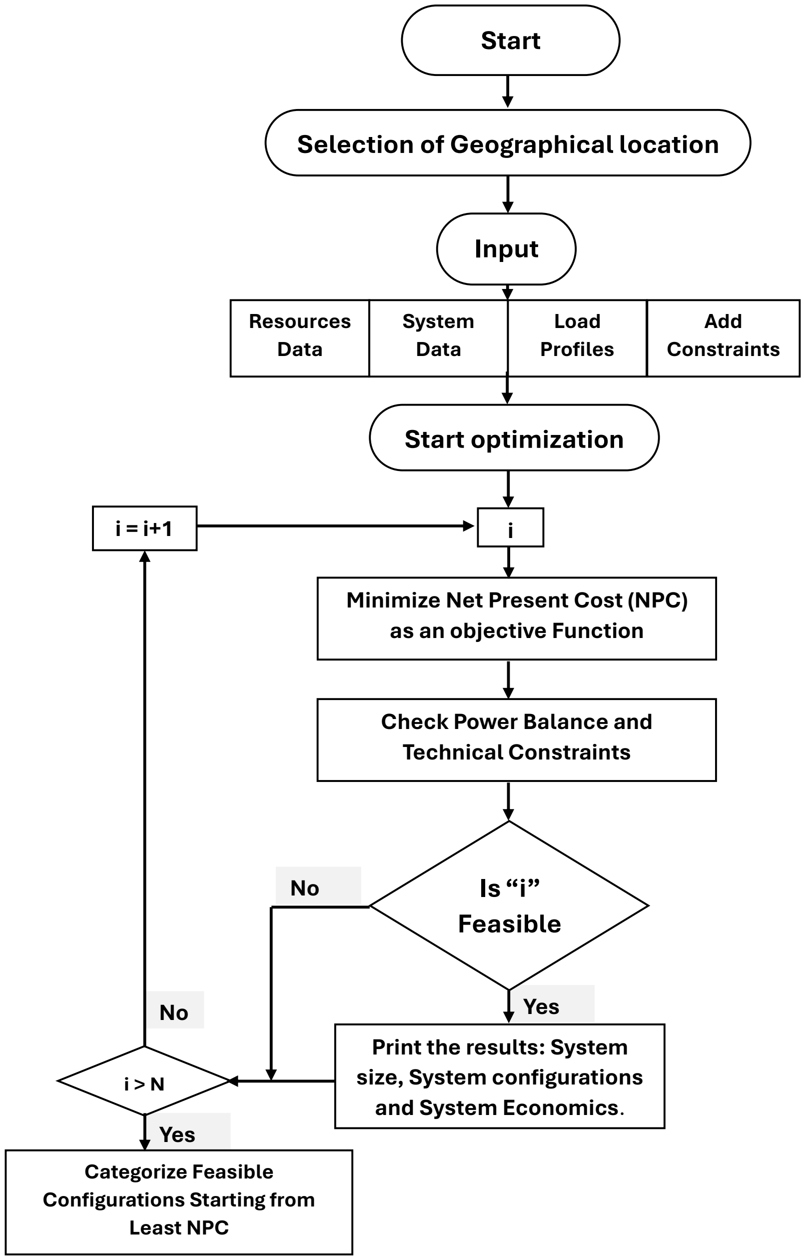


Figure 8.4: Methodology Used for Optimization.

of the power system design. This process depends on the ability of the system to efficiently provide the primary hydrogen and electrical loads while ensuring the minimum Net Present Cost (NPC), Levelized Cost of Hydrogen (LCOH), and Levelized Cost of Electricity (LCOE). Moreover, it calculates the total life cycle cost of the designed system, including installation cost, replacement cost, and operation and maintenance (O&M) expenses. The total revenue earned over the total project life is then subtracted. The optimization process of HOMER Pro is an iterative process that gives us the best possible solution for the system with minimum NPC, fulfilling all the user-defined constraints. The complete flowchart of the methodology used for optimization in HOMER Pro is shown in Figure 8.4.

The HOMER Pro simulates the system users want to optimize based on real location to integrate the actual weather data for that specific area. Hence, at the start, the user must define the study region. After region selection, the weather data can be downloaded from the NASA POWER database in HOMER Pro. Next, the user must input all relevant parameters, including system data such as costs for all components, load profiles that need servicing, and any constraints relevant to the user-defined system. The optimization process begins once the user has provided all the necessary data to HOMER Pro. The optimization process iteratively minimizes the NPC while ensuring power balance and meeting all constraints. Once this process is done, it will provide system size, configuration, and economics as a result. The system is illustrated by a single line in Figure 8.5. This study uses solar PV and wind energy to meet the hydrogen demand for public transport on Favignana island. The overall life of the project is set to 20 years. Each component of the system has been discussed briefly in the following sections.

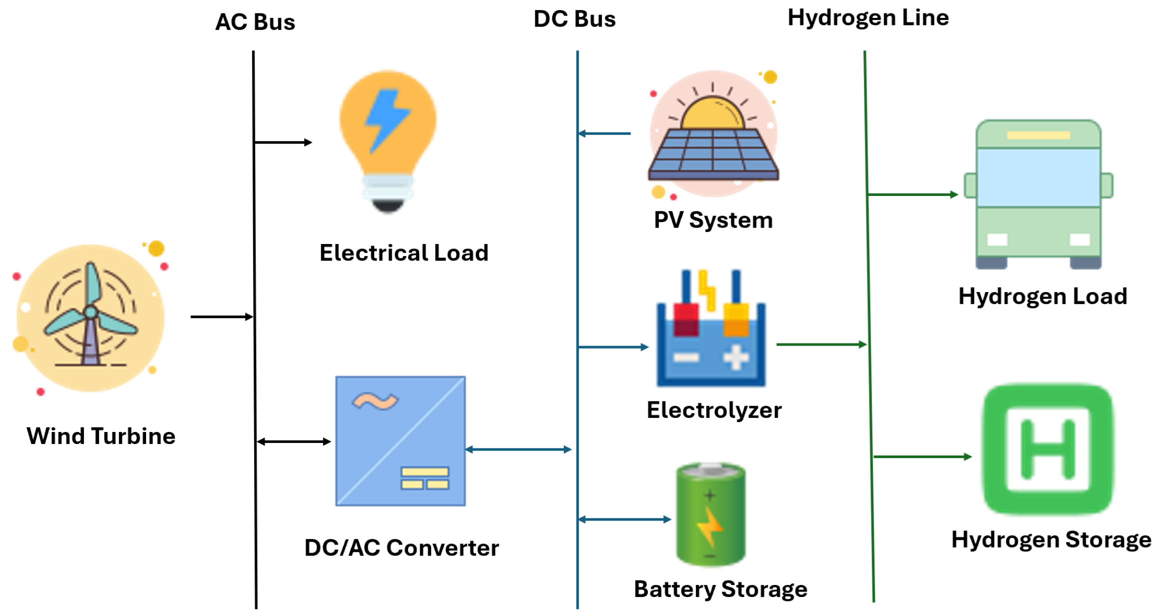


Figure 8.5: Single Line Diagram of the Designed System.

8.2.1 Description of the Components

This section provides details of each model component and utilizes them to fulfill the need for hydrogen load in the public transport of Favignana Island.

Solar PV system

Solar PV is the system's backbone for system optimization. The sunshine is abundant in summer on Favignana Island, shown in Figure 8.3a. This island has the potential to harness solar energy directly from the sun using PV panels to fulfill the energy needs of the region. In summer, this region has solar radiation of almost 7 kWh per square meter daily, with a clearness index of 0.6. The solar PV model used in the system is generic flat plate PV with no tracking system. The PV module has an efficiency of 13% at standard test conditions and a nominal cell temperature of 47 °C with the temperature effect on power is -0.5% /°C. The overall life of the PV system is selected to be 25 years with a derating factor of 80%. Hence, there will be no replacement cost for the PV system. The solar PV output has been calculated using the following equation 8.1:[193]:

$$P_{out} = R_c.D_f.(\frac{I_r}{I_{stc}}).[1 + \alpha_p.(T_{cell} - T_{stc})] \tag{8.1}$$

The R_c is the rated capacity of solar PV in kW, D_f is the derating factor in percentage. I_r represents the solar irradiance on PV module, while I_{stc} is the irradiance under standard test conditions. The temperature coefficient of power is α_p, with T_{cell} and T_{stc} are the temperatures of the PV cell under operation and under test condition respectively.

Wind Turbine

The wind speed in winter is high compared to summer for Favignana Island, with an average speed of 6 to 7.5 m/s. Harnessing this wind energy provides a promising opportunity to acquire a sustainable and clean power system in the region. A generic design of the 1 kW system available in the HOMER Pro library has been used with a 20-year lifetime and a hub height of 17 meters as a default. HOMER Pro calculates the wind output power using the following equation 8.2 [194].

$$P_{wt} = (\frac{\rho}{\rho_o}).P_{wstc} \tag{8.2}$$

Here P_{wt} is the output power of wind turbine and P_{wstc} is the output power at standard temperature and pressure. ρ represents the actual air density and ρ_o represents the air density at standard temperature and pressure.

Electrolyzer and Hydrogen Tank

Steam Methane Reforming (SMR) is the most common hydrogen production method [195]. However, carbon dioxide is the by-product of this method, so electrolysis is the alternative to producing green hydrogen. In electrolysis, the water molecules break down into oxygen and hydrogen gas in the electrochemical reaction using electricity. The electrolyzer is modeled straightforwardly in HOMER with the assumption of constant efficiency. Hence, it will always result in a certain amount of hydrogen and a certain amount of electricity. In this study, the generic electrolyzer model has been utilized with an efficiency of 85% and a lifetime of 20 years. The electrolyzer produces hydrogen at a very low pressure of 25 to 30 bars [196], and the fuel cell buses and storage tanks require the hydrogen to be at high pressure. Hence, the compressor will be used to increase the pressure of the hydrogen produced, which will be discussed in detail in the next section. The hydrogen storage tank used in the study has an initial tank level of 50%.

Compressor

The compressor is an essential component of the hydrogen refueling stations due to the low pressure of generated hydrogen through electrolysis. Most studies using HOMER Pro do not consider a compressor because there is no component for the compressor to use directly. In this study, the compressor load is represented by the electrical load, and the electrical power needed for hydrogen compression from 30 bars to 350 bars is calculated using the following equation 8.3 [197].

$$P_{comp} = C_p.\frac{T_1}{n_c}.(\frac{p_2}{P_1})^{\frac{\gamma-1}{\gamma}} - 1).m_f \tag{8.3}$$

Here C_p is the specific heat capacity of hydrogen at constant pressure. T_1 is the inlet temperature of hydrogen in Kelvin. n_c is the efficiency of the compressor. P_1 and P_2 are the initial and final pressure. γ is the ratio of specific heat; for hydrogen, it is 1.41, and m_f is the mass flow rate of hydrogen.

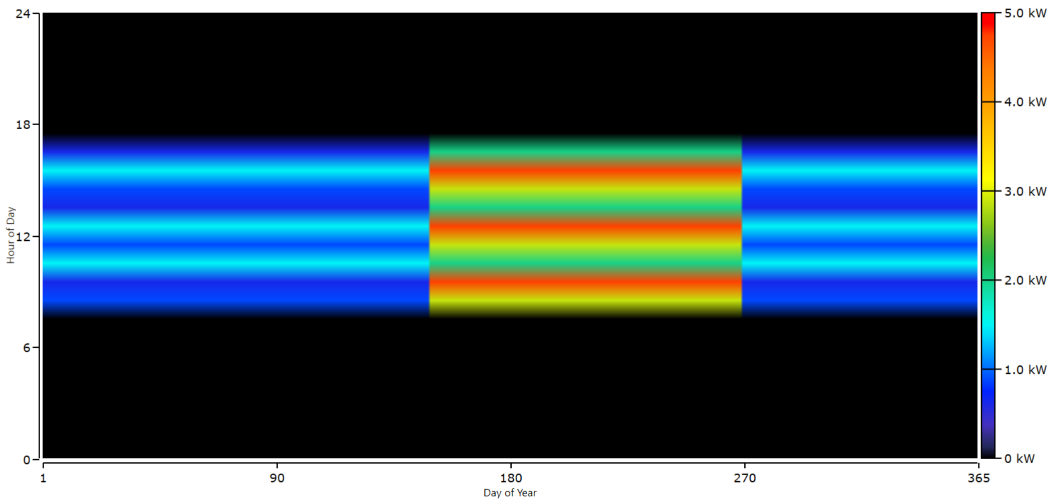


Figure 8.6: Electrical Load Required for Compressor Operation.

The electrical load, which represents the compressor power, is shown in Figure 8.6. It can be seen that the compressor load is high during the summer season. This is because of the high demand for hydrogen for buses in summer. In the winter season, the number of trips and demand for hydrogen buses decreased; hence, the compressor load decreased. The compressor load represents 8 to 10% of the LCOH, which cannot be ignored.

8.2.2 Economic Modelling

HOMER Pro needs economic parameters for the region under study, such as the nominal discount and inflation rates, to evaluate the project's economics over its lifetime. The following sections discuss all the economic parameters.

Total Cost of the System

The Total Cost (TC) of the system is the sum of the Capital Cost (CC) or capital expenditures, O&M cost, and Replacement Cost (RC) and can be calculated using equation 8.4. The CC is the initial cost of setting up the system's components like Solar PV panels, wind turbines, electrolyzers, storage systems, etc. This cost includes the design and engineering of the system, as well as the system's combined purchasing, transportation, and installation costs. The RC is the cost of replacing any component when its lifetime is over. This cost may not be the same as the initial CC of the component because all the parts of the component will not require replacement. Hence, in most cases, the RC will be reduced as compared to the CC. The third input parameter of TC is the O&M cost, which is related to the operation and maintenance of the different components of the system. This cost included any fuel cost, repair cost if there is any faulty part in the component, replacement of defective parts, cleaning and maintenance of the component, and labor cost.

$$TC = CC + RC + O \,\&\, M \tag{8.4}$$

Capital Recovery Factor

The Capital Recovery Factor (CRF) is a crucial financial metric used to calculate fixed annual payments to recover the initial investment in a project using equation 8.5. In the context of this report, HOMER Pro uses the CRF to determine the system's annual cost, which is a key factor in evaluating the economic feasibility of the proposed hydrogen refueling systems.

$$CRF = \frac{i_r.(1 + i_r)^n}{(1 + i_r)^n - 1} \tag{8.5}$$

Here i_r is the real discount rate and n represents the project's lifetime in years. The nominal discount rate and inflation rate are used to calculate the real discount rate using the following equation 8.6.

$$i_r = \frac{\alpha_i - f_i}{1 + f_i} \tag{8.6}$$

Here α_i is the nominal discount rate and f_i is the inflation rate. Italy's nominal discount and inflation rates are determined based on referenced sources [198, 199].

Net Present Cost

A system's total Net Present Cost (NPC) is the sum of the present value of all expenditures incurred during its operational life minus the present worth of all revenue generated during that time. These expenses include CC, RC, O&M expenses, fuel costs, emissions charges, and payments for grid power. Income sources contain retrieved value and revenue from selling power to the grid. HOMER Pro ranked the optimized systems based on the minimum NPC and is calculated using the following equation 8.7.

$$NPC = \frac{TC}{CRF} \tag{8.7}$$

Levelized Cost of Electricity and Hydrogen

The cost invested in generating one kilowatt-hour (kWh) of electricity is known as the levelized cost of Electricity (LCOE). The amount spent generating one kg of hydrogen is known as the levelized cost of hydrogen (LCOH) ($/kg). Both of these are the output parameters of HOMER pro simulations. HOMER Pro calculates the LCOE of the project by dividing the NPC by the useful energy generated over the lifetime of the project and is given by the equation 8.8:

$$LCOE = \frac{NPC}{E_u} \tag{8.8}$$

Here E_u is the useful electrical energy generated over the project's lifetime. On the other hand, the LCOH can be calculated using the following equation 8.9.

$$LCOH = \frac{NPC - E_{grid}}{H_g} \tag{8.9}$$

In this study, as the system is off-grid, E_{grid} will be zero as no electricity is sold back to the grid. H_g is the amount of hydrogen generated over the project's life.

8.2.3 Input parameters for the Components

The input parameters for all the components used for the simulation study are illustrated in Table 8.1.

Table 8.1: Input Parameters for Components.

System	Input Parameter	Value	Ref
Solar PV	Capital Cost €/kW	908	[200, 201]
	O&M Cost (€/kW/Yr)	13.62	
Wind Turbine	Capital Cost €/kW	1796	[202, 201]
	O&M Cost (€/kW/Yr)	20	
Electrolyser	Capital Cost €/kWh	500	[203, 204]
	O&M Cost (€/kW/Yr)	10	
Hydrogen Storage	Capital Cost €/Kg	600	[205, 204]
	O&M Cost (€/Kg/Yr)	1	
Battery Storage	Capital Cost €/kWh	127	[206, 207]
	O&M Cost (€/kWh/Yr)	10	
Converter	Capital Cost €/kWh	665	[208]
	O&M Cost (€/kW/Yr)	10	

8.3 Results & Discussion

HOMER Pro resulted in four optimized systems for the onsite hydrogen refueling station for the public transport of Favigana island, shown in Figure 8.7.

PV (kW)	WindTurbine	LI Battery (#)	Electrolyzer (kW)	H2Tank (kg)	AC/DC (kW)	NPC (€)
179	2	5	124	50.0	5.62	€325,214
189		9	117	50.0	5.86	€327,957
239	50		88.2	40.0	5.85	€461,842
926			75.5	40.0	5.59	€1.11M

Figure 8.7: Optimize Solutions for Hydrogen Refueling Station.

All four cases include a converter, electrolyzer, and hydrogen storage. The difference between these cases is the source of electricity generation and the battery storage system. Case 1 includes solar PV, wind turbines, and battery storage; Case 2 consists of solar PV and battery storage; Case 3 includes both solar PV and wind turbines without battery storage; and Case 4 at the bottom only has solar PV with no wind turbines and battery storage. The lower the system's NPC, the lower the LCOH for the system. Case 1 with NPC of 325214 Euros and Case 2 with NPC of 327957 Euros with minimal difference between them could be feasible solutions for this study. The capital cost, O&M cost, and the NPC of the four optimized solutions are given in Figure 8.8. Case 1, with the minimum NPC and lowest LCOH, is discussed in more detail below.

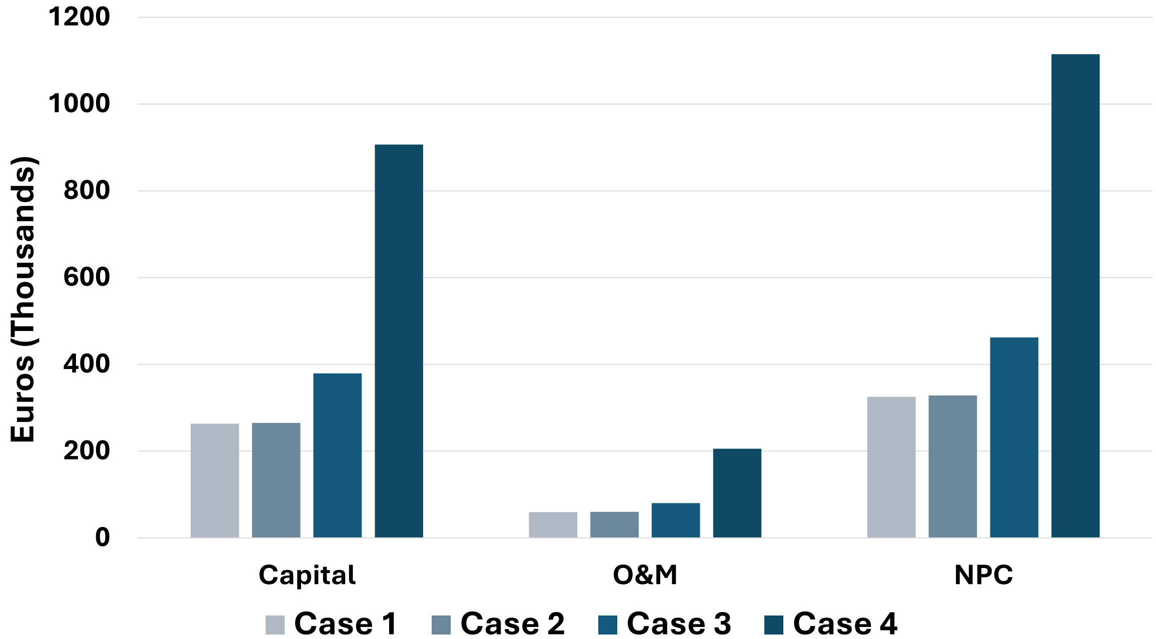


Figure 8.8: Capital, O&M and NPC of the Four Cases.

8.3.1 Feasible Solution

Case 1 and Case 2 emerge as the most cost-effective solutions for this study. The top-ranking system includes a 179-kW solar PV system, two wind turbines, each with a capacity of 1 kW, 5 kWh of lithium-ion battery storage, a 5.62 kW converter, electrolyzers with a capacity of

124 kW, and a hydrogen storage tank of 50 kg. The LCOH for this case is 5.19 euro/kg, a testament to the system's cost-effectiveness. The hydrogen load is 3 times higher in summer than in winter for Favignana island. While, from Figure 8.9, it shows that in summer, the PV system's generation is very high with minimal disruption. Hence, the main generation source is solar PV, which makes this islanded microgrid more feasible and sustainable. Thus most percentage of the NPC goes to solar PV system's capital cost followed by the electrolyzer. The lithium-ion battery storage only supports the compressor for a small period when there is no electricity available from the generating sources, further highlighting the system's cost-effectiveness.

Favignana Island has great solar energy potential in summer like we talked about. Figure 8.9 vividly illustrates the high output power from solar PV during the summer months. Conversely, wind turbines' output power is higher in winter than in summer due to constant wind at higher speeds. This system's ability to harness wind energy when there is no sunshine for some hours while the wind blows is a testament to its potential. This reduces the system's lithium-ion battery storage dependency, as seen from Figure 8.7. The system's need for battery storage is reduced to 5 kWh in case 1 compared to case 2, showcasing the promising future of renewable energy systems.

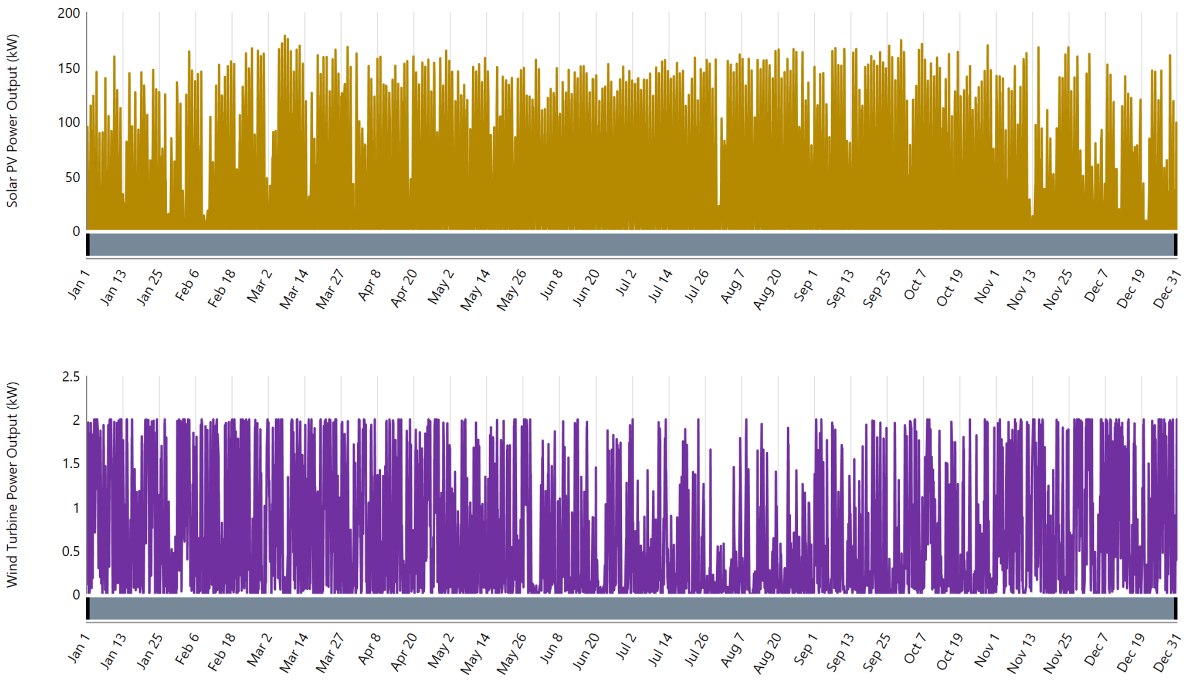


Figure 8.9: Solar PV and Wind Turbines Output Power.

Figure 8.10 shows the output of the electrolyzer and the status of the hydrogen stored in the storage tank. In the winter, the hydrogen load is very low, and the system is mainly stored in the tank to keep it full for peak times. With peak load in summer and less output from the electrolyzer, the system uses the stored hydrogen; as can be seen from Figure 8.10, at the end of July and in the first half of September, the electrolyzer output is reduced, forcing the system to use the store hydrogen to fulfill the need for hydrogen demands of the buses.

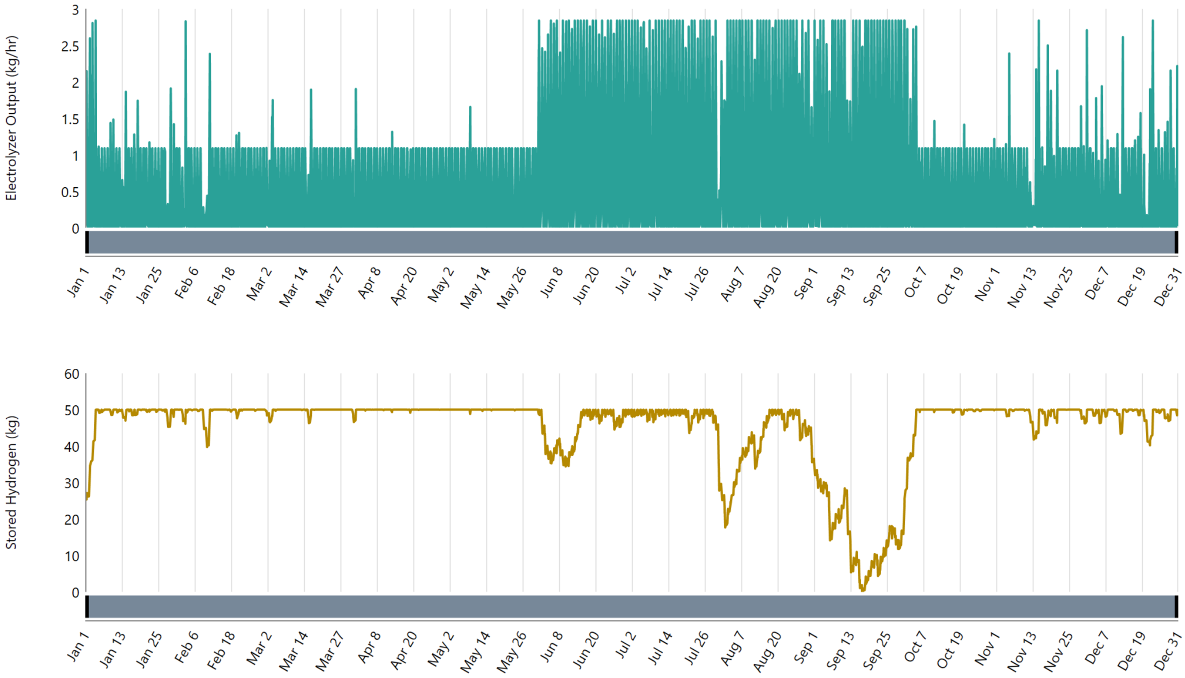


Figure 8.10: Hydrogen Generation and Storage.

8.3.2 Comparison of Conventional Transport vs Proposed Alternative

The conventional public transport of Favignana Island uses diesel-fueled buses. In this section, a detailed comparison with fuel cell buses that are entirely independent of any fossil fuel has been made to highlight the advantages of the proposed system. Table 8.2 shows the GHG emissions from the current public transport and all four cases proposed by HOMER Pro. This table also gives the total cost of transport for Favignana Island over 20 years, which is the assumed project life of the proposed systems. All four optimized cases have lower emissions than diesel buses due to the independence of fossil fuels, and green energy sources generate hydrogen. Case 1 has the lowest GHG emissions, followed by case 2. The main issue is the cost of the overall transportation system. The cost of the first three systems is lower than that of the conventional one. Case 4 is not even close to the traditional system when it comes to price. Also, the LCOH is 5.19 euro/kg for Case 1, 5.23 euro/kg for Case 2, 7.38 euro/kg for Case 3, and 17.8 euro/kg for Case 4. Hence, Case 4 is not a feasible solution for any criteria.

Table 8.2: Cost and GHG emissions for Different Cases

Cases	GHG Emissions in Tons	Cost of Transportation
Diesel Buses	1550	469814
Case 1	157.8	325214
Case 2	164.6	327957
Case 3	241.7	461842
Case 4	808	1110000

8.3.3 Impact Assessment on GHG Emissions

The GHG emissions from diesel buses are approximately 1.3 kg/km [209]. The total distance that Favignana Island public transport buses cover is 59609 kilometers per year. Using these numbers, the total emissions of diesel buses have been calculated, which are 1550 tons for 20 years. All four cases of the proposed green hydrogen transportation system are then compared with this value to see the environmental impact of each system, illustrated in Figure 8.11. Case 1 includes solar PV and wind turbines for hydrogen generation and battery storage. The indirect GHG emissions of solar PV and wind turbines are 26 g/kWh and 13 g/kWh, respectively [210]. The solar PV system for Case 1 generates around 301 MWh of energy per year, while wind turbines generate 66.5 MWh of energy per year. Hence, the total indirect GHG emissions related to Case 1 have been 157.8 tons for 20 years. This results in a reduction of almost 90% in GHG emissions as compared to conventional diesel buses. Case 2 includes only solar PV for generating green hydrogen and has a battery storage system. The total energy generated in Case 2 is approximately 317 MWh per year. The indirect GHG emissions for this system are 164.6 tons for 20 years. Hence, the GHG emissions will be reduced by 89.4% compared to diesel buses. Case 3 has 401 MWh of energy from solar PV and 127.8 MWh from wind turbines per year with no battery storage. The GHG emissions related to this case were 241.7 tons for 20 years and caused a reduction of almost 84.4%. For the final case, only solar PV systems with no battery storage generate energy of 1.55 GWh per year. The emissions from this system were 808 tons for 20 years and showed a reduction of only 48% compared to diesel buses. The impact of Cases 1, 2, and 3 is promising regarding GHG emissions.

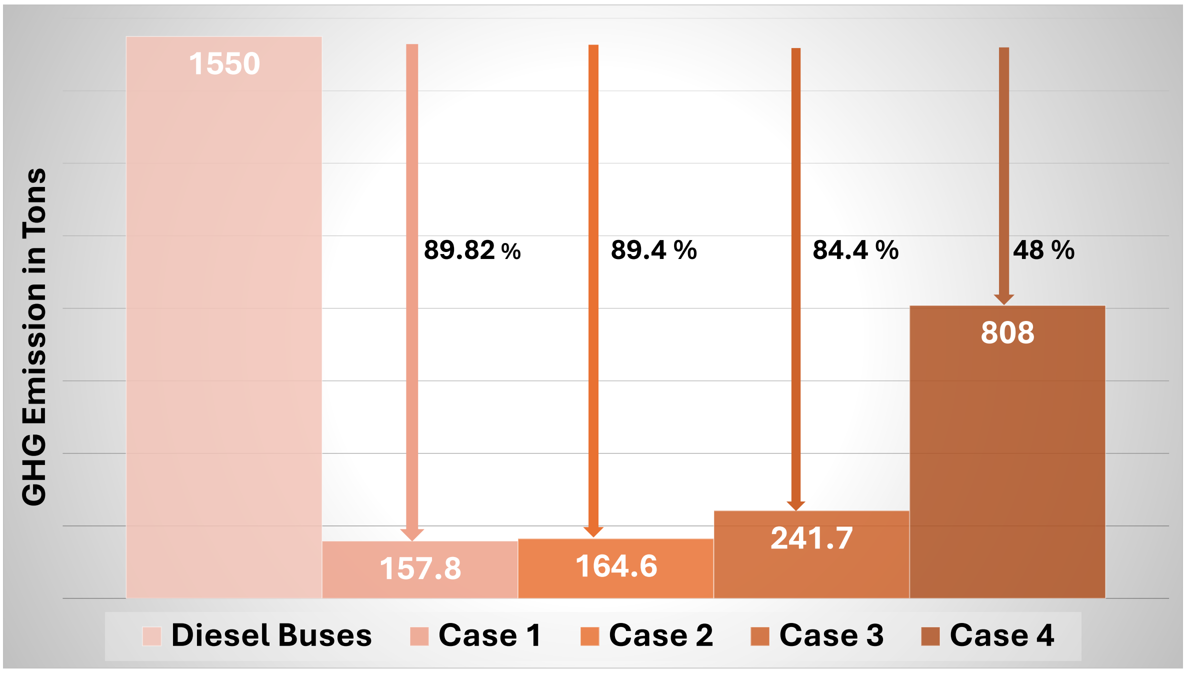


Figure 8.11: GHG Emissions for All Four Cases and Diesel Buses.

8.3.4 Impact Assessment of Cost

Diesel buses typically consume 0.24 liters per kilometer [211]. The diesel price in Italy is 1.642 euros per liter [212]. To cover the distance of 59,609 kilometers, the conventional public transport of Faviganana Island fuel cost will be 23,490 euros per year and 469,814 euros for 20 years, as shown in Figure 8.12. The most significant reduction was demonstrated by Case 1, which has solar PV and wind turbines with battery storage. The cost is reduced by 30.8% compared to Favignana Island's conventional public transport. Case 2 also shows a significant reduction of 30 percent, as shown in the figure. Case 3, which has no battery storage system and solar PV and wind turbines, shows a reduction of just 1.7% over 20 years. While Case 4 has only solar PV with no wind turbines and no battery storage, it shows a significant increase of 57% compared to conventional public transport. This indispensable result shows the importance of battery storage and a hybrid system when the generating sources are intermittent and variable. The impact of battery storage and hybrid RES systems will be discussed in detail in the upcoming section. Conventional bus transport costs 0.394 euros per kilometer. While Case 1 costs 0.272 euros per kilometer, Case 2 costs 0.275 euros per kilometer, Case 3 costs 0.387 euros per kilometer, and Case 4 costs 0.931 euros per kilometer. Hence, Cases 1 and 2 can be chosen as feasible economic solutions for public transport on Favignana Island. These two cases show a significant reduction in both cost and GHG emissions.

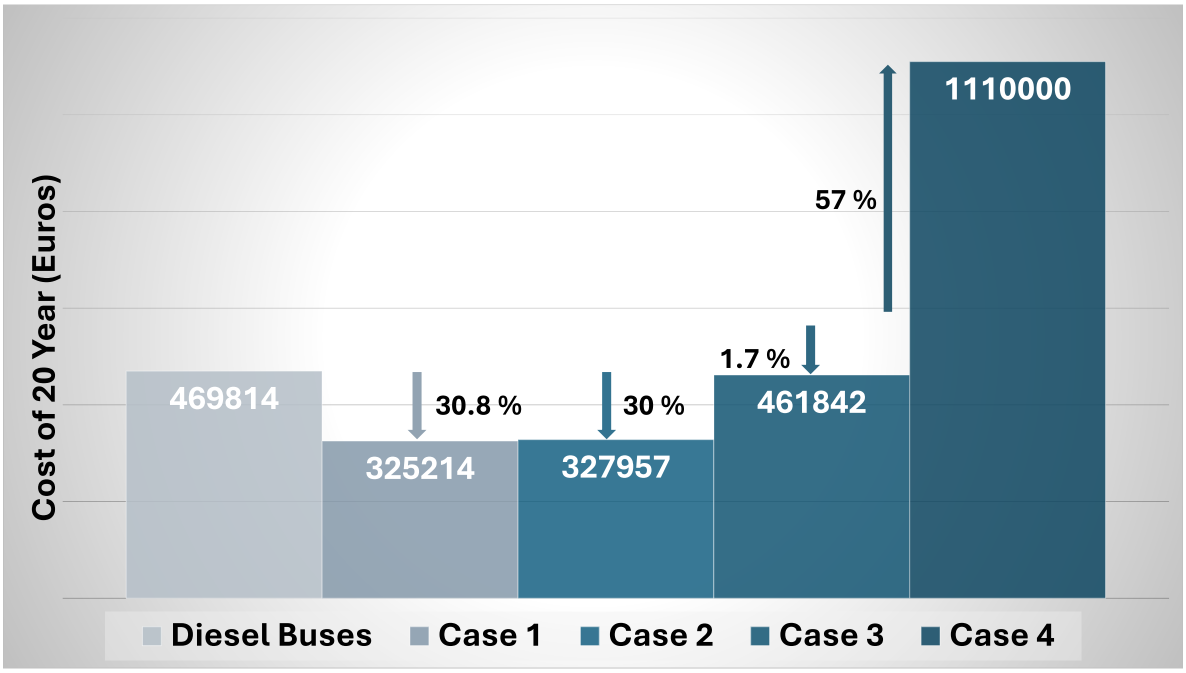


Figure 8.12: Costs for All Four Cases and Diesel Buses.

8.3.5 Impact Assessment of Storage System and Hybrid RES System

The intermittent and variable nature of RES plays a crucial role in the economics of any green project, highlighting the significant need for a battery storage system [213, 214, 215]. In this study, the electrical load is solely for the compressor used to compress the hydrogen generated by the electrolyzer. The maximum load reaches 5 kW, as illustrated in Figure 8.6. Despite being a relatively small load, it has a considerable impact on the techno-economics of the system across various configurations. In the proposed optimized scenarios of this study, all four cases share a similar configuration regarding the converter, electrolyzer, and hydrogen storage tank. The primary differences lie in the energy generation sources and the battery storage systems.

Case 1 is identified as the most feasible solution because it incorporates multiple RES along with a storage system. In Case 2, which features only a solar PV system and battery storage, costs increase by 0.84%. Both Case 1 and Case 2 show a minimal cost difference, primarily because they utilize a battery storage system to provide backup power.

In Case-3, things get a bit trickier, which combines both PV and wind turbines but lacks battery storage. In this case, costs rose by 29% compared to Case-1. Furthermore, the issue escalates in Case 4, where only solar PV is used for power generation. Without battery storage for periods of low sunlight or wind turbines for additional support, costs surge by 70% compared to Case-1 illustrated in Figure 8.13. These results underscore the critical importance of battery storage, even for small loads relying on intermittent and variable renewable energy sources.

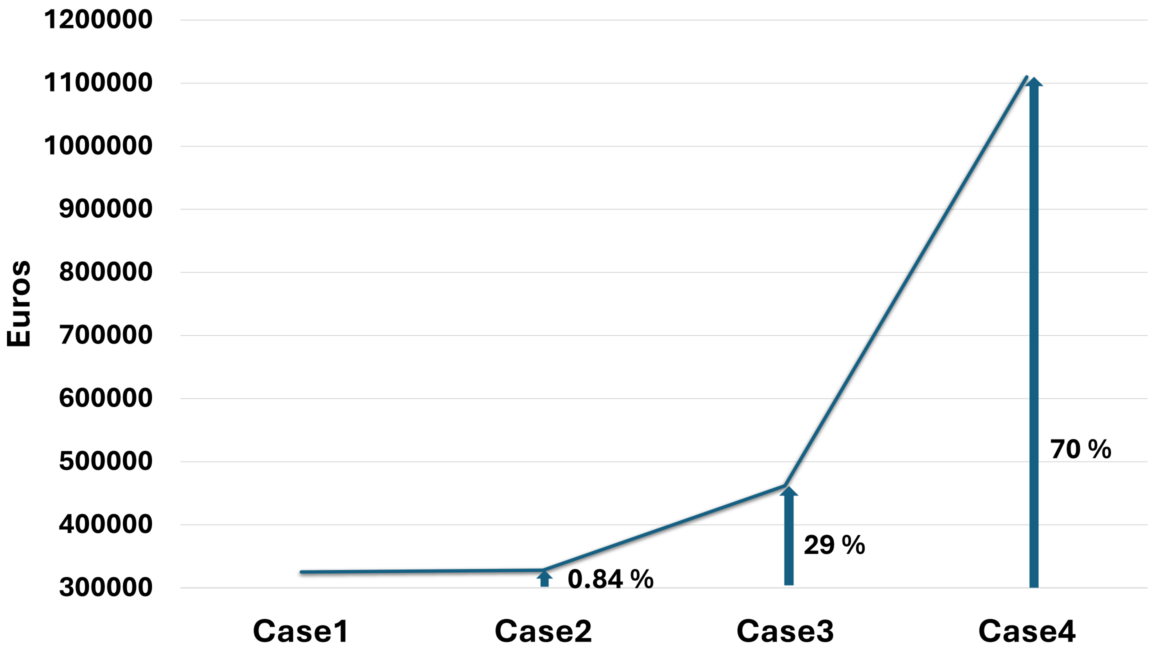


Figure 8.13: Impact Assessment of Storage System and Hybrid System.

8.4 Summary

This chapter underscores the feasibility and sustainability of transitioning the public transport of Favignana Island into a system powered by green hydrogen produced by RES. Four systems with different RES and storage configurations were proposed; case 1 emerged as the most feasible, cost-effective, and environmentally friendly solution. This system includes solar PV and wind turbines for producing green hydrogen and a battery storage system for compressor load operation and backup. The levelized cost of hydrogen of 5.19 €/kg is achieved with a reduction of 90% in greenhouse gas emissions compared to traditional diesel buses. Further, this system offers a reduction of approximately 31% over the course of 20 years. Case 2 also provides significant feasibility, with costs slightly higher than Case 1 and a comparable decrease in greenhouse gas emissions. The results of this study highlight the key role of hybrid renewable energy and battery storage systems in ensuring economic sustainability and reliable operations. Cases 3 and 4 illustrate that relying on a single energy source without a battery storage system reduces feasibility by increasing the system's cost. The presence of a complementary energy source or a battery storage system in Cases 1 and 2 proved to be a robust strategy for addressing the intermittency and variability of renewable energy sources. This research proposes a scalable and more practical model for decarbonizing public transport in remote, isolated regions. It emphasizes the pivotal role of site-specific renewable energy sources and potential and the integration of advanced optimization tools like HOMER Pro. Future work could maximize and enhance the proposed system's performance, scalability, and economic feasibility. Future work can include technological advancements in the system's key components, like improving the efficiency of the electrolyzer. Also, different hydrogen storage techniques can be applied to increase the system efficiency and decrease the system cost. Further, the results of this study showed how vital the battery storage system is for cost reduction of the whole system with RES. Hence, with ongoing declines in battery prices due to technical advancements and economies of scale, integrating state-of-the-art battery systems could improve system reliability and lower reliance on certain energy sources. The cost of the RES continues to decrease with increased efficiency; a sensitivity analysis could be done for the RES to showcase the significance of on-site hydrogen generation further. The suggested system should be scaled to other isolated regions or urban areas with distinct energy potential and transport demands. Comparative studies can identify optimizations for specific areas and test the feasibility and practicality of this approach. Moreover, alternative RES, such as biomass, hydro energy, geothermal energy, and tidal energy, could be evaluated to expand energy portfolios. By referring to these future directions, researchers can improve the suggested system, increase its applicability, and participate in a broader shift toward green and sustainable public transport systems globally.

Chapter 9

Conclusion

This thesis has offered a comprehensive, multi-dimensional investigation into the role of EVs in the ongoing energy transition, examining both their disruptive potential and the systemic solutions required for their sustainable integration. Across six interconnected studies, this research has not only assessed the environmental and grid-level implications of widespread EV adoption but also developed and validated innovative strategies to transform EVs from passive loads into active contributors to energy system resilience. One of the central findings is that the environmental benefits of EVs are highly dependent on the carbon intensity of the electricity used for charging. Study 1 demonstrated that in regions where fossil fuels dominate the generation mix, electrification alone may offer limited GHG reductions. However, in countries progressing toward cleaner grids, especially those aligning with the Net Zero Emission 2050 goals, EV adoption can result in substantial emissions savings. This theme was further localized in Study 2, which focused on three distinct Italian regions, illustrating the varying decarbonization potential based on regional electricity grid compositions. Beyond environmental impact, Study 3 revealed how increasing EV penetration poses challenges to both urban and insular power networks, highlighting issues such as peak load growth, voltage instability, and transformer stress. This research makes a unique contribution by evaluating these impacts under different penetration levels and regional grid structures, with simulation-based evidence drawn from Palermo and Favignana Island. To counteract these challenges, Study 4 introduced Demand Side Management strategies, most notably, Time-of-Use pricing, as a method to shift charging patterns and flatten load profiles. These strategies were further enhanced in Study 5 with the novel integration of digital twin technology. By simulating real-time conditions and enabling predictive load control, digital twins provide a sophisticated, adaptive tool for aligning EV charging with the availability of Renewable Energy Sources, ensuring both operational efficiency and environmental optimization. A further innovation of this thesis is the inclusion of Fuel Cell Electric Vehicles supported by onsite hydrogen production using RES. The Favignana Island case study uniquely combined real operational data, such as bus routes and seasonal demand variations, with techno-economic analysis to prove the feasibility of RES-based hydrogen infrastructure for public transport. This fills a research gap by offering a location-specific, costed-out model rather than a theoretical scenario, significantly advancing the discourse on hydrogen as a complementary decarbonization pathway. Together, these findings support the main theme of this work: that intelligent and coordinated strategies across grid management, digital technologies, and clean energy production can transform EVs and FCEVs from obstacles into essential solutions for decarbonization. This research presents a cohesive methodology that policymakers, grid operators, and urban planners can tailor for specific regional contexts.

Looking ahead, several promising avenues emerge. Future research can expand the digital twin framework into real-time hardware-in-the-loop systems for pilot-scale deployment. Additionally, hybrid DSM strategies incorporating AI and user behavior modeling can refine load forecasting and management. Finally, with the rise of bidirectional EV charging and hybrid hydrogen-electric fleets, there is scope to reimagine entire transport-energy ecosystems as active, decentralized grid components. Through its integrated approach and regionally grounded analyses, this thesis not only contributes new knowledge but also provides a strategic foundation for transforming the electrified transport sector into a resilient pillar of the low-carbon future.

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