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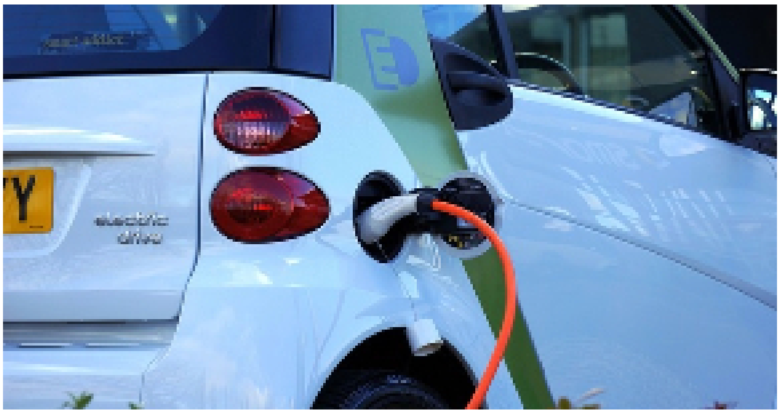

Impact of mass deployment of electric vehicles in energy and power systems

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Electrical and Computer Engineering

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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I sincerely thank my family for their understanding and consistent support during this transformative journey.

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Abstract

In the global pursuit of carbon neutrality, the widespread adoption of Electric Vehicles (EVs) has become an essential priority. While commendable for its environmental objectives, this transition introduces a dynamic and multifaceted set of challenges to the effective management and operation of power systems. This study focuses on understanding and mitigating these challenges within the specific context of Portugal, where recent projections indicate a substantial surge in EV adoption by 2030, 2040, and 2050. The driving force behind this surge is the proactive stance of the Portuguese government, which has implemented supportive policies to accelerate the shift towards sustainable transportation.

The imminent rise in EV adoption is anticipated to significantly transform the overall power demand landscape within the Portuguese power system. This study analyses the expected implications of widespread EV integration on the country's power infrastructure. This analysis considers multiple scenarios, including the evolution of power consumption patterns, changes in power production dynamics, diverse trajectories of EV adoption, and the potential effectiveness of implementing intelligent EV management strategies. To conduct this comprehensive analysis, a simulation framework has been developed. This framework incorporates diverse tools to simulate and assess the intricate interplay between EVs and the Portuguese power system. Moreover, it allows for a nuanced exploration of different scenarios and strategies, offering valuable insights into the potential challenges and opportunities associated with the mass deployment of EVs.

One of the primary conclusions drawn from this study is the need for coordinated efforts between EVs and renewable energy sources. The integration of EVs into the power system, when coupled with renewable sources, emerges as a strategic avenue to enhance the overall resilience, sustainability, and efficiency of the power infrastructure. This finding underscores the importance of aligning EV adoption trajectories with broader renewable energy objectives to achieve a harmonious and sustainable energy future.

Keywords

Electric Vehicles, Energy Transition, Intelligent EV Management Strategies, Power Systems Operation, Renewable energy integration

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Acronyms

AC	Air conditioning
ACAP	Associação Automóvel de Portugal
APS	Announced Pledges Scenario
BaU	Business as Usual Strategy
BEVs	Battery Electric Vehicles
CO2	Carbon Dioxide
CS	Charging Station
DL	Delayed Charging Strategy
DDL	Differentiate Delayed Charging Strategy
DDDL	Double Differentiate Delayed Charging Strategy
EPM	Electricity Planning Model
EU	European Union
EVs	Electric Vehicles
EVSE	Electric Vehicles Supply Equipment
GHG	Greenhouse Gas
GPS	Global Positioning System
GW	Gigawatt
Gt	Gigatonnes
GWh	Gigawatt-hours
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMT	Portuguese Institute for Mobility and Transport

INE	Portugal Statistics Institute
IPCC	Intergovernmental Panel on Climate Change
IPMA	Portuguese Institute for Sea and Atmosphere
IRENA	International Renewable Energy Agency
ISEG	Institute of Economics and Management at the University of Lisbon
Li-on	Lithium-ion
LULUCF	Land Use, Land Use Change, and Forestry
NZE	Net Zero Emissions by 2050 Scenario
OLS	Ordinary Least Squares
PS	Peak Shaving Strategy
PHEV	Plug-in Electric Vehicle
PNEC2030	National Energy and Climate Plan 2050
RDE	Real Driving Emissions
RNC2050	Roadmap for Carbon Neutrality 2050
RESP	Portuguese Electricity System
RES	Renewable Energy Sources
SEC	Specific Energy Consumption
SOC	State-of-Charge
STEPS	Stated Policies Scenario
TWh	Terawatt-hours
ToU	Time-of-Use
UK	United Kingdom
UN	United Nations
V2X	Vehicle-to-Everything

1

Introduction

Contents

1.1 Context and Motivation

Global apprehension persists regarding the detrimental impact of pollutant gases responsible for the greenhouse effect in the contemporary landscape. The upswing in Greenhouse Gas (GHG) emissions, namely Carbon Dioxide (CO2), remains a pivotal catalyst for climate change, with the power and transport sectors playing substantial roles in this alarming trajectory [1–3]. In 2022, CO2 emissions from the power sector witnessed a surge of 261 Mt, while the transport sector recorded a 254 Mt increase over 2021 [1]. This sector relies heavily on fossil fuels, constituting a fifth of the global energy-related CO2 emissions [2]. The Intergovernmental Panel on Climate Change (IPCC), in a synthesis report published in March 2023, underscored the imperative for swift and comprehensive transitions across all sectors and systems [4]. The European Union (EU) climate law has mandated achieving the EU's climate goal, which requires the reduction of EU emissions by at least 55% by 2030 [5]. EU countries are actively formulating new legislation to meet this goal and achieve climate neutrality by 2050 [5]. In response to the energy crisis, several governments have announced measures to address supply shortages and mitigate price hikes [3, 5]. Following the climate targets defined by the United Nations (UN) Environment Program [6] and the European Environment Agency [7], Portuguese targets were reviewed, with the country committing to limit its GHG emissions by at least -28.7% about its 2005 emissions by 2030 [8].

Moreover, Electric Vehicles (EVs) represent an essential opportunity to reduce emissions in the transportation sector. According to [3], EVs contributed to a net reduction of about 80 Mt of emissions in 2021. The EV market is witnessing exponential growth, with sales surpassing 10 million in 2022. As a matter of fact, 14% of all new cars sold in 2022 were electric, a substantial increase from around 9% in 2021 to less than 5% in 2020 [1]. In Europe, the second-largest market for electric cars, sales surged by over 15% in 2022, signifying that more than one in every five cars sold was electric [1]. Despite the benefits, mass adoption of EVs will bring a set of challenges that can affect the stability and reliability of the power grid due to the substantial increase in demand and to the unpredictability of the behaviour of the users of this ac EVs [9, 10]. The significant increase in the usage of EVs in recent years has introduced fresh challenges to power system operation, encompassing issues like the emergence of new consumption peaks, overloading, voltage instability, and potential degradation of local equipment, particularly when numerous EVs charge without proper control [9, 11]. Addressing these concerns calls for the development of effective strategies in EV management [12].

Thus, considering the presented advantages and challenges, it becomes evident that a thorough investigation into the impacts of mass EV adoption on the electrical system is imperative. This study is essential to maximise the benefits of these technologies while overcoming potential challenges. Studies like the one presented in this thesis play a crucial role in developing effective EV management strategies. In the face of a massive EV adoption scenario, ensuring that the electrical network can reliably and efficiently meet the total system demand is essential. This analysis will focus on the Portuguese electricity system. Modelling EVs becomes challenging since their consumption and efficiency depend on various factors external to the vehicle. For example, ambient temperature (variations can affect consumption), speed and acceleration, and user behaviour. These factors will be incorporated into the simulator developed by [13] to simulate the Portuguese scenario.

This study explores the intricate dynamics between EVs and the Portuguese energy system. Against this backdrop, three key research questions will guide our exploration in the coming Chapters, shedding light on critical aspects of the EV impact in the country. These questions address the overarching impact of EVs on the energy system and delve into the development of effective management strategies and behavioural factors on EV performance. By comprehensively examining these aspects, our study aspires to contribute to Portugal's broader discourse on sustainable mobility and energy transition. A simulation framework has been developed, including different tools to simulate the Portuguese scenario.

a) How do ambient temperature, driving speed, and user behaviour impact EV energy consumption and utilisation?

b) What EV management strategies should be adopted in the Portuguese electric system to mitigate the negative impact of EVs?

c) How will EVs impact the Portuguese energy system in the next few years if no strategy is adopted?

The primary objective of this thesis is to assess the impact of EVs on Portugal's energy and power systems. To achieve this goal, collecting diverse data about Portugal is imperative. In the initial phase, various EV evolution scenarios in Portugal for 2030, 2035, 2040, and 2050 were analysed. Using a computational tool, multiple EV profiles were created based on multiple inputs, including charger power ratings, prevalent EV models, and times of the day when EVs are charged, among other factors. The simulator outputs will then be used to formulate EV Management Strategies, whose aim is to identify solutions to minimise the impact of EVs on Portugal's power and energy systems. The analysis is facilitated through the examination of load curve evolution. Observing the impact of EVs on the power grid is only possible through in-depth network analysis, including power consumption evolution and power production evolution [14]. By integrating these inputs with the outcomes derived from the proposed management strategies, it becomes feasible to ascertain the potential impacts of EVs in Portugal.

1.2 Related projects and scientific outputs

The work carried out as part of this dissertation was developed under the scope of the following research project(s):

- Horizon Europe EV4EU – Electric Vehicles Management for carbon neutrality in Europe project, funded by the European Union under grant agreement no. 101056765. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the grating authority can be held responsible for them.

The developed work resulted in the submission of the following scientific paper outputs:

- Scientific articles: P.Pereira, V.Armindo, C.P.Guzman, P.M.S.Carvalho, L.A.F.M.Ferreira, H.Morais, Impact of Mass Deployment of Electric Vehicles in Energy and Power Systems, 23rd Power Systems Computation Conference, 2023, status: submitted

1.3 Organization of the Document

The initial chapter, Chapter 1, provides an overview of the research topic, outlines the problem statement, specifies the research objectives, and elucidates the significance and motivation behind the undertaken research. Moving forward, Chapter 2 conducts a comprehensive literature review, synthesising existing works on the impact of EVs on energy and power systems. Chapter 3 develops the framework used in the study, focusing on improving the simulation tool. This chapter delves into technical details, outlining methodologies and providing insights into implemented enhancements. Chapter 4 explores key trends, developments, and contextual information related to the country's current energy grid and the adoption and utilisation of EVs. Chapter 5 examines the future of the Portuguese electric network. It not only explores potential scenarios but also presents and analyses various EV Management Strategies. In the final chapter, Chapter 6, key findings from the analyses conducted in the preceding sections are summarised, reflecting on the study's broader implications and suggesting avenues for future research.

2

Background

Contents

2.1 Adoption of EVs around the world

The aftermath of the COVID-19 pandemic, coupled with the ramifications of the Ukraine crisis, has introduced additional complexities to the challenges associated with the energy transition. Prices for energy commodities have surged to unprecedented levels, ranging from five to ten times their historical norms in certain instances. This surge has contributed to the existing inflationary pressures that emerged after the COVID-19 pandemic, as the International Renewable Energy Agency (IRENA) documented in 2023 [3]. While the crisis has catalysed increased deployment and investment in clean energy, it has also spurred investment in fossil fuel supply. Addressing concerns about energy security remains a critical aspect in shaping policy frameworks guiding investment decisions [3].

Despite the robust economic rebound observed in advanced economies post-COVID-19, their energy sector emissions in 2022 reached a new record of 37 Gigatonnes (Gt) of CO2, surpassing the 2019 level by 1%. Moreover, emissions in 2022 for developing economies experienced around 4.5% higher (equivalent to roughly 1 Gt) than the 2019 level [15]. The Net Zero Emissions by 2050 Scenario (NZE), report for 2023, developed by International Energy Agency (IEA) highlights a deviation from the anticipated reduction in global energy sector emissions over the last two years, as outlined in the 2021 roadmap [15, 16]. Instead, emissions have risen to unprecedented levels, as depicted in Figure 2.1 from the source NZE report [15].

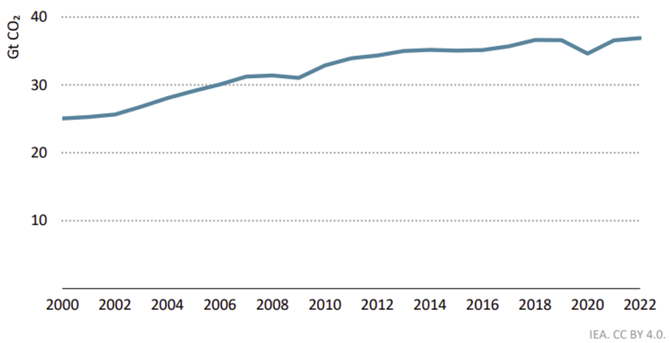


Figure 2.1: Global energy sector CO2 emissions, 2000-2022 (Source: [15])

Despite the strides made thus far, the implementation of energy transition technologies falls significantly short of the levels required to meet the ambitious 1.5℃ Paris climate goal. A trajectory aligned with the 1.5℃ target demands a comprehensive transformation in how societies consume and produce energy. Achieving this scenario requires attaining net-zero emissions in the energy sector globally by 2050 [3]. To accomplish this, global energy consumption must decrease by 6% from 2020 levels by 2050, which is only feasible through substantial improvements in energy efficiency. Simultaneously, the share of renewables in the global energy mix should escalate to 77% by 2050, a significant increase from the 16% recorded in 2020 [3].

Every end-use sector must transition towards a greater reliance on renewables. Achieving the requisite scale of electrification in the transport sector will demand an increase in renewable electricity capacity by 2050. A profound and systemic transformation of the global energy system must transpire within the next 30 years to avert catastrophic consequences from climate change and to uphold energy security [3].

The sixth assessment cycle of the IPCC [4] recently elucidated, with greater clarity than ever before, the dangers of surpassing the 1.5℃ limit, along with the availability and cost-effectiveness of various emissions reduction options. Concurrently, a political review assessing progress toward internationally agreed climate goals concludes this year (2023) in the form of the inaugural Global Stocktake under the Paris Agreement. Limiting global warming to 1.5℃ entails reducing CO_2 emissions and achieving net-zero emissions in the energy sector by 2050. A 1.5℃ compatible pathway mandates a comprehensive transformation in how societies produce and consume energy [1, 3].

The NZE Scenario [1, 16], outlines a normative but attainable pathway for the global energy sector to achieve net-zero CO_2 emissions by 2050. This scenario aligns with limiting the global temperature rise to 1.5℃, with no or minimal temperature overshoot, following reductions assessed by the IPCC in its special report on global warming of 1.5℃. Recognising the existence of multiple potential paths and uncertainties affecting them, viewing the NZE Scenario as a path among many rather than the singular path to achieving net-zero emissions is essential.

The transportation sector, heavily dependent on fossil fuels, emitted 6.9 Gt of CO_2 in 2020, constituting one-fifth of global energy-related CO_2 emissions. In 2019, the transport sector contributed to nearly a quarter of the global energy-related CO_2 emissions. The sector primarily relies on fossil fuels (95%), followed by biofuels (4%) and electricity (1%). Given the anticipated rise in global demand for transportation services in the coming years, a crucial imperative is the sustainable transformation of the transport sector into a zero-carbon entity [3].

Electrification is the main lever for emissions reductions in road transport. EV sales will account for around 65% of the new car market by 2030, and no new Internal Combustion Engine (ICE) cars will be sold after 2035 [15, 17]. From 2023 to 2030, around one-fifth of the emissions reductions in the NZE Scenario result from electrification of end-uses that would otherwise have used fossil fuels. In transport, most of the gains come from the deployment of EVs. EV success is influenced by a variety of things the key pillar is consistent policy support [15].

Global spending on EVs nearly reached USD 425 billion in 2022, marking a remarkable increase of up to 50% compared to 2021 [1]. Many countries have committed to phasing out ICE or have ambitious plans for car electrification in the coming decades. Simultaneously, several automakers are embracing electrification initiatives that extend beyond legislative requirements. However, EV sales continue to lag in many emerging and developing nations where available models still need to be reached for mass-market buyers. In 2022, the global EV fleet consumed approximately 110 Terawatt-hours (TWh) of power, doubling the consumption in 2021 [1].

Across most segments, EVs emerge as the most cost-effective low-emission technology in both the short and long term, gradually dominating the road transport sector. EVs utilise the energy stored in batteries to power electric motors for propulsion, whose power is then exclusively derived from electrical energy. The key advantages [18] of these vehicles include:

- Being free of GHG emissions, particularly at the local level;
- Demonstrating significantly higher efficiency compared to ICE;
- Enabling recharging with renewable energy sources [18].

According to [1], the decarbonisation of the transport sector hinges primarily on two fundamental shifts. The initial step involves transitioning to electricity adopting EVs and hydrogen fuel cell electric cars for road transportation. The second entails directly utilising low-emission fuels, including biofuels, hydrogen, and hydrogen-based fuels, especially in aviation and shipping.

The global transportation industry currently consumes a quarter of the total final energy and is responsible for approximately 40% of emissions from end-use sectors. Oil, for instance, dominates the transportation sector, constituting 90% of its usage [1]. In the NZE Scenario, envisaged by the early 2040s, electricity is anticipated to become the predominant fuel in the global transport sector, contributing over half of the total final consumption and two-thirds of useful energy by 2050, surpassing the role of oil. Nevertheless, oil plays a significant role in all end-use sectors [1].

In the 1.5 ℃ Scenario [3] crafted by the IRENA, the electrification of transportation is expected to rise alongside an increased deployment of charging infrastructure. A combination of efficiency measures and low-carbon technologies will keep the transportation sector's final energy usage in 2030 at similar levels to those of 2020. The diverse array of energy transition alternatives outlined in IRENA's 1.5 ℃

Scenario (refer to Figure 2.2 - Source: [3]) will lead to a substantial reduction in transport emissions, plummeting to a mere 0.6 GtCO2 annually by 2050—a 91% reduction compared to 2020.

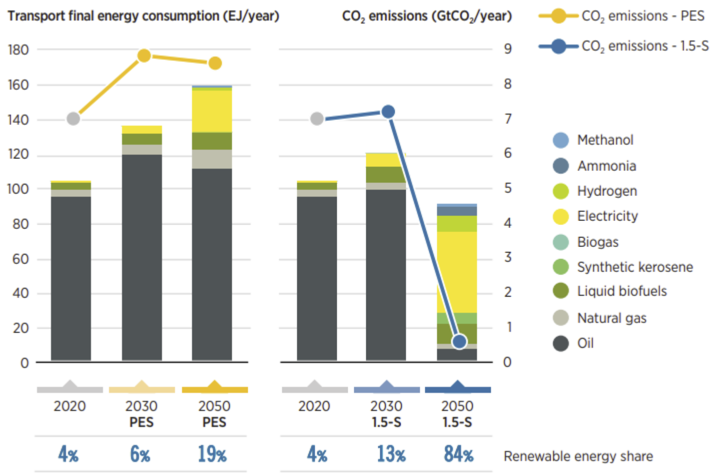


Figure 2.2: Transport: Final energy consumption under the Planned Energy Scenario and 1.5ºC Scenario in 2020, 2030 and 2050, and corresponding emissions (Source: [3]

Efficiency impacts are anticipated to manifest in the 2030s as the composition of the vehicle stock undergoes significant changes. In this scenario, EVs are projected to constitute 20% of all vehicles on the road by 2030, surging to 60% by 2040. These projections mark a substantial increase from the less than 1% share of electricity consumption in road transport demand witnessed in 2021. The global EV stock is anticipated to surpass 150 million vehicles in 2026, escalate to 380 million by 2030, and soar to nearly 2 billion by 2050. The road transportation industry is poised to achieve practical carbon neutrality by this juncture. Electricity emerges as the pivotal substitute for oil, contributing to over two-thirds of total energy consumption and accounting for nearly 90% of total road activity by 2050 [1].

In automotive Lithium-ion (Li-on) batteries, demand experienced a notable uptick, increasing by approximately 65% to 550 Gigawatt-hours (GWh) in 2022, compared to about 330 GWh in 2021. This surge can be attributed essentially to the growth in electric passenger car sales, witnessing a 55% rise in new registrations in 2022 compared to the previous year. However, the manufacturing capacity for lithium-ion automotive batteries that year stood at roughly 1.5 TWh, which translates to a utilisation rate of around 35%, a considerable drop from the approximately 43%, rate registered in 2021 [1].

The illustrations below, derived from the "Global EV Outlook 2023" (report by the IEA) [1], offer predictions regarding the worldwide inventory of EVs and the corresponding electrical demand from each EV fleet. Incorporating two additional scenarios ensures a thorough benchmark for assessment, from [1]:

- Stated Policies Scenario (STEPS): This scenario forecasts energy demand, supply, and emissions, considering established and planned policies and regulations. It includes the latest available data, projections on technology costs, manufacturing capacity, and the industrial strategies of countries and companies in the energy sector [1].
- Announced Pledges Scenario (APS): This scenario assumes the complete and timely implementation of all climate commitments made by governments worldwide, including those outlined in Nationally Determined Contributions and long-term net-zero emissions pledges [1].

The NZE scenario is particularly rigorous and realistic due to the consistent increase in demand for EVs over the years. It is also expected to be the foundation for forthcoming work in the short term. The figures below (Figure 2.3 and 2.4 - Source: [1]) depict the projected inventory of EVs across the different scenarios outlined by the IEA, along with the forecasted electricity demand for each vehicle type, region, and country in these.

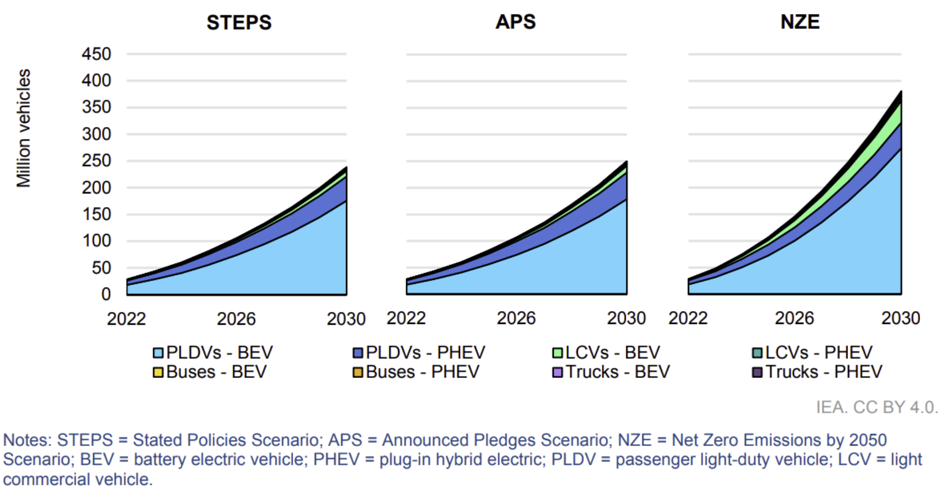


Figure 2.3: Global EV stock by mode and scenario, 2022-2030 (Source: [1])

IRENA advocates for a substantial increase in the share of electricity in final energy consumption for transportation, projecting a climb from 0.4 per cent in 2019 to 9 per cent by 2030. Anticipated growth in the EV sector includes the expansion of the electric car fleet from 18 million to over 380 million by 2030, with electric trucks expected to reach 3 million by the same year. IRENA's 1.5℃ Scenario determines that EV's contribution must cover over 80% of total road transport activity by 2050. Recognising the situation's urgency, there is a pressing need to expedite transportation electrification, aiming to integrate more than 30 million EVs annually throughout this decade [19].

In the future decades, transportation will witness increased electrification and the simultaneous deployment of charging infrastructure. Three-quarters (75%) of the predicted worldwide growth in power

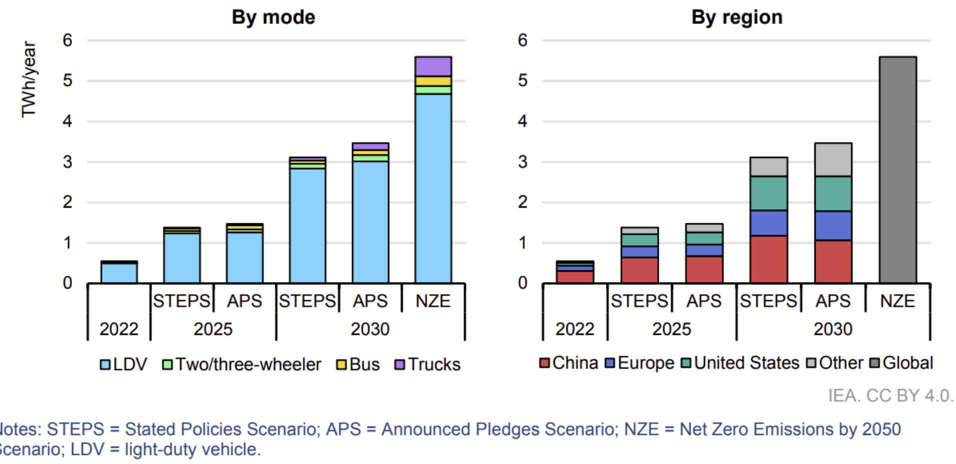


Figure 2.4: Electricity demand from the global EV fleet by scenario, 2022-2030 (Source: [1])

consumption to 2050 is accounted for by emerging markets and developing nations. The demand will double by 2030 and triple by 2050, driven by growing incomes and living standards and new sources of application connected to decarbonisation [16]. Although achieving full electrification of road transport is feasible, it may introduce further challenges and unintended consequences. For instance, it might escalate the strain on electricity grids, demanding substantial additional investments and amplifying the transport system's susceptibility to power disruptions [15]. A rise in power demand will almost certainly change the electrical load curve, which presents a difficulty for the operator's energy firms. The most noticeable consequence is predicted to be an increase in evening peak loads, associated with users charging their EVs when they get home from work or after doing errands [20].

The charging network is expanding, transitioning from pilot initiatives to global projects. As it is impractical to predict each user's EV charging behaviour, various methods can be employed to mitigate the impact of charging EVs and prevent peak loads resulting from uncontrolled customer charging. Given the expectation that most EV charging will occur at residences, distribution grids must effectively manage substantial additional loads. Power system operators face the constant challenge of balancing supply and demand on the grid, pressing for sufficient power resources through generation or storage and ample network capacity [1]. Coordination in developing and upgrading grids is essential to harness the potential of EVs as a resource for grid stability [21]. In the NZE Scenario, global grid investment is projected to reach nearly USD 750 billion annually by 2030, maintaining high levels through 2050, with approximately 70% allocated to distribution grids for expansion, reinforcement, and digitalisation [2].

Electricity security is paramount in the NZE Scenario, especially with the growth of global economy, demanding for the assurance of a safe and reliable electricity supply. With the increasing number of consumers and applications, energy security relies on upgraded and digitalised grids to facilitate advanced and innovative operations. The aforementioned Scenario goes on to detail how power system flexibility must double between now and 2050 due to the growing contribution of variable renewables and shifts in the energy consumption patterns [2]. Power losses should be at most 5% of the transmitted power to comply with European rules. The rising number of charging stations will escalate the load, voltage drop, and power losses. Voltage deviations from the specified norms by more or less than 10% can pose challenges, especially in systems with significant EV infiltration and an inadequate grid. Coordinating intelligent EV charging should help smooth out spikes in peak demand [1].

2.2 Driving Change: The Surge of EVs in Portugal

Following the Paris Agreement and the EU targets, Portugal embraced achieving Carbon Neutrality by 2050 and formulated, in 2019, the Roadmap for Carbon Neutrality 2050 (RNC2050) [22]. This roadmap established the vision, trajectories, and guidelines for implementing policies and measures over this time. The RNC2050 charts a sustained path to carbon neutrality, not only providing essential guidelines but also identifying cost-effective options across different socio-economic development scenarios. Consistent with the findings of the IPCC Report [4] on 1.5ºC, the most significant efforts to reduce emissions are anticipated by 2030, with a clear emphasis on energy transition and sustainable mobility.

In harmony with what was settled by the RNC2050, ambitious yet achievable targets for 2030 were established in the National Energy and Climate Plan 2050 (PNEC2030) [8]. Addressing the challenges requires coordinated action between energy and climate policies to chart a feasible trajectory towards a carbon-neutral economy and society. This approach aims to promote economic growth and simultaneously improve quality of life. The PNEC2030 is pivotal in ensuring the realisation of energy and climate targets by 2030 and is oriented towards Portugal's long-term goals. Currently undergoing revision until the end of June 2024, the information provided is based on the draft, which contains more recent data than the PNEC2030 released in 2019 [8].

Following a rapid increase in GHG emissions throughout the 1990s, Portugal reached its peak national emissions in 2005. Afterwards, a substantial and sustained decline has been observed, establishing a trajectory towards the decarbonisation of the national economy. In 2005, emissions increased by approximately 46% compared to 1990 levels [8]. According to the latest update, GHG emissions, excluding Land Use, Land Use Change, and Forestry (LULUCF) emissions, are estimated at around 56.5 Mt CO2eq in 2021. These values represent a decrease of 5.1% from 1990 and 2.8% from 2020. When considering the LULUCF sector, the total emissions in 2021 are estimated at 50.5 Mt CO2eq, reflecting a reduction of 24.3% from 1990 and 5.5% from 2020 [8]. The emission trend in Portugal is illustrated in Figure 2.5 (Source: [8]), in which the orange line represents total emissions with LULUCF, and the blue line represents total emissions without LULUCF, as presented by [8] and [23].

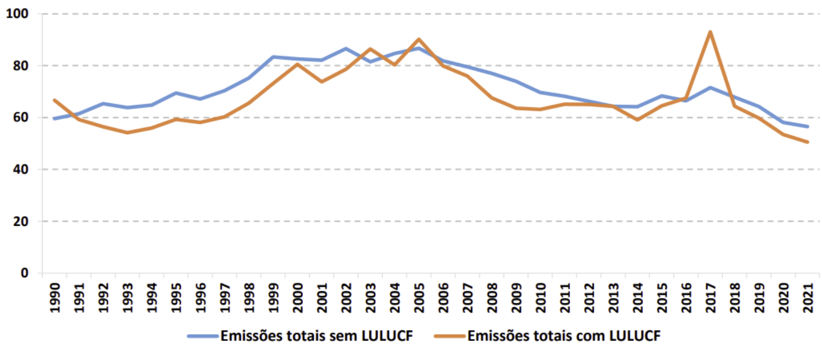


Figure 2.5: Portugal GHG emissions 1990-2021 (Source: [8])

Several factors contribute to this trend, including the growth of less polluting energy sources such as natural gas (compared to coal). This shift is made easier through the construction of combined-cycle power plants and more efficient cogeneration units. Other contributing factors include the substantial increase in electricity generated from renewable sources, primarily wind and hydropower, and the implementation of energy efficiency measures [8, 22, 24].

The energy sector, encompassing transportation and energy production, is the most significant contributor, accounting for approximately 28% and 15% of total emissions, respectively [8]. In 2016, the Portuguese government committed to achieving carbon neutrality by the end of 2050, setting intermediate reduction targets of at least 55% by 2030 and between 65% and 75% by 2040 compared to 2005. These targets translate into even more pronounced reductions for the energy system [8].

Profound changes are anticipated in the transportation and mobility sector, driven by the widespread adoption of EVs. This shift is expected to result in a 43% reduction in sector emissions by 2030 compared to 2005, increasing to approximately 86% by 2040, and an impressive 98% decrease in GHG emissions when compared to the same reference levels [8, 22, 24].

The decarbonisation of mobility and transportation is particularly crucial, given its implication on primary energy consumption and greenhouse gas emissions at the national level. The current decade marks a paradigm shift in this sector, significantly influenced by European measures under the "Fit for 55" package [5]. This initiative introduces progressive emission reduction targets for passenger cars and light commercial vehicles, promotes the use of renewable fuels, and invests in charging infrastructure for

EVs. The future of mobility is envisioned as sustainable, autonomous, and shared [8, 22]. The electricity sector will focus on electrical installations and the widespread adoption of "smart" charging strategies for EVs. These vehicles are expected to participate in local or system flexibility services actively and to help mitigate variations in the daily load profile on the public electricity grid [24, 25].

The shift towards sustainable mobility and the electrification of transportation stands as a cornerstone in the journey towards the decarbonisation of the economy. EVs have been making strides, and in the not-so-distant future, they are poised to replace combustion engine vehicles. Several European cities have already taken measures towards prohibiting the circulation of combustion engine vehicles in the short to medium term [24]. Figure 2.6 (Source: [24]), represents the trend of EVs in Portugal until 2021, illustrated by [24] using data from [26–28]:

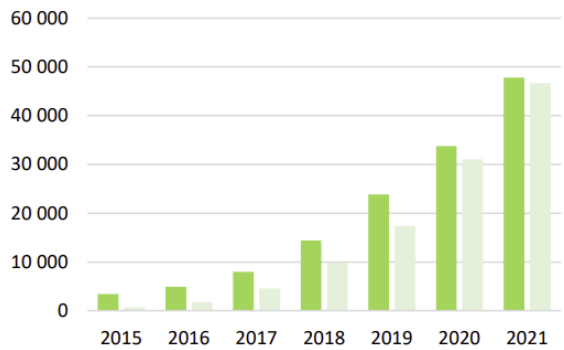


Figure 2.6: Progression of BEV (dark green) and PHEV (light green) Fleet in Portugal: 2015-2021 (Source: [24, 26–28])

Analysing Figure 2.6 leads to the conclusion that there has been significant growth in the insertion of these vehicles in the automotive fleet in recent years, both in Battery Electric Vehicles (BEVs) and Plug-in Electric Vehicle (PHEV) technologies. Consequently, for EVs, continuous growth in sales is assumed in this scenario, which reflects more favourable economic conditions and ambitious energy policy goals based on widespread transportation electrification.

As per data provided by the Portugal Statistics Institute (INE) [28], the number of EVs witnessed a further surge of 43.3% in 2021 compared to the preceding years, with increases of +41.1% and +49.1% in 2020 and 2019, respectively [26]. This growth is even more pronounced when considering only BEVs. In 2022, 20,230 BEVs were sold, setting a new annual sales record in this category. This figure significantly surpasses the 14,057 units sold throughout the entire year of 2021 ([29], [30]). Figure 2.7 (Source: [26, 29]) illustrates the sales of EVs in Portugal for the years 2021 and 2022.

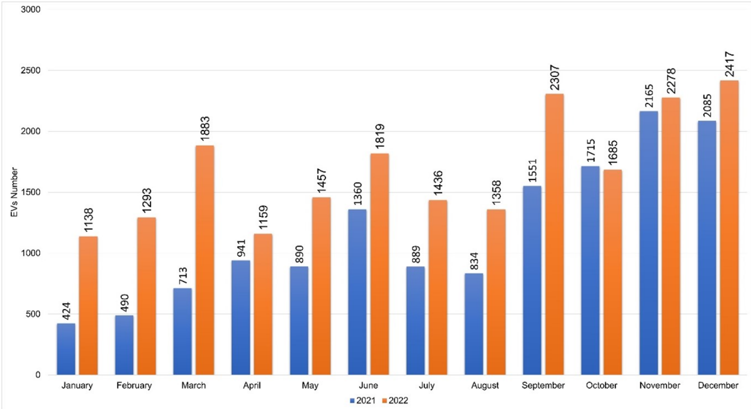


Figure 2.7: BEV in Portugal - Registrations of Official Brand Representatives (Source: [26, 29])

In alignment with the global projections for EVs in the coming years and as outlined in the preceding section of this chapter, the Portuguese government is actively committed to electrifying the transportation sector and achieving the stipulated objectives outlined in the RNC2050 and PNEC2030 documents. The integration of EVs poses a substantial challenge to the power system, primarily stemming from uncertainties related to user behaviour. The recent surge in EV usage has presented unique challenges to power system operation. These challenges include new consumption peaks, overloading, voltage instability, and potential degradation of local equipment, namely when many EVs charge without adequate control mechanisms [9, 11]. Addressing these concerns compels for the development of effective strategies in EV management [12].

Conducting a comprehensive analysis of Chapters 3 and 5 will be essential to the understanding of the potential mitigation of these challenges. The intent is to formulate an EV Management Strategy tailored to the Portuguese electrical system, considering its unique characteristics and challenges. This strategy aims to ensure the seamless integration of EVs into the existing power infrastructure while mitigating potential disruptions and optimising overall system performance.

2.3 Related Work - Impact of EVs on energy and power systems

The charging network is growing and moving from pilot to world projects. Since it is impossible to predict the charging of each user's EV, some methods can be used to reduce the effects of charging EVs and avoid peak loads caused by uncontrolled charging by customers. Coordination of grid development and upgrade plans, including the use of digital technology to enable two-way communication and pricing between EVs and grids., are needed now to ensure that EVs can become a resource for grid stability [21]. In the NZE Scenario, global investment in grids will reach nearly USD 750 billion per year by 2030 and continue high through 2050. Approximately 70% of this expenditure is for distribution grids to extend, reinforce, and digitalise networks [2].

Most EV charging is expected to occur at residences, so the distribution grids must manage significant additional loads. Power system operators must always balance supply and demand on the grid. To do so requires sufficient power resources through generation or storage and ample network capacity [1]. Losses should not exceed 5% of transmitted power, according to European rules. The increased number of charging stations will increase the load, voltage drop, and power losses. Voltage in the network cannot deviate from the norms by more or less than 10%. The consequences can be challenging, especially in systems with significant EV stock penetration and a poor grid [2]. This new infiltration leads to the risk of the power grid becoming overloaded, damaging existing equipment, or even causing blackouts in case of grid overload. Maintenance, new power plants and upgrades in transmission lines will be required in the distribution network, i.e., investment by grid operators. EVs connected to the distribution grid without charging control can cause impacts such as load spikes, drop voltages, and frequency variations.

Developing EV management strategies for EVs is essential for a successful transition of the power sector to net zero. Most of these EVs will charge using grid energy. It will be vital to manage the time and pace of charging to prevent sufficiency or flexibility difficulties for the power supply. Intelligent charging solutions may be indispensable to lowering peak load, decreasing grid congestion, and minimising flexibility concerns. To be a part of the energy transformation, EVs must become flexible grid resources. For now, policymakers should focus on accelerating the deployment of EVs. All players in the EV industry (such as regulatory authorities, grid operators, energy retailers, charging station operators, and others) must collaborate to build effective regulatory regimes for the widespread deployment of EVs and grid integration [19].

With increasing electrification in the world to meet NZE targets, it is essential to analyse the impact of EVs on power systems. Researchers have used different methods to find the best solution for this problem. However, verifying the economic, technical, and environmental implications of these proposed solutions is also fundamental. This section presents some studies in the current literature that present different methodologies for the assessment of the impact of EVs.

In July 2018, "McKinsey & Company" conducted a study [20] on the potential impact of EVs on German energy systems. Using the Monte Carlo statistical method, a statistical analysis approach in which analysts use repeated sampling along predefined parameters to obtain the statistical properties of a phenomenon, changes were predicted in the load curve in residential areas as accurately as possible [20]. The study foresees that in Germany, total energy demand will increase by about 1% by 2030. Around five Gigawatt (GW) more power will be needed in peak hours in response to the additional demand. That amount could grow to roughly 4% by 2050, requiring an additional capacity of about 20 GW. This study predicts that in Germany, around 7% of total vehicles will be EVs by 2030 and 40% by 2050 [20].

A part of that study consisted of a circuit of 150 homes at 25% local EV density with two vehicles per household. The results indicated that the local peak load would increase by approximately 30%. With the same residential feeder circuit but with a charging time-of-use electricity tariffs which gave incentive to EV owners to charge after midnight instead of in the early evening, with a rate of 90% of users adoption, 3.7 kW average power charges reduced the local peak load to 16%. Based on this study, it is possible to conclude that the diffusion of EVs will increase the load curve as expected with a higher impact on uncontrolled charging since this will increase peak loads at peak hours. The solution presented by the authors with electricity tariffs encourages consumers to postpone charging their EVs to avoid charging in the hours when energy demand is higher.

Another study [31], conducted in the city of São Luís, in Northeast Brazil, demonstrates the impact of EV charging operations and forecasts EV fleet and energy consumption until 2030. The main goal was to create a load profile based on some consumers' habits, such as their residence, geographic location, vehicle usage and charging habits on business days and weekends and charging time and frequency [31]. A ten-year forecast EV fleet was developed to observe and analyse the impact of the EVs in the Maranhão electricity sector. The forecast was based on a Bass (Logistic) diffusion model, which verifies the increase in energy consumption over the years [31]. It was necessary to portion the fleet according to its use to estimate the critical scenarios related to the energy consumption of EVs. Some data was used, such as vehicle segments, average battery capacity, autonomy, efficiency (km/kWh), annual mileage per vehicle and annual consumption [31].

Based on the Bass diffusion model implemented, the study attained the following results: the fleet will reach 17,700 EVs in 2030 and will represent 7.80% of the power demand in the city during peak demand hours [31]. A growth rate of 46.18% should occur between 2025 and 2030 [31]. The forecast of energy consumption with the charge of EVs is 123.27 TWh by 2030, which represents approximately 16.37% of the total Brazilian consumption [31]. The authors suggest some solutions, such as shifting the period of residential charging to the period after the grid peak period and adopting demand-response programs or dynamic pricing focusing on reducing power and the impact on peak hours [31].

In April 2020, a comprehensive study [32], conducted in Alberta, Canada, investigated the implications of EVs on consumption and sustainability. The authors established an EV electricity demand simulation model within the existing modelling framework, crafting various scenarios to represent diverse EV density rates and charging methodologies.

Built upon a hybrid simulation model developed by Pruckner for Germany's electricity system [33], the simulation model in this study extended its capabilities. It estimated the energy required to charge EVs, factoring in diurnal and seasonal variations, weather conditions, vehicle characteristics, evolving electricity infrastructure, parked duration, distance driven, climate policies, and charging methods related to passenger transportation data. The charging curve for each EV was calculated daily, considering that if the vehicle did not operate, the entries in the daily charging curve were set to zero; otherwise, the charging curve was computed [32].

This study considered six scenarios, each representing different levels of EV penetration and distinct charging methods. The impact of EVs was analysed, with a specific focus on evaluating the effects of three charging methods: Uncoordinated/Uncontrolled Charging, Delayed Charging, and Valley Filling, which will be expounded upon in detail in Chapter 5 of this thesis.

The reference scenario employed was the "No EV" scenario, assuming the absence of (EVs) in passenger transportation. Five alternative scenarios (EV20-UC, EV30-UC, EV40-UC, EV30-DL, and EV30-VF) were modelled to represent varying levels of EV penetration (20% - Low penetration, 30% - Medium penetration, or 40% - High penetration) and the different charging methods mentioned earlier. Compared to the reference scenario without EVs, the increase in electricity demand to meet passenger transportation's energy needs under all three EV penetration levels is marginal. Specifically, the electricity demand rises by 2.6%, 4%, and 5.3% in 2031 under EV penetration levels of 20%, 30%, and 40%, respectively [32].

The additional electrical energy required to meet the charging demand of EVs under all penetration levels considered in this analysis remains marginal, reaching up to 5% in 2031. This additional energy implies a modest increase in generating capacity beyond the scenario without EVs. However, the combination of demand growth and uncontrolled EV charging is projected to elevate peak demand by approximately 15% more than the No EV scenario and 4% more than the EV30-UC scenario with no demand growth.

Uncoordinated EV charging, in particular, poses challenges to Alberta's electrical infrastructure, as it may complicate the delicate balance between supply and demand. This uncoordinated charging exacerbates peak demand situations within the energy system, requiring an increased capacity for power production. The situation intensifies when households resort to domestic energy distribution infrastructure for uncoordinated EVs recharging. Regrettably, renewable energy sources such as solar power are insufficient to meet the increased power demand since their electricity output depends on resource availability, which does not always align with EV charging demand [32].

In 2017, a study [34] was conducted to illustrate the evolution of electric car penetration and to initiate research into the impact of EVs on the Italian electric power system. The authors proposed a simulation model with hourly temporal resolution for electric power systems, accounting for the anticipated growth of electric car infiltration in the Italian electric power system in the coming years. The simulation framework allowed for an assessment of the impact of EVs on the Italian power system, an estimation of CO2 emissions from the transportation and electric power sectors, and an exploration of the CO2 saving potential associated with a high EV penetration rate in Italy.

The model's comprehensive logic incorporated interactions among various components, addressing crucial processes in electrical power systems. Charging routines of EV users were also a significant factor, revealing that public charging stations were predominantly used between 8 AM. and 10 PM., while home charging occurred between 2 PM. and 11 PM. The intention was to resort to profiles to distribute the daily power usage of all EVs throughout the day. Consequently, the pre-existing power consumption increased due to the additional need for charging EVs. As power demand escalated, so did the residual load. Various assumptions, including the number of EVs, annual mileage (in km), and consumption (in kWh/100 km), contributed to determining the daily power consumption of all EVs [34], [35].

The simulation framework promoted the investigation of diverse scenarios over a planning horizon of ten to twenty years at a high temporal resolution of one hour. According to the study on the impact of EVs on the Italian electric power system, there exists a CO2 saving potential of approximately 30%, assuming that 60% of EVs are (PHEV) with a combustion engine, implying CO2 emissions occur in the transportation sector as well. In conclusion, the objective of this paper was to initiate research into the influence of EVs on the Italian electric power system, employing simulation approaches to estimate cross-sector CO2 emissions. The presented strategy was based on realistic data for renewable energy sources, power plants, and commodities [34].

The case study from 2021 in Malé City, Maldives, as outlined in [36], delved into the impact of heightened EVs load on power systems—scrutinising functionality, costs, emissions, and investment choices. It also proposed a method to seamlessly integrate EV charging demand into a long-term capacity expansion model. Commencing with annual power usage predictions for each EV mode, the study assumed standard charging profiles for diverse procedures. Merging yearly charging demands with normalised profiles allowed for the generation of EV load curves for typical days, subsequently embedded into the planning model. To gauge the surge's effect on daily peak and load profiles, the yearly demand transformed into hourly cycles through defined assumptions [36].

Two EV charging scenarios were explored: uncoordinated and optimised. The first scenario occurred at night, the predominant period for such incidents. alternatively, the latter scenario strategically distributed portions of EV load for cost efficiency, considering hourly and daily dynamics [36]. The Electricity Planning Model (EPM) was the least-cost planning tool, examining additional EV load impact. For uncoordinated and optimised EV charging, the EPM crafted baseline least-cost generation and alternative plans with incremental EV load from 2021 to 2030.

Results disclosed a moderate EV scenario, with a 30% vehicle transition to EVs by 2030. However, if a substantial portion is charged during evenings under an "uncoordinated" regime, the impact on the evening peak could be detrimental. In contrast, the enhanced regime, monitoring charging limits, forecasted a 3% rise in total power system costs and a 16% surge in total generation by 2030, requiring an extra 29 MW capacity. The findings underscored the importance of precise modelling for comprehending the consequences of EV load impact on power systems, revealing a notable capacity increase and potential emissions rise in a fossil-fuel-dominated setting [36]. Visual representation of additional EV load in the Malé electricity system is in Figure 2.8 (Source: [36])

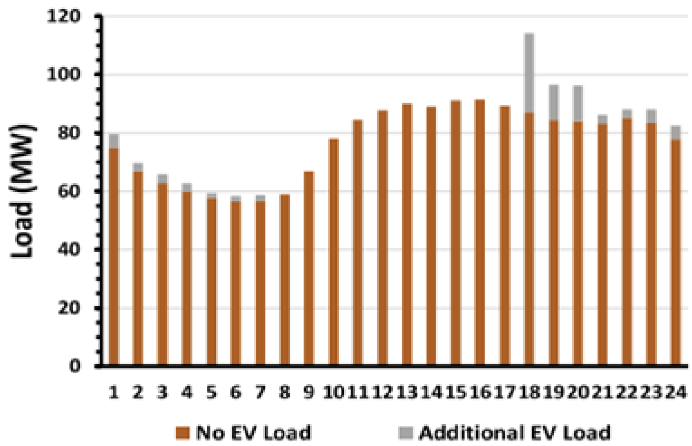


Figure 2.8: Load in Malé on a typical working day for 2030 (Source: [36])

In conclusion, this study provided critical insights. The considerable impact of heightened EV demand calls for meticulous planning and strategic adjustments. The impact on the distribution system might require a substantial rebuild. Nevertheless, optimised charging helps mitigate this impact despite introducing the challenge of potential emissions increase [36]. Table 2.1 summarises the articles mentioned in this section, as well as the assumptions used and their impact on the power systems.

Table 2.1: Impact of EVs on Power Systems in Different Studies

Country	Assumptions	Impact on the Power Systems
Canada [32]	EV penetration rising to 20% by 2031, corresponding to an additional demand of 2500 GWh.	With uncoordinated charging, 350 MW of new generation capacity is needed in 2031.
Germany [20]	A Monte Carlo statistical method was employed to predict changes in the load curve.	Around five GW, more power will need to be produced. That amount could grow to roughly 4% by 2050, requiring an additional capacity of about 20 GW. This study predicts that in Germany, around 7% EVs by 2030 and 40% by 2050.
Brazil [31]	The fleet will reach 17,700 EVs in 2030 and will represent 7.80% of the power demand during peak demand hours.	A growth rate of 46.18% should occur between 2025 and 2030. The forecast of energy consumption with the charge of EVs is 123.27 TWh by 2030, approximately 16.37% of the total consumption.
Maldives [36]	Two EV charging scenarios were explored: uncoordinated and optimised.	With a 30% vehicle transition to EVs by 2030, the optimised regime forecasted a 3% rise in total power system costs and a 16% surge in total generation by 2030, requiring an extra 29 MW capacity.
Italy [34]	Evaluate CO_2 emissions of the transport and electric power sector.	There is a CO_2 saving potential of approximately 30% under the assumption that 60% of EVs.

3

Enhancing EV-Grid Coexistence: Global Strategies and Their Applicability in Portugal

Contents

3.1 Simulation Framework Overview

The anticipated shift towards EVs in Portugal brings with it a transformation in user behaviour and mobility patterns. As EVs become integral to daily life, users will likely adapt their charging behaviours and travel routines. Understanding these evolving patterns is essential for optimising the integration of EVs into the energy grid. Factors such as preferred charging times, daily travel distances, and the influence of workplace charging infrastructure on commuting habits are pivotal in shaping the overall impact of EVs on Portugal's energy landscape.

The primary objective of the developed framework is to assess the impact of EVs on the energy and power systems in Portugal. In the initial phase, various EV evolution scenarios in Portugal for 2030, 2035, 2040, and 2050 were analysed, as documented in [14,22,28,37]. A computational tool detailed in this section will create EV profiles based on multiple inputs. These inputs include charger power ratings, prevalent EV models, and times of the day when EVs are charged, among other factors. The simulator's outputs will be used to formulate EV Management Strategies. These strategies aim to identify solutions to minimise the impact of EVs on Portugal's power and energy systems. This analysis is facilitated through the examination of the Load Curve Evolution.

Observing the impact of EVs on the power grid is only possible through in-depth network analysis, including Power Consumption Evolution and Power Production Evolution [14]. Integrating these inputs with the outcomes derived from the proposed management strategies makes it feasible to ascertain the potential impacts of EVs in Portugal. The overarching methodology is presented in Figure 3.1. The present work benefits from the papers mentioned in the literature using a similar methodology. Nevertheless, some important contributions can be identified, namely:

- **Improvement in EVs behaviour modelling :** A better representation of EVs behaviour has been proposed considering different aspects such as the characteristics of the EVs, the characteristics of Electric Vehicles Supply Equipment (EVSE), travel distance, the temperature and the travel conditions (in the city, highways, speed, etc).
- **EVs smart management strategies:** EVs management strategies proposed in the literature have been extended to consider different demand response programs and the coordination with renewable energy sources.
- **Evolution Scenarios for Portugal (2022-2050):** A Portuguese scenario has been developed, allowing a comprehensive evaluation of the impact of EVs on the Portuguese power system.

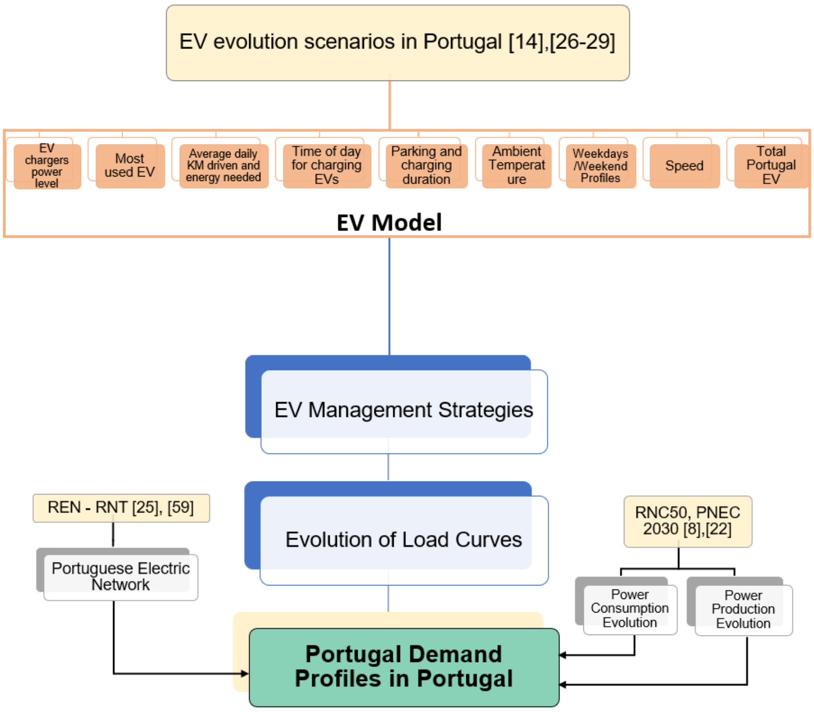


Figure 3.1: Proposed Methodological Framework (Source: Pedro Pereira)

3.2 EVs scenarios generation tool

According to [1], society, particularly utility services, should prepare for the anticipated global surge in EV adoption. While EVs offer numerous advantages, their widespread adoption poses a significant challenge to the power system, primarily due to the unpredictability nature introduced by user behaviour. New consumption peaks, overloading, voltage instability, and degradation of local equipment may occur in the electric distribution system when numerous EVs charge without coordination [9, 11].

Therefore, there is a critical need to develop tools and solutions for estimating and determining EV power demand. This estimation plays a pivotal role in defining the deployment requirements for charging stations and evaluating their impact on power systems [32]. From the power system's perspective, the variability in EV power demand, influenced by factors such as driving patterns, charging station types, trip duration, and power rating of charging stations, introduces an uncertainty that can manifest in challenges like significant voltage fluctuations throughout the day or congestion at specific points in the network [9, 13].

The simulation tool employed in this study is designed to produce daily profiles for EVs. The main purpose of the tool is to calculate not only the total energy required to meet the demand for EVs but, more importantly, to outline the daily power profile [14]. Initially, inputs encompassing trip-related aspects, EV characteristics, and user profiles are considered. These inputs are instrumental in defining the EVs profiles. Subsequently, in the second phase, the processing of these inputs unfolds to derive information concerning daily trips, types of EVs, user profiles, user-driven trips, trip durations, and associated energy needs. Here are some examples of inputs used in the simulator developed by the authors [13] and applied in this work:

- **EVs Characteristics:** This includes data information on various aspects of EVs, such as the total number of EVs, the most prevalent EV models, the usage probability, EV models, battery types, State-of-Charge (SOC), and energy consumption per kilometre.
- **User's Patterns:** Information regarding users' travel patterns, including typical trip start and end times, trip categorisation (short, medium, or long), and the average trip speed.
- **EVSE Information:** Details about EVSE profiles, including public ultrafast, public fast, public semi-fast, public slow, private ultrafast, private fast, and private slow.

Subsequently, these inputs are processed to derive insights such as daily trips, EVs types, user profiles, trip details, trip durations, and energy requirements. Real-world data specific to Portugal, such as the prevalent EV models, average trip distances, average speeds, and the abundance of Charging Station (CS)s, is integrated into the tool. This data guarantees the delevopment of dependable EV charging profiles [13, 14, 26, 38, 39]. For a more in-depth understanding of the daily profile creation simulator, refer to [13].

The proposed case studies in [13] substantiate the effectiveness of the computational implementation. These studies demonstrate that the EV profiles, when created for varying numbers of EVs, provide reliable insights into EV charging profiles and charging station usage across various simulation days, encompassing both weekdays and weekends [13]. Remarkably, the tool showcases commendable scalability, facilitating the generation of EV charging profiles for many EVs.

This approach ensures that the EV charging profiles encompass essential details, including daily trip patterns, types of EVs, user profiles, trip durations, and energy requirements. The model employs random values derived from a normal distribution and the percentage distribution of users in each profile, resulting in the creation of unique EV profiles [13]. User behaviours, encompassing driving hours, recharging locations (private or public), power usage levels, and the types of EVs and charging stations (slow, fast, ultrafast), introduce uncertainty into EV charging demand. This uncertainty, in turn, can lead to various technical challenges within energy and power systems [14]. The initial inputs related to trips, EV characteristics, and user profiles serve as foundational elements for defining the EV profiles within the simulation tool [13].

To achieve the objectives of this paper, several enhancements and adaptations were incorporated into the simulator developed by [13]. These modifications focus on three key aspects: the influence of ambient temperature on EV consumption, the consideration of daily profiles for weekdays and weekends, and an examination of the impact of speed on EV consumption. The following subsections will delve into the improvements and adaptations implemented in the simulator.

3.3 Influence of Temperature on the EV consumption

Ambient temperature plays a significant role in determining EVs energy consumption and driving range. The use of auxiliary devices, such as Air conditioning (AC) in high-temperature weather and heaters in cold weather conditions, has been observed to increase energy consumption in EVs. Cold weather conditions activate heating systems, leading to higher energy usage and reduced battery performance. Conversely, high temperatures can reduce the efficiency of cooling systems, resulting in increased energy consumption [40,41]. Laboratory tests conducted on various EV models with different battery types, using operation data from different cities in China, have shown energy consumption increases of 20% and 67% at ambient temperatures of 30ºC and -7ºC, respectively, compared to moderate temperatures (15ºC-25ºC) [42].

Several studies have investigated the relationship between ambient temperature and EV performance. Dost et al. [41] monitored a representative sample of 500 people in Germany during a field test, using 24 EVs to measure the parameters affecting energy consumption over a distance of 700,000 km. The study revealed a 60% increase in energy consumption during moderate wintry weather conditions at 10ºC, highlighting the need for more efficient heating and air conditioning units in vehicles. Liu et al. [40] conducted a study that modelled the effect of ambient temperature on EV energy consumption using Global Positioning System (GPS) trajectory data for 68 EVs in Japan over two years. The research concluded that the most economical temperature for driving is around 23ºC and observed simultaneous use of the heater and air conditioner during high-energy-consuming trips. S. Reyes et al. [43] performed experiments in Canada using a Nissan Leaf and a Mitsubishi i-MiEV to determine the sensitivity of electricity consumption to ambient temperature [43]. Comprehensive analysis of factors affecting energy consumption can be achieved by analysing big data, such as vehicle trajectory data [43]. The derived model exhibits distinct plateaus at different temperature ranges in the vehicle's range. Above approximately +20ºC, the range reaches its maximum capacity without heating or AC [43]. In contrast, at temperatures below approximately -15ºC, the range is predominantly influenced by the heating system's operation [43].

Enhancing the design and performance of these systems enables EVs to withstand temperature variations more effectively and maintain efficiency in diverse climatic conditions. A comprehensive understanding of the intricate relationship between ambient temperature and EV performance is crucial to unlocking the full potential of EVs and promoting their widespread adoption as a sustainable mode of transportation.

To investigate the impact of ambient temperature on EV consumption in Portugal, conducting on-road tests to collect vehicle data is essential. However, due to the unavailability of such tests, it becomes necessary to establish a correlation between existing empirical data from the literature and the ambient temperature conditions in Portugal. The following three studies and their corresponding correlation to Portuguese temperature conditions provide insights into this relationship. It is crucial to emphasise that the correlation between the three studies and Portugal may introduce a slight margin of error. This is because the studies were conducted through real-world tests and present a different geographical location, thus featuring distinct meteorological conditions compared to Portugal.

3.3.1 Impact of Temperature in EVs consumption - United Kingdom (UK) study

The study proposed in [44] aimed to investigate the impact of different driving and ambient conditions on the energy consumption of EVs using data obtained from real-world driving on roads in the West Midlands region of the United Kingdom (UK). The research specifically examined the effects of ambient temperature on trip characteristics such as distance, stop percentage, and average speed and their impact on energy consumption [44]. The dataset used in the study was collected from a Nissan Leaf EV equipped with a 24-kWh battery during random road operations in Birmingham, UK, from January 2016 to September 2019. EVs had the lowest energy consumption at an average speed of 55 km/h in cold temperatures ranging from 0℃ to 15℃. In moderate temperatures from 15℃ to 25℃, the lowest Specific Energy Consumption (SEC) value is achieved at 45 km/h [44]. The results indicate that SEC increases at low temperatures, with significant changes associated with auxiliary energy demand and trip characteristics, especially in cold temperatures [44].

The study provides incalculably important insights into the energy consumption patterns of EVs. The findings indicate that EVs demonstrate lower SEC for urban driving, particularly in moderate temperatures. Furthermore, the study reveals a 28% decrease in trip range for EVs operating in urban areas with temperatures ranging from 0 ℃ to 15 ℃. These results furnish practical data that can be leveraged to accurately predict EV driving ranges and explore potential solutions for reducing energy consumption across diverse ambient and driving conditions [44].

In this current analysis, two equations have been derived, where ”x” represents the ambient temperature (ºC) value, and ”y” corresponds to the value of SEC (kWh/km). Equation 3.1 reflects the actual data obtained, while equation 3.2 represents the outcomes from Real Driving Emissions (RDE) testing. The RDE testing procedure is employed by vehicle manufacturers to assess a car's emissions under similar driving conditions, excluding a laboratory setting [45]. The graphical representation of the study's results in Figure 3.2 (crafted by [44]) visually encapsulates the essential findings and trends observed during the investigation. These discoveries contribute significantly to our understanding of EV performance concerning temperature variations and urban driving conditions.

$$y = 0.00037x^2 - 0.0147x + 0.2817 \tag{3.1}$$

$$y = 0.00013x^2 - 0.00535x + 0.1903 \tag{3.2}$$

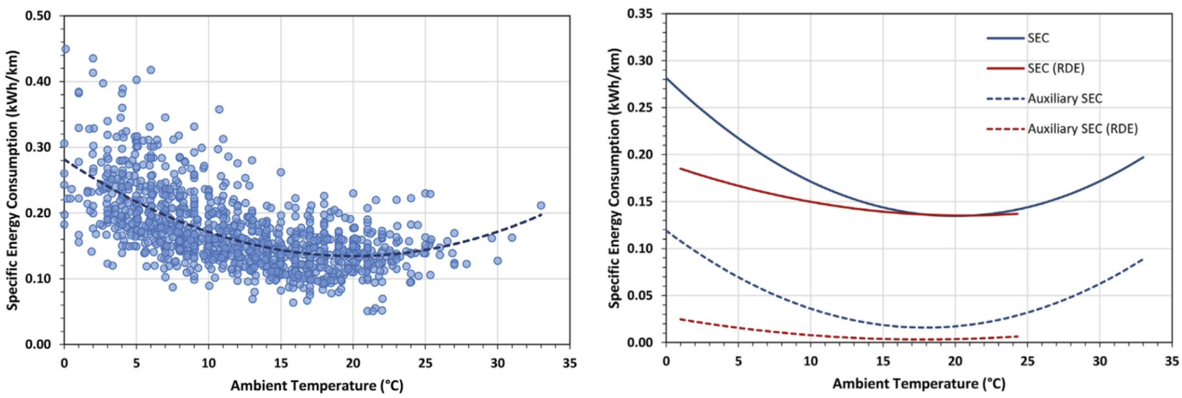


Figure 3.2: (a) Variations in EV-specific energy consumption in response to ambient temperature. (b) Analysing the variations in average EV SEC and auxiliary SEC concerning ambient temperature across all random trips and RDE sections. (Source: [44])

Based on the article mentioned above, a correlation between objective test results and Portugal's ambient temperature can be established. By using ambient temperature data at a 10-minute time scale throughout the year 2022, provided by the Portuguese Institute for Sea and Atmosphere (IPMA) [46], it is possible to correlate this data with the study's findings, as illustrated in Figure 3.3. Based on the equations obtained 3.1, 3.2 by the authors in [44] and using the ambient temperature in Portugal, it is possible to obtain the curves presented in Figure 3.3.

The blue curve was derived using the equation the study's authors obtained, employing the ambient temperature in Portugal. The yellow curve is computed using RDE tests [45], encompassing various tests in different driving situations. Compared with the original curves, a shift is observed due to the higher ambient temperature values in Portugal compared to the UK. The ambient temperature value for the curves obtained with Portugal's data, reflecting the lowest consumption, was 19.9℃ for the curve with equation 3.1 and 20.6℃ for the curve with equation 3.2. Portugal experiences a more significant influence on EV consumption at higher temperatures. While Portugal does not reach temperatures as low as those in the study for colder conditions, the study results [44] show that a decrease in temperature leads to an increase in EV consumption.

Given the impracticality of conducting these tests in Portugal, the graph may present an error. This impracticality is because the energy consumption of EVs was calculated using equations derived from road tests that considered the ambient temperature in Portugal. The ambient temperature data [46] for Portugal data was obtained from a meteorological station in the centre of Lisbon and will be used for the correlation in subsequent studies.

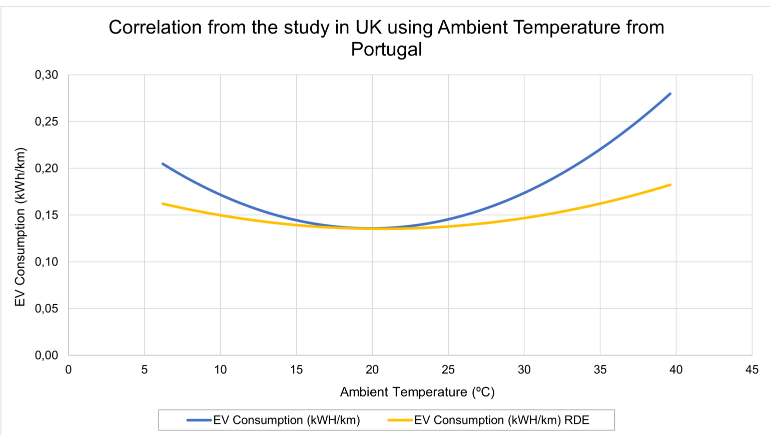


Figure 3.3: Correlation from the study in UK using Ambient Temperature from Portugal

3.3.2 Impact of Temperature in EVs consumption - Kuwait study

This article [47] presents an analysis of data collected from over 3000 EV rides in Kuwait, representing typical automobile usage. The statistical modelling used in this study examines the relationship between temperature and energy consumption. To investigate the association between the starting temperature recorded by the car at the beginning of each trip and the energy consumption, the researchers used Ordinary Least Squares (OLS) regression [47]. The data-fitted polynomial model shows that the association between starting temperature and EV consumption reaches a minimum of 130 Wh/km at 22.8ºC. The selected model indicates that, at a starting temperature of 30ºC, the vehicle's range would be reduced by 6% [47]. The reduction in the range becomes more significant with higher starting temperatures, manifesting as a 22% reduction at 40ºC and a 32% reduction at 50ºC. Contrarily, the range also diminishes at starting temperatures below 20ºC, exhibiting a 10% reduction at 15ºC and escalating to a 25% reduction at 10ºC [47]. The data demonstrate that driving an EV in the hot conditions commonly experienced in Kuwait results in significant efficiency penalties, and these conditions are frequently encountered during journeys. The decrease in range caused by increasing energy intensity at higher temperatures also has implications for the design of charging infrastructure [47].

Similar to the previous study, the mathematical equation 3.3, obtained by the authors through real tests, is represented in Figure 3.4, where "x" represents the ambient temperature, and "y" represents the energy consumption by EVs. The figure presented below (Figure 3.4) is credited to [47] and illustrates the findings from the study conducted in Kuwait.

$$y = 287 - 16x + 0.502x^2 - 0.00439x^3 \quad (3.3)$$

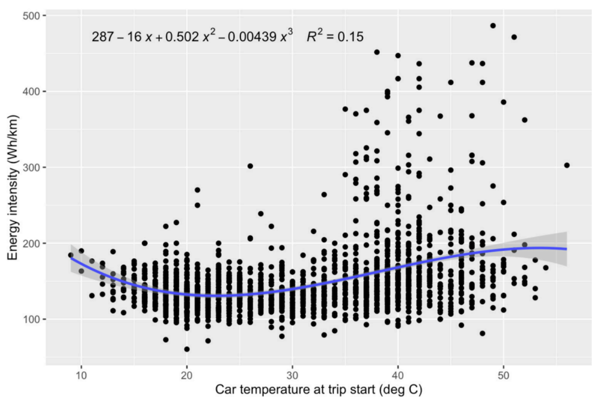


Figure 3.4: Energy intensity of trips against car temperature at start of journey (Source: [47])

As depicted in Figure 3.6, the presented curve offers valuable insights into the correlation between ambient temperature and EV energy consumption. This curve was derived using the equation provided by the authors [47] as outlined in their article. Despite the constraints on conducting tests in Portugal, it is noteworthy that the graph still imparts valuable information for comprehending the influence of ambient temperature on EV energy consumption. The curve obtained with Portugal ambient temperature data exhibits similarities to that of [47] and is similar to the findings in the UK study [44]. There is a distinguishable trend of exacerbated EV consumption at lower and higher temperatures, as illustrated in Figures 3.4 and 3.6.

The authors of the study [47] acknowledged the importance of investigating the energy consumption of EVs under different temperature conditions, as this factor plays a significant role in determining the driving range and overall performance of these vehicles.

3.3.3 Impact of Temperature in EVs consumption - China study

The study [48] aims to enhance the accuracy of estimating real-world energy consumption and driving ranges for BEVs. The results highlight significant variations in electricity consumption, travel patterns, and charging patterns based on the type of vehicle application and season. Personal vehicles have an average electricity consumption of 17.6 kWh/100 km, taxis consume 16.8 kWh/100 km, and ridesharing vehicles consume 17.1 kWh/100 km [48].

The main factor influencing electricity consumption is ambient temperature. At an average temperature of 12ºC-28ºC, the electricity consumption has a low basic statistical average of 14.9 kWh/100 km. When the temperature drops below 10 ºC, the electricity consumption increases by 2.4 kWh/100 km for every 5 ºC decrease. Conversely, when the temperature exceeds 28 ºC, the electricity consumption increases by 2.3 kWh/100 km for every 5ºC increase. Cold weather increases electricity consumption due to increased heater usage and decreased battery performance. At 10 ºC, electricity consumption is 73.4% higher than in the basin temperature range [48]. The equation 3.4 represents the formulation obtained by the authors, where, similar to previous studies, ”x” represents the ambient temperature, and ”y” represents the energy consumption of electric vehicles. Figure 3.5, authored by [48], illustrates the achieved results regarding the relationship between ambient temperature and EV consumption.

$$y = 0.000001x^3 + 0.00006x^2 - 0.0067x + 0.2581 \tag{3.4}$$

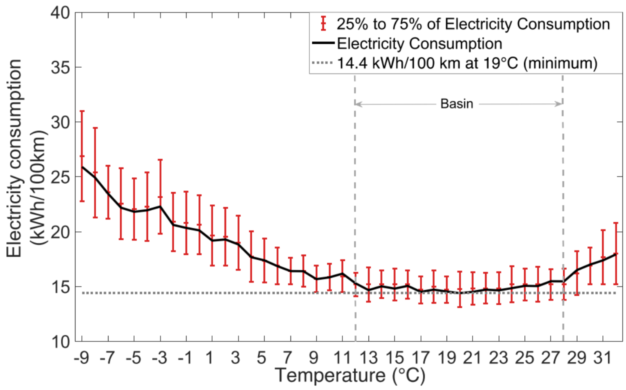


Figure 3.5: Variation in electricity consumption with ambient temperature from -10ºC to 35ºC (Source: [48]).

It's worth noting that the study's findings are based on data from a single BEVs model operating within one city, which limits generalizability. Further research is required to examine, confirm, and refine the statistical relationship between temperature and electricity consumption. Additional data, such as drivers' use of AC systems, would help uncover the underlying factors [48]. Understanding the impact of ambient temperature on BEVs range can inform technological advancements, including the development of auxiliary heating devices, and guide consumers in optimising their BEVs usage.

This study [48] examines the impact of ambient temperature and its implications for EV energy consumption under investigation. Equations obtained from road tests conducted in China and specific ambient temperature data for Portugal are used to analyse and extrapolate the collected data for use in Portugal. The resulting curve can be observed in Figure 3.6. It is possible to observe an exacerbation in EV consumption at lower temperatures, as in the study [48], where EVs were exposed to sub-zero temperatures, as evident in Figure 3.5.

3.3.4 Development of the Portuguese Curve: Correlations and Insights

As previously mentioned, based on the polynomial equations obtained in the studies [44, 47, 48] through real-world experiments, the ambient temperature in Portugal was applied to these equations, resulting in the curves showcased in Figure 3.6, which illustrates the curves obtained from the abovementioned studies. The green curve represents the average value derived from all the curves that define equation 3.5, and it is based on this equation that the energy consumption of EVs was adapted in the simulator. The curve aligns with the expected outcomes and showcases values consistent with the other curves.

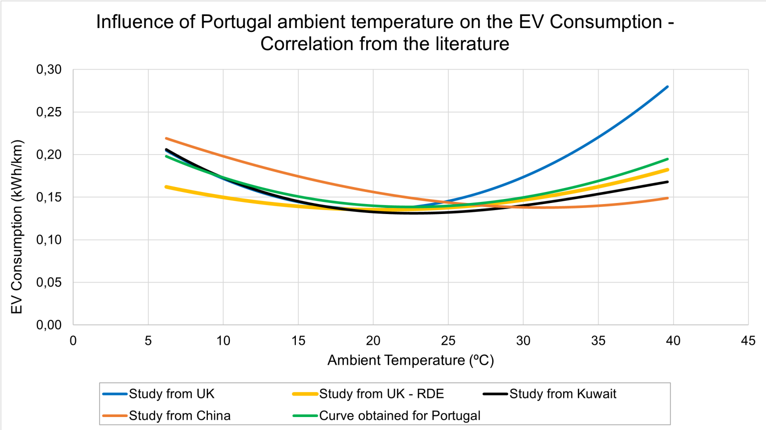


Figure 3.6: Influence of Portugal ambient temperature on the EV consumption - Correlation from the literature

It is essential to acknowledge a slight margin of error associated with these calculations is crucial, given that the studies were conducted in different countries with different atmospheric conditions. The temperature data for Portugal was sourced from the Portuguese IPMA [46], explicitly corresponding to Lisbon, the capital of Portugal, for the year 2022, with a temporal integration interval of 10 minutes. Equation 3.5 corresponds to Figure 3.6, where the "yy" axis represents EV consumption (kWh/km), and the "xx" axis corresponds to ambient temperature (ºC):

$$y = 0.0002x^2 - 0.0097x + 0.2484 \tag{3.5}$$

The curve derived from correlating the findings of these three articles [44, 47, 48], analysed earlier, reveals a potential influence of ambient temperature on EV consumption. Similar to the observations in the three articles, there is increased EV consumption at the extremes of the U-shaped curve. In other words, there is an uptick in EV consumption at low and high ambient temperatures, leading to reduced efficiency. The chosen meteorological station in Lisbon did not experience extremely low temperatures, as observed in the study conducted in China [48]. The lowest temperature recorded in 2022 at this weather station was 6.2ºC, corresponding to the highest consumption of 0.198 kWh/km based on the obtained curve. The highest recorded temperature was 39.6ºC, with consumption hovering around 0.195 kWh/km. The lowest consumption recorded, i.e., the lowest point on the curve, was 0.139 kWh/km at 22.6ºC. Consequently, EVs are more efficient at this temperature, exhibiting lower consumption.

These results suggest that ambient temperature directly impacts EV consumption, particularly at lower and higher temperatures. This reduces efficiency for EVs, leading to diminished range (km) and a need for earlier recharging than initially anticipated due to accelerated battery wear. While the correlation-derived data from the three studies will be incorporated into the simulator [13] through simulated journeys, adjusting EV consumption based on date and time, it is essential to recognise a minor limitation. As previously explained, the derived curve results from a correlation of studies conducted in a context significantly distinct from Portugal. In a future project, conducting real-world studies with EVs would be valuable to solidify the impact of ambient temperature on EV consumption in Portugal.

3.4 Influence of speed on the EV consumption

The energy consumption of EVs is influenced by a variety of factors, encompassing elements such as traffic conditions, infrastructure, environmental factors, and driving behaviour, as noted by [44]. Among these factors, one crucial determinant is the vehicle's speed. Given the dynamic nature of real-world driving scenarios, it is essential to understand the impact of speed on EVs consumption is pivotal.

As noted by [44], traffic conditions significantly influence vehicle speed and acceleration, affecting energy consumption. However, the influence of speed extends beyond mere traffic conditions. It delves into the broader spectrum of driving scenarios, including various speeds, accelerations, and distances. To enlighten this point, [49] emphasises the distinction between idealised laboratory testing and real-world driving experiences, specifically long-distance travel at high speeds, such as inter-city journeys across remote areas [49]. In the context of EVs, the difference between controlled laboratory conditions and the diverse, unpredictable conditions of real-world driving has a pronounced impact on energy consumption and, consequently, the drivable range. Unlike traditional ICE cars, EVs are more sensitive to subtle changes in parameters such as vehicle weight, auxiliary load (AC and heating), and speed [44, 49].

This section of the thesis delves into the complex relationship between speed and EVs energy consumption, with the purpose of unravelling the nuanced interplay of factors that define the drivable range in real-world scenarios. By examining existing literature and empirical analysis, this research seeks to contribute valuable insights to understanding how speed influences the overall energy efficiency and practical range of EVs.

3.4.1 Influence of speed on the EV consumption - UK study

Considering the influence of ambient temperature, the study [44] previously analysed also involved correlating trip characteristics, such as driving distance, stop time percentage, and average vehicle speed, with temperature data. The data for this analysis was obtained from real-world driving experiences of an EV over nearly four years in one of the UK's most densely populated metropolitan regions. To help with real-time data processing a dedicated monitoring software was employed. The collected data underwent meticulous further processing and filtering using MATLAB software. This allowed for the calculation of distance and duration for each trip based on recorded time intervals and vehicle speeds [44].

In accordance with the RDE regulation, the datasets for each trip were categorised into three sections based on vehicle speeds: urban (below or equal to 60 km/h), rural (between 60 km/h and 90 km/h), and motorway (above 90 km/h) [44]. Significantly, the efficiency of the electric motors diminishes under low-speed and low-power conditions, increasing energy consumption during urban driving scenarios [44]. Contrarily, when the vehicle travels at higher speeds for rural and motorway operations, elevated air resistance decreases efficiency, demanding more power to overcome aerodynamic drag and consequently increasing specific energy consumption [44].

Figure 3.7 from [44] depicts the correlation between SEC and the average vehicle speed at temperature ranges of 0ºC - 15ºC and 15ºC - 25ºC in urban, rural, and motorway operations within RDE sections [44]. Usually, the energy consumption is higher in the lower temperature range regardless of average speed. Within the temperature range of 15ºC to 25ºC, the minimum SEC is observed at an average speed of 45 km/h, while in the range of 0ºC to 15ºC, the minimum SEC occurs at 55 km/h, both in urban operation [44].

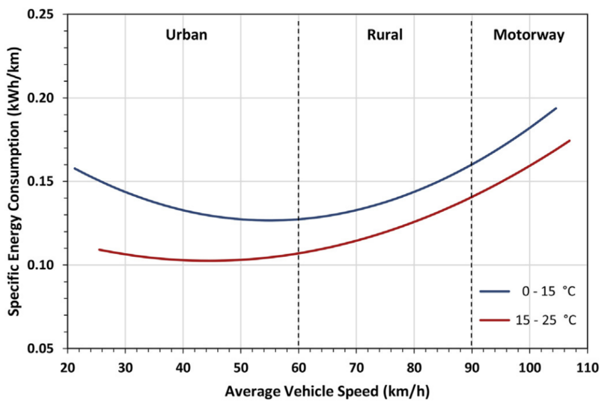


Figure 3.7: Variation of specific energy consumption with average vehicle speed (Source: [44]

The significant increase in SEC at lower speeds in the low-temperature range is attributed to the dominant factor of energy consumed by auxiliary systems. Additionally, as previously discussed, trips with lower average vehicle speeds tend to have a more significant stop time percentage, contributing to an increase in SEC. Optimal efficiency is achieved within a speed range of 45 km/h to 56 km/h. In the context of rural and motorway operations, SEC increases with the rise in average vehicle speed in both low and moderate temperature ranges [44]. The EV demonstrates minimal energy consumption at an average speed of 55 km/h under cold conditions (0ºC to 15ºC), and for moderate temperatures (15ºC to 25ºC), the lowest SEC is recorded at 45 km/h. These results underscore the EV's efficient operation in urban regions, advocating its deployment in metropolitan areas. This comprehensive analysis provides valuable insights into the dynamic relationship between trip characteristics, environmental conditions, and EV energy consumption [44].

3.4.2 Influence of speed on the EV consumption - China study

This study [50] conducted an in-depth analysis of real-world driving data collected from fifty-five electric taxis in Beijing (China) over an extensive period of nearly four years. The research focused on understanding the factors influencing energy consumption, categorised into vehicle-related, environment-related, and driver-related aspects. In response to these influences' complex and non-linear nature, the study introduced a novel machine learning-based energy consumption prediction framework [50]. The developed framework, incorporating driving condition prediction, demonstrated its effectiveness in accurately predicting energy consumption. The manufacturer's nominal Energy Consumption Rate (ECRb) was 0.145 kWh/km [50].

Remarkably, the study by Zhang et al. (2020) [50] emphasised the intricate relationship between energy consumption in EVs and various influencing factors, such as velocity, acceleration profiles, and auxiliary usage. The researchers explicitly acknowledged the challenge of addressing these interconnected influences through a purely theoretical approach, recognising the importance of real-world driving data in capturing the complexity of EV energy consumption dynamics [50].

Figure 3.8 from [50] visually depicts the nuanced Energy Consumption Rate (ECRb) pattern concerning velocity and acceleration. This graph highlights the significance of considering real-world driving conditions and dynamic driving profiles. For instance, under constant acceleration, as represented in Figure 3.8, energy consumption in EVs is notably higher during acceleration phases and remains elevated after reaching speeds beyond 60 km/h [50]. Interestingly, the graph reveals that the most energy-efficient range for EVs, considering constant acceleration, lies between 20 km/h and 60 km/h. Within this speed range, EVs exhibit lower energy consumption, showcasing a critical insight into optimal driving conditions for energy efficiency.

This observation aligns with the broader understanding that maintaining a moderate and consistent speed range contributes to lower energy consumption in EVs. However, the intricate interplay of velocity and acceleration, as illustrated in the figure, emphasises the need for a comprehensive understanding of these dynamics to formulate effective strategies for enhancing EV energy efficiency [50]. Further research and analysis in this direction are crucial for refining predictive models and developing practical recommendations for EV drivers to optimise energy use across diverse driving conditions. In conclusion, the study [50] provided valuable insights into the complex dynamics of energy consumption in electric taxis, offering practical implications for predicting and optimising energy usage in real-world driving scenarios.

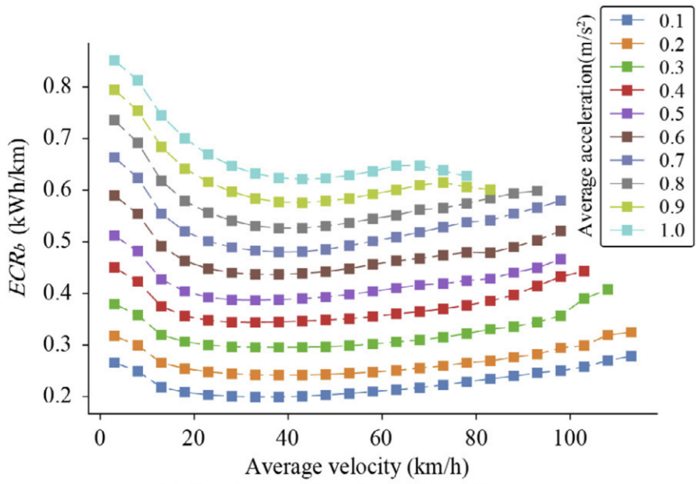


Figure 3.8: Relationship of velocity and acceleration with ECRb (Source: [50])

3.4.3 Evaluation of Speed Impact on EV Consumption: In this Study

Throughout this subsection, a compelling body of evidence has been presented emphasizing the direct impact of speed and acceleration on the energy consumption of EVs, similar to the precedent set by the influence of temperature. The studies by Yazan et al. [44] and Zhang et al. [50] have conducted extensive analyses based on real-world driving data gathered over several years. Both investigations affirm a pronounced surge in EV consumption during acceleration (up to 20 km/h), reaching a stable phase at moderate speeds (30 km/h - 60 km/h), where the EV attains its peak efficiency. However, consumption rises as speeds escalate beyond 60 km/h.

These findings assume a pivotal role in the simulator used in this thesis. Due to the impracticality of conducting real-world tests and the correlation of the abovementioned studies, reference values from [51] were utilised. Taking the Tesla Model 3 as an example, with a 57.5 kWh battery, the manufacturer specifies a rated consumption of 14.4 kWh/km (144 Wh/km). In [51], three types of journeys—"City," "Combined," and "Highway"—correspond to speeds used in the simulator: 60 km/h, 80 km/h, and 100 km/h, By using estimates developed by [51], it is observed that for temperatures below -10ºC, the consumptions are as follows:

- City - Cold Weather = 15.3 kWh/km
- Combined - Cold Weather = 17.2 kWh/km
- Highway - Cold Weather = 19.8 kWh/km

For temperatures above -10ºC, the values from [51] are:

- City - Mild Weather = 9.7 kWh/km
- Combined - Mild Weather = 12.1 kWh/km
- Highway - Mild Weather = 14.9 kWh/km

Thus, for the exact vehicle, considering different speeds, consumption can vary between 9.7 kWh/km and 19.8 kWh/km. Values for all brands and models used in the simulator [13] were sourced from estimates calculated by [51].

Similar to the adaptation of the influence of temperature on EV consumption, integrating this adjustment into the simulator [13] is crucial as it accounts for the impact of speed during simulated journeys. In summary, if the ambient temperature at the start of each trip is below -10ºC, the simulator uses the data from [51]: City - Cold Weather, Combined - Cold Weather, Highway - Cold Weather, for each simulated brand and model. For temperatures above -10ºC, the values from [51] are City - Mild Weather, Combined - Mild Weather, and Highway - Mild Weather. The speeds used in the simulator correspond to 60 km/h, 80 km/h, and 100 km/h, assigned to City, Combined, and Highway, respectively. By incorporating temperature and speed into EV consumption, the simulator now considers these parameters, making the results more reflective of real-world scenarios.

3.5 Understanding driving behaviour of EV owners

EV drivers' habits play a crucial role in the study and forecasting of electric charging patterns, thereby contributing to the electrical grid's stability. The increasing uptake of EVs may present challenges in optimising the energy system's structure and efficiency. However, comprehensively characterising the diverse driving patterns of individual users proves complex. Therefore, certain assumptions from existing literature will be considered in this section. Consequently, researching EV consumption patterns remains a constant concern in the implementation and maintenance of EV charging infrastructures.

3.5.1 Understanding driving behaviour of EV owners - United States (US) study

Between November 2004 and April 2006, 429 vehicles were analysed in this study [52] using the GPS to examine vehicle usage patterns and investigate seasonal variations. The Puget Sound Regional Council, based in the United States, conducted the data and tests [53]. A total of 127,500 trips were considered throughout the study.

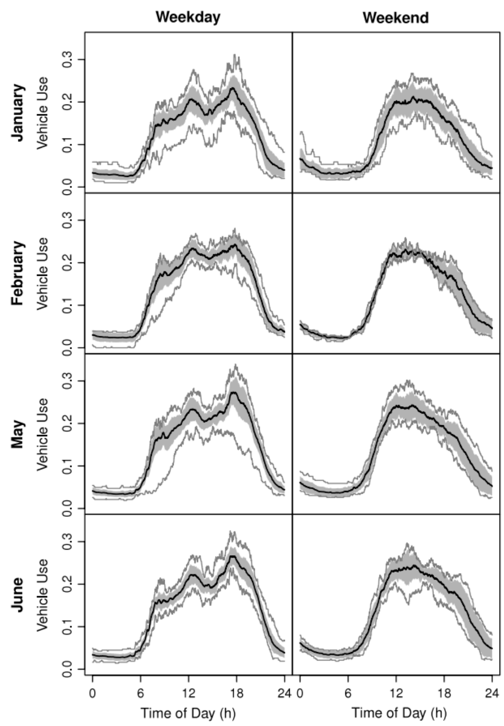


Figure 3.9: Trends in-vehicle use on weekdays (left panel) or weekends (right panel) appear similar across months, suggesting that changes in weather or daylight hours are not significant factors. (Source: [52])

This study examined vehicle usage patterns across various time frames, including daily, weekly, and monthly variations. Based on 3.9 extracted from [52], it is evident that weekdays exhibit a distinctive usage pattern. They experience a rapid increase in vehicle usage during the early morning hours, likely correlated with the morning commute to work, followed by a gradual rise, peaking around midday. Weekdays were categorised into three distinct periods—early morning surge, midday peak, and afternoon peak [52]. In contrast, weekends display a different pattern, with a single peak in vehicle usage occurring around midday and lower activity in the morning, gradually declining throughout the afternoon and evening hours [52].

Significantly, the findings do not demonstrate significant deviations in the timing of peaks across different months, indicating that weekday usage times are primarily influenced by work or schedule requirements, resulting in consistent patterns throughout the year. The authors posit that seasonal variations may be attributed to climatic conditions, particularly in regions facing severe winters. Limited daylight and adverse weather conditions during the winter months could limit mobility, resulting in decreased overall vehicle usage and a potential reduction in the hours with heightened vehicle activity [52].

3.5.2 Understanding driving behaviour of EV owners - Ireland study

The study conducted in Ireland [54] delves into the charging and trip-making behaviour of an EV fleet, focusing on understanding trip event characteristics, consumer preferences, and charging patterns. Valuable insights were obtained by analysing accurate data collected through data loggers installed in EVs. The fleet consisted of Mitsubishi i-MiEV, four-seater vehicles. Data collection spanned three years, from March 2011 to February 2014, during which 15 EVs completed 44,411 trips and recorded 5838 charge events. The data was meticulously collected using data logging equipment, accessing information from each vehicle's control area network (CAN) bus and GPS tracking for location and time data [54].

The analysis revealed interesting patterns in the start and finish times of journeys. As depicted in Figure 3.10 from [54], weekdays exhibited three distinct peaks during the day (07:00-10:00, 13:00-15:00, and 17:00-19:00), reflecting the morning commute to work and other routine activities. Weekends. However, weekends showed a single peak around midday, indicating different driving behaviours during leisure time. The average daily distance travelled for all scenarios was 32.17 km, with a median value of 26.39 km and a maximum reported daily trip distance of 426.47 km. [54].

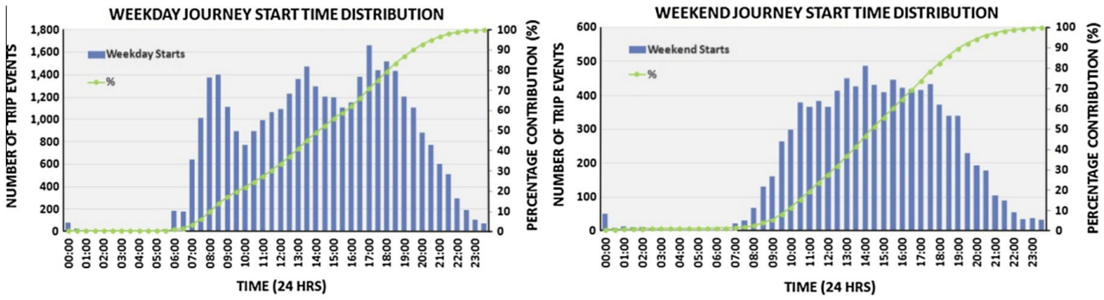


Figure 3.10: Distributions of weekday and weekend travel start times for an aggregated dataset (Source: [54])

When compared with the previous study, it becomes evident that the usage patterns of EVs by users are similar concerning the start of trips on both weekdays and weekends. The weekdays exhibit peaks in the morning, mid-day, and late day, which are influenced by work routines. On weekends, morning trips start later, resulting in a more uniform curve throughout the day. Additionally, the study assessed the charging patterns of EV users, identifying a substantial early morning peak in charge start times in the early morning, followed by consistent charging throughout the day. The results also suggest potential variations in energy demand between weekdays and weekends. Overall, the analysis provided essential insights into EV users' behaviour and charging practices, which are pivotal for optimising the integration of EVs into the energy grid and facilitating sustainable mobility in Ireland.

3.5.3 Understanding driving behaviour of EV owners - China study

The previously examined study [50], previously analysed, delves into real-world driving data collected from fifty-five electric taxis in Beijing, with the objective of understanding factors influencing energy consumption in EVs. The researchers propose an innovative machine learning-based framework that predicts energy usage while considering driving conditions. The data used in this research is gathered from the National Monitoring and Management. The electric taxis utilised in the study are BAIC EV200 models equipped with 30.4 kWh battery packs and a nominal driving range of 200 km [50]. The analysis uncovers significant peaks in traffic indexes during morning and evening rush hours, surpassing non-rush hour levels, as observed in Figure 3.11 from [50]. On weekdays, the highest energy consumption occurs during morning rush hours, followed by evening rush hours, as illustrated in Figure 3.12 from [50]. During weekends or holidays, rush hour timings change, but the consistently higher consumption remains evident. Furthermore, the prediction framework can support EV driver services and optimise city transportation, offering insights into remaining range prediction, intelligent navigation, and efficient charging infrastructure operation [50].

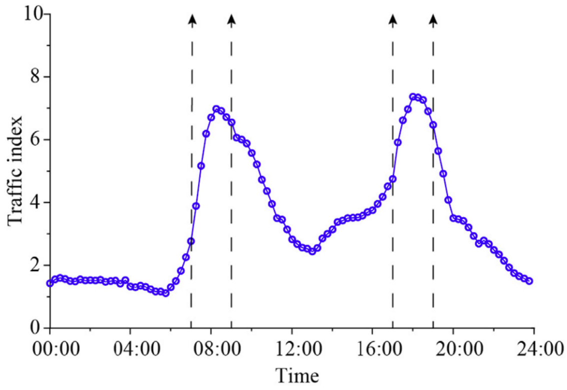


Figure 3.11: The weekday traffic index distribution in Beijing (Source: [50])

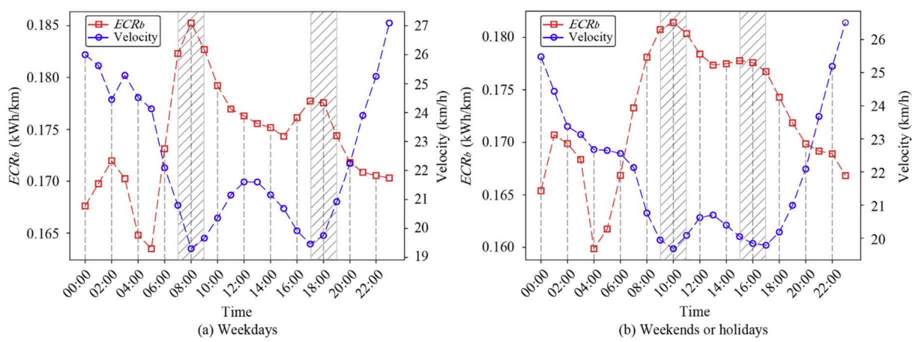


Figure 3.12: The hourly ECRb and EV velocity statistics for weekdays (a) and weekends (or holidays) (b) (Source: [50])

3.5.4 Adaptation of Driving Patterns for Portugal: User Behaviour and Distance Modelling in the Simulator

Examining previous articles has revealed distinctive usage patterns among EV users during weekdays compared to weekends. On weekdays, EVs experience increased usage in the morning, noon, and late afternoon periods. These patterns are closely associated with users' work schedules, involving commuting to work, lunch breaks, and returning home. Weekday trips tend to cover shorter distances. In contrast, weekends exhibit different habits, with trips occurring later and remaining relatively constant throughout the day until the return home. Significantly, spaces covered on weekends are generally bigger compared to weekdays. In the simulator proposed by Guzman et al. [13], five user profiles were initially considered, consisting of four residential and one work-related profile. For this thesis, three additional profiles were introduced, totalling eight (five residential and three work-related). Additionally, eight profiles tailored for weekends were incorporated. The simulator was adjusted to distinguish between weekdays and weekends, ensuring correct profile assignments.

The calculation of trip distances used two probability distributions: gamma and normal. Specifically, for defining trips during the day, the tool processed information on the number of EVs and average trip distances using a gamma distribution function [13, 55]. In adapting the simulator [13] for the findings of this thesis, the gamma distribution, initially used for all days, was retained with the same parameters and used for weekdays. However, for weekends, the normal distribution was employed. This decision was influenced by a study conducted in China [50] (analysed previously), aligning with the habits of EV users during weekends, where there is a higher tendency to cover longer distances in their trips. Figure 3.13 visually represents the normal distribution utilised for weekends.

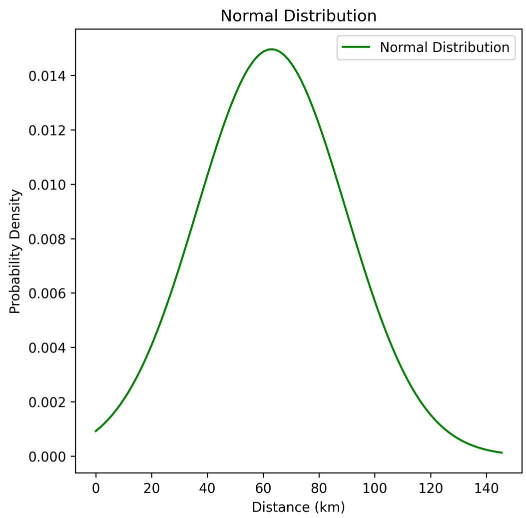


Figure 3.13: Normal Distribution used in the Simulator

It is essential to emphasise that the user behaviour profiles used in this study were designed as hypothetical scenarios. Various complex influence user behaviour, rendering creating a synthetic model that precisely replicates real-world behaviour a challenging endeavour. To address this complexity, the study adopted an approach that simplifies assumptions aligning with existing literature.

In the context of modelling in Portugal, the data was based on results found in the existing literature. For weekdays, the original gamma distribution developed by [13] was retained, with the distribution curve having a leftward skew, reflecting a higher probability of shorter trips. A normal distribution was assumed for weekends, with the distribution curve having a rightward skew, reflecting a higher probability of longer-distance trips. This distribution was based on the findings of [56], a study conducted in the Azores (an archipelago of Portugal) to analyse regional control strategies. The average distance travelled by EVs displays a significant variance across different reports in the literature. While one article suggests a daily average of 46 km in Portugal [38], alternative sources indicate a spectrum of daily distances ranging from 7 to 28 km [57]. Additionally, survey data from a separate study suggests an average daily coverage of 25 km for EVs [57]. These discrepancies highlight the significant influence of individual user profiles and mobility requirements on the reported figures.

In response to this information, the model underwent calibration to address the observed disparities in the literature. The gamma distribution exhibited a slight left-skew, emphasising a more uniform distribution for shorter distances. For weekends, an assumption of heightened activity levels was made, recognising the potential deviation from reality in specific cases. Once again, the literature provided a reference point to illustrate these asymmetries and the values for probability distribution were assumed and calibrated as simplifying approximations.

3.6 Daily EV Profiles

The adjustments made in the simulator used in this study are exemplified, Tables 3.1 and 3.2 showcasing tan examples of daily profiles. Thirty-two profiles were randomly selected and used in the simulation. Table 3.1 provides an overview of the journeys undertaken on January 26, displaying the departure and arrival times of the EVs, the distance covered, the total energy consumption for each trip, and the simulated travel speed. Table 3.2 furnishes information about charging sessions at CS for the EVs mentioned in Table 3.1 after their respective journeys. Details such as the start and end times of charging, CS power, and charging power remained constant, with no fluctuations, along with the total energy consumption during charging. These data represent a small sample of the simulated 1000 EVs, providing a comprehensive insight into the daily profile of these EVs and the data to be explored in the subsequent chapters.

Table 3.1: EV - Trip Data

Profile	EV Model	Start Time	End Time	Length (km)	Consumption (kWh)	Speed (km/h)
Residential1, T:Short	Audi Q4 e-tron (55 kWh)	08:30	08:34	4.50	0.76	60
Residential1, T:Short	BMW 530e (70.2 kWh)	08:30	08:34	4.49	0.72	60
Residential1, T:Short	Renault Zoe (52 kWh)	18:51	18:55	4.47	0.76	60
Residential1, T:Short	Hyundai Kauai (74 kWh)	17:30	17:34	4.44	0.85	60
Residential2, T:Medium	Hyundai Kauai (74 kWh)	04:16	04:37	29.07	5.58	80
Residential2, T:Medium	Tesla Model 3 (95 kWh)	05:34	05:54	28.01	5.04	80
Residential2, T:Medium	Jaguar I-Pace (85 kWh)	17:37	17:58	28.87	6.35	80
Residential2, T:Medium	Tesla Model 3 (95 kWh)	17:46	18:08	29.16	5.25	80
Residential3, T:Short	Peugeot e-Expert (68 kWh)	08:06	08:07	1.93	0.50	60
Residential3, T:Short	Tesla Model 3 (95 kWh)	09:09	09:10	1.88	0.34	60
Residential3, T:Short	Tesla Model 3 (95 kWh)	18:06	18:07	1.89	0.34	60
Residential3, T:Short	Audi Q4 e-tron (55 kWh)	18:50	18:51	1.87	0.32	60
Residential4, T:Long	Jaguar I-Pace (85 kWh)	07:48	08:32	74.62	16.42	100
Residential4, T:Long	Tesla Model 3 (95 kWh)	08:26	09:17	85.17	15.33	100
Residential4, T:Long	Hyundai Kauai (74 kWh)	14:50	15:32	71.35	13.70	100
Residential4, T:Long	Renault Zoe (52 kWh)	17:07	17:59	86.53	14.71	100
Residential5, T:Short	Nissan Leaf (59 kWh)	09:57	09:57	0.46	0.08	60
Residential5, T:Short	Nissan Leaf (59 kWh)	19:08	19:08	0.48	0.08	60
Residential5, T:Short	Nissan Leaf (59 kWh)	19:42	19:42	0.46	0.08	60
Residential5, T:Short	Mercedes E300 (13.5 kWh)	19:59	19:59	0.42	0.76	60
Work1, T:Long	Volvo XC40 (78 kWh)	07:14	07:28	19.09	3.36	80
Work1, T:Long	Hyundai Kauai (74 kWh)	08:23	08:37	19.14	3.67	80
Work1, T:Long	Volvo XC40 (78 kWh)	15:01	15:15	18.65	3.28	80
Work1, T:Long	Hyundai Kauai (74 kWh)	17:43	17:57	19.42	3.73	80
Work2, T:Medium	Jaguar I-Pace (85 kWh)	07:52	08:02	10.10	2.22	60
Work2, T:Medium	Audi Q4 e-tron (55 kWh)	08:08	08:18	9.99	1.70	60
Work2, T:Medium	Peugeot e-Expert (68 kWh)	18:47	18:56	9.94	2.58	60
Work2, T:Medium	Tesla Model 3 (95 kWh)	19:07	19:17	9.96	1.79	60
Work3, T:Medium	Volkswagen ID.3 (58 kWh)	08:46	08:54	8.31	1.29	60
Work3, T:Medium	Audi Q4 e-tron (55 kWh)	09:32	09:40	8.35	1.42	60
Work3, T:Medium	Peugeot e-Expert (68 kWh)	19:06	19:14	8.36	2.17	60
Work3, T:Medium	Jaguar I-Pace (85 kWh)	19:27	19:35	8.53	1.88	60

Table 3.2: Charging Station Data

EV Model	CS Start Time	CS End Time	Station Power (kW)	CS Energy Used (kWh)
Audi Q4 e-tron (55 kWh)	08:34	08:40	22	2.06
BMW 530e (70.2 kWh)	08:34	08:39	22	1.96
Renault Zoe (52 kWh)	18:55	19:12	7.2	2.09
Hyundai Kauai (74 kWh)	17:34	17:53	7.2	2.33
Hyundai Kauai (74 kWh)	04:37	05:18	22	14.89
Tesla Model 3 (95 kWh)	05:54	06:33	22	14.03
Jaguar I-Pace (85 kWh)	17:58	20:23	7.2	17.36
Tesla Model 3 (95 kWh)	18:08	22:06	3.6	14.30
Peugeot e-Expert (68 kWh)	08:07	08:11	22	1.39
Tesla Model 3 (95 kWh)	09:10	09:13	22	0.91
Tesla Model 3 (95 kWh)	18:07	18:23	3.6	0.93
Audi Q4 e-tron (55 kWh)	18:51	18:59	7.2	0.88
Jaguar I-Pace (85 kWh)	08:32	10:33	22	44.23
Tesla Model 3 (95 kWh)	09:17	11:07	22	40.21
Hyundai Kauai (74 kWh)	15:32	17:23	22	36.81
Renault Zoe (52 kWh)	17:59	23:17	7.2	38.19
Nissan Leaf (59 kWh)	09:57	09:58	22	0.21
Nissan Leaf (59 kWh)	19:08	19:12	3.6	0.22
Nissan Leaf (59 kWh)	19:42	19:44	7.2	0.21
Mercedes E300 (13.5 kWh)	19:59	19:59	22	0.21
Volvo XC40 (78 kWh)	07:28	07:51	22	8.59
Hyundai Kauai (74 kWh)	08:37	09:02	22	9.35
Volvo XC40 (78 kWh)	15:15	15:20	50	4.51
Hyundai Kauai (74 kWh)	17:57	18:15	22	6.61
Jaguar I-Pace (85 kWh)	08:02	08:18	22	5.96
Audi Q4 e-tron (55 kWh)	08:18	08:30	22	4.63
Peugeot e-Expert (68 kWh)	18:56	19:55	7.2	7.09
Tesla Model 3 (95 kWh)	19:17	20:39	3.6	4.93
Volkswagen ID.3 (58 kWh)	08:54	09:03	22	3.53
Audi Q4 e-tron (55 kWh)	09:40	09:51	22	3.90
Peugeot e-Expert (68 kWh)	19:14	20:04	7.2	5.99
Jaguar I-Pace (85 kWh)	19:35	21:01	3.6	5.16

4

A Comprehensive Exploration of Portugal's Energy Grid and Electric Vehicle Landscape (2022-2050)

Contents

The current chapter is divided into two sections, each contributing to comprehensively exploring this subject matter. The first section delves deep into Portugal's current energy grid status, evaluating its present capacity, infrastructure, and alignment concerning the integration of EVs. Moreover, it provides an insightful glimpse into the future of energy generation and demand trends, delivering valuable insights into Portugal's continually evolving energy landscape, projecting up to the year 2050. The second section focuses on consolidating data regarding the existing population of EVs in operation within Portugal. Additionally, this section extends its scope by projecting the future growth trajectories and composition of EVs in Portugal, with these forward-looking forecasts spanning until 2050. This investigation provides an essential foundation for evaluating potential factors and challenges in integrating EVs into Portugal's unique energy ecosystem.

4.1 Portugal's Power Grid: Present and Future Perspectives

As stated in the introduction of this chapter, this section aims to scrutinise the current state of the grid in Portugal and assess the predictions for energy demand and generation capacity up to 2050. The analyses will focus on 2030, 2035, 2040, and 2050. These projections will be based on literature articles and the Portuguese government's objectives for decarbonising Portugal. For the year 2035, the data was obtained using a linear interpolation function. This analysis for 2035 is relevant as the EU aims to ban the sale of combustion engine vehicles by 2035 and achieve decarbonisation across the entire European continent by 2050 [5, 17]. The years under examination align with the EU's objectives for the coming years.

In 2022, the reference year for this thesis, Portugal's total energy consumption reached 50.4 TWh, representing a 1.81% increase compared to the preceding year, 2021, during which the consumption was 49.5 TWh [25,58]. This value encompasses the net production injected into the Portuguese electricity system (Portuguese Electricity System (RESP)) from renewable and non-renewable power sources alongside the international trade balance. This calculation also factors in the energy consumed for hydroelectric pumping. Table 4.1 provides an overview of monthly energy consumption for 2021 and 2022 in Portugal. Indeed, the year-to-year consumption showed minimal variance, with a marginal increase of 0.9 GWh in 2022 compared to 2021. The maximum synchronous load peak of consumption was recorded at 8,595 MW and occurred on January 26th at 7:30 PM. This figure is approximately 1,293 MW lower than the historical maximum peak in 2021, 9 888 MW (on January 12th, 2021) [25, 58].

Table 4.1: Portugal Energy Consumption - 2021 and 2022 (Source: [25, 58])

Month	2021	2022
January	4984	4642
February	3996	4115
March	4069	4459
April	3743	4005
May	3921	4051
June	3843	3977
July	4130	4420
August	3961	4030
September	4011	3997
October	4026	4058
November	4286	4187
December	4501	4424
Total in MWh	49471	50365
Total in GWh	49.5	50.4

According to REN's data, as of the end of 2022, the total installed production capacity reached 20,675 MW, with 16,187 MW of renewable origin and 4,489 MW of non-renewable. The installed capacity in 2022 saw an increase of 1,518 MW compared to 2021, resulting in a total connected capacity of 20,675 MW by the end of the year. Renewable energy production supplied 49% of the total consumption in 2022, marking a decrease from the previous year, primarily due to unfavourable hydrological conditions. Despite some precipitation in December 2022, it was an arid year, with mainland Portugal experiencing its highest-ever recorded average temperature [25]. Over recent years, renewable production has typically contributed to about 60% of mainland national consumption under average meteorological conditions [25]. Additionally, one can visually assess the distribution of energy production in Portugal for 2021 and 2022 through graphical representations in Figure 4.1.

Hydroelectric and wind energy production represented approximately 13% and 25% of consumption, respectively. In the renewable energy production component, biomass, including classic and cogeneration plants, maintained a 7% consumption share, as in the previous year. Solar energy contributed 5%, consistently achieving new annual share records. In non-renewable production, gas-fired power plants, including combined cycle and cogeneration, accounted for 32% of consumption. Similar to 2021, Portugal's national electricity system continued to have a trend of being a net importer in 2022, with an annual balance equivalent to about 18% of consumption. Therefore, with a consumption of 50.4 TWh, the production injected into RESP was 44.0 TWh, resulting in a net import balance of 9.3 TWh, while pumping operations consumed 2.9 TWh [25, 58].

Regarding power in Portugal, Figures 4.2 and 4.3 present a comprehensive overview of power generation and demand throughout the year 2022 and on January 26, 2022 (the day with the highest consumption in the reference year), respectively [25]. It is noteworthy to emphasise the pivotal role of

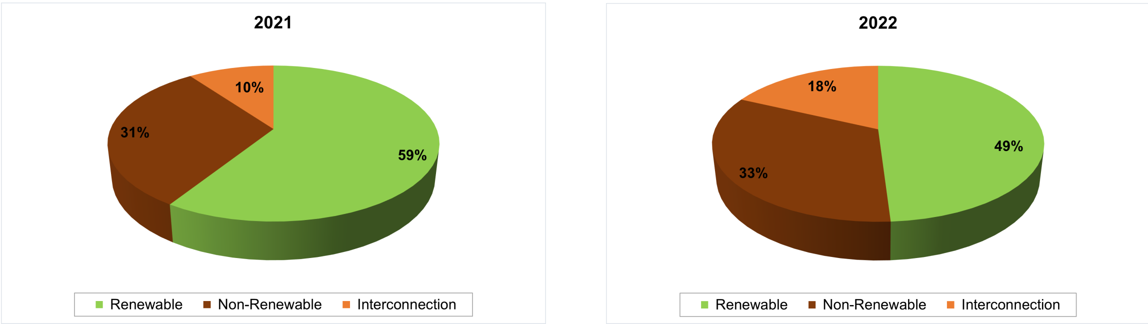


Figure 4.1: Comparison of Portugal Energy Generation in 2021 and 2022 (Source: [25, 58])

renewable energy sources within the Portuguese electrical system and the concurrent dependence on non-renewable energy sources and energy imports to fulfil Portugal's consumption needs. The overarching goal entails a substantial increase in the utilisation of renewable energy sources, thereby mitigating reliance on non-renewable sources and reducing energy imports from neighbouring countries. In the next paragraph, this study will delve into energy consumption and installed power forecasts for Portugal over the forthcoming years, shedding light on the trajectory towards a more sustainable and resilient energy landscape.

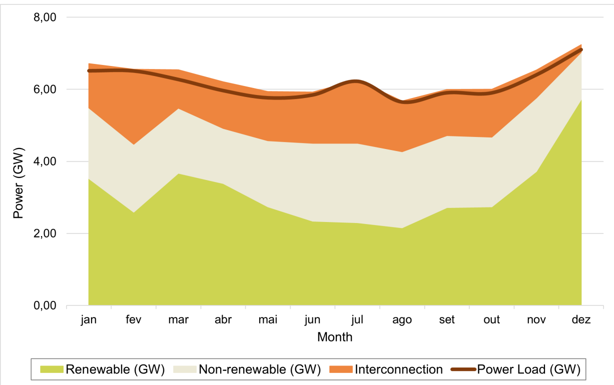


Figure 4.2: Portugal's Monthly Peak Generation and Demand Curve - 2022

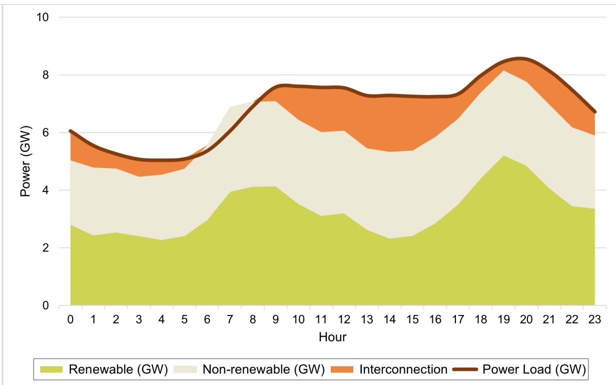


Figure 4.3: Portugal's Hourly Peak Generation and Demand Curve - January 26, 2022

Based on study [14], which leveraged references [22, 24, 25] to develop forecasts for Portugal's installed power and energy consumption in the upcoming years (2030, 2040, 2050), resorting to 2021 as a reference, it was possible to build upon this work and adapt it to the objectives of this thesis. The forecasts in the mentioned study were obtained through direct communication with the authors, who relied on the data shown in Tables 3 ("Evolution of final energy consumption, up to 2050") and 8 ("Evolution of final energy consumption and energy intensity in the transport sector") of the RNC2050, found on pages 28 and 38, respectively [22].

For power capacity forecasts, the predictions were based on Figure 11 from page 32 in [22]. At the same time, for energy consumption, the total consumption data was drawn from Table 3 of the RNC50, with electricity consumption related to EVs subtracted, as detailed in Table 8 [22]. Nevertheless, the energy consumption forecasts presented here need to consider the consumption of EVs, which will be addressed in a subsequent section of this chapter.

The reference year for this thesis is 2022, which calls for the recalculation of the forecasts for 2030, as energy consumption in 2022 exceeded the previously projected figure for 2030. The growth rate was calculated annually between 2022 and 2040. This annual growth was then added to the previous value for 2030, resulting in a new projection. As for 2035, the results were determined using a mathematical formula involving linear interpolation.

Figures 4.4 and 4.5 present the foreseen outcomes for installed power and energy consumption in Portugal up to 2050, data was provided by the authors of [14]. These graphical representations offer an expansive view of Portugal's evolving energy landscape over the next several decades. In the graph illustrating power capacity trends over time, it is noteworthy to emphasise the significant reduction in Portugal's reliance on non-renewable energy sources. This transition towards cleaner and more sustainable energy aligns seamlessly with Portugal's ambitious objectives for 2050, including substantial reductions in carbon emissions and enhanced energy efficiency. These forecasts underscore Portugal's commitment to a greener and more environmentally conscious future, serving as a valuable resource for policymakers, energy experts, and stakeholders shaping the nation's energy strategy.

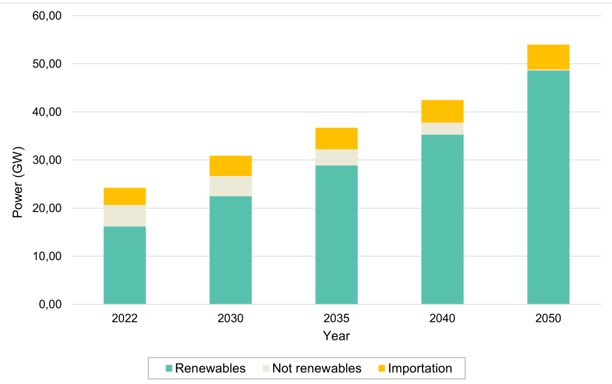


Figure 4.4: Forecast Power Generation in Portugal from 2022 to 2050

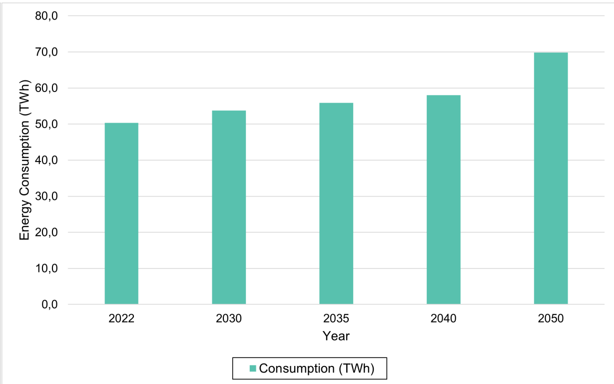


Figure 4.5: Forecast Energy Consumption in Portugal from 2022 to 2050

Figure 4.6 illustrates the forecast for daily consumption on January 26th (the reference day for this study, based on Portugal's highest consumption day in 2022) for 2030, 2035, 2040, and 2050, considering no EVs. The curves were derived as follows: The consumption values for January 26th were used as reference values, extracted from [59]. A consistent profile was assumed across the simulation years, considering the expected increase in energy consumption as outlined in [22]. For energy consumption, total consumption data was extracted from Table 3 of RNC50 [22], with electricity consumption related to EVs subtracted, as detailed in Table 8 [22]. The values chosen in the tables were the highest and converted from Petajoule (PJ) to Terawatt (TW).

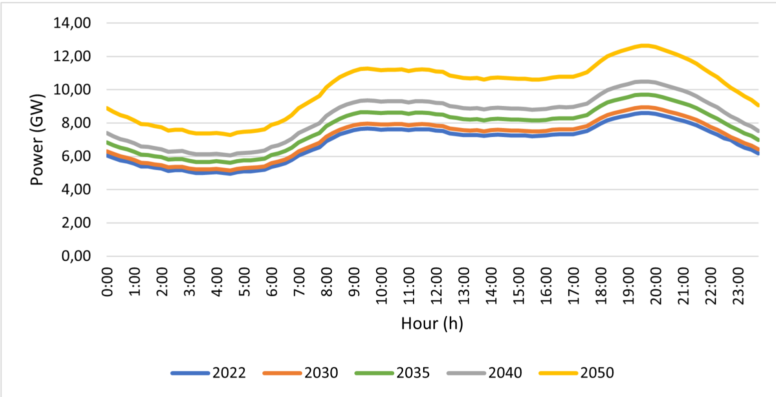


Figure 4.6: Projections for Portugal's Daily Consumption on January 26th in the Coming Years - No EVs

4.2 EV Landscape in Portugal: Current Status and Future Projections (2022-2050)

Upon analysing the current data regarding the electrical grid in Portugal and forecasts for the upcoming years, this section will delve into an analysis of EVs figures for the near future. The transport sector and the electricity production system are pivotal in national emissions, contributing to approximately 25% of the total emissions. Over the past decades, the transport sector has exhibited the most substantial growth in terms of emissions. This sector encompasses various modes of transportation, including road, rail, maritime, and aviation, further categorised into passenger and freight transportation [22].

Within these categories, road transportation accounts for an overwhelming 96% of emissions in the transport sector, while railways, domestic aviation, and maritime activities contribute with merely 4%, individual automobile use, for instance, is responsible for a significant 60% of total emissions within road transportation. The introduction of electrification, sourced from renewable energy, which extends across all final consumption sectors, can expedite the transition from ICE to EVs. This transition anticipates that electricity will represent approximately 70% of the total energy consumption in the transport sector by 2050. Such a shift will bolster a more sustainable and environmentally friendly transition [22].

Based on the data provided by the RNC2050 study [22], it is evident that there is a clear commitment towards the decarbonisation of the transportation sector. Projections for EVs in Portugal are nothing short of ambitious, as highlighted graphically in Figure 4.7. The year 2022 concluded with 81,026 EVs in the country, a figure obtained via email correspondence from the Portuguese Institute for Mobility and Transport (IMT) and cross-referencing in [27].

An academic study from the Institute of Economics and Management at the University of Lisbon (ISEG), on behalf of the Associação Automóvel de Portugal (ACAP), has envisioned three potential scenarios for 2025. These scenarios encompass a low estimate of 126,723 EVs, a moderate projection of 150,873 EVs, and an optimistic scenario of 201,323 units in Portugal. Details of this study were obtained through email correspondence with the authors, and a related news article is accessible at [37]. For subsequent years, data has been sourced from the EV4EU project's report [14], found explicitly on page 24. It is important to note that the figures for 2035 were derived through linear interpolation, maintaining the integrity of the dataset.

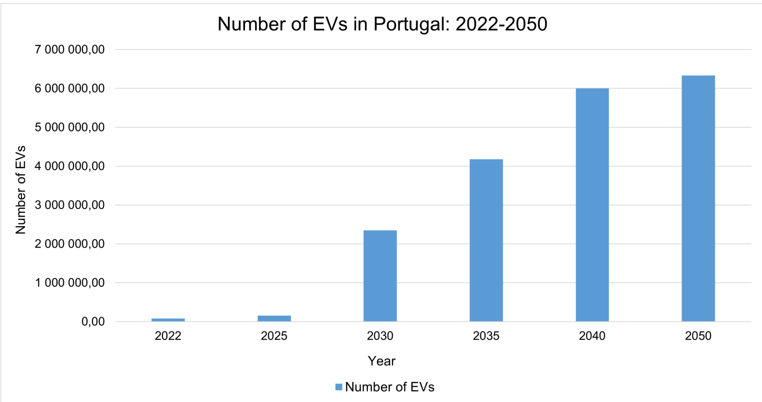


Figure 4.7: Number of EVs in Portugal: 2022-2050, Graphic representation

With all the meticulously gathered data and the applied modifications in the simulator created by [13], as elaborated upon in Chapter 3, a comprehensive simulation was conducted for 1000 EVs for one year (specifically, 2022). This rigorous simulation considered a range of charging station types, encompassing public ultrafast, public fast, public semi-fast, and public slow chargers, each with its distinct charging capacity, as thoughtfully presented in Table 4.2. It is important to note that a constant charging power was assumed throughout the charging process, ensuring the precision of the results. As detailed in Table 4.3, the computed energy consumption for these 1000 EVs amounted to 4.15 GW, which translates to 0.004 TWh over the entire year.

Establishing a resilient foundation, the figure facilitates accurate projections of future energy demands. It plays a crucial role as a pivotal reference point to facilitate computational processing within the simulation tool. Each year's annual energy consumption was calculated by extrapolating this result to the projected number of EVs anticipated for the upcoming years. This method streamlines the estimation process and ensures that our projections align with the evolving landscape of EVs adoption and charging infrastructure.

Table 4.2: Charging Station Types and Power (kW)

Charging Station Type	Charging Identification	Charging Power (kW)
Public Stations	Public Ultrafast	150
	Public Fast	50
	Public Semi-fast	22
	Public Slow	7.2
Private Stations	Private Fast	50
	Private Semi-fast	22
Residential	Residential Semi-fast	22
	Residential Slow (Type 1)	7.2
	Residential Slow (Type 2)	3.6

Table 4.3: Number of EVs and Energy Consumption

Year	Number of EVs	Energy (GWh)	Energy (TWh)
-	1,000	4.15	0.004
2022	81,026	336.23	0.34
2025	150,873	626.08	0.63
2030	2,350,000	9,751.83	9.75
2035	4,175,000	17,325.07	17.33
2040	6,000,000	24,898.30	24.90
2050	6,330,000	26,267.71	26.27

The influence across 2035 exhibits remarkable consistency, manifesting disparities of 34.38% in energy consumption and 43.27% in additional power relative to the benchmark year 2022. However, it is important to underscore that these graphical depictions must incorporate the anticipated progression of energy consumption and installed capacity in Portugal for the coming years. As a result, a comprehensive analysis of the impact of EVs within this extensive time frame (1 year) may offer a somewhat limited perspective of their influence on the Portuguese electrical grid.

For a more comprehensive examination of the impact of EVs on the Portuguese electrical system, the focus will shift to the worst consumption day of the year: January 26, 2022. Similar to and through the same method as Figure 4.6, Figure 4.8 was developed using projections for the upcoming years revised in [22]. This approach will enable a more profound understanding of the impact and offer insights into potential strategies for mitigating these effects.

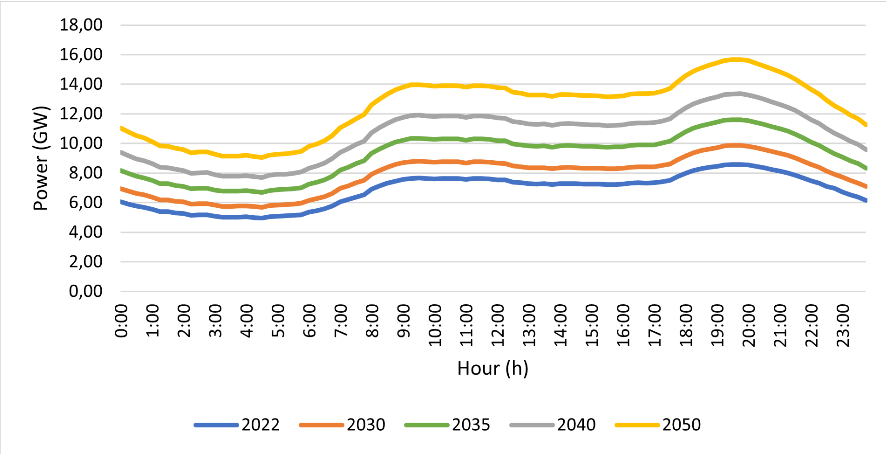


Figure 4.8: Projections for Portugal's Daily Consumption on January 26th in the Coming Years - With EVs

5

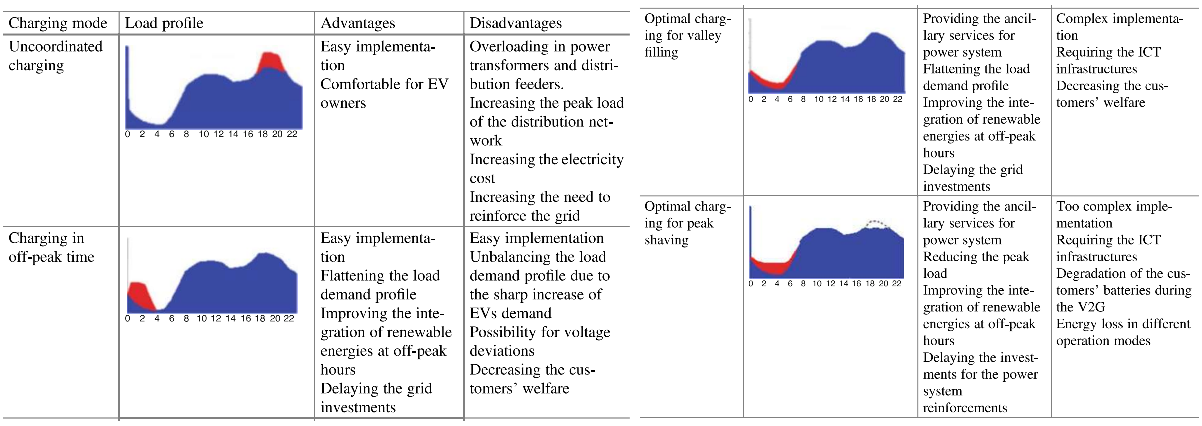
EVs Management Strategies

Contents

As outlined in Chapter 2, the existing body of literature provides a wealth of strategies designed to harmonise the integration of EVs into power grids and energy systems, thereby alleviating their impact. This chapter pivots its focus towards examining these strategies and their implications within the unique context of Portugal. Firstly, lays the groundwork for the comparative analysis of global strategies to facilitate the coexistence of EVs and power grids. Each strategy undergoes an assessment, considering its adaptability, efficacy, and potential impact, explicitly focusing on the unique circumstances present within Portugal. The second section forms the summary of this chapter. This section unveils insights into the most effective and tailored approaches for EV incorporation by scrutinising their real-world applicability and outcomes in Portuguese.

5.1 Introduction of EVs Management Strategies

According to [3], innovative charging techniques have the potential to reduce the grid reinforcement costs to between 40% and 90%, depending on the network's conditions and the country in which it is implemented. The implementation of smart EVs charging requires communication among all infrastructure components must communicate with different components and stockholders, including users and grid operators [18]. Consumers cannot be expected to deal with highly detailed signals or manage several levels of energy markets on their own. Network operators can perform this function by contracting individual customers to supply flexibility services and managing a pool of flexibility providers to optimise revenues and benefits for both consumers and the system [21]. Figure 5.1 (Source: [18], [60–62]) summarises some EV charging methods as well as the advantages and disadvantages of each.



Charging mode	Load profile	Advantages	Disadvantages
Uncoordinated charging		Easy implementation Comfortable for EV owners	Overloading in power transformers and distribution feeders. Increasing the peak load of the distribution network Increasing the electricity cost Increasing the need to reinforce the grid
Charging in off-peak time		Easy implementation Flattening the load demand profile Improving the integration of renewable energies at off-peak hours Delaying the grid investments	Easy implementation Unbalancing the load demand profile due to the sharp increase of EVs demand Possibility for voltage deviations Decreasing the customers' welfare
Optimal charging for valley filling		Providing the ancillary services for power system Flattening the load demand profile Improving the integration of renewable energies at off-peak hours Delaying the grid investments	Complex implementation Requiring the ICT infrastructures Decreasing the customers' welfare
Optimal charging for peak shaving		Providing the ancillary services for power system Reducing the peak load Improving the integration of renewable energies at off-peak hours Delaying the investments for the power system reinforcements	Too complex implementation Requiring the ICT infrastructures Degradation of the customers' batteries during the V2G Energy loss in different operation modes

Figure 5.1: Advantages and disadvantages of different charging approaches (Source: [18], [60–62])

This project aims to implement a practical simulation framework that analyses the impact of EVs on energy and power systems in Portugal. As previously discussed, large-scale EV charging can create problems in the power quality and security of the national grid, especially when it comes to uncontrolled charging in hours of higher energy demand by consumers. As alluded to earlier, the mass adoption of EVs results in a simultaneous surge in energy consumption, potentially leading to several intricate challenges for the power system. These challenges encompass issues such as grid congestion, power lines and transformers overload, and voltage and frequency fluctuations, among other technical concerns [20, 31, 32, 36].

Given these significant developments, it has become critical to formulate comprehensive strategies for evaluating the extensive impact of this impending EV adoption on energy consumption and the energy system as a whole. These strategies aim to serve a dual purpose. First, they aim to facilitate intelligent EV management systems that guarantee the reliability and resilience of the power grid. Second, they strive to capitalise on green energy sources to bolster electric mobility, consequently substantially reducing CO2 emissions [12, 63–65]. The development and implementation of these strategies are grounded in the insights drawn from the simulator delineated in Chapter 3 [13]. The simulator is a valuable tool for evaluating the potential mitigation of the impact of EVs and identifying viable strategies for adoption within the Portuguese context.

The evaluation process demanded a comprehensive array of data. Initially, it was essential to deeply understand daily EV usage patterns, encompassing various factors such as travel requirements, energy demands, and charging power requisites (referred in Chapter 3). Subsequently, access to data related to energy consumption, production, and grid interconnections became indispensable (Section 4.1). This section outlines the data requirements and delves into a detailed examination of various EV management strategies in the subsequent subsections. As mentioned in the concluding section of the previous chapter, the analysis is focused on January 26th, 2022, a date recognised for having the highest electricity demand in Portugal that year, often referred to as the ”worst day.” At approximately 8:00 PM, Portugal experienced its peak consumption of 8.55 GW, a figure lower than that of 2021 (9.84 GW). During this peak hour, renewable sources contributed 56.84% (4.86 GW) of the energy production, non-renewable sources accounted for 34.04% (2.91 GW), and interconnections contributed 9.12% (0.78 GW) [25, 58, 59]. Figure 5.2 from [59] provides an overview of the energy demand and renewable energy generation curves, which will be instrumental in forthcoming strategies.

These consumption and generation profiles have subsequently been projected for 2030, 2035, 2040, and 2050. These projections are based on the percentage changes in consumption in Portugal, sourced from [14]. It is important to underscore that the daily profiles will remain consistent with those documented in [14]. The daily usage patterns of EVs closely align with the profiles delineated in [14]. Various

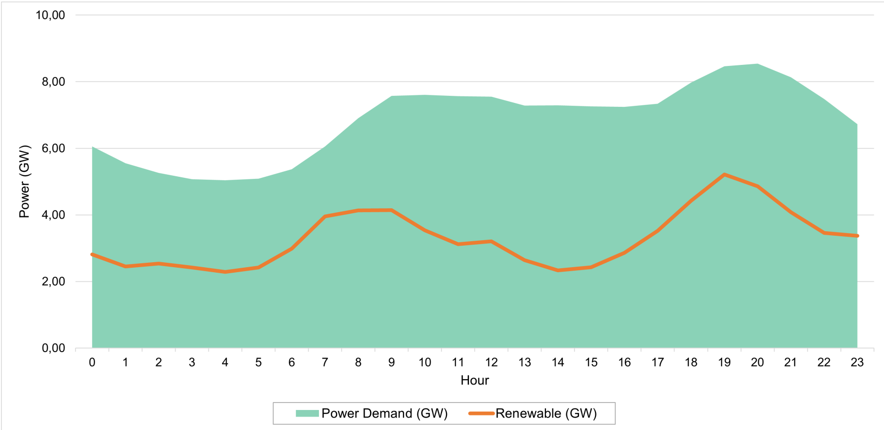


Figure 5.2: Portugal's Power Demand and Renewable Generation - January 26th, 2022 (Adapted from [59])

driver profile scenarios consider a range of trip types (short, medium, and long), as formulated in the simulator by [13] and mentioned in the Tables 3.1 and 3.2 from Chapter 3.

5.1.1 Business as Usual Strategy (BaU)

In the Business as Usual Strategy (BaU) strategy, EV owners can charge their vehicles without restrictions or supervision, filling their EV batteries to maximum capacity as soon as they park at home. While the BaU approach offers several advantages, such as its straightforward implementation and convenience for EV owners, it also has notable drawbacks. The potential overloading of power transformers and congestion in the lines is a significant concern in this context. Such overloading can strain the distribution network, increasing electricity costs and the need for grid reinforcement measures. Essentially, the BaU strategy allows uncontrolled and unrestricted EV charging, offering users convenience to users but potentially straining the power infrastructure and increasing costs associated with electricity distribution and grid maintenance [14, 18, 32]

As depicted in Figures 5.3 and 5.4, a noticeable pattern emerges, characterised by two distinct peaks in global energy consumption. In the context of the year 2035, these peaks manifest at 9 AM and 7 PM, registering values of 24.34 GW and 19.24 GW, respectively. Fast forward to the year 2050, and these peaks escalate further, reaching 35.22 GW at 9 AM and 27.28 GW at 7 PM. The morning peak can be ascribed to EV users arriving at their workplaces, typically necessitating a charge for their vehicles upon arrival. Conversely, the evening peak corresponds to these users returning home following their workday, often coinciding with the demand for EV charging.

In 2035, it is anticipated that EV adoption will substantially increase with a projected fleet of 4,175,000 EVs in Portugal. This figure surges even higher to 6,330,000 EVs by 2050, reflecting a considerable growth from the 81,026 EVs in the national automotive landscape in 2022. The morning and evening peaks observed in both years are noticeably influenced by different charging patterns associated with workplace charging (where users charge their vehicles at their workplace) and residential charging profiles (users charging their EVs at home). These peaks are attributed to the high charging activity volume during the morning and evening hours, coinciding with heightened energy demand for other services, excluding EVs. It is important to emphasise that the simulation involved 1000 EVs, as detailed in Chapter 4, and the obtained results were scaled to align with the projected EV numbers for each respective year (refer to Figure 4.7 in the preceding chapter).

Tables 5.1 and 5.2 summarise the assumptions used in the simulation. These tables present the morning and evening peak hours, the number of EVs charging during the respective peak hours, the average power (P(kW)) of each charging session, the average duration of each charging session (Charging Duration (hh:mm:ss)), the peak consumption reached by the EVs (i.e., the maximum value achieved by the charging sessions, excluding grid consumption, denoted as EVs Peak (GW)), and the overall peak consumption, which encompasses both EV and grid consumption (Global Peak (GW)).

Table 5.1: EV Charging Statistics in 2035

Hour	**Number of EVs**	**P(kW)**	**Charging Duration**	**EVs Peak (GW)**	**Global Peak (GW)**
9 AM	475,950	22	00:14:49	14.11	24.34
7 PM	926,850	7.58	00:35:47	7.81	19.24

Table 5.2: EV Charging Statistics in 2050

Hour	**Number of EVs**	**P(kW)**	**Charging Duration**	**EVs Peak (GW)**	**Global Peak (GW)**
9 AM	721,620	22	00:14:49	21.40	35.21
7 PM	1,405,260	7.58	00:35:47	11.84	27.28

These trends underscore the significance of managing EV charging during these peak periods to mitigate potential grid strain and excessive electricity costs. Furthermore, aligning the optimisation of EV charging with these consumption patterns can alleviate the need for extensive grid reinforcement, offering a more sustainable and economically viable approach. This realignment of charging behaviour in response to daily routines presents a pragmatic strategy to harmonise the growing EV landscape with the broader demands of the electricity grid.

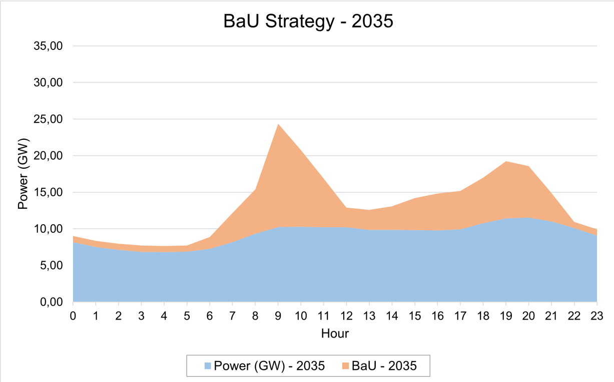


Figure 5.3: BaU Strategy - 2035

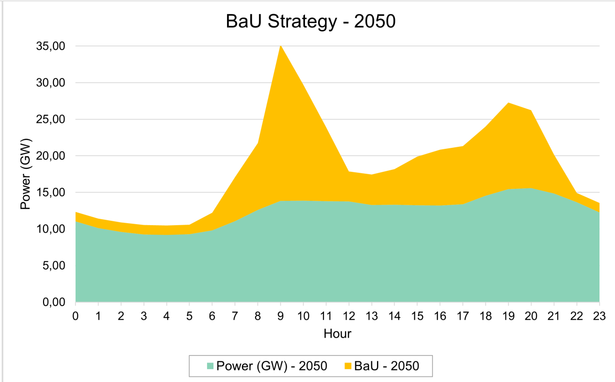


Figure 5.4: BaU Strategy - 2050

5.1.2 Delay Charging Strategy (DL)

The Delayed Charging Strategy (DL) strategy aims to shift the charging of EVs to off-peak hours by delaying it for a minimum of four hours after the vehicle's return home. This strategy primarily mitigates peak electricity demand by encouraging EV owners to schedule charging sessions during periods of lower demand, typically at night [18, 32].

A series of simulations were conducted using the simulator to evaluate the impact of the DL strategy. These simulations replicated typical travel patterns but introduced a 4-hour delay in the charging process for the residential profiles. The results for the years 2035 and 2050 are presented in Figures 5.5 and 5.6, respectively. Detailed graphs for other years of the study are provided in the appendix. A distinctive pattern emerges after examining these figures: two distinct peaks in energy demand materialise, specifically at 9 AM and midnight. In the context of the year 2035, these peaks exhibit global consumption values of 24.34 GW and 16.89 GW, respectively. Fast forward to 2050, and we witness these peaks amplifying, with global consumption surging to 35.22 GW at 9 AM and 24.10 GW at midnight.

Implementing the Delayed Charging strategy strategically positions EV charging sessions in a manner that distinctly deviates from these peak-demand hours. This innovative approach strategically avoids conducting EV charging when the power grid experiences its zenith in energy consumption. Instead, it orchestrates these charging sessions to predominantly occur during nighttime hours when overall energy consumption significantly diminishes.

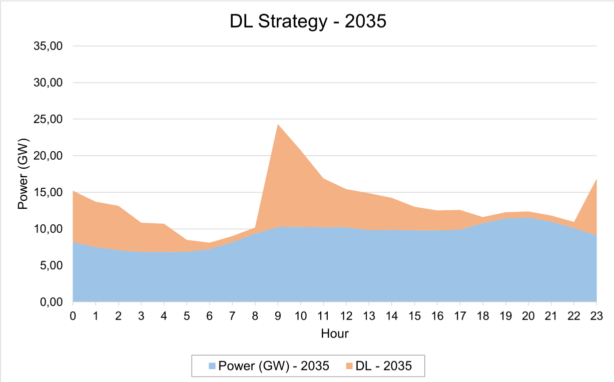


Figure 5.5: DL Strategy - 2035

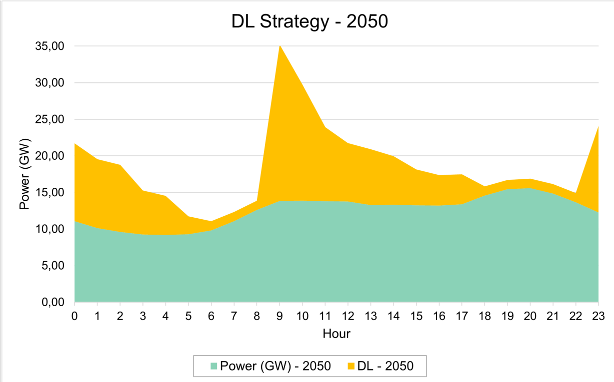


Figure 5.6: DL Strategy - 2050

5.1.3 Differentiate Delayed Charging Strategy (DDL)

The DL strategy shifts the peak to the late afternoon, aligning with users arriving at their residences, using a 4-hour delay. This shift creates a new peak at midnight, which can potentially cause problems in the grid and some discomfort to users since their vehicles will only be charged 4 hours after their arrival home. As a response, a Differentiate Delayed Charging Strategy (DDL) has been devised. DDL bears a resemblance to the DL strategy previously described, with the distinction that 20% of EVs undergo no delay, another 20% experience a 1-hour delay, a further 20% encounter a 2-hour delay, followed by 20% with a 3-hour delay, and the remaining 20% with a 4-hour delay. Table 5.3 succinctly presents the distribution of these delay periods applied to EV charging sessions. According to the data from [66], in Europe, it is projected that by 2030, roughly 54% of EVs will primarily use private home charging stations, while an additional 46% will make use of private workplace charging stations. These proportions are anticipated to remain consistent in scenarios projected for 2035, 2040, and 2050.

Table 5.3: Percentage of EVs and Time of Delay (for DDL Strategy)

Percentage of EVs	Time of Delay
20%	No Delay
20%	1h
20%	2h
20%	3h
20%	4h

The results depicted in Figures 5.7 and 5.8 show significant improvements compared to the initial DL strategy. These visual representations reveal a substantial decrease in peak energy demand for the midnight peak and a more balanced distribution of energy consumption throughout the day. This strategic realignment takes advantage of lower-demand hours while mitigating the strain on high-demand periods. A noticeable peak occurs around 9 AM, followed by one at midnight. The first peak, peaking at 24.34

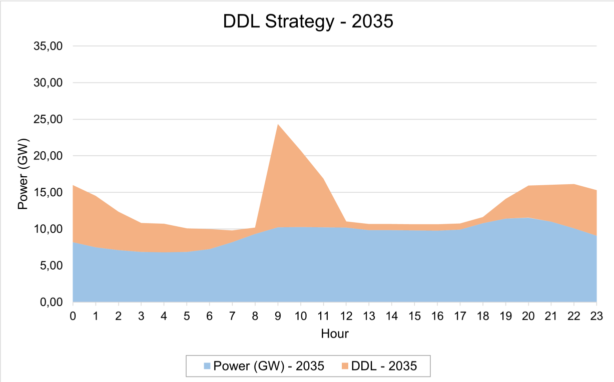


Figure 5.7: DDL Strategy - 2035

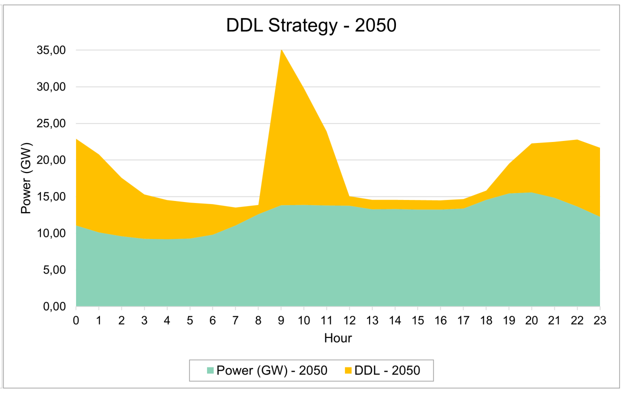


Figure 5.8: DDL Strategy - 2050

GW in 2035 and 35.22 GW in 2050, indicates that charging during this timeframe has a more substantial impact due to increasing energy demand as people return workplace during this period. In contrast, the midnight peak, reaching 15.99 GW in 2035 and 22.89 GW in 2050, corresponds to the late hours when energy demand is at its lowest ebb. The charts for the remaining years are attached in the appendix.

5.1.4 Double Differentiate Delayed Charging Strategy (DDDL)

The DDL strategy outperforms the DL strategy, providing enhanced benefits for EV users. It provides more convenience by postponing charging within the 1h-4h window. Users are randomly selected for the delay, ensuring a rotation in the assignment. However, a notable drawback of the DDL strategy is its inability to address morning peaks caused by workplace charging, focusing solely on residential profiles. Examining the results of the DDL strategy reveals that the 9 AM peak persists.

The introduction of the Double Differentiate Delayed Charging Strategy (DDDL) aims to reduce the morning peak caused by users charging their vehicles at the workplace. Therefore, the following delays were applied to workplace charging sessions: 25% of EVs experience no delay, 25% of EVs experience a 30-minute delay, 25% of EVs experience a 60-minute delay, and the remaining 25% experience a 120-minute delay. Table 5.4 summarises the distribution of these delay periods applied to the EV charging sessions at the workplace.

The results illustrated in Figures 5.9 and 5.10 show significant improvements compared to both the initial DL strategy and DDL strategy. These visual representations reveal a substantial decrease in peak energy demand for the midnight peak apex and a more even distribution of energy consumption

Table 5.4: Percentage of EVs and Time of Delay (for DDDL Strategy)

Percentage of EVs	Time of Delay
25%	No Delay
25%	30 min
25%	60 min
25%	120 min

throughout the day. This strategic realignment effectively benefits lower-demand hours while mitigating the strain on high-demand periods. A peak is noticeable around 9 AM, followed by one at midnight. The first peak occurs at 17.29 GW in 2035 and 24.57 GW in 2050. Regarding the DDL strategy, there was a decrease of 7.05 GW for 2035 and 10.64 GW for 2050 in the overall peak consumption. In contrast, the midnight peak, reaching 15.99 GW in 2035 and escalating to 22.89 GW in 2050, corresponds to the late hours when energy demand is at its lowest. These values remained the same as in the previous DDL strategy. The charts for the remaining years are attached in the appendix.

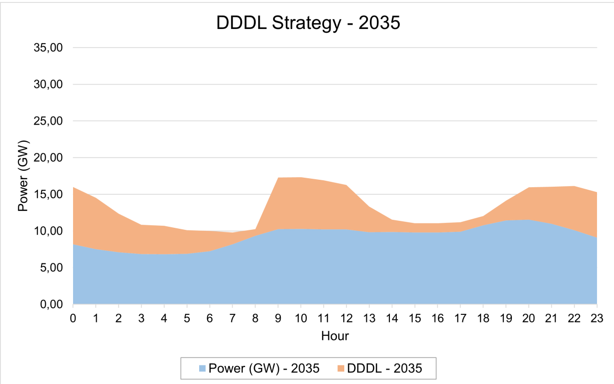


Figure 5.9: DDDL Strategy - 2035

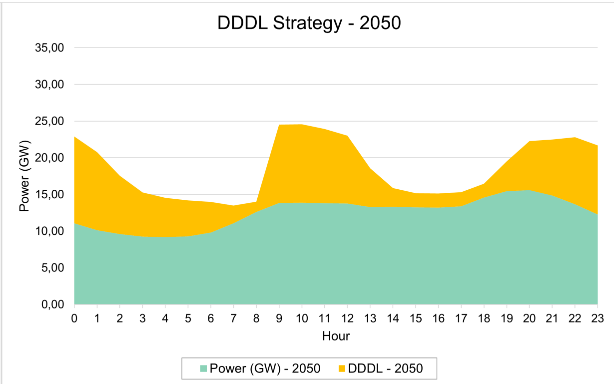


Figure 5.10: DDDL Strategy - 2050

5.1.5 Time-of-use Strategy (ToU)

The Time-of-Use (ToU) demand response program establishes dynamic energy prices that vary throughout the day such as tri-hourly and bi-hourly rate structures. Within the ToU strategy, users are motivated to charge their EV batteries when energy prices are at their lowest. Implementing ToU tariffs significantly encourages EVs users to charge their vehicles during reduced power prices. ToU systems are providing to be an effective approach for reducing peak electricity demand and mitigating substantial capacity-related costs linked with the growing adoption of EVs, especially within distribution, transmission, and power generation [14,67,68]. This simulation specifically used the tri-hourly option was utilised, aligning with Portugal's legal winter-time schedule:

- Off-Peak ("Vazio" in Portuguese): 22:00 - 08:00
- Standard ("Cheias" in Portuguese): 08:00 - 08:30; 10:30 - 18:00; 20:30 - 22:00
- Peak ("Ponta" in Portuguese): 08:30 - 10:30; 18:00 - 20:30

These timetables can be found at [69]. In this context, "off-peak" represents the day when energy costs are lowest, "standard" corresponds to a moderate pricing range, and "peak" represents the time-frame with the highest energy prices due to increased demand.

In Figure 5.11, the implementation of the ToU strategy showcases a favourable impact on the Portuguese energy system, reducing the overall peak demand compared to the BaU strategy. Prominently, the same peak occurs at 9 AM, reaching 24.34 GW. Another significant surge in energy consumption is noted at 10 PM, reaching 17.91 GW, aligning with the start of the "off-peak" tariff period for a typical winter schedule in Portugal, as shown in [69].

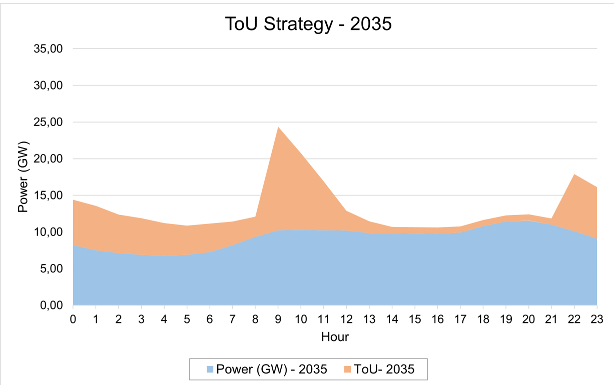


Figure 5.11: ToU Strategy - 2035

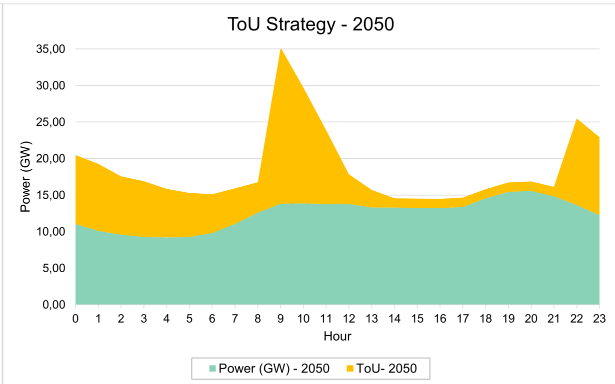


Figure 5.12: ToU Strategy - 2050

Figure 5.12 depicts a similar trend for the 2050 scenario, where implementing ToU pricing reduces the overall peak demand. Similar to the 2050 scenario, a noticeable peak occurs at 9 AM, reaching 35.22 GW. Another significant apex in energy consumption is recorded at 10 PM, amounting to 25.48 GW. Once more, this peak aligns with the beginning of the "off-peak" tariff period for a typical winter schedule in Portugal, as outlined in [69].

5.1.6 Peak Shaving Strategy (PS)

Peak Shaving Strategy (PS) is a critical aspect of EV management, designed to exert control over EV charging processes to limit peak energy demand to a predefined threshold, which should be grounded in historical maximum demand data. In this strategy, the threshold is defined for the global peak demand (15 GW for 2035 and 20 GW for 2050), prohibiting EV charging once surpassed [70]. PS strategies offer other advantages such as rapid response, high utilisation rates of available energy, and substantial economic benefits. These benefits extend to reducing grid-related investment and maintenance costs and reducing user charging expenses [71]. More advantages and disadvantages of this strategy are described in Figure 5.1, displayed at the beginning of this chapter.

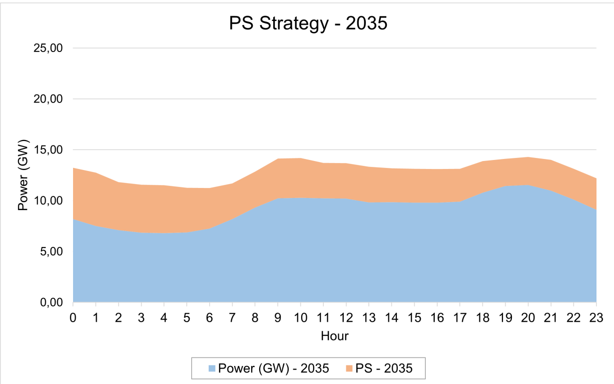


Figure 5.13: PS Strategy - 2035

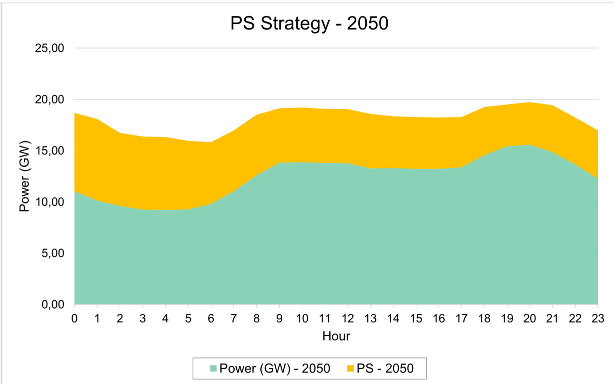


Figure 5.14: PS Strategy - 2050

The PS strategy for the years 2035 (Figure 5.13) and 2050 (Figure 5.14) demonstrates promising outcomes when compared to the previously tested strategy. The impact of EV consumption is, in fact, remarkably consistent throughout the day, with no significant peaks observed. In 2035, the maximum global peak consumption reached 14.14 GW at 9 AM, and another one would occur at 8 PM with 14.29 GW. Similarly, in 2050, the peak consumption reached 19.14 GW at 9 AM and 19.75 at 8 PM. These are significantly lower values when compared to the previously discussed strategies. This strategy proves to be suitable for mass EV adoption in Portugal, considering the advantages and disadvantages previously addressed. The even distribution of energy demand throughout the day helps alleviate grid stress during peak periods, thus enhancing grid reliability and efficiency.

5.1.7 Renewable Energy Sources Strategy (RES)

This strategy involves two distinct study phases. In the initial phase, the assumption was that renewable energy production would remain constant throughout the study years. In other words, the renewable energy production curve for 2022 was used and held constant for the entire study period. Subsequently, in the second phase of the simulation, the forecasted renewable energy production curves for the study years, as developed by [14], were incorporated, and EV consumption followed the trend of a line, which is 10% of the global peak consumption throughout the day. In the case of Renewable Energy Sources (RES) (using 2022 renewable data), the simulated global peak consumption reached 14.17 GW at 9 AM and 15.09 GW at 8 PM (Figure 5.15), which was concurrent with the period of highest energy demand, where EV consumption aligns with the RES generation curve.

Nevertheless, when employing RES (NEW RES - 2035), the simulated global peak consumption reached 17.06 GW at noon and 13.79 GW at 7 PM (Figure 5.17), with EV consumption still closely mirroring the RES generation curve. This simulation outperformed the first in 2035 due to two crucial factors. For instance, in the initial simulation, the peak occurred at a time of greater energy consumption, resulting in a higher peak demand, especially considering that the renewable data used dates back to 2022. However, in the second simulation, the EV charging pattern aligned with the forecasted renewable energy production curve for 2035, leading to a consumption peak at noon. The increased availability of renewable energy, particularly solar power, can be attributed to this peak. Both sets of results exhibit similarity to the prior peak shaving strategy outcomes, suggesting their viability as effective strategies for the mitigation of the impact of EV charging in Portugal.

Furthermore, for the year 2050, the RES strategy (with 2022 renewable data) experienced its global peak consumption at 9 AM and 8 PM, reaching 19.78 GW and 20.96 GW, respectively (Figure 5.16), while the RES strategy (NEW RES - 2050) peaked at noon, registering 23.84 GW and 19.01 GW at 7 PM (Figure 5.18). The rationale behind these outcomes mirrors that of the 2035 results. The variables that change in this scenario include the forecasted renewable energy production, EV consumption, and power for 2050.

In summary, these findings indicate that Portugal's energy system can capitalise on solar energy production (between 10 AM and 5 PM) and subsequently, during peak demand (from 5 PM to midnight), effectively meet the increased energy requirements. This strategy is quite significant, as it leverages the high forecast of renewable energy for Portugal in the coming years. In other terms, EV charging can rely on and take advantage of renewable production, thereby reducing the impact on the grid during peak demands.

5.2 Comparative Analysis of Strategies and Discussion of Results

The simulation of EV management strategies offers a comprehensive analysis of their potential impact in Portugal's energy landscape up to 2050. Projections indicate a significant surge in EV adoption

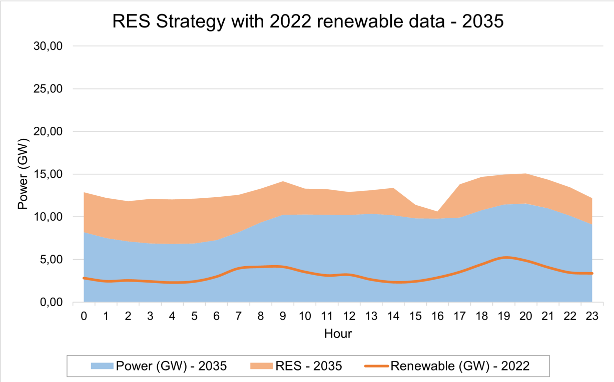


Figure 5.15: RES Strategy with 2022 renewable data - 2035

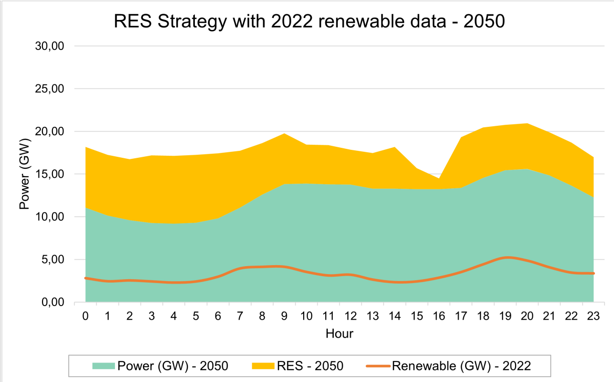


Figure 5.16: RES Strategy with 2022 renewable data - 2050

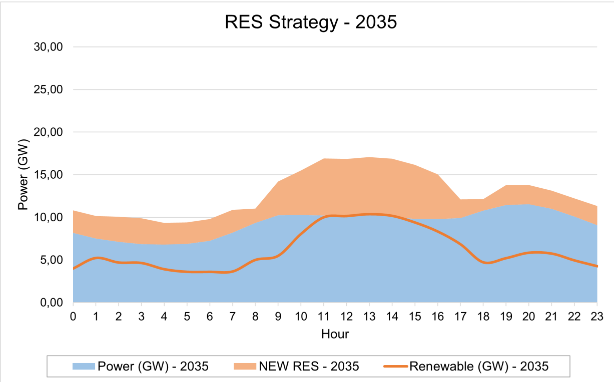


Figure 5.17: RES Strategy - 2035

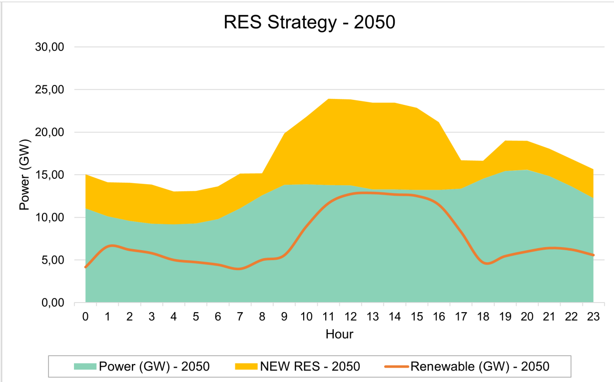


Figure 5.18: RES Strategy - 2050

in Portugal, with an expected 6,330,000 EVs on the roads by 2050 [14]. Uncontrolled EV charging, observed across various scenarios and strategies, generates new consumption peaks that can strain the country's power system. However, the near future envisions a substantial reduction in non-renewable energy production, which indicates that the integration of EVs with RES coordination is a crucial step towards achieving decarbonisation goals. Tables 5.5 and 5.6 depict the peaks of global consumption reached in the morning and late afternoon for 2035, along with the improvement in percentages, when compared to the BaU strategy, which lacks control over EV charging. This year, the PS and RES strategies showcase the most favourable outcomes compared to the BaU strategy. There is a noteworthy reduction in peak consumption levels, coupled with the effective utilisation of the anticipated abundance of renewables around noon.

As for the year 2050, shown in Table 5.7 and 5.8, the results mirror those of 2035. Once again, the PS and RES strategies exhibit notable improvements, suggesting these strategies could be compelling options for implementation in Portugal in the coming years. The DDDL strategy also yields highly favourable results for the Portuguese context and may be a viable option for implementation. This option proves more efficient in the short term or with fewer EVs to be charged, as it demonstrates a higher global peak consumption than the PS and RES strategies.

Table 5.5: Peak Consumption for Different Strategies in 2035

Strategy	Hour	Peak Consumption (GW)	Hour	Peak Consumption (GW)
BaU	9 AM	24.34	7 PM	19.24
DL	9 AM	24.34	12 PM	16.89
DDL	9 AM	24.34	12 PM	15.99
DDDL	9 AM	17.29	12 PM	15.99
ToU	9 AM	24.34	10 PM	17.91
PS	9 AM	14.14	8 PM	14.29
RES (2022 data)	9 AM	14.17	8 PM	15.09
RES (NEW)	12 AM	17.06	7 PM	13.79

Table 5.6: Peak Consumption and Improvement Compared to BaU Strategy in 2035

Strategy	Hour	Improvement %	Hour	Improvement %
BaU	9 AM	-	7 PM	-
DL	9 AM	0.00%	12 PM	12.21%
DDL	9 AM	0.00%	12 PM	16.89%
DDDL	9 AM	28.96%	12 AM	16.89%
ToU	9 AM	0.00%	10 PM	6.91%
PS	9 AM	41.91%	8 PM	25.73%
RES (2022 data)	9 AM	41.78%	8 PM	21.57%
RES (NEW)	12 AM	29.91%	7 PM	28.33%

Table 5.7: Peak Consumption for Different Strategies in 2050

Strategy	Hour	Peak Consumption (GW)	Hour	Peak Consumption (GW)
BaU	9 AM	35.22	7 PM	27.28
DL	9 AM	35.22	12 PM	24.10
DDL	9 AM	35.22	12 PM	22.89
DDDL	9 AM	24.57	12 PM	22.89
ToU	9 AM	35.22	10 PM	25.48
PS	9 AM	19.14	8 PM	19.75
RES (2022 data)	9 AM	19.78	8 PM	20.96
RES (NEW)	12 AM	23.84	7 PM	19.01

The BaU approach will soon become a practical consideration for EV management strategies. However, anticipating the year 2050, alterations in peak consumption patterns could transpire due to a concentration of charging activities during traditionally low-demand periods. In the context of Portugal, this results in a peak of 24.34 GW by 2035 and 35.22 GW by 2050, both at 9 AM. This signifies a substantial 68.90% and 78.5% increase in peak consumption, respectively, compared to the levels observed in 2022 during the corresponding hours. Another peak of 19.24 GW is projected for 2035, and another for 2050, a peak of 27.28 GW at 7 PM. This represents a significant 56.03% and 68.99% increase in peak consumption, respectively, when compared to the levels observed in 2022 during the corresponding hours.

Table 5.8: Improvement Compared to BaU Strategy in 2050

Strategy	Hour	Improvement %	Hour	Improvement %
BaU	9 AM	-	7 PM	-
DL	9 AM	0.00%	12 PM	16.53%
DDL	9 AM	0.00%	12 PM	22.82%
DDDL	9 AM	43.71%	12 PM	22.82%
ToU	9 AM	0.00%	10 PM	9.36%
PS	9 AM	66.02%	8 PM	39.14%
RES (2022 data)	9 AM	63.39%	8 PM	32.85%
RES (NEW)	12 AM	46.71%	7 PM	42.98%

In the context of Portugal DL strategy results in a peak of 24.34 GW by 2035 and 35.22 GW by 2050, both at 9 AM. This translates to a substantial 68.90% and 78.5% increase in peak consumption, respectively, compared to the levels observed in 2022 during the corresponding hours. Another peak of 16.89 GW is projected for 2035, and another for 2050, of 24.10 GW at midnight. This represents a significant 64.12% and 74.85% increase in peak consumption, respectively, in comparison to the levels observed in 2022 during the corresponding hours.

Addressing this potential shift in consumption dynamics, the DDL strategy emerges as a plausible alternative to the DL strategy. The DDL strategy forecasts a peak consumption of 15.99 GW for 2035 and 22.89 GW for 2050, with both peaks occurring at midnight. This indicates a 62.10% and 73.53% increase in global peak consumption, respectively, compared to the 2022 levels at the same hour. Notably, the 9 AM peak remains consistent in both strategies, reflecting the practical constraint that not all users can charge their vehicles at home, leading to charging activities occurring upon arrival at workplaces. Furthermore, featuring a midnight peak, the DDL strategy presents 5% enhancement over the DL strategy. This improvement is attributed to a more distributed charging pattern throughout the day, showcasing a nuanced approach to the management of peak loads and to the optimization of the overall efficiency of the EV charging infrastructure. The DDDL strategy was developed to incorporate charging delays at workplace locations, which were not accounted for in the DDL strategy. This adaptation resulted in an apex of 17.29 GW at 9 AM and another of 15.99 GW at midnight for 2035. This signifies a 56.02% and 62.10% increase in global peak consumption, respectively, compared to the 2022 levels during the same hours. For the year 2050, peaks were observed at 9 AM with 24.57 GW and at midnight with 22.89 GW. This indicates a 69.19% and 73.53% increase in global peak consumption, respectively, compared to the 2022 levels.

Similarly, price-based strategies, such as ToU, exhibit effectiveness soon. However, projecting to the year 2050, these strategies might inadvertently contribute to the emergence of new peaks during traditionally off-peak hours. In the Portuguese context, this scenario could manifest with a peak at 9

AM, reaching the same values as the strategies mentioned earlier for 2035 and 2050. Another apex at 10 PM registers a value of 17.91 GW for 2035 and 25.48 GW for 2050. This would represent a substantial increase of 58.24% in 2035 and 70.64% in 2050, in peak consumption during the same hour observed in 2022. This specific pinnacle aligns with the time when electricity prices commence their decline until 8 AM, as illustrated in 5.1.5. The correlation between pricing dynamics and peak consumption underscores the potential impact of price-based strategies on charging behaviour and system load patterns. PS strategy also proves itself auspicious, as they are recommended for implementation in all study years. In Portugal, peak consumption is estimated to reach 14.14 GW by 2035 and 19.14 GW by 2050, both at 9 AM, with EVs contributing to 46.46% and 61.67%, respectively, which poses as an increase compared to the same hour in 2022. Another peak consumption is estimated to reach 14.29 GW by 2035 and 19.75 GW at 8 PM, with EVs contributing to 43.30% and 57.16%, respectively, also an increase when compared to the same time period in 2022.

RES coordination strategies are an imperative consideration in 2050 for Portugal. For the RES use 2022 data, peak consumption is expected to reach 14.17 GW by 2035 and 19.78 GW by 2050, both at 9 AM. This reflects a 46.58% and 61.73% increase, respectively, compared to 2022 during the same hour. At 8 PM, peak consumption is expected to reach 15.09 GW by 2035 and 20.96 GW by 2050, following the 2022 renewable energy line trend. They reflected a 43.34% and 59.21% increase, respectively, when compared to the same hour of reference year predominantly due to the integration of RES into the power grid. The following results for the RES strategy with a projected renewable energy curve for each year were obtained: peak consumption is expected to reach 17.06 GW by 2035 and 23.84 GW by 2050, both at noon. This reflects a 55.74% and 68.33% increase, respectively, compared to 2022 during the same hour. At 7 PM, the new peak is 13.79 GW for 2035 and 19.01 GW for 2050. This represents a 38.65% and 55.50% increase, respectively, compared to 2022 during the same hour, primarily due to the integration of RES into the power grid.

Accordingly, it becomes evident that the PS and RES strategies are particularly noteworthy, especially in years with a higher projected number of EVs on Portuguese roads. The DDDL strategy emerges as a potential solution for implementation in the forthcoming years. While it exhibited beneficial outcomes for the grid, it is essential to point out that its effectiveness tends to be surpassed by the PS and RES strategies for a more extensive fleet of EVs. This underscores the nuanced considerations required when selecting optimal strategies for managing the increased integration of EVs into the energy grid.

6

Conclusion

This comprehensive analysis of the impact of widespread EV adoption within the Portuguese power system and the implementation of tailored EV management strategies emphasises the critical need for a nuanced and forward-looking approach to navigate the evolving energy landscape.

The integration of a sophisticated computational tool dedicated to crafting representative EV charging profiles has been a cornerstone of this research. This tool iteratively throughout the study, this tool has been instrumental in assessing the multifaceted repercussions of increasing EV prevalence. Drawing on real-world data specific to Portugal, encompassing critical details such as prevalent EV models, travel patterns, driving speeds, and the spatial distribution of CSs, the resulting charging profiles serve as authentic representations of the current and potential impact of EV on the Portuguese power grid.

The choice of a winter day as a reference scenario, depicting peak electricity consumption in 2022, stands as a pivotal benchmark. The findings unequivocally demonstrate the urgent need for implementing EV management strategies to effectively mitigate their impact, projected through the year 2050. The empirical evidence emphasises that optimal strategies require the coordination of EV management with renewable energy generation, in addition to the prudent application of peak-shaving measures. Nonetheless, it's acknowledged that the successful execution of these strategies mandates the deployment of advanced control infrastructure, representing a crucial area for future advancements.

Envisioning future trajectories, this research asserts the necessity for a comprehensive examination of expanded EV management strategies. This exploration aims to enhance our understanding of their effects on the distribution system and investigate their potential influence on the overarching energy infrastructure. Additionally, a longitudinal analysis, particularly during the summer when photovoltaic generation is abundant, is proposed as a pathway for ongoing research to unravel the intricate seasonal dynamics of EV impact.

In future work, the creation of additional user profiles to obtain results closer to reality would be crucial. Analysing more strategies tailored specifically to the Portuguese context, such as the Vehicle-to-Everything (V2X) strategy found in the literature, could provide valuable insights and enhance the study's comprehensiveness. Furthermore, exploring the impact of these strategies under diverse scenarios and conditions would contribute to a more comprehensive understanding of their effectiveness and applicability. This thesis contributes to the ongoing discourse on sustainable energy transitions, advocating for strategic EV management synergised with renewable energy sources. It serves as a testament to the complex interplay between evolving technology, energy demand, and the imperatives of a carbon-neutral future.

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A

Simulation Graphics

A.1 EVs Management Strategies per strategy

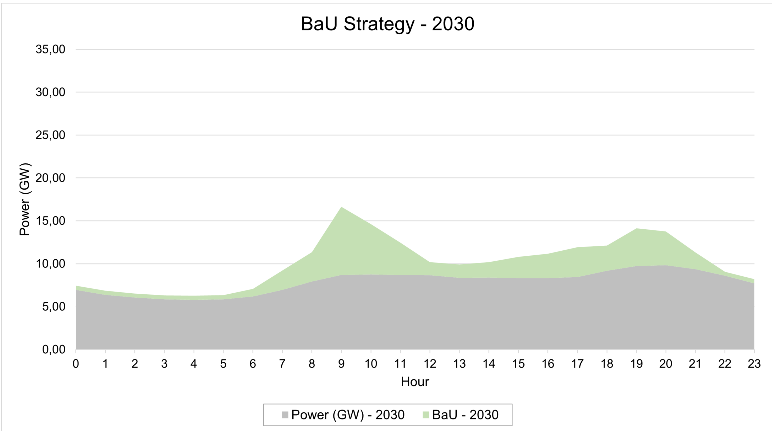
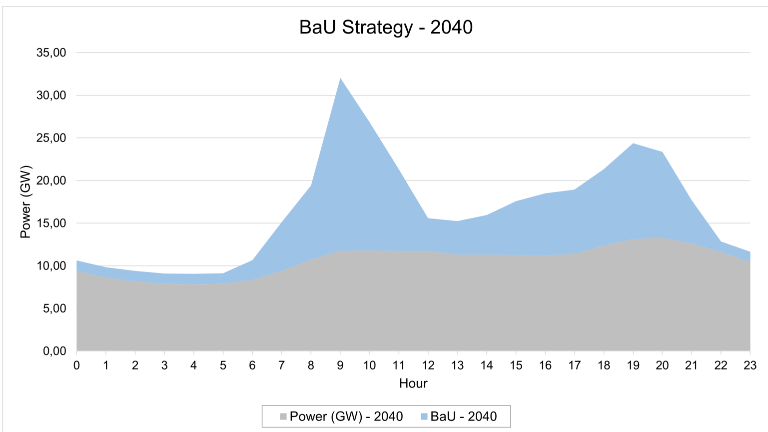


Figure A.1: BaU Strategie - 2030



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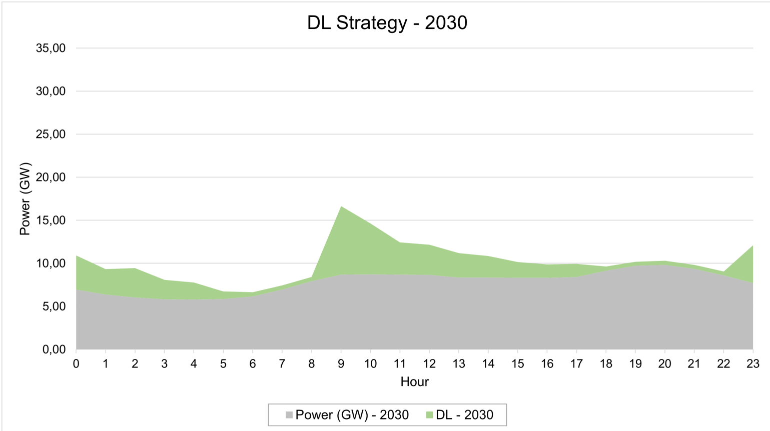

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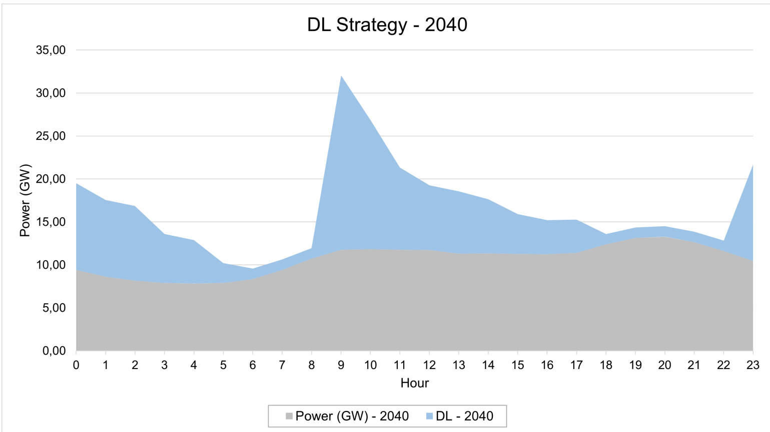

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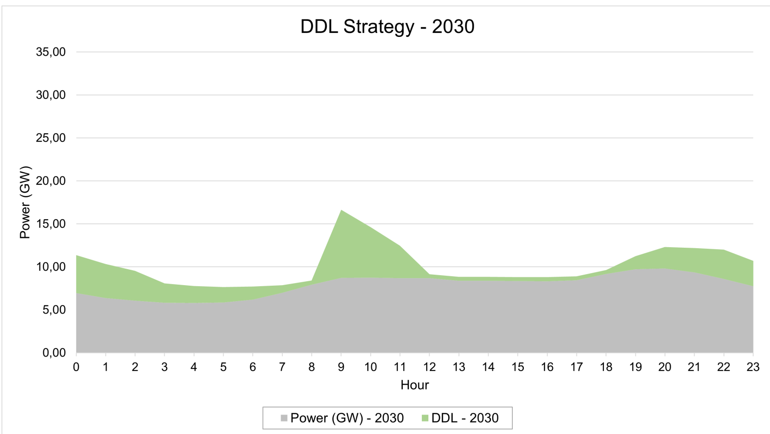

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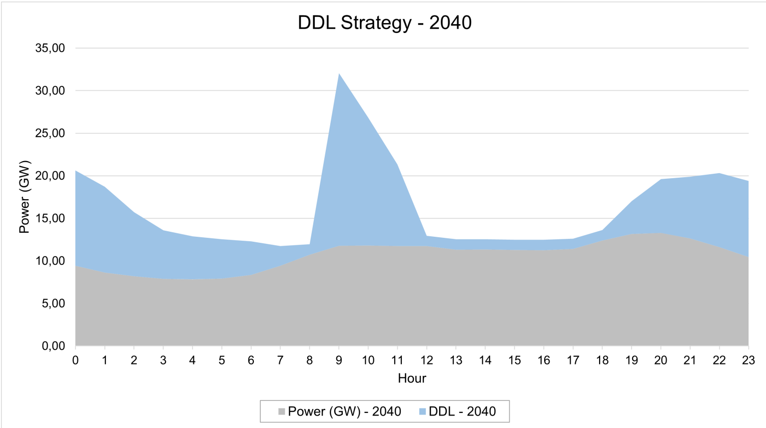

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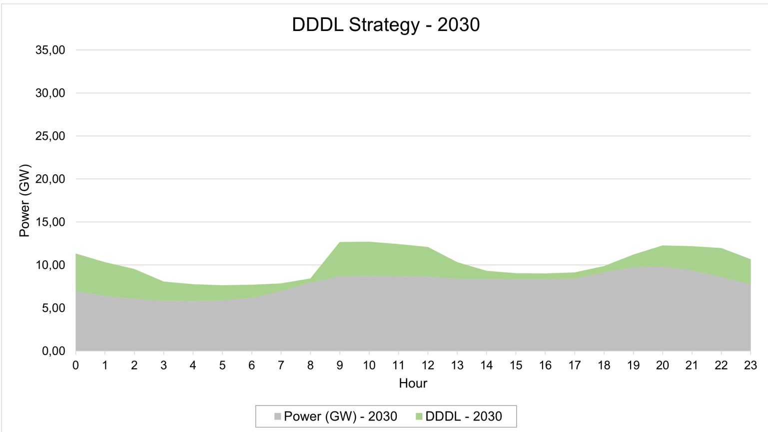

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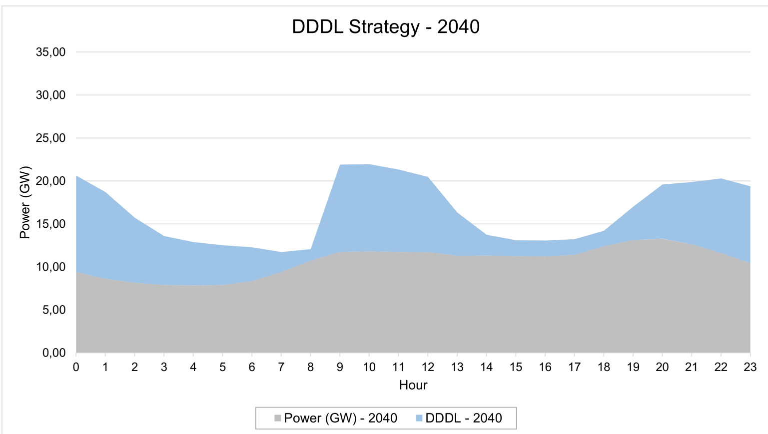

Figure A.8: DDDL Strategy - 2040

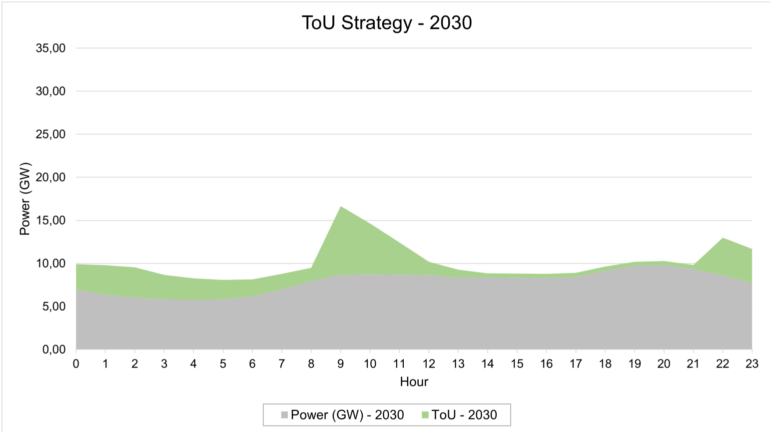

Figure A.9: ToU Strategie - 2030

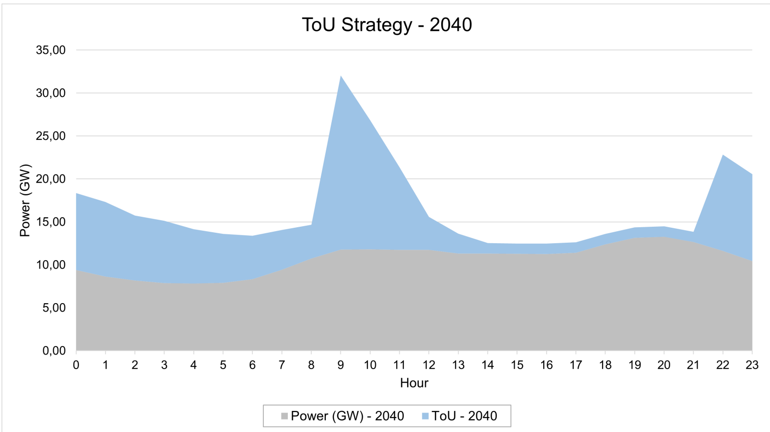

Figure A.10: ToU Strategie - 2050

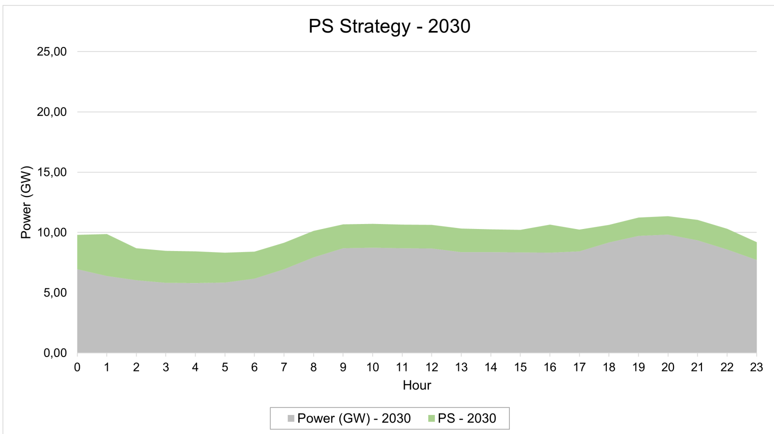

Figure A.11: PS Strategie - 2035

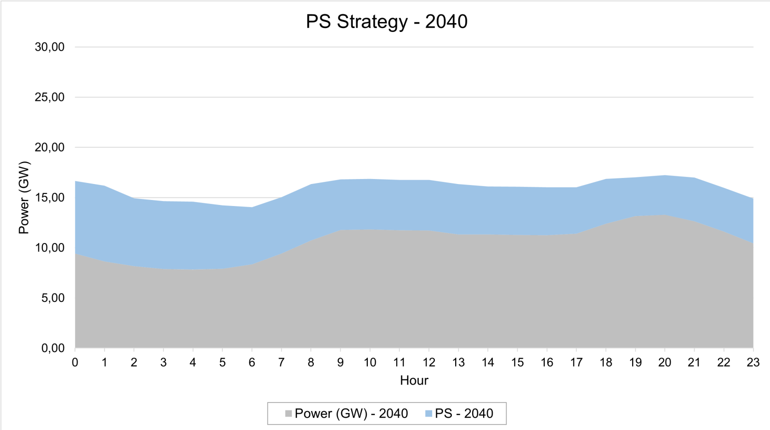

Figure A.12: PS Strategie - 2050

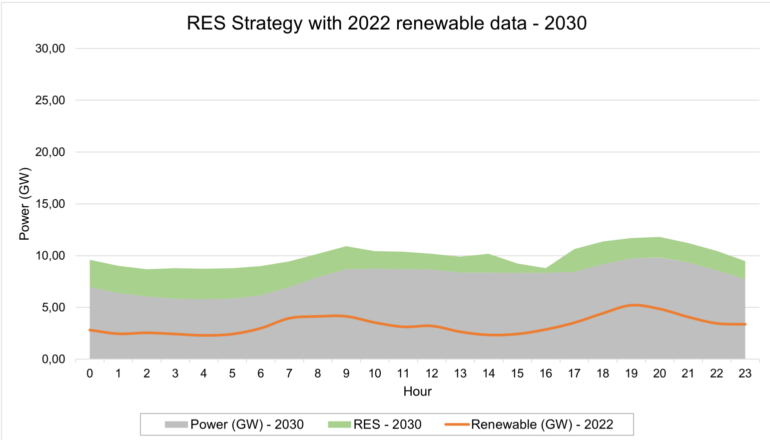

Figure A.13: RES Strategie with 2022 renewable data - 2030

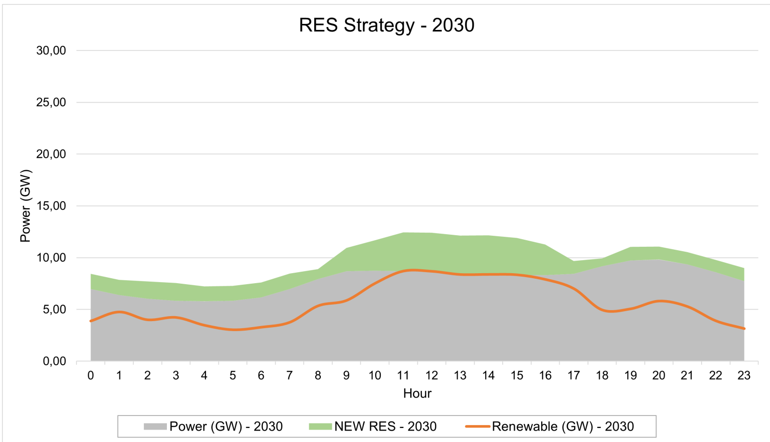

Figure A.14: RES Strategie - 2030

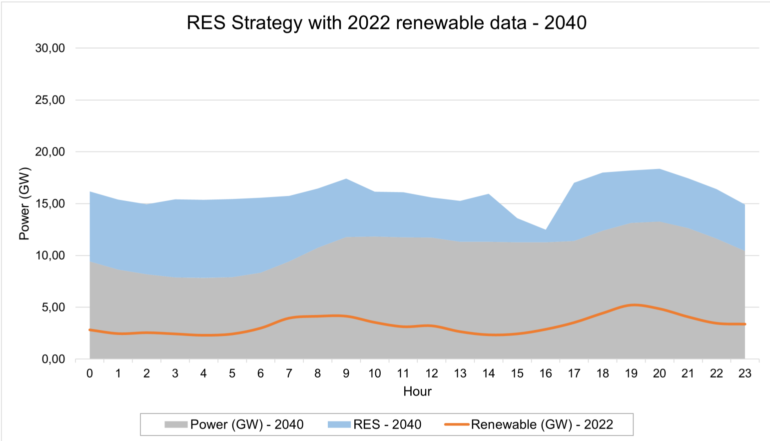

Figure A.15: RES Strategie with 2022 renewable data - 2040

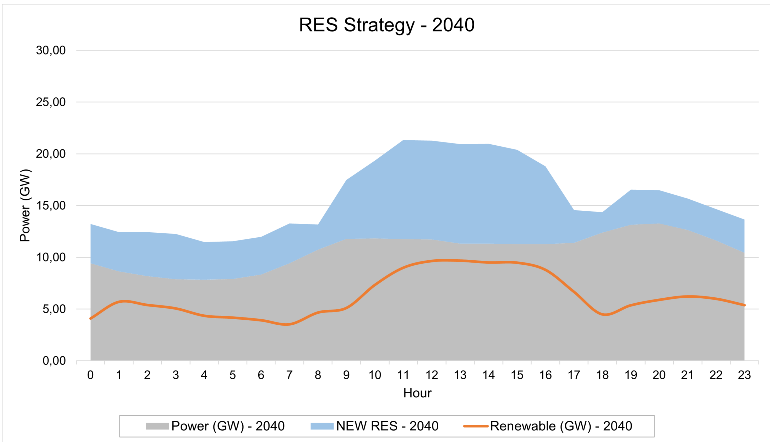

Figure A.16: RES Strategie - 2040