NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTMENT OF ELECTRICAL
AND COMPUTER ENGINEERING

GUILHERME CASANOVA FERNANDES ROQUE DOS SANTOS

BSc in Electrical and Computer Engineering

B2G (BUGGY-TO-GRID): VEHICLE-TO-GRID (V2G) CONCEPT IN MICROGRIDS WITH STRONG ELECTRIC VEHICLES PENETRATION

MASTER IN ELECTRICAL AND COMPUTER ENGINEERING

NOVA University Lisbon
March, 2022

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GUILHERME CASANOVA FERNANDES ROQUE DOS SANTOS

BSc in Electrical and Computer Engineering

Adviser: Prof. Dr. João Murta Pina
Assistant Professor, NOVA University Lisbon

Co-adviser: Engr. Ricardo Belém
Technical Director, Dom Pedro Investimentos

Examination Committee

Chair: Prof. Dr. Ana Inês da Silva Oliveira
Assistant Professor, FCT-NOVA

Rapporteurs: Prof. Dr. Rui Miguel Amaral Lopes
Assistant Professor, FCT-NOVA

Prof. Dr. João Murta Pina
Assistant Professor, NOVA University Lisbon

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To my Grandfather, in loving memory.

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ABSTRACT

Golf resorts are complex systems and require considerable amounts of electricity and fossil fuels to operate, which provides an opportunity to improve their energy efficiency. This thesis aims to evaluate the potential of integrating vehicle-to-grid (V2G) technology into the Dom Pedro Golf Courses, with the addition of a self-consumption photovoltaic (PV) system that would support the integration of this technology, by utilising the surplus generated energy to charge the buggies and later discharge it according to the course needs. The V2G and PV system together can be of great benefit by performing peak load shaving and load levelling services to the golf course's load profiles and energy consumption, reducing the resort's carbon emissions by displacing the fossil fuels utilised in its energy consumption.

This system compromised 244 solar panels for a total of 97.6 kWp, with an annual first-year generation of 176.70 MWh. Every month had windows of excessive generation except for September, October and November, resulting in 9.34 MWh that the golf buggies could charge and then discharge through V2G technology.

The results of the study implementation were quite positive. With these two technologies in conjunction, the results for the first year of investment were a performance ratio of 87%, a self-consumption ratio of 100% and a self-sufficiency ratio of 35%, and the benefit-cost ratio of the V2G technology alone for the whole investment period of ten years was 1.79. By performing an economic analysis on the subject, the results followed the same positive trend, and the outcome was a net present value of 50,353.42€, an internal rate of return of 13%, a payback period of seven years, and a levelized cost of energy of 0.1315 €/kWh. These results point to a beneficial and feasible result for the investment period.

Keywords: Energy efficiency, energy storage, photovoltaic plant, self-consumption, vehicle-to-grid (V2G), technology.

RESUMO

Os resorts de golfe são sistemas complexos e requerem quantidades consideráveis de eletricidade assim como combustíveis fósseis para operar, o que oferece uma oportunidade para melhorar sua eficiência energética. Esta tese tem como objetivo avaliar o potencial de integração da tecnologia vehicle-to-grid nos campos de golfe Dom Pedro, com a adição de um sistema fotovoltaico para autoconsumo que serve de apoio à integração desta tecnologia, utilizando a energia gerada excedente para carregar os buggies e posteriormente descarregar de acordo com as necessidades da rede. Este sistema vehcile-to-grid em conjunto com um sistema fotovoltaíco pode ser de grande benefício ao reduzir as cargas nas horas de ponta e balancear as cargas dos consumos energéticos dos campos de golfe, reduzindo as emissões de carbono dos resorts, ao substituir os combustíveis fósseis utilizados no seus consumos de energia.

Este sistema acomoda 244 painéis solares para um total de 97,6 kWp, com uma geração anual para o primeiro ano de investimento de 176,70 MWh. Todos os meses apresentaram períodos horários nos quais a geração excedia os consumos, exceto setembro, outubro e novembro, resultando em 9,34 MWh que os buggies podem carregar e depois descarregar através da tecnologia vehicle-to-grid.

Os resultados do estudo desta implementação foram bastante positivos. Com as duas tecnologias em conjunto, os resultados para o primeiro ano de investimento são um *performance ratio* de 87%, um *self-consumption ratio* de 100% e um *self-sufficiency ratio* de 35%, e a relação custo-benefício da tecnologia vehicle-to-grid, para o período de investimento de dez anos é de 1,79. Ao realizar uma análise económica sobre o estudo, os resultados seguiram a mesma tendência positiva, com um valor atual líquido de 50353,42€, uma taxa interna de retorno de 13%, um período de retorno de sete anos e um custo nivelado de energia de 0,1315 €/kWh. Estes resultados apontam para um resultado benéfico e viável para o período de investimento.

Palavras-chave: Eficiência energética, armazenamento de energia, sistema fotovoltaico, auto-consumo, vehicle-to-grid (V2G), tecnologia.

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Acronyms

AC	Alternate Current. *(pp. 3, 8–10, 18, 25, 37, 38, 49)*
AMI	Advanced Metering Infrastructure. *(p. 11)*
B2G	Buggy-to-Grid. *(pp. 2, 5, 29)*
DC	Direct Current. *(pp. 3, 8–10, 17, 18, 25, 37, 49)*
EV	Electric Vehicle. *(pp. 1, 5–11, 13, 15, 17–29, 31, 68)*
EVSE	Electric Vehicle Supply Equipment. *(pp. 8–10, 24, 25, 31)*
GHG	Greenhouse Gases. *(pp. 1, 20)*
ICEV	Internal Combustion Engine Vehicle. *(pp. 6, 20)*
ISO	Independent System Operator. *(p. 8)*
NOCT	Nominal Operating Cell Temperature. *(p. 36)*
O&M	Operation and Maintenance. *(pp. 63, 64)*
PEU	Power Electronic Unit. *(pp. 24, 25)*
PV	Photovoltaic. *(pp. ix, 2, 3, 19, 29, 31, 32, 34, 36–42, 49, 54, 55, 63–66, 68, 69)*
PVGIS	Photovoltaic Geographical Information System. *(pp. 2, 3, 32, 34, 43)*
SLV	Special Low-Voltage. *(p. 43)*
STC	Standard Test Conditions. *(pp. 36–39, 68)*
UTC	Coordinated Universal Time. *(p. 43)*
V1G	Smart Charging. *(pp. 11, 13)*

V2B	Vehicle-to-Building. *(pp. 13, 26)*
V2G	Vehicle-to-Grid. *(pp. ix, 1–3, 5–11, 13, 15, 17–27, 29, 31, 32, 53, 56, 59, 63–66, 68, 69)*
V2V	Vehicle-to-Vehicle. *(pp. 13, 26)*
V2X	Vehicle-to-Anything. *(pp. 13, 26)*

SYMBOLS

A_{FV}	Total area of the installed PV modules (m^2). *(p. 39)*
α	Solar module inclination angle (°). *(p. 36)*
α_p	Module temperature coefficient of power (%/°C). *(p. 37)*
β_N	Solar altitude angle at noon (°). *(pp. 35, 36)*
A_{Module}	Module implementation area (m^2). *(p. 36)*
A_{Total}	Total available area (m^2). *(p. 36)*
BCR	Benefit-cost ratio. *(pp. 40, 66, 68, 69)*
$CF_t[Benefits]$	Cash flow of the project benefits ratio (€). *(p. 40)*
$CF_t[Costs]$	Cash flow of the project costs ratio (€). *(p. 40)*
CF_t	Cash flow for the year t (€). *(pp. 38, 39)*
C_t	Total costs in year t (€). *(p. 39)*
n	Number of the day in a calendar year. *(p. 34)*
δ	Solar declination angle (°). *(p. 34)*
Δ_T	Difference between the cell temperature and 25 °C (°C). *(p. 37)*
E_{cons}	Annual prosumer consumption needs (kWh). *(p. 40)*
E_{FV}	Total PV energy generated in a year (kWh). *(pp. 39, 40)*
E_{inj}	Energy injected into the grid when the generation exceeds the consumption. (kWh). *(pp. 39, 40)*
E_t	Total energy produced in year t (kWh). *(p. 39)*
η_{STC}	Solar panel efficiency at STC conditions (%). *(p. 39)*
H	Yearly irradiation at the solar modules plane (kWh/m^2). *(p. 39)*
I_0	Initial investment (€). *(pp. 38, 39)*
$\eta_{inverter}$	Solar inverter efficiency (%). *(p. 37)*

$P_{inv,DC}$	Solar inverter nominal power (kW). *(p. 38)*
IRR	Internal return rate (%). *(pp. 38, 68)*
G	Irradiance (kW/m^2). *(p. 37)*
L	Latitude (°). *(p. 35)*
$LCOE$	Levelized cost of energt (€/kWh). *(pp. 39, 68)*
b	Module length (m). *(p. 36)*
d	Module distance to avoid shadowing (m). *(p. 35)*
l	Module width (m). *(p. 36)*
$NOCT$	Nominal operating cell temperature (°C). *(p. 37)*
NPV	Net present value (€). *(pp. 38, 68)*
N	Total number of modules. *(pp. 36, 38)*
P_{AC}	Module AC power output (kW). *(p. 37)*
$P_{AC_{Losses}}$	Module AC power losses (%). *(p. 37)*
$P_{AC_{Max}}$	Maximum module AC power (kW). *(p. 37)*
$P_{AC,Total}$	Total installed AC power (kW). *(p. 38)*
P_{DC}	Module DC power output (kW). *(p. 37)*
$P_{DC_{Losses}}$	Module DC power losses (%). *(p. 37)*
$P_{DC_{Max}}$	Maximum module DC power (kW). *(p. 37)*
$P_{FV,peak}$	Total maximum peak power installed at STC conditions (kWp). *(p. 38)*
$P(G, 25°C)_{max}$	Maximum module DC power at a temperature of 25°C for any given irradiance (kW). *(p. 37)*
PP	Payback period (yr.). *(pp. 39, 68)*
PR	Performance ratio (%). *(pp. 39, 68)*
P_{STC}	Module maximum peak power at STC conditions (kWp). *(p. 37)*
r	Discount rate (%). *(pp. 38, 39)*
SCR	Self-consumption ratio (%). *(pp. 39, 68)*
SSR	Self-sufficiency ratio (%). *(pp. 40, 68)*
t	Investment year. *(pp. 38, 39)*
T_{amb}	Ambient temperature (°C). *(p. 37)*
T_{cell}	Solar module cell temperature (°C). *(p. 37)*

1

INTRODUCTION

1.1 Motivation

Energy is pivotal to our economic and social development and provides a significant role in improving the quality of life around the globe. However, a large percentage of the world's energy is presently produced and consumed in non-sustainable ways. The growing need to limit climate change and reduce atmospheric emissions of greenhouse gases (GHG) and other harmful substances will increasingly need to rely on the efficiency of the energy generation and transportation sectors since some of the most significant issues of this century, such as peak oil, climate change, and energy independence, are directly connected with these sectors [2, 3].

With the growing expectation for environmentally friendly means of transport, one of the most significant needs in the world becomes the search for a clean and energy-efficient transport system. Alternative vehicle technologies, like Electric Vehicles (EVs), are being developed and improved because of their reduction of fossil fuel dependency, gas emissions, and transportation costs, which translates into a more robust ecological and economic viability associated with these vehicles [4–6].

Not only this, but EVs can also act as distributed energy sources by utilising their batteries to store energy that can later be returned to the grid through Vehicle-to-Grid (V2G) technology. V2G can promote the penetration and diffusion of these vehicles into the grid because of the technology's benefits for EV owners and grid operators. The power bidirectionality between these vehicles and the grid achieved through this technology leads to the creation of new income sources for vehicle owners and provides multiple beneficial services to the electrical grid, leading to a plethora of economic, environmental, social, and technical benefits to the involved parties and society in general [7, 8].

1.2 Objectives

This dissertation work is developed in partnership with *Dom Pedro Investimentos*, which possesses five golf courses on their actives, with an overall penetration of 343 electric golf carts (buggies). Golf resorts are complex systems that require considerable amounts of electricity as well as fossil fuels to operate, which provides an opportunity to improve their energy efficiency.

This thesis objective is to evaluate the potential of integrating energy storage provided by a fleet of buggies into the golf courses through V2G technology (hence the term adaptation Buggy-to-Grid, or B2G for short), with a self-consumption Photovoltaic (PV) system. The V2G and PV system can significantly benefit by performing peak load shaving and load levelling services to the golf course's load profile. Furthermore, this dual implementation can reduce the resort's carbon emissions by displacing fossil fuels utilised in its energy consumption, turning these resorts into more environmentally friendly systems by storing excessive generated renewable energy and discharging it when needed.

Recent studies in V2G literature help fuel these thesis objectives, as this technology is currently only employed in personal transport vehicles; however, because of its flexibility, there have been recent studies on the feasibility of its use in other means of transport, like vans, school buses, delivery trucks, city buses, and garbage trucks. Furthermore, with the technology increasing diffusion and the continued electrification of the transport sector, the range of vehicles V2G technology can be applied to will increasingly grow, with motorcycles, boats and planes as possible future implementations [9].

Not only this, but according to the Global Energy Review 2020 by the International Energy Agency, in 2019, one-fifth of all renewable capacity deployed worldwide consisted *"of individuals and small-to-medium-sized enterprises installing solar PV panels on their roofs or business sites"* [10], which suggests a possible viable implementation of PV energy in the golf resorts, along with the use of V2G technology.

1.3 Summary of the Work Developed

The initial stage of this dissertation was the literature review, which was quite extensive and served as a basis for the whole study. This review was followed by the development and implementation of a simulation model, whose initial steps were the automatic connection with the Photovoltaic Geographical Information System (PVGIS) in order to retrieve the solar irradiance data, followed by the calculation of the solar angles at the golf course location. The module self-shadowing distance and the total number of modules were the next steps, followed by the calculation of the total PV generation that can be used by choosing the best solar module and solar inverter according to the study characteristics. After the generation, the resort's load profile data was analysed, and the net power was calculated. After this, the optimal V2G discharging windows were calculated and following this discharging, a new net power was obtained. Finally, the energy and economic analyses were performed to assess the study's feasibility.

1.4 Original Contributions

The original contributions referent to this dissertation are the development of a simulation model aimed to analyse and simulate the integration of V2G technology into golf courses ecosystems, with a PV system to support the technology integration, with the end goal of assessing the viability of this technologies implementation.
According to the user's input data, this tool automatically retrieves solar information from PVGIS, estimates the total DC and AC PV power that can be generated, performs the golf courses energy analysis by depicting the power flows between the golf resort's generation and consumption, studies the possible V2G technology integration and usage into the resort's energy demands through the golf buggies, and performs an economic and energy analysis of the system.

1.5 Dissertation Organization

The present dissertation is organised into six chapters, including the current one, **Introduction**. These chapters are briefly summarised as follows:

- **2 Literature Review:** this chapter comprehends an extensive study and literature review regarding Electric vehicles and Vehicle-to-Grid technology, with an increased focus on the latter, and it also introduces a new concept which is the application of the Vehicle-to-Grid concept in golf buggies, named Buggy-to-Grid for the purposes of this thesis.

- **3 Methodology:** in this chapter, the proposed methodology is exposed and dissected, as well as the developed simulation model. The methodology is compromised by the golf resort's solar resource characterisation, the PV study, and the study's economic, energy analysis and optimisation.

- **4 Case study:** where the case study for the Dom Pedro Victoria Golf course is assessed. Starting with a brief description of the golf course site, it is then followed by a detail of the electricity tariffs considered for the study. The driver and buggy data from the golf resort is then exposed. Afterwards, the golf resort's load profile and energy consumption data are analysed, and the solar irradiance data is automatically retrieved according to the user's input. With the solar irradiance data, the PV generation is calculated accordingly.

- **5 Results and Discussion:** in which the case study results are discussed. This chapter analyses the golf resort's net power, calculated with the energy consumption and PV generation data. Optimal V2G charging and discharging opportunities are then assessed, and a new net power is obtained. The additional battery degradation this technology causes is analysed, and afterwards, an energy and economic analysis are performed on the study.

- **6 Conclusions and Future Work:** in this final chapter, the study's conclusions are presented as well as any future work to be possibly implemented.

2

LITERATURE REVIEW

The literature review of this dissertation will be presented throughout the present chapter. This review is structured in the following sections: **Electric Vehicles (EVs)**, **Vehicle-to-Grid (V2G)** and **Buggy-to-Grid (B2G)**. In the first section of the chapter, **Electric Vehicles**, a summary of this vehicle type is introduced through its definition, advantages over regular fossil-fueled vehicles, projection of global market share in new vehicle sales and connection with V2G technology. In the following section, **Vehicle-to-Grid**, which is the focal point of this thesis, an extensive analysis of the concept is presented. This section starts with a contextuality of the technology, through its history and definition, followed by a description of a typical V2G system along with its components. Afterwards, other concepts related to this technology are described. Posteriorly, the role of V2G in electricity markets is analysed as well as the technology services and applications, followed by the study of the technology benefits and, in contrast, its challenges and barriers. Finally, the discussion and conclusion of the whole section are presented. The last section of this chapter, **Buggy-to-Grid**, starts with an introduction to this concept, followed by a summary of non-personal vehicle V2G studies, and lastly, an introduction to the microgrid concept.

2.1 Electric Vehicles (EV)

An EV is a type of vehicle that uses electricity from its battery as its driving force, instead of the conventional petroleum-based fuels used by Internal Combustion Engine Vehicles (ICEVs). Although EVs can be more expensive than ICEVs, EVs' fuel and operation costs are much lower due to their high-efficiency electric motor, which diminishes the environmental impact of the transportation sector, in general[1], by reducing local CO_2 emissions even in grid systems that heavily rely on fossil fuels for their energy generation. With the proper infrastructure and modelling approach, these vehicles can also enhance the grid power quality and stability and ease the integration of renewable energy sources (mainly wind and solar energy), potentially further reducing carbon emissions for the generation and transportation sectors [5].
Because of these factors, EVs have quickly gained popularity worldwide over the years, and although global COVID-19 lockdown measures impacted car sales worldwide, according to Deloitte's light-duty vehicle sales projection for 2030, the EV share in new car sales could be around 32% by the end of the next decade [12], as shown in Figure 2.1.

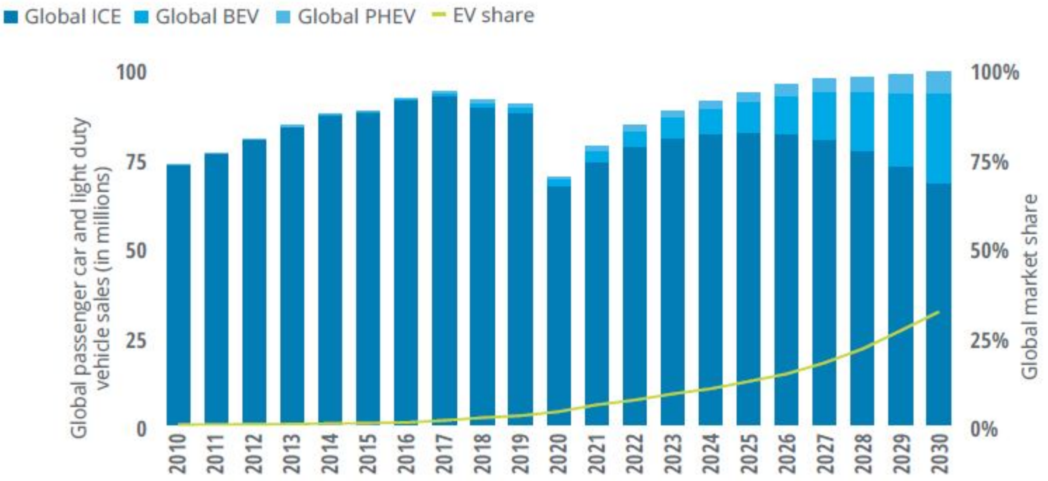

Figure 2.1: Outlook for annual global passenger-car and light-duty vehicle sales to 2030, retrieved from [12].

A vehicle covers an average distance of 53 km daily, translating to approximately less than one hour of travel time. Meaning that daily an automobile is parked, either in a parking lot or a home garage, over 95% of the time, opening the possibility of EVs being charged and discharged during this portion of the day [13]. Because of this and the increasing popularity and penetration of EVs in recent years, the interactive technology connecting these vehicles with the electric power grid in a bidirectional energy flow, called V2G, has quickly developed, bringing different benefits to all the participants in this system [14].

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[1] EVs reduce dependence on fossil fuels but increase the demand for electricity and raw materials such as rare earth elements needed for the vehicle's electronic components (e.g. lithium for batteries), which are subject to supply constraints and concentrated in a few geographic areas [11].

2.2 Vehicle-to-Grid (V2G)

In this section, the literature review of V2G technology will be presented. Since it is the main subject of this thesis, this section will be considerably more extensive when compared to the others. V2G history is initially briefly described, followed by its concept definition and connection with the electrical power grid. The derived technology concepts are also summarily explained. Afterwards, this technology's role is evaluated in electricity markets, and its services and applications are detailed, along with its benefits and, in contrast, the technology's challenges and barriers, with the exploration of some case studies. Thereupon, and to terminate the section, a conclusion and discussion of the section and this technology is followed.

2.2.1 Concept History and Definition

The origin of the V2G concept dates back to the turn of the previous century. First proposed by Amory Lovins in 1995, the idea was further expanded and explored by Willet Kempton and Steven E. Letendre in 1997. At the time, major automobile manufacturers announced their forthcoming plans to mass-produce and market battery-powered, grid rechargeable EVs. Due to this and the projected increase in connections between these vehicles and electric utilities over the following decades, Kempton and Letendre envisioned a concept in which stationary EVs would have a bidirectional, computer-controlled connection to the grid, meaning that the grid could receive power from a parked EV as well as provide power to it. Their goal was to prove that these vehicles' penetration is considerably more attractive to electric power systems and the grid when the benefits of vehicle peak power and energy storage are considered. They also provided analysis about selling energy stored in the EVs, suggesting an economic transaction that would benefit all parties involved since the power supplied by the vehicle batteries could be of practical use to the electric grid, and these vehicle owners could generate income from their garaged automobiles [15]. As depicted in Figure 2.2, V2G is then the concept of the bidirectional, two-way power flow system between an EV and the electric power grid. In addition to regular

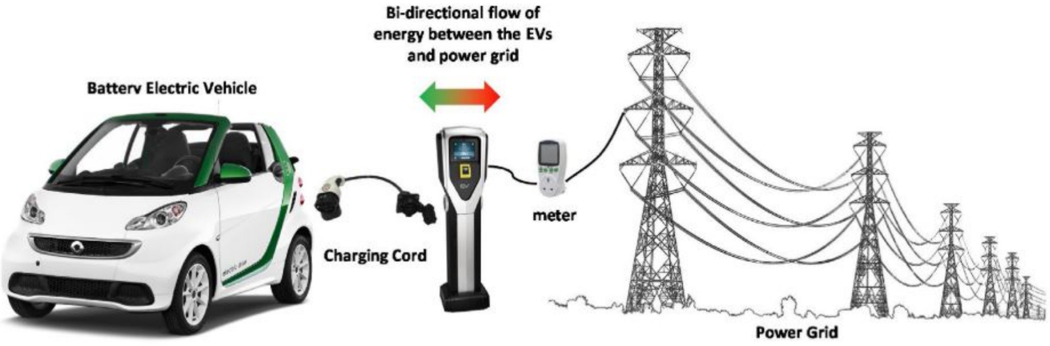


Figure 2.2: Simple V2G Schematic, retrieved from [16].

charging capabilities, this technology allows the discharge of the energy stored in the vehicle's battery back to the grid, adding value to the automobile when parked and not in use, creating a passive source of income for the vehicle owner. A single-vehicle battery has limited capacity energy-wise, but when a group of EVs reaches a certain amount, the energy capacity of the fleet can affect and benefit the power grid. This technology also allows vehicle owners that participate in this energy system to sell electricity back to the grid during peak hours for a higher fee, charging their vehicle battery during off-peak periods, such as night time and early morning, for a lower fee [14, 17].

Typical V2G charging and discharging strategies can be classified as uncoordinated or coordinated. *Uncoordinated strategies* are defined as charging and discharging processes that occur in an uncoordinated manner without any scheduling or optimisation technique between the EVs connected to the same transformer and without following any pricing mechanism, and *coordinated strategies* are the opposite; charging and discharging processes that do occur in a coordinated manner, following scheduling or an optimisation technique between the vehicles connected to the same transformer, following a pricing mechanism. These strategies are aimed at optimising their end goal, which can be financial, by providing maximum benefit according to the price of electricity during peak and off-peak hours, reduce power losses on the grid side, provide ancillary services, reduce and optimise charging timings, reduce detrimental impacts to the EV, and reduce environmental impacts [18, 19].

2.2.2 V2G System

In order to perform the mutual power flow between an EV and the grid, there are three critical elements in a typical V2G system, all of which will be explained below: **(1)** a power connection to the electrical grid, **(2)** a control connection to communicate with the grid operators and aggregators (however, for the purpose of this thesis and similar implementations in which V2G technology reduces local peak demand according to an agreed electricity tariff and without any discharging to the grid, this element is not necessary), and **(3)** a precision metering device to analyse the services exchanged with the grid. This typical system architecture is depicted in Figure 2.3, in which the Independent System Operator (ISO) sends a request signal for services to either a single vehicle or to an aggregator of a vehicle fleet [8].

(1) Connecting the EV and the grid: To connect an EV with the grid, the vehicle needs to have a specially designed charger that can be on-board the automobile or off-board in the Electric Vehicle Supply Equipment (EVSE). These chargers can be unidirectional or bidirectional and are typically categorised into three power levels, depending on the vehicle characteristics and the owner's needs, and are depicted in Table 2.1. While L1 and L2 chargers use Alternate Current (AC), L3 chargers use Direct Current (DC), meaning that in order to charge the vehicle DC battery, L1 and L2 chargers need an onboard AC-DC converter. L2 chargers are the best fit with V2G technology because of their cost and power

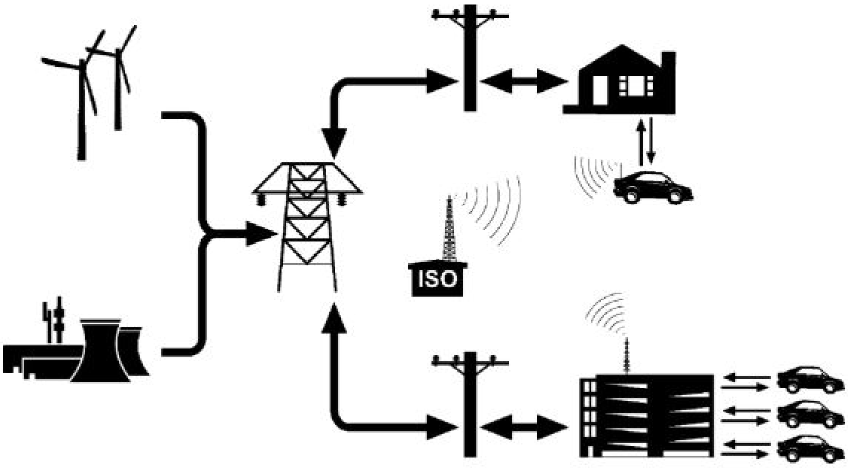


Figure 2.3: Typical schematic of a V2G system and its connections, retrieved from [8].

output ratio.

Table 2.1: Types of EV Chargers, adapted from [20].

Level	Voltage Type	Power Output	Cost	Charging Time	Applications
Level 1 (L1)	Single-phase AC	1.2 kW to 2.4 kW	€	Slow	Residential
Level 2 (L2)	Tri-phase AC	4 kW to 20 kW	€€	Intermediate	Residential, working or public
Level 3 (L3)	DC	over 50 kW	€€€	Fast	Public and Industrial

The EVSE is responsible for feeding the charger and establishing the power flow between the vehicle and the grid. In order for this power flow to be bidirectional and accommodate V2G technology and services, the EV, EVSE and charger AC-DC converter need to be bidirectionally capable of allowing the discharging of energy stored in the vehicle battery back to the grid through the EVSE, which means that fundamental and intrinsic design level changes need to be made to these elements [9, 20]. Figure 2.4 depicts a typical V2G system bidirectional charger block diagram.

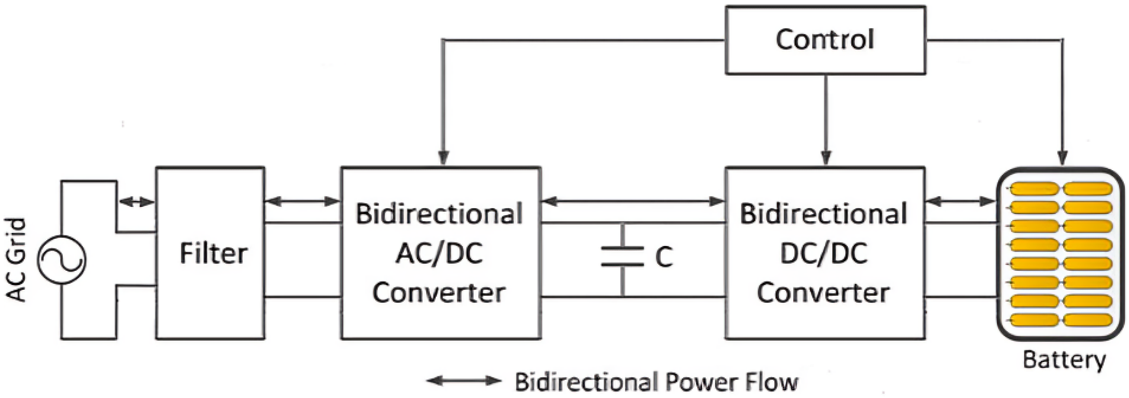


Figure 2.4: V2G Bidirectional charger block diagram, adapted from [20].

While the vehicle is charging, the power flows from the grid to the EV battery. The filter is responsible for blocking any harmonic currents, and the bidirectional AC-DC converter is responsible for power factor correction and operates as a rectifier, converting AC power to DC power. The DC-Link capacitor is responsible for stabilising DC-Link voltage by suppressing ripple voltage, and the bidirectional DC-DC converter allows DC voltage conversion between two different levels, stepping down the DC-Bus voltage to the EV battery charging voltage. While discharging the vehicle power to the grid, the Bidirectional DC-DC Converter steps up the DC battery charging voltage back to DC-Bus voltage, and the bidirectional AC-DC converter acts as an inverter, converting DC power to AC power to be sent back the grid through the EVSE [20].

(2) Communication and aggregation: Not only a bidirectional power flow is required, but a communication means between the EV, and the grid is also needed in order to manage and control a V2G system. Since the EVSE is connected via the internet to an aggregator or grid operator that instructs and coordinates the required power exchanges, a communication protocol is required to control the power flows between the vehicle and the grid, which is usually made at the automobile level through the addition of an onboard communication chip. A V2G communication diagram example is shown in Figure 2.5.

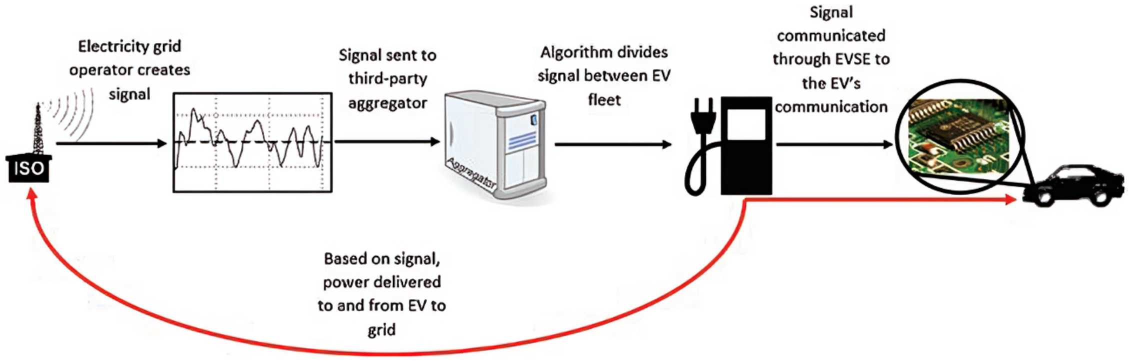


Figure 2.5: Example of communication in a V2G system, with the black lines representing communication flows and the red line representing power flow, retrieved from [9].

Aggregators are fundamentally important in the connection between the grid and EVs since they receive a main signal from the grid operators and afterwards spread the pertinent information to the connected vehicles. Aggregation enables the consolidation of these automobiles batteries in a single controllable load of appropriate size, which allows the participation of vehicle owners in large electricity markets since many of these require a minimum power capacity that a single EV cannot supply, which leads to a more viable penetration of V2G technology in these markets for maximum economic efficiency. An aggregation example is portrayed in Figure 2.6.

Aggregation also allows the combined EV capacity to help level the grid load profiles, charging vehicles during periods of low demand. The use of an aggregator can also lead to stability and flexibility as a market participant through the implementation of predictive

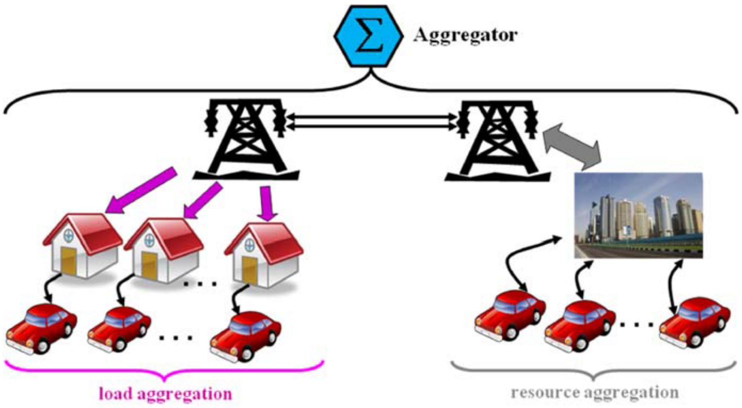


Figure 2.6: Example of aggregation to level the grid load profile or supply services to the grid, retrieved from [21].

and control algorithms that can anticipate the vehicles' behaviour patterns and evaluate, in real-time, the available power that can be used and optimise the energy flows among the connected vehicles [8, 9, 21].

(3) Metering: After a mutual power exchange has been established, with proper communication and aggregation means between the parties, metering is necessary to measure the bidirectional electrical data exchanges in real-time and accurately supply the aggregated EV power capacity according to the grid operator requests.

An example of this process results are depicted in Figure 2.7, and metering is typically made through an Advanced Metering Infrastructure (AMI), a two-way system composed of smart meters, data management and communication components that allow a bidirectional commutation between the aggregated vehicles and the grid. The use of an AMI improves the quality and reliability of V2G systems with minimal response delay and ensures that the aggregated automobile's power capacity can correspond with the grid's needs [8, 9, 22, 23].

With a bidirectional connection with the grid, communication and aggregation abilities, and precision metering, a typical V2G framework is characterised. Figure 2.8 shows the power flows that occur between these elements in a V2G environment.

2.2.3 Concepts Related to V2G Technology

There are many concepts related to V2G technology, and their primary purpose is to integrate and connect flexible loads with the grid intelligently, depending on the customer needs and available infrastructures. Smart charging, also known as V1G or Unidirectional V2G, is considered to be the initial phase of V2G technology, and it enables the ability to dynamically vary the charging rate of an EV based on specific energy schedules or incentive systems, like off-peak hour charging or limiting the charging during peak hours. However, it is a one-way technology that does not allow the stored energy in the vehicle battery to be discharged back to the power grid [25]. A comparative summary between

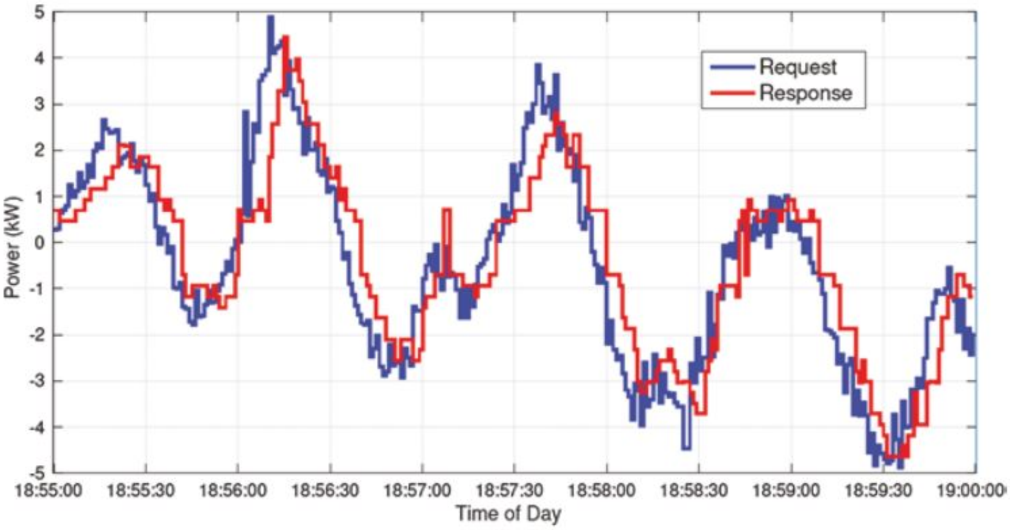


Figure 2.7: Example of metered data from V2G services over a five minute period. The blue line represents the grid operator's power requests, and the red line the EV power response, retrieved from [23].

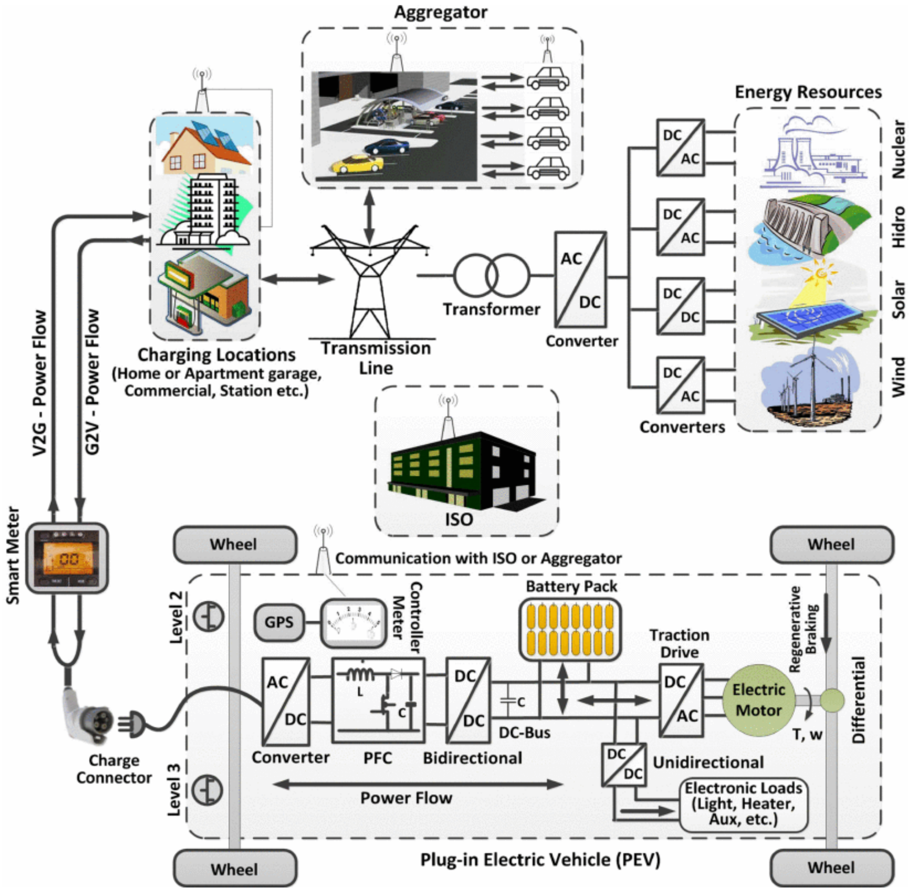


Figure 2.8: Example of typical power flows in a V2G system, retrieved from [24].

V2G and V1G applications, benefits, and drawbacks is presented in Table 2.2.

Table 2.2: V1G and V2G technologies comparison, adapted from [26].

Technology	Applications	Benefits	Drawbacks
V1G	(1) Load levelling	(1) Minimise power losses (2) Minimise operation costs (3) Minimise emissions (4) Maximise profit	(1) Limited service available
V2G	(1) Spinning reserve (2) Frequency regulation (3) Load levelling and peak load shaving (4) Reactive power support (5) Harmonic filtering (6) Support for the integration of renewable energy resources (7) Motor starting	(1) Minimise power losses (2) Maximise profit (3) Minimise operation cost (4) Minimise emissions (5) Prevent power grid overload (6) Improve load profile (7) Regulate voltage level (8) Failure recovery (9) Maximise renewable energy generation	(1) Battery degradation (2) Complex hardware infrastructure (3) High investment cost (4) Social barriers

Since V2G technology is a very flexible concept, it can derive into additional categories based on the receiving end of the bidirectional energy flow with the EV, such as Vehicle-to-Building (V2B) and Vehicle-to-Vehicle (V2V), leading to the creation of the Vehicle-to-X concept (V2X). V2X, also known as Vehicle-to-Anything or Vehicle-to-Everything, is the concept of the bidirectional power flow between an EV and any entity (besides the grid) in order to fulfil its imagined use. Figure 2.9 depicts a framework of these V2G derived technologies.

V2B has a small range of operations because its applications are within a building or home automation network. The connected EV battery can serve as additional energy storage mean, which holds power generated in excess from the building renewable energy sources, if existing, and discharge said stored energy into the building smart appliances if the building's renewable generation is running low. It also serves as an energy backup in case of any emergency or energy disruption affecting the building. V2B creates an environmentally friendly and energy-efficient system for the connected building purpose.

V2V allows vehicles to share energy and can be significantly used in environments like EV parking lots or commercial buildings. V2V offers benefits like the reduction of EV charging costs, grid load reduction, faster-charging cycles, and direct load control on battery charging [9].

2.2.4 V2G in Electricity Markets

The three generic markets surrounding the electric power grid are baseload, peak load, and ancillary services, and each one of these markets has a different fit for a V2G implementation [9]. Figure 2.10 depicts these markets and their suitability for this technology.

The baseload refers to the market of continuous production of wholesale energy, typically generated from low production cost sources with limited flexibility (like coal power plants), to fulfil the grid's minimal needs during a specific time frame. Because of the

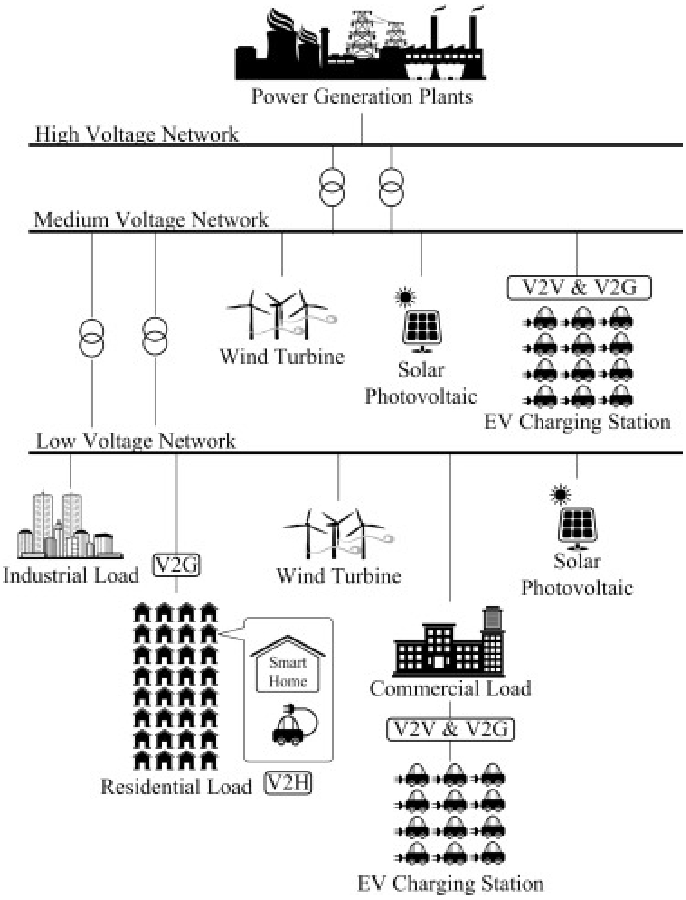


Figure 2.9: Framework example of V2G, V2B, and V2V technologies, retrieved from [26].

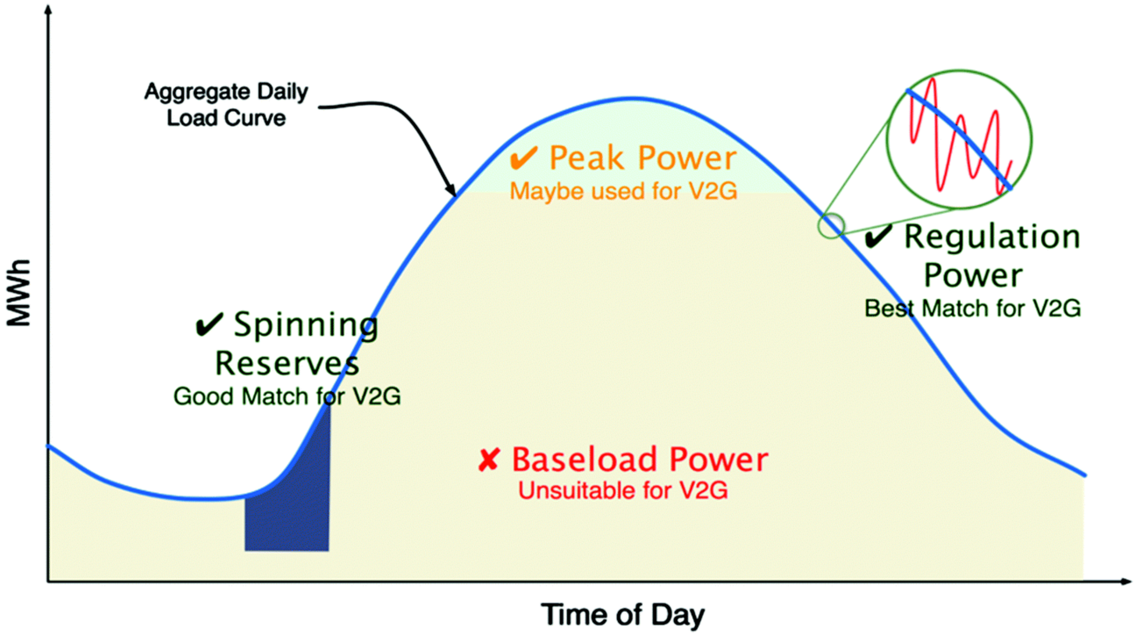


Figure 2.10: Electricity Markets and their V2G Suitability, retrieved from [9].

continuous energy demand and highly competitive energy costs, V2G is generally a bad fit for this market. Electricity demands differ substantially throughout the day, meaning that baseload power can be insufficient to meet said demands, leading to the peak load market. Instead of wholesale production, energy production costs tend to be higher in this market, although more flexible. Peak load is an acceptable but rare market for V2G. Even though peak power can be of high value, it is very energy-intensive, leading to a high drain of the EV battery, preventing vehicle usage for transportation. In addition, when the grid does not actively use peak power from a vehicle battery, the V2G system typically does not receive any remuneration. The third market, ancillary services, is the most adequate to integrate this technology. Ancillary services refer to the necessary services to support a healthy and stable transmission of electric power from generation to consumers in order to maintain grid reliability. The most common of these services associated with V2G technology are frequency regulation and spinning reserves because they match significantly with the technology's high availability and valuation power discharging over energy capacity [9, 17, 27].

2.2.5 V2G Services and Applications

V2G technology is a very flexible concept with numerous applications and benefits, and the critical aspects of this technology are the services it provides to the electric power grid. These key services and applications will be discussed in the current section, divided into two categories: **Active power services** and **Power Quality Services**.

- **Active Power Services** are the type of services that actively discharge the EV battery. The active power services discussed are: **Peak Shaving and Load Leveling**, **Frequency Regulation** and **Spinning Reserve**.

  1. **Peak Shaving and Load Leveling:** Peak power demands affect power systems negatively, harming their economic efficiency. These peaks increase power system planning costs since lower efficiency generation units need to be activated to suppress and cover these power peaks. Commonly, these peaks only last a short period. It is advantageous to level the peak load profile to safeguard the power grid against overloads, protect the grid equipment, prevent unnecessary degradation, and optimise the energy and economic efficiency of the grid.
     Peak shaving and Load levelling techniques, depicted in Figure 2.11, are similar energy charging and discharging processes. The peak shaving objective is to remove the load peaks, while the load levelling purpose is to flatten the load profile. Both concepts accomplish their objective by storing energy during off-peak periods and discharging that energy during peak hours.
     V2G can provide peak shaving services to the grid by injecting excessive local EV energy into it, providing active power during peak load hours in order to reduce the distribution system peak power demands. This technology also

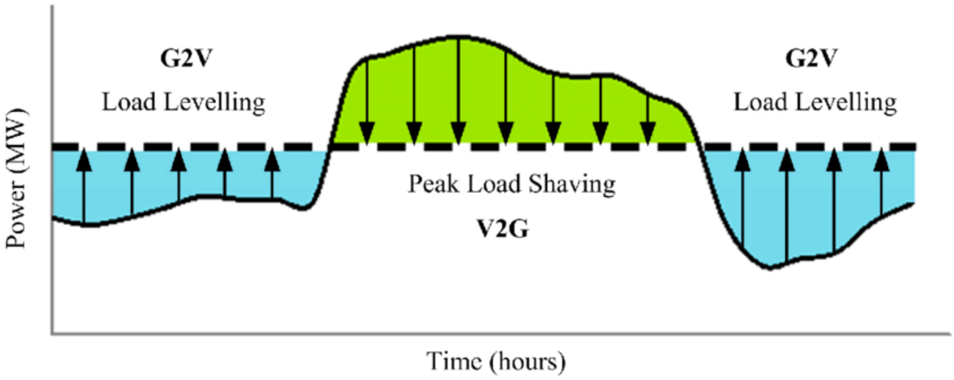


Figure 2.11: Peak Shaving and load levelling concepts, retrieved from [28].

allows load levelling to the grid by charging the vehicles during off-peak hours [26, 29].

2. **Frequency Regulation:** The grid constantly requires frequency fine-tuning to maintain its quality and stability. Because of the mismatch between power generation and consumption, the grid can have fluctuations in its frequency, so control services are required to stabilise it back to its standard value. As depicted in Figure 2.12, frequency regulation is an ancillary service responsible for maintaining the grid's frequency at its nominal value of 50 or 60 Hz. This service requires a constant bidirectional flow of energy between its participants and the grid, depending on the energy supply and demand needs, in order to match them and suppress these imbalances.

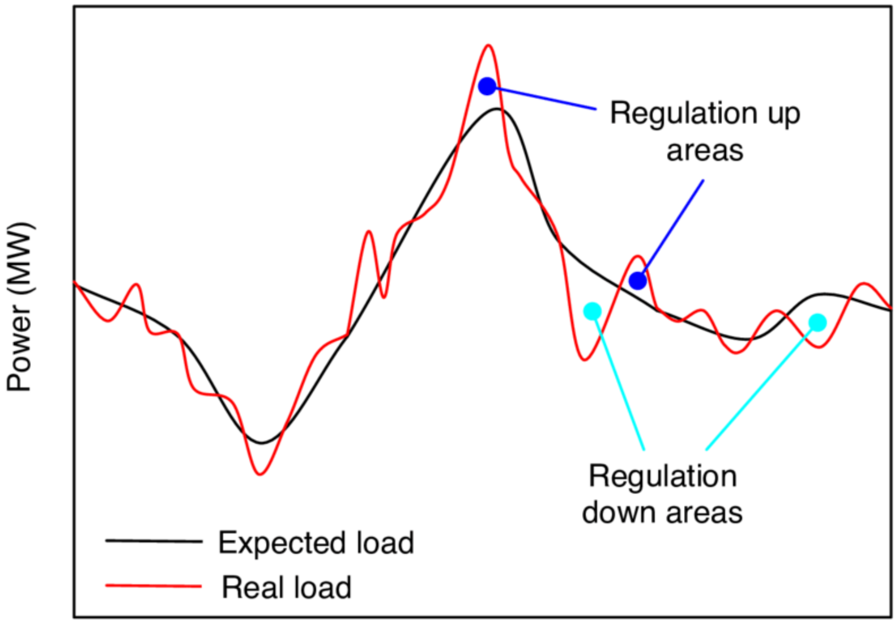


Figure 2.12: Example of Frequency Regulation, retrieved from [30].

   Since frequency regulation is a service of constant need and use, V2G technology is of great value to this service because of its high availability since a fleet of parked EVs can quickly react to the grid's constant needs. Frequency regulation is the most profitable ancillary service and has the highest market value for V2G capable vehicle owners [9, 26, 30].

3. **Spinning Reserve:** Spinning reserve is the ancillary service that helps the grid respond to any sudden and unexpected outage or contingency event. V2G technology's high availability and fast response rate allow EVs to continually provide the grid with an additional generation capacity, thus compensating for any power outage or disruption. This allows the creation of a failure recovery system and reduces the grid backup generation capacity needs. However, spinning reserves are used infrequently and require a large amount of energy in their occurrences, possibly depleting the vehicles' batteries completely, meaning that the overall fit of V2G with this service is good, but not great [9, 26].

- **Power Quality Services** are the services that do not discharge the battery or only require small amounts of battery charge. The ones discussed are: **Reactive Regulation**, **Harmonic Filtering**, **Support for renewable energy integration** and **Motor Starting**.

   1. **Reactive Regulation:** In order to regulate voltage and correct the power factor of high-voltage transmission systems, reactive power needs to be provided to the grid quickly and effectively. Static volt-ampere reactive compensators are the standard method to do this without delay and within an unlimited range, resulting in improved transmission power and transient stability. The bidirectional charger of V2G capable vehicles allows reactive power regulation since its DC-link capacitor is able to supply reactive power to the grid without engaging the EV battery, resulting in no additional battery life degradation. This feature makes the bidirectional charger the perfect option to perform reactive power regulation because it is in its idle mode most of the time (the battery is not drawing active power from the grid), thus capable of injecting reactive power into the grid [26, 29].

   2. **Harmonic Filtering:** Harmonic filters are circuits specially designed to block harmonic currents that originate from high power, non-linear loads. EV chargers inherently produce harmonic currents because of their converter switching, meaning that a successful V2G implementation requires proper filtering measures to solve the harmonic problem. With appropriate control, these chargers can be used as active filters to remove the charger-generated harmonics and other harmonics created by non-linear loads. With proper filtering measures, the own charger converter can act as a variable impedance for each harmonic [26].

3. **Support for renewable energy integration:** V2G technology, with proper management and implementation strategies, opens the door for a solution to mitigate the renewable energy intermittency issue. This technology allows EVs to charge their batteries when renewable energy is generating excessive power and discharge energy to the grid when renewable generation is low. V2G technology also increases the viability of adding more renewable energy sources to the grid, achieving a more sustainable electrical power system [26].
4. **Motor Starting:** Starting most motors requires a large and instant amount of reactive power, and this depletion of reactive power can cause disturbances to the power grid. The sudden need for current during a motor startup causes momentary voltage drops in the adjacent buses of the distribution systems the motor is connected with. V2G capable vehicle charging stations can provide that reactive power, through their AC-DC inverters, in order to start motors flawlessly without briefly harming the grid. This local reactive power injection substantially reduces the reactive power losses in transmission lines since the distribution system does not waste its line capacity by transmitting this type of power [29].

The required energy for each of these services depends on its duration and power demands. Table 2.3 shows the average duration of the V2G services and applications described above, according to [29].

Table 2.3: Average V2G service duration, adapted from [29].

Service	**Duration**
Peak shaving	15 minutes to 2 hours
Frequency regulation	1 to 5 minutes
Spinning reserve	15 to 20 minutes
Reactive regulation	seconds to 5 minutes
Motor Starting	seconds

Peak shaving requires a large amount of energy from the EV, intensively draining its battery during the service. In addition, it can also last a significant amount of time, which may completely discharge the battery, precluding the use of the vehicle as a means of transport until it is recharged. Although of good value, peak shaving is not the most attractive service to V2G capable vehicle owners.

In order to maintain the grid frequency steady, frequency regulation is used. Even though frequency regulation is required several times per day, generally, this service has a short duration, offering great value to EV owners since it requires small amounts of energy, has a brief duration, and allows users to charge their battery between regulations.

Spinning reserve requires immediate power to the grid and generation capacity that can respond within ten minutes to compensate for any contingency event. EV batteries are well suited for this service because of their quick response capability; however, there needs to be a sufficient amount of vehicles connected to the grid and with enough battery to be used as spinning reserves to the system.

Reactive regulation is advantageous to the grid since it improves its power quality. With no additional infrastructure cost, the EV charger can inject reactive power into the grid without even engaging the vehicle battery. This reduces the grid need for local static volt-ampere reactive compensators and creates great net value for both the customer and the grid.

During their startup, motors require a large amount of reactive power. This power can be provided by local EV charging stations, reducing the power system costs in order to compensate for this reactive power need when starting motors [29]. Table 2.4 compares the average value to the cost of these V2G services based on their battery discharge, according to [29].

Table 2.4: V2G services comparison, adapted from [29].

Service	**Value**	**Infrastructure cost**	**Battery discharge**
Peak shaving	3/5	4/5	5/5
Frequency regulation	3/5	4/5	3/5
Spinning reserve	3/5	4/5	4/5
Reactive regulation	2/5	1/5	0/5
Motor starting	2/5	1/5	1/5

2.2.6 V2G Benefits

V2G technology offers a wide array of potential benefits to our present society. These benefits can be divided into three themes, each with its beneficial aspects: Technical, Social and Environmental, and Economic.

- **Technical Benefits:** V2G provides great benefits to the grid's ever-changing needs because of the technology's high availability and adaptability, offering a possible low-cost, high energy capacity solution. As discussed in the previous subsection, a V2G system is an efficient solution for multiple grid needs, improving its quality mainly by providing peak shaving, ancillary services, and other power quality services. These services allow this technology to enhance the quality of the grid power transmission system, reducing its load congestion with high reliability. V2G also eases the integration of renewable energy sources into the grid, which may also improve grid efficiency. The main renewable sources that are integrated into these systems are eolic and PV energy, and these sources are heavily dependent on the current weather, meaning that the efficiency of these energy sources is highly unpredictable. V2G technology improves renewable efficiency by storing the peak excessive renewable power and returning it to the grid during renewable generation off-peaks [9, 16].

- **Social and Environmental Benefits:** As mentioned, V2G offers flexibility for renewable energy integration, which can displace conventional fossil fuel sources and potentially increase the sustainability of the electricity sector, mainly by providing an environmentally friendly approach to the ancillary service market. This can lead to this market decarbonisation since it heavily relies on natural gas to perform its services.
  The technology can also reduce the environmental hazards of the transportation sector. ICEVs heavily dominate the current automobile market, and these vehicles run on fossil fuels and have a very inefficient engine, making them one of the most significant pollution sources, with their CO_2 and GHG emissions and other harmful substances. The migration into EVs and V2G systems helps mitigate this issue by reducing fossil fuel dependency and harmful gas emissions, which translates into a more environmentally friendly transportation sector. Another often overlooked benefit is noise pollution reduction, mainly in urban areas and large cities, since EV engines are almost entirely silent compared to standard internal combustion engines [9, 16].
- **Economic Benefits:** V2G can provide different economic benefits to all the parties involved, affecting not only EV owners but also grid operators and society in general. This technology allows the creation of new income sources by EV owners when their vehicles are not in use, whose primary income is through participation in the ancillary service market, mainly frequency regulation. This also improves the cost-effectiveness of ancillary services, reducing the overall expenses from the grid operator's point of view. V2G also allows the vehicle owner to store energy during low fare periods, like nighttime, and discharge that energy to the grid during peak periods for a higher fee creating revenue from this price difference. This also decreases the grid generation costs, peak power generation strains, and peak period electricity costs, since the prices from EV services are more competitive and flexible than those from traditional generation sources. V2G and EV migration also provide fossil fuel and operation costs reduction, and with the increasing popularity of this technology, massive savings can also be achieved by society in general [9, 16, 31].

In order to study net revenues and emissions savings of V2G technology in the frequency regulation market, Noori et al. conducted a study [32] in five of the biggest independent system operators of the United States of America, depicted in Figure 2.13.
Their model predicted the market share of EVs in these regions by 2030. Based on this prediction, and assuming that 1% of these vehicles are V2G capable, they projected the GHG emission reductions in the frequency regulation market, shown in Figure 2.14. They also projected the net value in these regions over sixteen years per V2G vehicle owner, depicted in Figure 2.15, taking into account possible frequency regulation price changes in the form of error bars. They estimated that hundreds of thousands of climate change emissions in the form of GHG (mainly CO_2) could be avoided in the frequency regulation

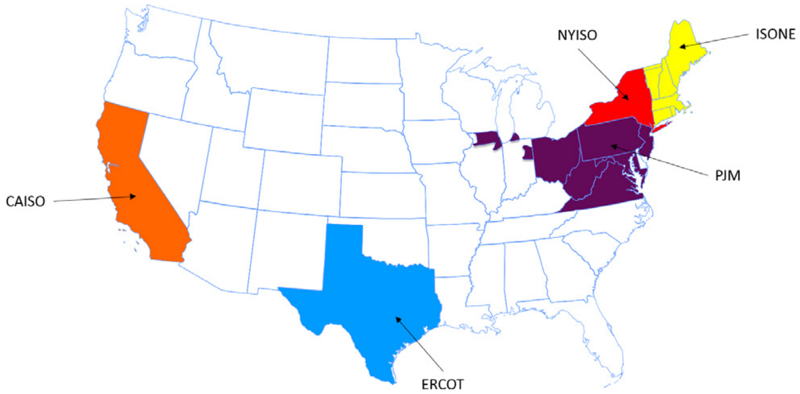


Figure 2.13: The five study regions: California ISO (CAISO), Electric Reliability Council of Texas (ERCOT), PJM Interconnection (PJM), New York ISO (NYISO), and ISO New England (ISO-NE), retrieved from [32].

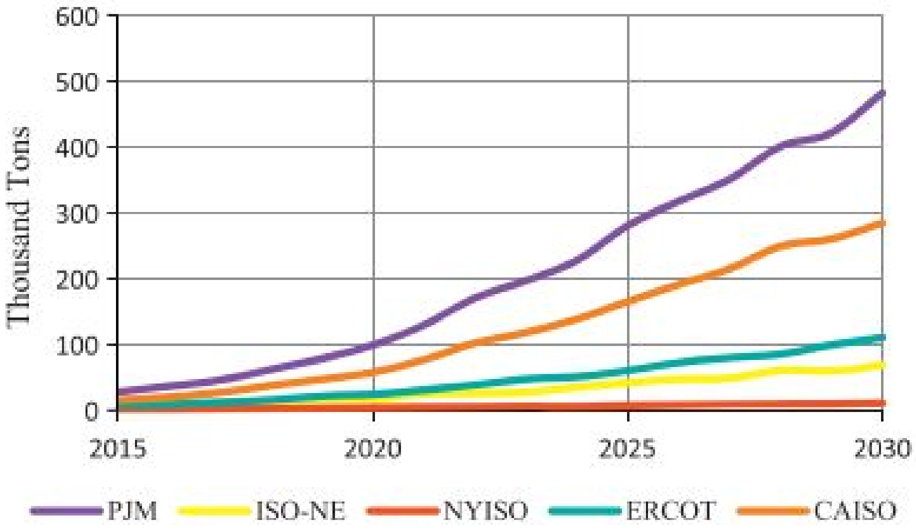


Figure 2.14: GHG emissions savings per region, retrieved from [32].

market, leading to a possible circumvention of almost one million tons of CO_2 by 2030 in these five regions, assuming a measly 1% of the EV market share is V2G capable. This also leads to a positive net revenue per vehicle owner over sixteen years, indicating that frequency regulation can be profitable to V2G vehicle owners. During the projected period, the total net revenues per vehicle owner fluctuated from short of $20,000 to over $45,000 in the five studied regions.

This study concludes that from both an economic and environmental approach, the integration of V2G capable vehicles within the grid could prove to be beneficial. If renewable energy sources are also integrated into the grid, this technology will complement and enhance these benefits [32].

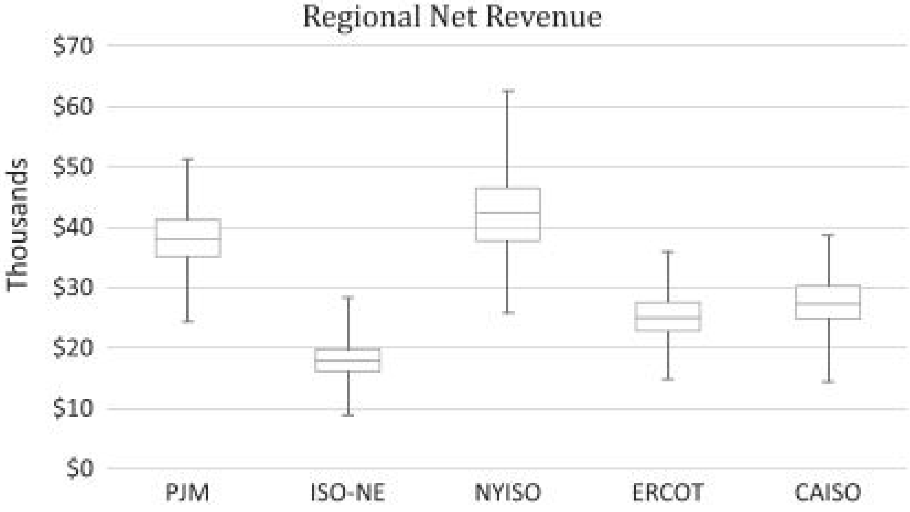


Figure 2.15: Net Revenue per region during a 16 year period, retrieved from [32].

2.2.7 V2G Challenges and Barriers

As seen in the previous subsection, V2G technology has numerous benefits in several areas; however, since it is a recent technology, it also presents several barriers and challenges. Understanding these obstacles is essential in order to improve the technology and enhance its benefits. These drawbacks are categorised into two areas: Technical and Social Economic.

- **Technical Challenges:** The main technical challenge that affects V2G technology is battery degradation since the major factor utilised to evaluate an EV efficiency and viability is its battery capacity. The more capacity, the more distance a vehicle can cover before recharging, so it is paramount to conserve the battery health and capacity to maintain the vehicle's efficiency. With its natural use, a battery ages over time and loses its capacity over the years. Not only this, but the charging and discharging cycles of a battery further reduce its life cycle. The battery's ageing also depends on several factors like its operation temperature, the number of cycles, and the charge and discharge power rates, making battery degradation capacity a complex factor to calculate. With V2G technology, the charging and discharging rates are widespread to fulfil the vehicle energy needs and to support the grid, leading to aggravated wear of the vehicle battery, reducing its capacity, and affecting the overall feasibility of this technology's systems [9, 16, 33].
  With the purpose of evaluating the effects of V2G technology in battery degradation, Wang et al. methodology [33] first started with accessing the averaged battery degradation of EVs without V2G capabilities, depicted in Figure 2.16, assuming regular driving and charging behaviours. Their detailed model was based on two different charging level scenarios: L1 of 1.44 kW and L2 of 7.2 kW.

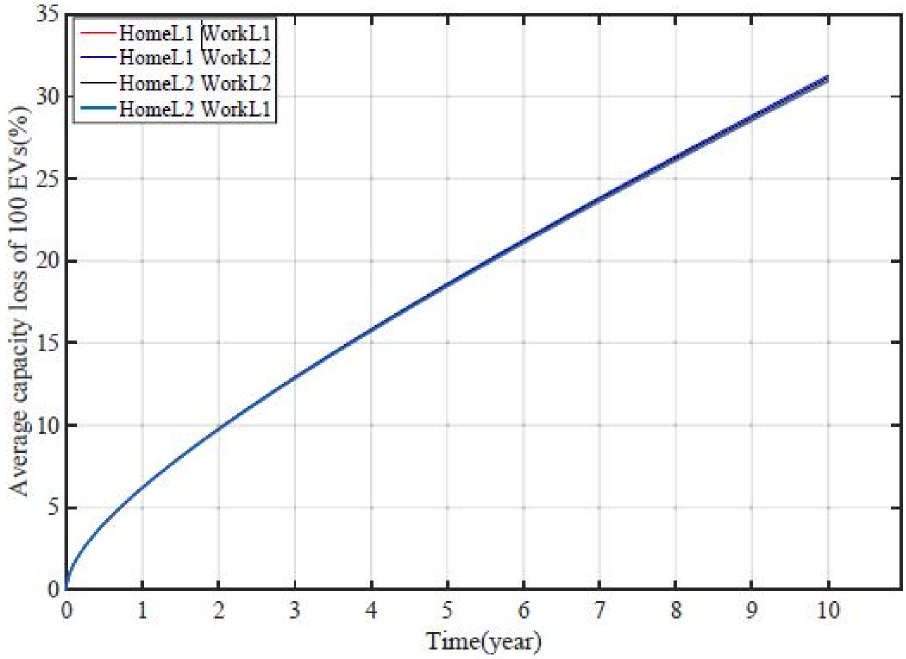


Figure 2.16: Average EV battery degradation over 10 years, retrieved from [33].

They concluded that the average degradation of an EV battery is close to 31%, and the charging level had minimal effects on battery degradation, with L2 having a slightly higher percentage. They also concluded that the battery ageing was faster at the beginning and then flattened at the end. Although the curve is not linear, a mean battery degradation of slightly above 3% per year can be assumed.

In order to understand V2G services' impacts on battery degradation, on top of regular driving and vehicle use, their proposed method was to simulate the impacts of peak shaving, frequency regulation, and netload shaping (also known as load levelling). Each of these services impacts is analysed and separated into two different cases: Extreme cases, where the service is used every day for ten years, and base cases where the service is used twenty times per year. For both cases, the considered hours for the frequency regulation and peak shaving services are from 7:00 pm to 9:00 pm, and for net load shaping, it is considered that this service is required for almost the entire day.

Figure 2.17 shows the battery degradation results during the ten years of the three V2G services considering both the extreme and base case. It is also considered that the end-of-life of the battery is set at 30% degradation of its original capacity.

Analysing the results, it is possible to conclude that in extreme cases, the added capacity losses were about 3.62% and 5.6% for frequency regulation and peak shaving services, respectively. With the net load shaping service, the degradation is much higher because the EV is charging and discharging for almost the entirety of the day. Considering the base case of these services, the results show insignificant added

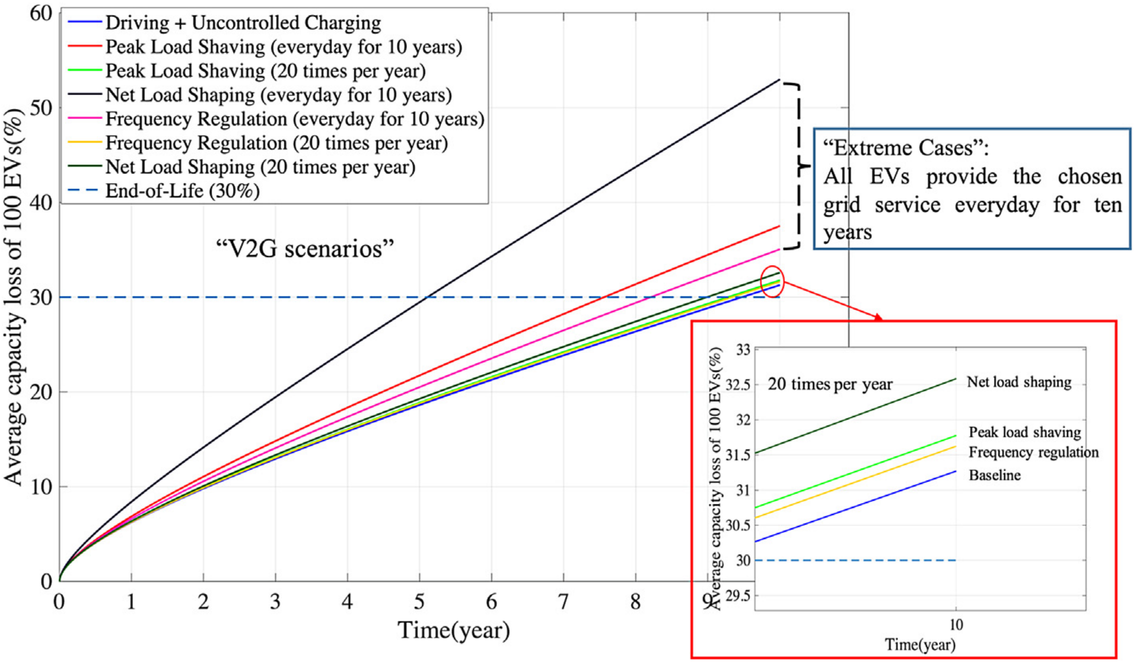


Figure 2.17: Average battery degradation of EVs by performing different V2G services over ten years, retrieved from [33].

impacts on the battery degradation of 0.38%, 0.21%, and 1.18% for peak load shaving, frequency regulation, and netload shaping, respectively. It is also concluded that these services shorten the battery's life by 0.25, 0.19, and 0.51 years, assuming 30% degradation as end-of-life.

It can be concluded that battery degradation is indeed increased with the addition of V2G services; however, this increase is inconsequential compared to the natural battery wear and ageing, which suggests a positive trade-off of V2G services to the grid for revenue, that justifies and compensates the minimal damage to the battery life. Frequency regulation and peak shaving will not significantly increase battery degradation in comparison to regular battery wear over time, even when considering the extreme cases [33].

Even though V2G technology has high efficiency, another technical challenge it faces is the power losses that occur in the system during the charging and discharging processes. Since these losses impact the amount of power that flows from the EV battery to the grid, and vice versa, reducing these electrical losses is critical to increase the technology's efficiency further and achieve the best benefits possible. Apostolaki-Iosifidou, Codani, and Kempton studied these losses [34] in the components of a V2G system for the charging and discharging processes and two different current levels. Their model was calculated considering the temperature, current, and the state of charge of the battery, and the studied components of the system were: the EV battery, EVSE, Power Electronic Unit (PEU), breakers, and transformer. The transformer, breakers, and EVSE are grid-level components, and the EV battery and

PEU are vehicle-level components. Table 2.5 depicts the losses per component in a V2G system during the charging and discharging processes for two different current levels.

Table 2.5: Percentage energy losses in V2G system for charging and discharging at two different current levels, adapted from [34].

Component	AC Current (A)	Charging Losses (%)	Discharging Losses (%)
EV battery	10	0.64	0.64
	40	1.69	1.91
EV PEU	10	6.28	16.67
	40	5.77	19.23
EVSE	10	0.10	1.42
	≈ 40	0.29	1.39
Breakers	10	0.00	2.80
	≈ 40	1.30	0.60
Transformer	10	10.20	14.60
	≈ 40	3.33	6.65
Total	10	17.22	36.13
	40	12.38	29.78

The total losses range from 12% to 36%, and they are higher during discharging when compared to charging. These losses mainly occur in the PEU, which is responsible for the AC-DC conversion, and at the transformer. Since the power loads of the modelled transformer were unusually low, its losses were abnormally higher. Based on this, the transformer losses results were inflated. The authors proposed two solutions to decrease the overall losses of the system, first by adequately sizing the EVSE current and voltage capacity, and second by implementing control algorithms to optimise the efficiency of the system, which proved to decrease overall energy losses by up to 8.5% [9, 34].

- **Social-Economic Barriers:** V2G technology faces some social-economic barriers, Besides the technical challenges described. Replacing an EV battery is quite expensive, and as discussed, V2G services cause further degradation to the vehicle battery, which reduces its life cycle. However, with the increasing popularity of these vehicles, the battery cost tends to decrease with the high volume production of these vehicles. According to BloombergNEF, battery pack prices have decreased by 89% since 2010, from $1,100 per kWh in 2010 to $137/kWh in 2020. They also predicted that by 2023 this number would be close to $100/kWh [35].
  Since V2G systems require high investments and infrastructure changes, they can be considered risky investments. For all the parties to communicate and exchange energy mutually, high investments need to be made at the infrastructure level in the form of plug-in connectors, bidirectional converters, and metering equipment. Also, for the bidirectional flow of energy to happen, highly efficient communication

systems need to be established to connect all the involved sides in real-time. Besides this, to affect and benefit the grid and its large markets, aggregation needs to happen to connect the thousands of EVs seamlessly together. Aggregating this large amount of vehicles together is quite complex and requires strict control algorithms in order to maximise the system outputs and the involving parties' revenues because of the stochastic nature of EVs.

Another barrier that this technology faces is the privacy and security concerns of EV owners since there is a constant bidirectional exchange of information between the grid and them. By analysing the vehicle's travelling pattern, one can access the vehicle owner's work and home addresses, which can also expose his identity. However, some new privacy policies are being implemented that offer data protection for the owners, anonymising and randomising the user data, relieving the vehicle owners of any possible privacy and security concerns [9, 16, 36].

Since V2G is a recent technology, there are some challenges and barriers that affect it. Understanding these obstacles is vital to evolve and improve this technology since we need to understand its current problems in order to overcome them. As shown in this subsection, the technology's challenges and barriers can be improved and mitigated with specific optimisation techniques. As technology evolves, these obstacles become increasingly more minor and insignificant.

2.2.8 Discussion and Conclusions

Throughout this section, V2G technology has been thoroughly desiccated. Even though it is a recent and evolving technology that originated in the late years of the 20th century, it can benefit the several involved parties and society through the services it can provide, as shown in Figure 2.18.

In brief, V2G is the concept of the bidirectional power flow between EVs and the electrical grid, and the technology can provide several services to the grid according to its needs. A V2G system is typically composed of several aggregated and bidirectionally connected vehicles, that communicate with the electrical grid through a third-party aggregator, and a metering infrastructure to audit the two-way power flows.

There are several other concepts derived from this technology, which are classified based on the receiving end of the bidirectional power flow with the grid, like V2B and V2V, leading to the creation of the V2X concept.

The primary electricity market that this technology affects is the ancillary service market, which is responsible for supporting reliable and efficient power transmission from generation to consumers. In this market, the most profitable service V2G technology can perform is frequency regulation, with spinning reserve and peak shaving also being of suitable employment, depending on the conditions. Although of lesser value, other power quality services like reactive power regulation and harmonic filtering can be achieved with this technology, with minimal battery usage and additional infrastructure cost.

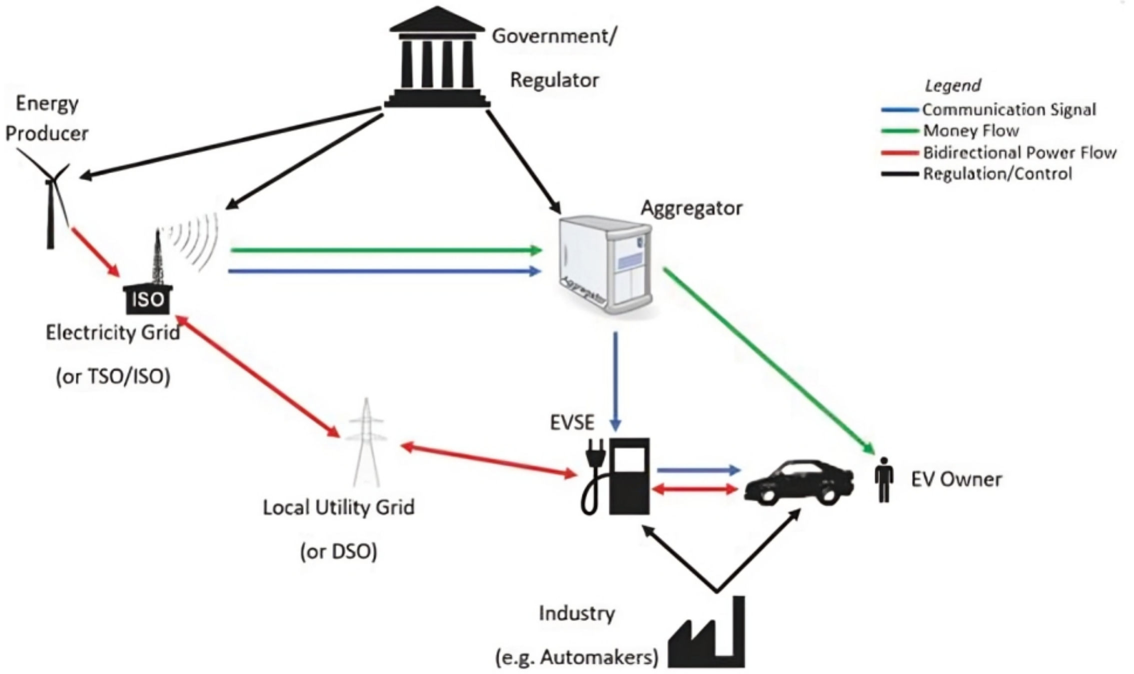


Figure 2.18: Schematic of the involved parties in a typical V2G system, retrieved from [9].

V2G technology potential benefits can be separated into three categories: Technical, Social Environmental, and Economic. The aggregated EVs' power capacity acts as cheap and quick storage means that can provide multiple services to the grid and ease the integration of renewable energy sources. V2G leads to the decarbonisation of the transportation sector, mainly by replacing typically ancillary service sources that rely on non-renewable energies for their functioning, reducing the fossil fuel dependency, on top of the reduction already associated with EV diffusion. This technology also provides numerous economic benefits to all the involved parties, mainly by creating new income sources for the technology-capable vehicle owners and reducing the grid generation costs.

However, a V2G transition is not easy, especially being such a recent technology, and there are some barriers and challenges that need to be overcome to enhance the benefits and improve the technology. These obstacles are divided into technical challenges and social-economic barriers. The main technical challenge affecting this technology is battery degradation; however, as studied, the technology-associated services add minimal battery life wear on top of natural wear, and the remuneration compensates for the decrease in the battery life caused by these services offered to the vehicle owner. The significant social-economic barriers of V2G technology are the high battery replacement prices and the high initial infrastructure costs of these systems. However, with the advances in this technology, these challenges and barriers can be mitigated, increasing the diffusion and attractiveness of the technology to vehicle owners.

In summary, V2G technology can be of great benefit to the involved parties, and it is expected in the near future that the adoption of this technology will increase, with an example being the transition to this technology by Tesla, which is the current most valuable automaker in the world and specialises in manufacturing EVs [37].

2.3 Buggy-To-Grid (B2G)

Even though Buggy-to-Grid is not a scientifically acknowledged term, for the purpose of this thesis and to ease the text interpretation, the abbreviation B2G will be used when referring to the implementation of V2G technology with golf buggies. Although of lower battery capacity, the grid-connected buggies are able to provide most of the V2G services that regular personal vehicles allow. However, to compete in larger electricity markets, the number of aggregated buggies needs to be substantially higher to compensate for their lower battery storage.

As previously mentioned, V2G is a highly efficient, quick and cheap energy storage technology, and because of its nature, there have been several recent studies to assess the viability of this concept for other vehicles besides regular personal vehicles, like vans [38] school buses [39], delivery trucks [40] and garbage trucks and city buses [41].

With the development of the technology and the projected diffusion and consequent electrification of the transportation sector, several other vehicles are expected to be subject to V2G feasibility studies in the future, like motorcycles, boats, and planes [9].

The implementation of this technology and a PV system in the golf resorts ecosystems will act as a microgrid. Microgrids are defined as intelligent and self-sufficient energy systems composed of generators that operate as a single aggregated load, energy storage components, and a control unit. Microgrids tend to use renewable energy sources, mainly PV and eolic energy as their distributed energy resources. Microgrids also ease the integration of large fleets of EVs in the system because of their smart technologies and control units, which allow the coordination of the vehicles charging [42].

3

METHODOLOGY

This thesis aims to evaluate the integration V2G technology and a self-consumption PV system into microgrids with a strong EV (in the form of golf buggies) penetration. The schematic of the proposed methodology to be implemented is depicted in Figure 3.1.

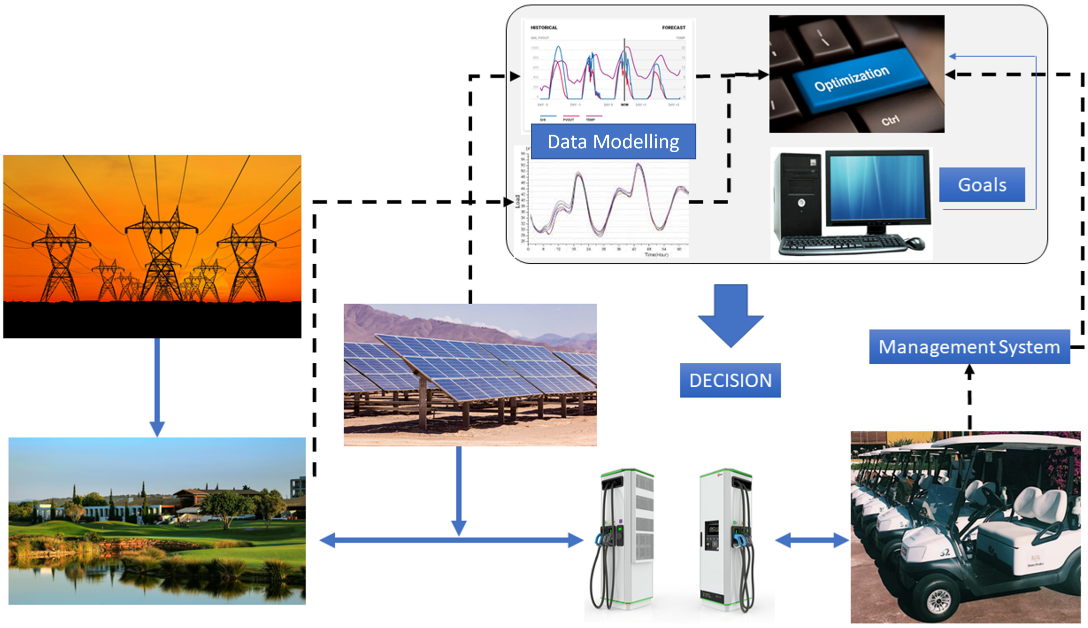
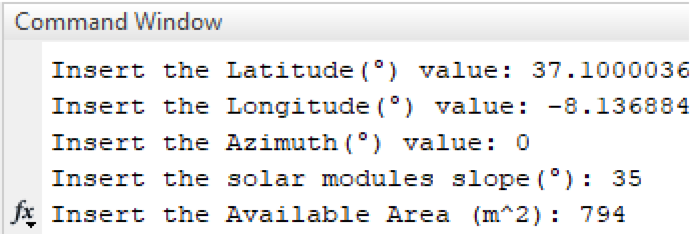


Figure 3.1: Schematic of the proposed methodology implementation.

The proposed idea is that V2G capable buggies will be connected to their respective EVSE at the golf resort, which is then connected to the power grid. The PV system will ease the integration of the V2G technology into the golf courses, which will be used to support two-way power flows. The PV system energy production and the golf resort energy consumption data are used to develop a simulation model, in addition to the bidirectional capable buggy management system data, with an end goal of producing an optimised decision about the most viable implementation of the system, according to a set of goals. This methodology is achieved through the development of a simulation model in Matlab, whose purpose is to analyse and simulate the integration of V2G technology and a PV system into the golf courses ecosystem to assess the viability of this implementation. This tool automatically retrieves solar information from PVGIS, estimates the total PV power that can be generated, performs the golf courses energy analysis, depicts the power flows between the golf resort's generations and consumptions and studies the possible V2G technology usage and integration by the golf buggies into the resort's energy demands, and performs an economic and energy analysis of the system, all of these based on the user's input data. Figure 3.2 depicts an example of the user input data process, and Figure 3.3 depicts a block diagram that describes the main operating steps of the developed simulation model.



```
Insert the Latitude(°) value: 37.1000036
Insert the Longitude(°) value: -8.136884
Insert the Azimuth(°) value: 0
Insert the solar modules slope(°): 35
Insert the Available Area (m^2): 794
```

Figure 3.2: Example of user input for the simulation model.

The essential steps to fulfil these work objectives and develop the simulation model are the following:

- **Solar resource characterisation -** in which the golf courses' geographic data, as well as temperature and solar irradiance values, are analysed.
- **PV study -** where an optimal PV system implementation is studied based on the solar resource characterisation data.
- **Economic and Energy Analysis and Optimisation -** this phase aims to assess the economic and energy viability of the system optimally.

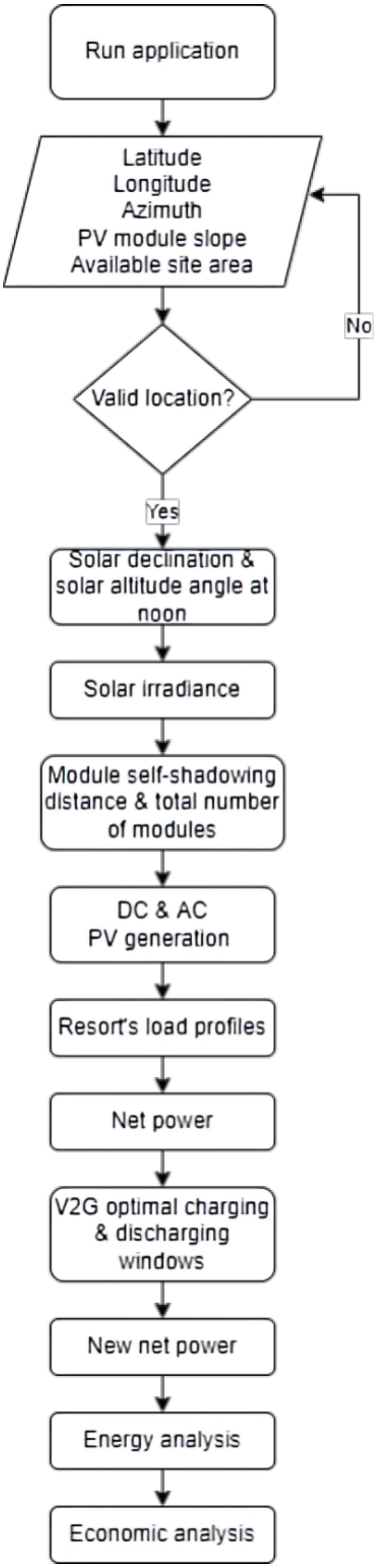


Figure 3.3: Block diagram of the main operating steps of the developed simulation model.

3.1 Solar Resource Characterisation

In order to analyse and implement solar PV systems, it is paramount to know how much sunlight is available at the system location. It is imperative to accurately predict the sun's position in the sky at any given location and day of the year to optimise a PV installation. With this information about solar angles, and with the help of PVGIS, it is possible to know the solar irradiance for a specific location, during a certain time interval, in order to implement and develop a PV system. In this subchapter, the solar resource algorithm is described to estimate solar irradiance and develop the simulation model.

3.1.1 Solar Declination

Earth's spin axis is currently tilted by 23.45°with the ecliptic plane, as seen in Figure 3.4. This axial tilt is responsible for the Earth's seasons, equinoxes and solstices [43].

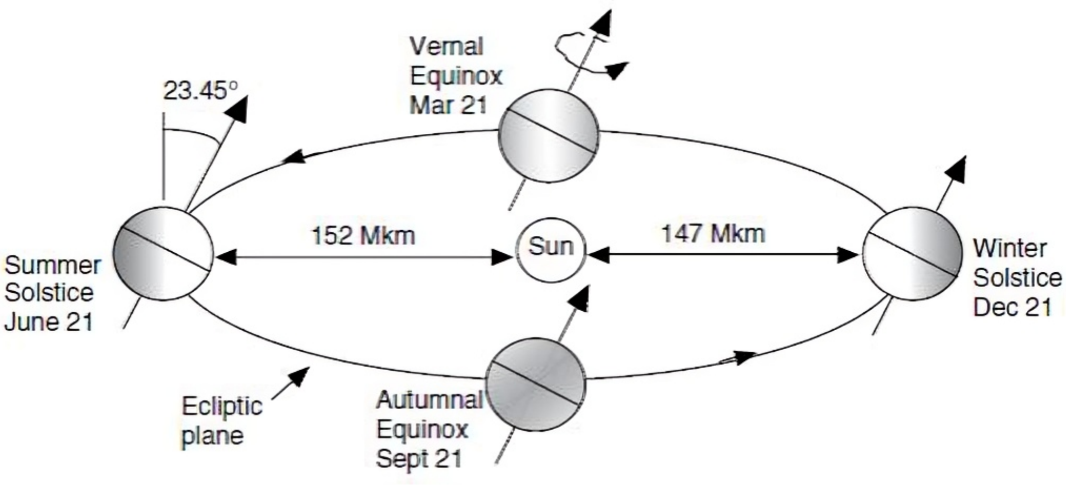


Figure 3.4: Earth's spin axis tilt with respect to the ecliptic plane, retrieved from [43].

Solar declination (δ) is the angle formed by the imaginary line that unites the sun's centre with the centre of the Earth and the Equator plane. It has a sinusoidal variation per 365-day year, fluctuates between ±23.5°, and is given by Equation 3.1:

$$\delta = 23.45^\circ \times \sin\left(\frac{360^\circ}{365}(n-81)\right) \tag{3.1}$$

with n being the current day of the year. The solar declination is minimum in the Winter solstice, 21st of December, which corresponds to the longest night of the year, and it is maximum in the Summer solstice, 21st of June, which in turn correlates to the longest day of the year. During equinoxes, the solar declination is equal to zero [43]. Figure 3.5 shows a representation of solar declination.

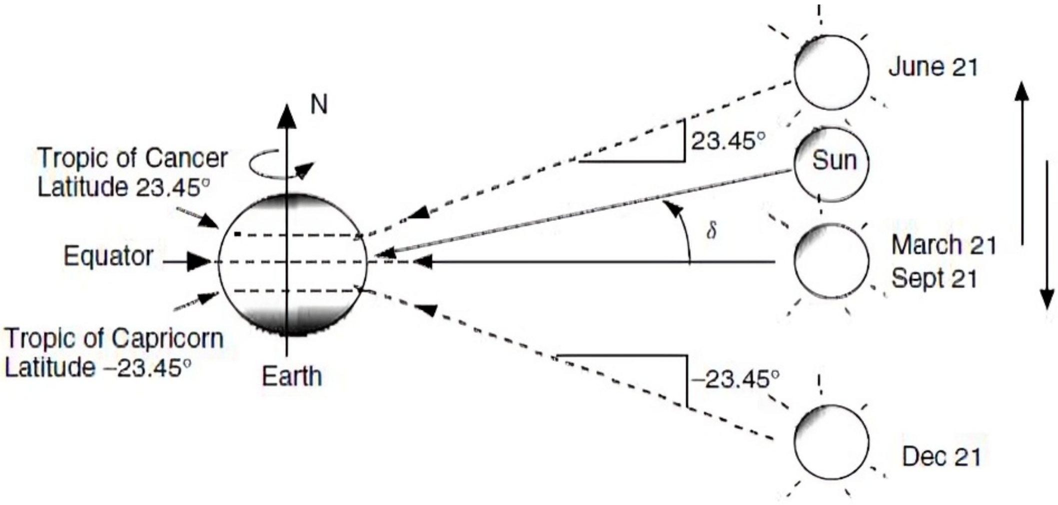


Figure 3.5: Representation of the solar declination angle between the sun and the equator, retrieved from [43].

3.1.2 Solar Altitude Angle at Noon

Solar altitude angle at noon (β_N) is the angle between the Earth's horizon plane and the sun, and is given by Equation 3.2:

$$\beta_N = 90° - L + \delta \tag{3.2}$$

where L is the Latitude. Figure 3.6 shows a representation of the solar altitude angle at noon, along with a representation of the term Zenith which refers to the axis overhead the site [43].

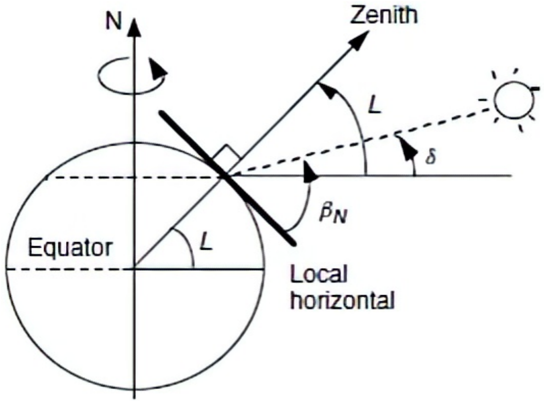


Figure 3.6: Representation of the altitude angle at solar noon, retrieved from[43].

3.1.3 Module Distance to Avoid Self-Shadowing

The altitude angle at solar noon is needed to calculate the distance each module needs to be from each other in order to avoid module self-shadowing. This distance (d) can be calculated through Equation 3.3

$$d = b \times (\cos(\alpha) + \frac{sin(\alpha)}{\tan(\beta_N)}) \tag{3.3}$$

with b being the module length, α the module inclination and β_N the minimum tolerable solar altitude angle at noon at the winter solstice [43].

3.1.4 Solar Module Implementation Area

With this distance calculated and with the module width from the data-sheet, it is possible to calculate the implementation area of each module (A_{Module}) through Equation 3.4

$$A_{Module} = d \times l \tag{3.4}$$

with l being the module width [43].

3.1.5 Maximum Number of Solar Modules

Taking into consideration the total available site area to implement the PV system, the number of modules that can be deployed (N) is given by Equation 3.5

$$N = \frac{A_{Total}}{A_{Module}} \tag{3.5}$$

with A_{Total} being the total available area [43].

3.2 PV Study

In order to estimate the total PV power to be installed on the site, the modules and inverter characteristics (which vary between manufacturers) need to be accounted for. These characteristics are determined in a laboratory in Standard Test Conditions (STC), which are the industry standard conditions in which a PV module is tested. These conditions are the following:

- Solar irradiance of 1 kW/m^2;
- Solar cell temperature of 25 ºC.

Besides these standardised conditions, manufacturers typically provide an indicator called NOCT (Nominal Operating Cell Temperature), which corresponds to the cell temperature in the following conditions:

- Solar irradiance of 0.8 kW/m^2;
- Solar cell temperature of 20 ºC;
- Wind speed (parallel to the cell plane) of 1m/s.

In this subsection, the PV study algorithm is described in order to size the adequate PV installation to develop the simulation model [43].

3.2.1 Solar Cell Temperature

With these parameters, the cell temperature (T_{cell}) can be calculated through Equation 3.6

$$T_{cell} = T_{amb} + \frac{NOCT - 20°C}{0.8\ (\mathrm{kW/m^2})} \times G \tag{3.6}$$

where T_{amb} is the ambient temperature, $NOCT$ is the nominal operating cell temperature, and G is the irradiance [43].

3.2.2 DC Power Calculation

With T_{cell} calculated, it is possible to estimate the maximum PV module power only taking into account irradiance variations, with a cell temperature of 25 °C ($P(G, 25°C)_{max}$), per Equation 3.7

$$P(G, 25°C)_{max} = \frac{P_{STC} \times G}{1\ (\mathrm{kW/m^2})} \tag{3.7}$$

where P_{STC} is the module's maximum peak power at STC conditions. Finally, the maximum DC power of a PV module ($P_{DC_{Max}}$) can be calculated for any given irradiance and cell temperature through Equation 3.8

$$P_{DC_{max}} = P(G, 25°C)_{max} \times (1 + \alpha_p \times \Delta_T) \tag{3.8}$$

where $P(G, 25°C)_{max}$ is the maximum PV module power at a cell temperature of 25 ºC, α_p is the module temperature coefficient of power, and Δ_T is the difference between the cell temperature and 25 ºC. In order to calculate the actual DC power (P_{DC}) from the PV modules to the solar inverter, the DC power losses must be subtracted according to Equation 3.9

$$P_{DC} = P_{DC_{max}} \times (100\% - P_{DC_{Losses}}) \tag{3.9}$$

where $P_{DC_{Losses}}$ are the DC power losses in percentage [43].

3.2.3 AC Power Calculation

After this, the maximum AC power ($P_{AC_{Max}}$) is calculated by multiplicating the DC power with the inverter efficiency through Equation 3.10

$$P_{AC_{max}} = P_{DC} \times \eta_{inverter} \tag{3.10}$$

in which $\eta_{inverter}$ is the solar inverter efficiency, in percentage. Finally, in order to calculate the AC power that each PV module can inject into the grid (P_{AC}), the AC losses must be taken into consideration according to Equation 3.11

$$P_{AC} = P_{AC_{max}} \times (100\% - P_{AC_{Losses}}) \tag{3.11}$$

where $P_{AC_{Losses}}$ are the AC losses in percentage [43].

3.2.4 Total Available AC Power

With the knowledge of the AC power that each module can inject into the grid, the total installed PV power ($P_{AC,Total}$) can be calculated per Equation 3.12

$$P_{AC,Total} = P_{AC} \times N \tag{3.12}$$

with N being the total number of PV modules that can be installed on the site [43].

3.2.5 Solar Inverter Compatibility

Different topologies can be employed according to the PV system dimensions regarding the solar inverter. The inverter nominal power ($P_{inv,DC}$) must be between a set of values according to Equation 3.13

$$70\% \times P_{FV,peak} < P_{inv,DC} < 120\% \times P_{FV,peak} \tag{3.13}$$

where $P_{FV,peak}$ is the total installed maximum peak power at STC conditions [43].

3.3 Economic and Energy Analysis and Optimisation

In order to evaluate the viability of the project, financial indicators and metrics are typically utilised to assess its rentability over its investment period. Not only this but also to evaluate the energy feasibility and efficiency of a project, specific indicators and ratios are also utilised to perform this evaluation. In order to evaluate this study's practicality and implementation, the following metrics were taken into consideration [44].

3.3.1 Net Present Value

The net present value (NPV) quantifies the concept of the time value of money and takes into consideration that the cash flows spent or obtained in the future will have a different value than the present-day cash flows, according to a discount rate, and is given by Equation 3.14

$$NPV = \sum_{t=1}^{t} \frac{CF_t}{(1+r)^t} - I_0 \tag{3.14}$$

where t is the investment year, CF_t is the cash flow at year t, r is the discount rate, and I_0 are the initial investment costs [44].

3.3.2 Internal Rate of Return

The internal rate of return (IRR) corresponds to the discount rate that makes the NPV of a project equal to zero, meaning that if the IRR is superior to the discount rate, then the project is viable, and is given by Equation 3.15

$$0 = \sum_{t=1}^{t} \frac{CF_t}{(1+IRR)^t} \tag{3.15}$$

where t is the investment year, and CF_t is the cash flow at year t [44].

3.3.3 Payback Period

The payback period (PP) indicates the period of time that a project takes in order to recover the initial capital investment of a project completely, and is given by Equation 3.16

$$\sum_{t=1}^{PP} \frac{CF_t}{(1+r)^t} > I_0 \tag{3.16}$$

where t is the investment year, CF_t is the cash flow at year t, r is the discount rate, and I_0 are the initial investment costs [44].

3.3.4 Levelized Cost of Energy

The levelized cost of energy ($LCOE$) defines the cost to produce energy based on a determined technology, in this case, a PV installation, considering the investment period of the project, and is given by Equation 3.17

$$LCOE = \frac{I_0 + \sum_{t=1}^{t} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \tag{3.17}$$

where t is the investment year, r is the discount rate, I_0 are the initial investment costs, C_t are the total costs in year t and E_t is the total energy produced in year t [44].

3.3.5 Performance Ratio

The performance ratio (PR) is one of the most applied energy criteria to evaluate a PV installation. It consists of the reason between the annual generation of the installation, and the yearly generation in ideal STC conditions, and is given by Equation 3.18

$$PR = \frac{E_{FV}}{H \times A_{FV} \times \eta_{STC}} \times 100 \tag{3.18}$$

where E_{FV} is the total PV energy generated in a year, H is yearly irradiation in the PV modules plane, η_{STC} is the solar panels' efficiency at STC conditions, and A_{FV} is the total area of installed solar modules [44].

3.3.6 Self-Consumption Ratio

The self-consumption ratio (SCR) represents the fraction of annual energy generated that is self-consumed in the prosumer installation, and is given by Equation 3.19

$$SCR = \frac{E_{FV} - E_{inj}}{E_{FV}} \times 100 \tag{3.19}$$

where E_{FV} is the total PV energy generated in a year, and E_{inj} is the energy injected into the grid when the generation exceeds the consumption [44].

3.3.7 Self-Sufficiency Ratio

The self-sufficiency ratio (SSR) quantifies how much the generated energy covers the prosumer annual energy needs, and is given by Equation 3.20

$$SSR = \frac{E_{FV} - E_{inj}}{E_{cons}} \times 100 \tag{3.20}$$

where E_{FV} is the total PV energy generated in a year, E_{cons} is the annual prosumer consumption needs and E_{inj} is the energy injected into the grid when the generation exceeds the consumption [44].

3.3.8 Benefit-Cost Ratio

The benefit-cost ratio (BCR) represents the ratio between the present-day revenues and the present-day costs of a project, and is given by Equation 3.21

$$BCR = \frac{\sum_{t=1}^{t} \frac{CF_t[Benefits]}{(1+r)^t}}{\sum_{t=1}^{N} \frac{CF_t[Costs]}{(1+r)^t}} \tag{3.21}$$

where $CF_t[Benefits]$ represent the cash flows of the project revenues, and $CF_t[Costs]$ represent the cash flows of the project costs [44].

4

CASE STUDY

In this chapter, the Dom Pedro Victoria Golf Course case study is presented, starting with a description of the course and the calculation of the solar angles at the course location. Afterwards, the electricity tariffs of the resort are analysed and depicted, following a tetra-hourly rate. After this, and according to the data from the golf buggy management provided by the golf resort, the driver and buggy characterisation are analysed. Then an analysis is performed on the course average daily load profiles and the monthly energy consumption. Similarly, the average daily and average monthly irradiation values are obtained. The average daily and monthly PV generation data is calculated following the irradiation values. In order to increase the authenticity of this study, several losses were applied to the generation data to depict a real scenario. The load profile and PV generation data are summarised in tables for their average daily and average monthly values, and then they are differentiated by their corresponding electricity tariff for their monthly values.

4.1 Golf Course Site

The Dom Pedro Victoria Golf Course, depicted in Figure 4.1, was designed by golf legend Arnold Palmer, and it is considered one of the best golf courses in Europe, hosting the Portugal Masters since 2007, and has served as the central stage for the World Cup Championships in 2005. With an area of about 90 hectares and housing 60 electric buggies, the venue is located in Caminho da Fonte do Ulme, Zip code 8125-406 Vilamoura, in the Algarve Region, and it is one of the most complex golf courses in Europe, requiring considerable amounts of electric energy, along with water and fossil fuels to correctly operate [45].

Figure 4.1: Dom Pedro Victoria Golf Course, retrieved from [45].

The Dom Pedro Victoria Golf Course coordinates are **latitude: 37.100036°** and **longitude: -8.136884°**, with latitude being the distance to the Equator along the Greenwich Meridian, and longitude the distance to the Greenwich Meridian along the Equator. Since the site takes place in the Northern hemisphere, and with a Latitude above the Tropic of Cancer (23.45°), the installation PV **Azimuth (ϕ_{PV})** is equal to 0°, meaning that the PV panels should be displayed facing South. Table 4.1 depicts the Dom Pedro Victoria Golf Resort geographical data, and its solar angles calculated through Equation 3.1 and Equation 3.2.

Table 4.1: Site solar angles and geographical data.

Latitude (°)	**Longitude (°)**	**PV Azimuth (°)**	**PV slope (°)**	**Solar Declination (°)**	**Solar noon altitude (°)**
L	L_{ong}	ϕ_{PV}	α	δ_{min} | δ_{max}	$\beta_{N_{min}}$ | $\beta_{N_{max}}$
37.100036	-8.136884	0 (facing South)	35	-23.45 | 23.45	29.449964 | 76.349964

With the data from Table 4.1, it is now possible to retrieve the average daily global solar irradiance data for the golf resort site using PVGIS.

4.2 Electricity Tariffs

Since the Dom Pedro Victoria Golf Course has such high load demands, it is framed in the Special Low-Voltage (SLV) electricity market regimen, precisely tetra-hourly rate. At this rate, the electricity tariffs are the following: Super Off-Peak, Normal Off-Peak, Half Peak, and Peak [46].

For this study, the daily tetra-hourly rate was chosen to be implemented, and it is depicted in Figure 4.2.

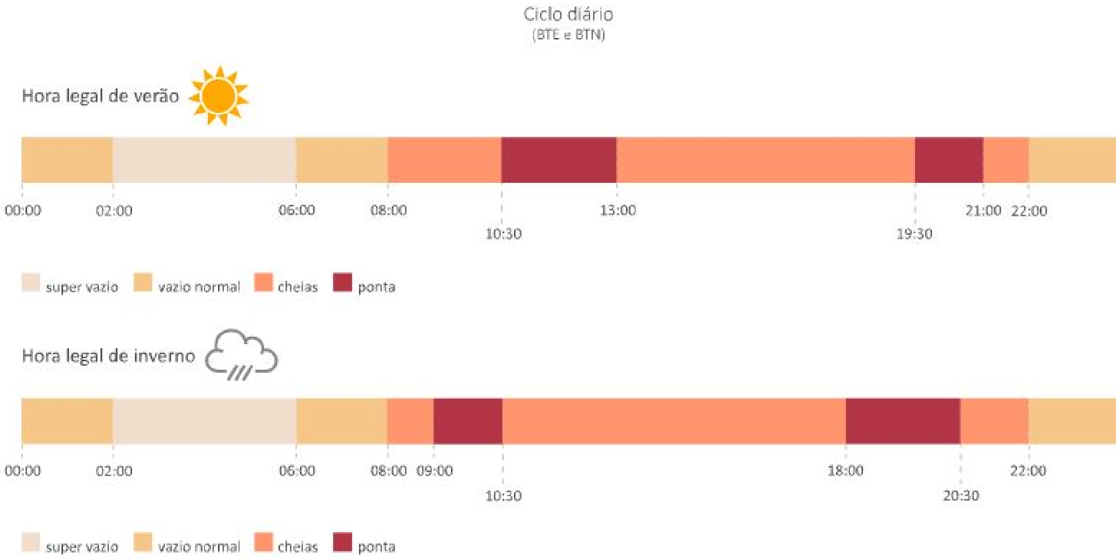


Figure 4.2: Daily tetra-hourly electricity cycle, retrieved from [46].

As it can be observed, the tetra-hourly rate is divided into two daily cycles for the legal winter hour and the summer legal hour. The winter legal hour occurs from the first Coordinated Universal Time (UTC) hour of the last Sunday of October to the first UTC hour of the last Sunday of March. Contrarily the summer legal hour occurs from the first UTC hour of the last Sunday of March to the first UTC hour of the last Sunday of October [47]. To simplify this study, it was assumed that the winter legal hour would occur from November through March and that the summer legal hour would occur from April through October, inclusively.

Another simplification that had to be made to conduct this study was the alteration of the Half Peak and Peak tariff periods since load data of the golf resort was acquired in hourly and not half-hourly periods. Figure 4.3 depicts the utilised tetra-hourly electricity cycle. For the chosen electricity rate, the price per kilowatt-hour for each tariff is represented in Table 4.2.

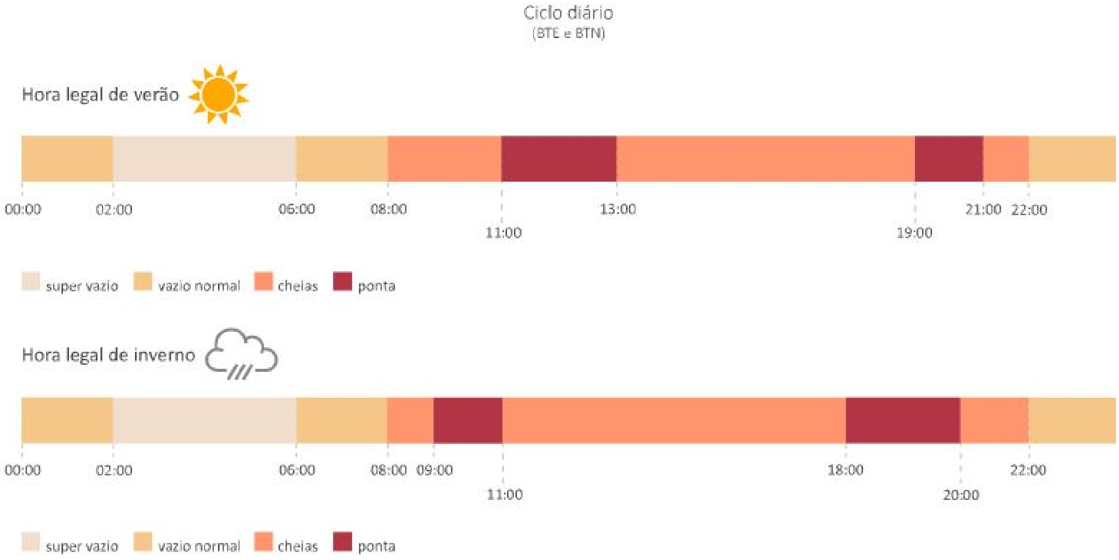


Figure 4.3: Daily tetra-hourly electricity cycle utilised, adapted from [46]

Table 4.2: Electricity tariff prices, data from [48].

Super Off-Peak (€/kWh)	Off-Peak (€/kWh)	Half Peak (€/kWh)	Peak (€/kWh)
0.0812	0.0923	0.1358	0.2164

4.3 Driver and Buggy Characterisation

Following the most recent data from the golf resort, the golf course has 7623 buggy utilisation per year, 5112 on weekdays and the remaining 2511 on weekends. By dividing the yearly buggy usage data by the number of days in a year, we can assume an approximate use of 21 golf buggies per day, meaning that, on average, there are 39 free buggies to be discharged at the same time; however, it is considered that the buggies interchange with each other throughout the day in order to minimise battery damage.

The Dom Pedro Victoria Golf Course has a golf buggy fleet of 60 vehicles. Each buggy has six 8V lead-acid batteries with 170 Ah (C20) capacity, and each typically consumes on average 4 kWh per usage. The battery capacity of these buggies is 8.160 kWh, and it takes 10 hours to fully charge or discharge them, according to the provided data. However, since these are lead-acid batteries, in order to preserve the state of the batteries, it was assumed that these batteries would never discharge when below a 50% threshold of their maximum capacity, resulting in a buggy autonomy of 4.08 kWh for 10 hours, or 0.408 kWh per hour. A total buggy fleet load of 15.912 kWh per hour to be charged and discharged is obtained by multiplying this value by the average number of available buggies.

4.4 Load Profile and Energy Consumption Data

The Dom Pedro Victoria Golf Course load profiles and energy consumption data are exposed in this section. Since golf is predominately a seasonal leisure activity, along with the fact that Algarve is a well-known tourist destination mainly due to its hot weather, the load profiles are higher during the summer months and the typical vacation months in Europe, like July, August and September. Conversely, the load profiles are lower during the coldest months and the months with the most negligible tourist incidence, like December, January and February. The month with the most prominent energy consumption is August, and contrariwise December is the month with the lowest consumption.

Figure 4.4 depicts the average daily load profile for the month of August, which is the month with the most significant load profile. Figures I.1 to Figure I.11 depict the average daily load profile for the remaining months and are displayed in Annex I. Figure 4.5 portrays the monthly energy consumption for a whole year, Table 4.3 represents the daily and monthly energy consumption values, and Table 4.4 depicts the monthly energy consumption data per electricity tariff.

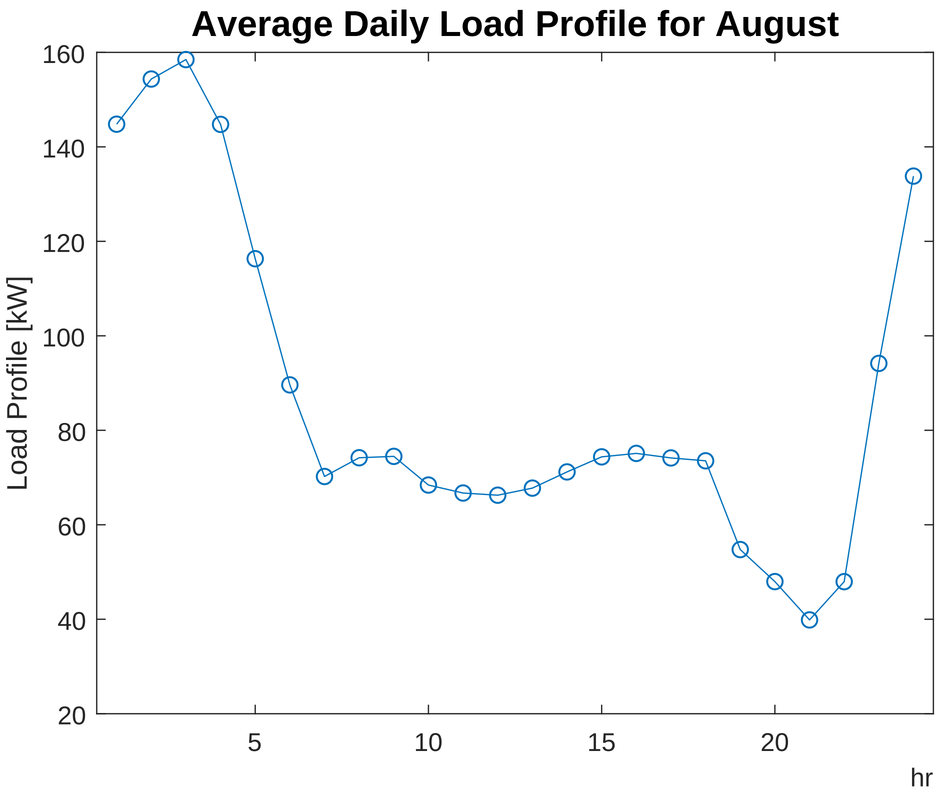


Figure 4.4: Average daily load profile for the month of August.

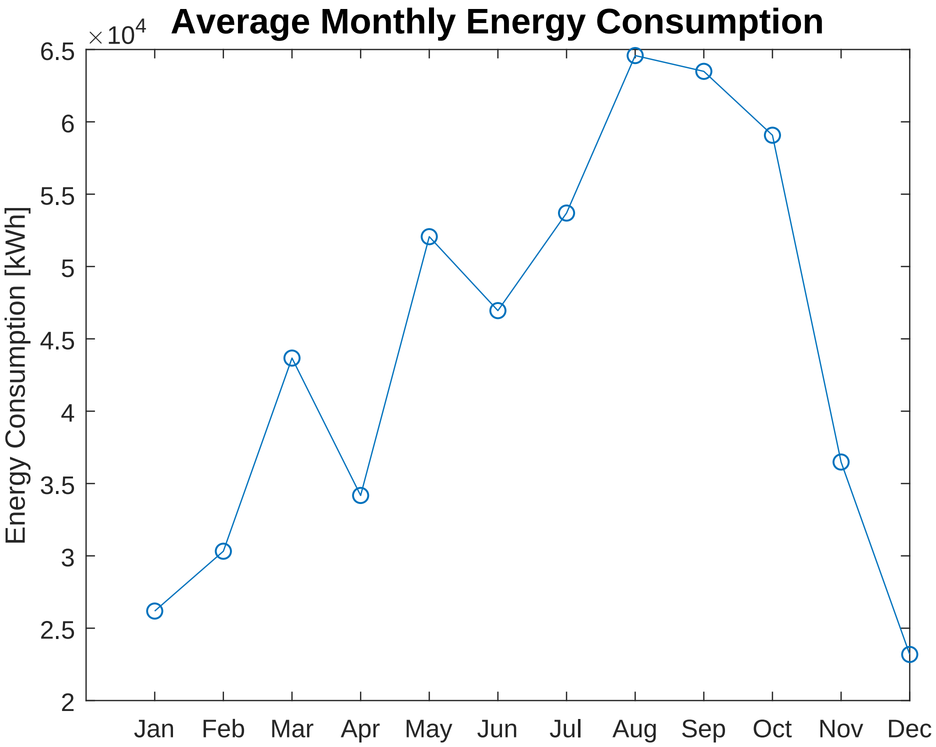


Figure 4.5: Average monthly energy consumption.

Table 4.3: Average Daily and monthly energy consumption.

	Average Daily Energy Consumption (kWh)	**Average Monthly Energy Consumption (kWh)**
January	844.68	26185.08
February	1082.88	30320.64
March	1408.75	43671.25
April	1139.18	34175.40
May	1679.43	52062.33
June	1565.03	46950.90
July	1732.10	53695.10
August	2083.25	64580.75
September	2116.31	63489.30
October	1905.62	59074.22
November	1216.19	36485.70
December	747.91	23185.21
Total		533875.88

Table 4.4: Monthly energy consumption per electricity tariff.

	Super Off-Peak Energy Consumption (kWh)	**Off-Peak Energy Consumption (kWh)**	**Half Peak Energy Consumption (kWh)**	**Peak Energy Consumption (kWh)**
January	3045.44	6377.94	11742.49	5019.21
February	4284.56	6486.48	13650.84	5898.76
March	8530.58	12090.93	16232.53	6817.21
April	4548.90	5934.30	17280.90	6411.30
May	12413.64	16723.57	16993.89	5931.23
June	3766.20	10659	22391.10	10134.60
July	10802.26	17661.63	19394.22	5836.99
August	15784.27	20817.74	21101.39	6877.35
September	12858	17991.30	24163.20	8476.80
October	10937.73	12513.15	26062.63	9560.71
November	3862.80	7605.90	18524.10	6492.90
December	3100	4917.84	10996.63	4170.74
Total	93934.38	139779.78	218533.92	81627.8

4.5 Solar Irradiance Data

Algarve is one of the locations in Portugal and Europe with the most intense daily irradiation. August is the month where this parameter reaches its highest value, and December, on the other hand, is the lowest. As expected, the typical peak of the daily irradiation occurs from 12:00 to 14:00, hours in which the sunshine reaches its maximum value.

Figure 4.6 depicts the average daily irradiation for the month of August, which is the month with the most prominent solar irradiance values, and Figure 4.7 shows the average daily solar irradiance per month. Figures I.12 to Figure I.22 depict the average daily solar irradiance for the remaining months and are displayed in Annex I.

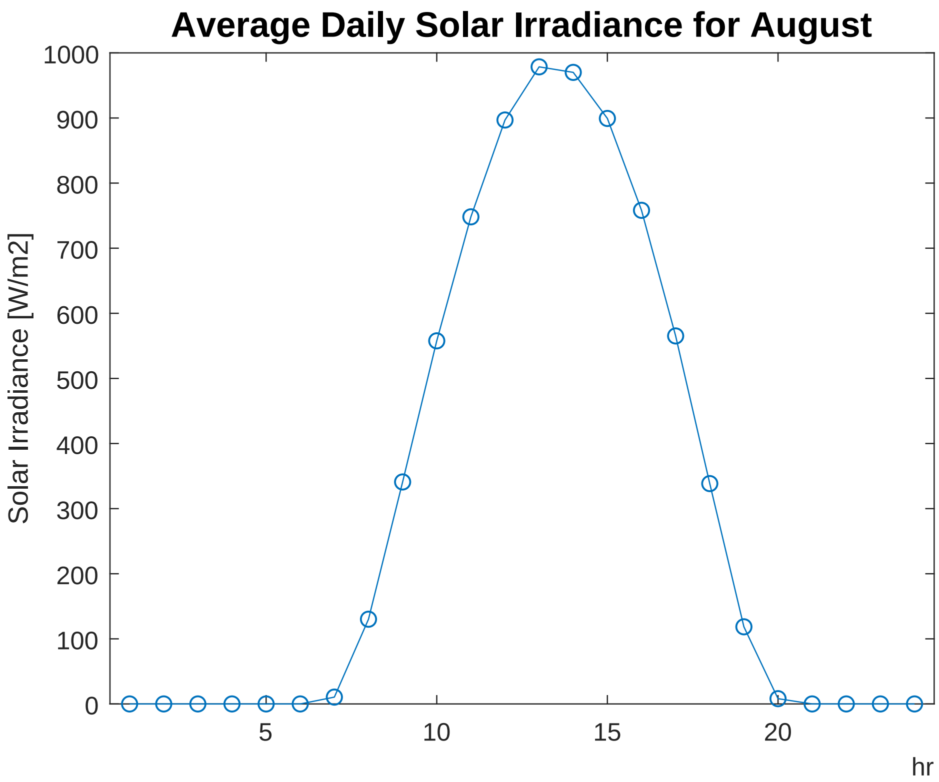


Figure 4.6: Average daily solar irradiance for the month of August.

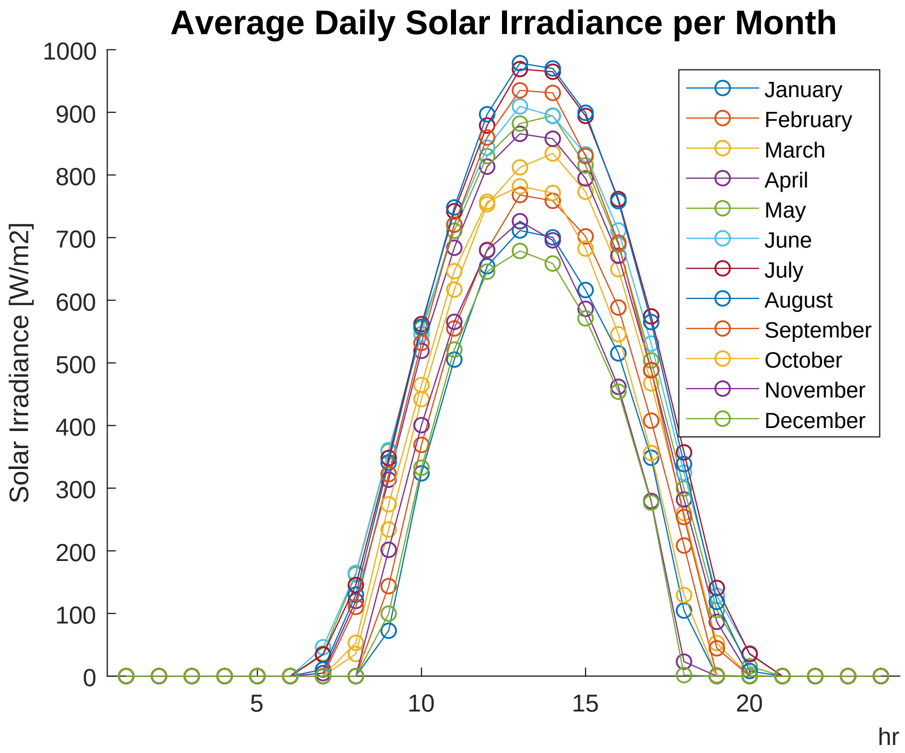


Figure 4.7: Average daily solar irradiance per month.

4.6 PV Generation Data

With the Irradiation data from the previous section, it is possible to estimate the total number of PV panels and power generation for the Dom Pedro Victoria Golf Course. The chosen solar module to implement this study was the SunPower Maxeon 3 400 W[1], and the solar inverter the GoodWe GW80KBF-MT[2].

The total available area to implement the PV system correlates to 794 m^2, and with the chosen module dimensions and following equations 3.3 through 3.5, the total number of PV panels that the Dom Pedro Victoria Golf Course can accommodate, without module self-shadowing, is 244, for a total of 97.6 kWp.

Following Equation 3.6 through Equation 3.8, the module maximum DC power was calculated. In order to estimate a real system, different power losses were considered: DC power losses, which correlate to global losses resulting in module differences, dirt and Joule losses in the DC cables, AC power losses which correspond to the Joule losses in the AC cables, and the solar inverter efficiency which is the ratio of the usable AC output power compared to the DC input power. These considered power losses are depicted in Table 4.5.

Table 4.5: Power losses considered for the PV implementation.

DC Losses (%) $P_{DC_{Losses}}$	**Solar Inverter Efficiency (%)** $\eta_{inverter}$	**AC Losses (%)** $P_{AC_{Losses}}$	**Total Losses (%)** $Total_{Losses}$
2	90	2	86.44

Considering these losses, and using Equation 3.9 through Equation 3.12, the average daily total PV generation for the total number of modules was acquired, and utilising Equation 3.13, the chosen solar inverter was validated. Figure 4.8 depicts the average daily PV generation for the month of August, which is the month with the most significant PV generation. Figure 4.9 depicts the average daily PV generation per month, and Figure 4.10 represents the average monthly PV generation. Table 4.6 describes the daily and monthly PV generation values, and Table 4.7 represents the monthly generation data per electricity tariff. Figures I.23 to Figure I.33 illustrates the average daily PV generation for the remaining months and are displayed in Annex I.

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[1] Datasheet available at: https://sunpower.maxeon.com/au/sites/default/files/2022-05/sp_max3_104c_390-400_res_dc_ds_en_a4_544451.pdf

[2] Datasheet available at: https://br.goodwe.com/Public/Uploads/productsbr/pdf/GW_MT_Datasheet-PT.pdf

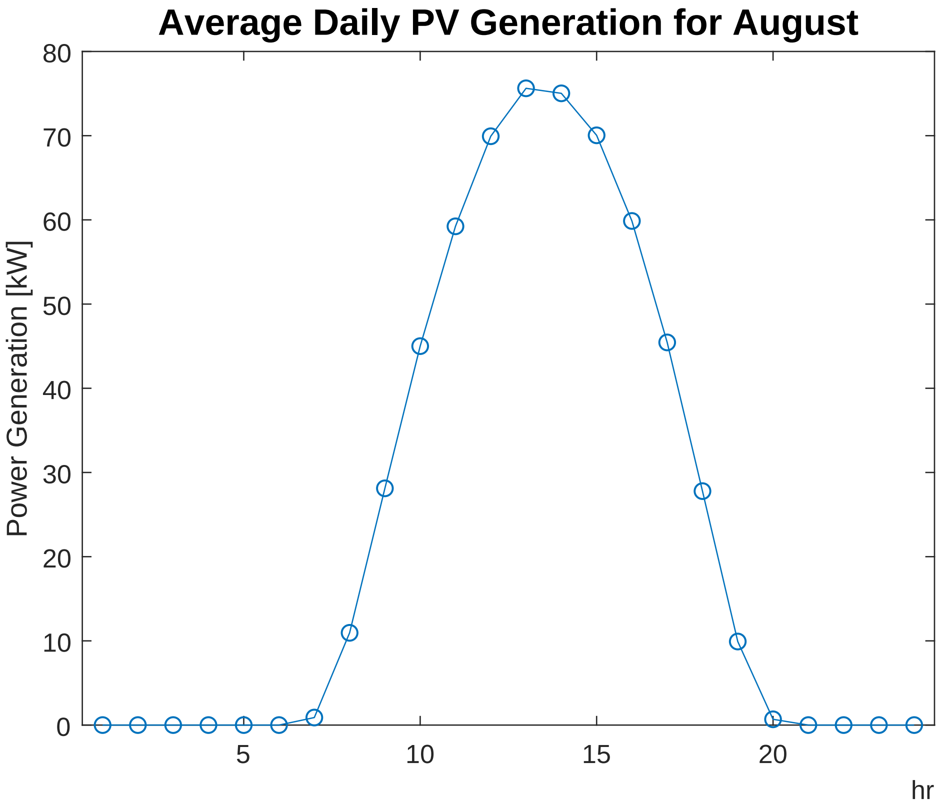

Figure 4.8: Average daily PV generation for the month of August.

Table 4.6: Daily and monthly PV generation.

	Daily Generation (kWh)	**Monthly Generation (kWh)**
January	376.63	11675.50
February	427.24	11962.72
March	485.64	15054.81
April	528.56	15856.73
May	553.1	17146.07
June	564.38	16931.49
July	586.93	18194.87
August	578.54	17934.78
September	534.77	16043.02
October	441.13	13674.94
November	378.74	11362.19
December	350.366	10861.05
Total		176698.17

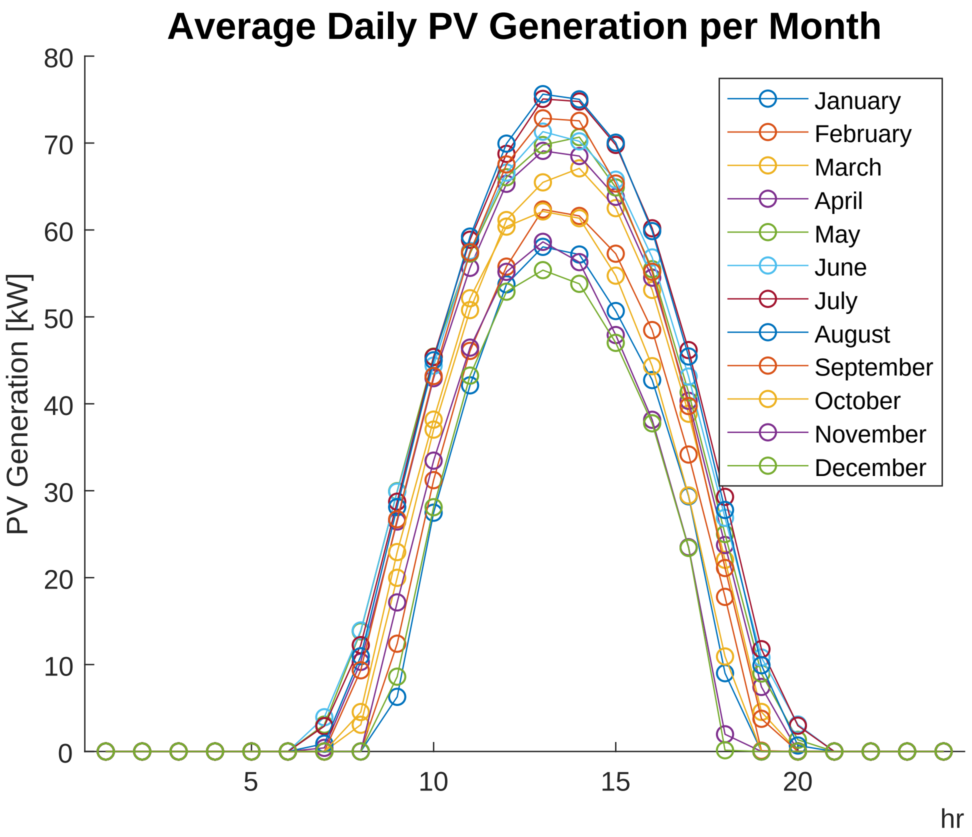

Figure 4.9: Average daily PV generation per month.

Table 4.7: Monthly PV generation per electricity tariff.

	Super Off-Peak Generation (kWh)	Off-Peak Generation (kWh)	Half Peak Generation (kWh)	Peak Generation (kWh)
January	0	0	9518.02	2157.48
February	0	0	9795.72	2166.99
March	0	95.32	12096.27	2863.22
April	0	321.77	11501.64	4033.32
May	0	524.06	12369.45	4252.55
June	0	535.78	12165.34	4230.37
July	0	469.66	13174.31	4550.90
August	0	367.36	13033.89	4533.53
September	0	280.24	11551.26	4211.53
October	0	140.66	9736.21	3798.07
November	0	0	8964.52	2397.68
December	0	0	8649.35	2211.70
Total	0	2734.85	132555.97	41407.35

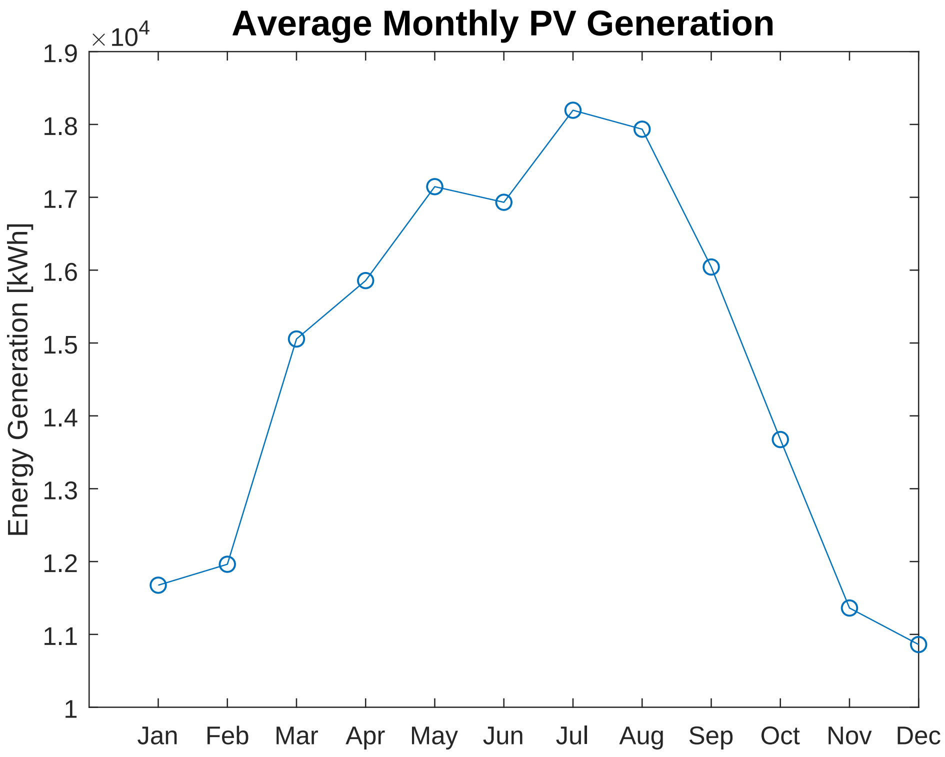

Figure 4.10: Average monthly PV generation.

5

RESULTS AND DISCUSSION

In this chapter, the case study's results are presented and discussed. Following the data acquired in the previous chapter, first, the average daily net power and average monthly net energy of the Dom Pedro Victoria Golf Course are obtained. Then the V2G discharging opportunities are assessed according to a defined set of rules, and then they are integrated into the net power, creating a new average daily net power and new average monthly net energy. This V2G discharged energy is then separated according to its electricity tariff. After acquiring this new net power, an energy analysis is carried out. Not only this, but the additional battery degradation caused by the V2G technology is studied and weight upon, followed by an extensive economic analysis, of all the golf course cash flows, over a ten-year investment period, in order to assess the feasibility of this study.

5.1 Net power

With the PV generation and the load profile and energy consumption data, manifested in the previous section, each month's average daily net power was obtained, representing the hourly subtraction between the daily load profile and the solar generation.
Figure 5.1 depicts the average daily net power, power consumption and generation for the month of August, which is the month with the most significant PV generation and load profiles. Figure 5.2 represents the average monthly net energy per year. Figure II.1 to Figure II.11 represent the average daily net power, along with the power consumption and generation for the remaining months, and are displayed in Annex II.

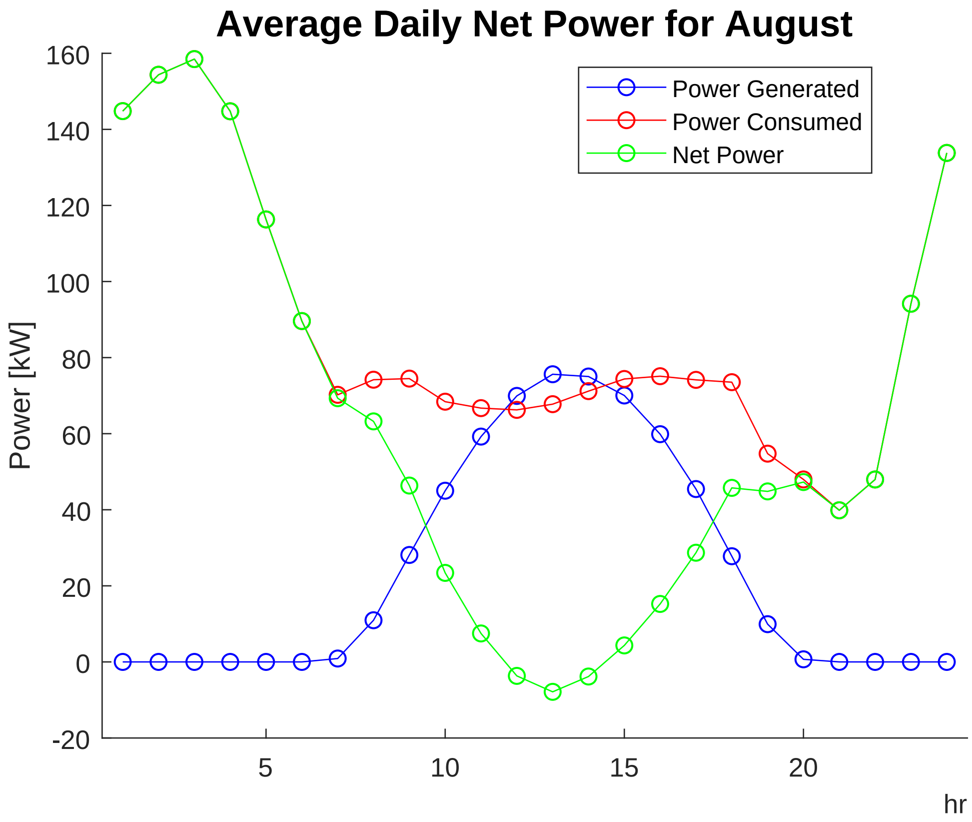

Figure 5.1: Average daily net power for the month of August.

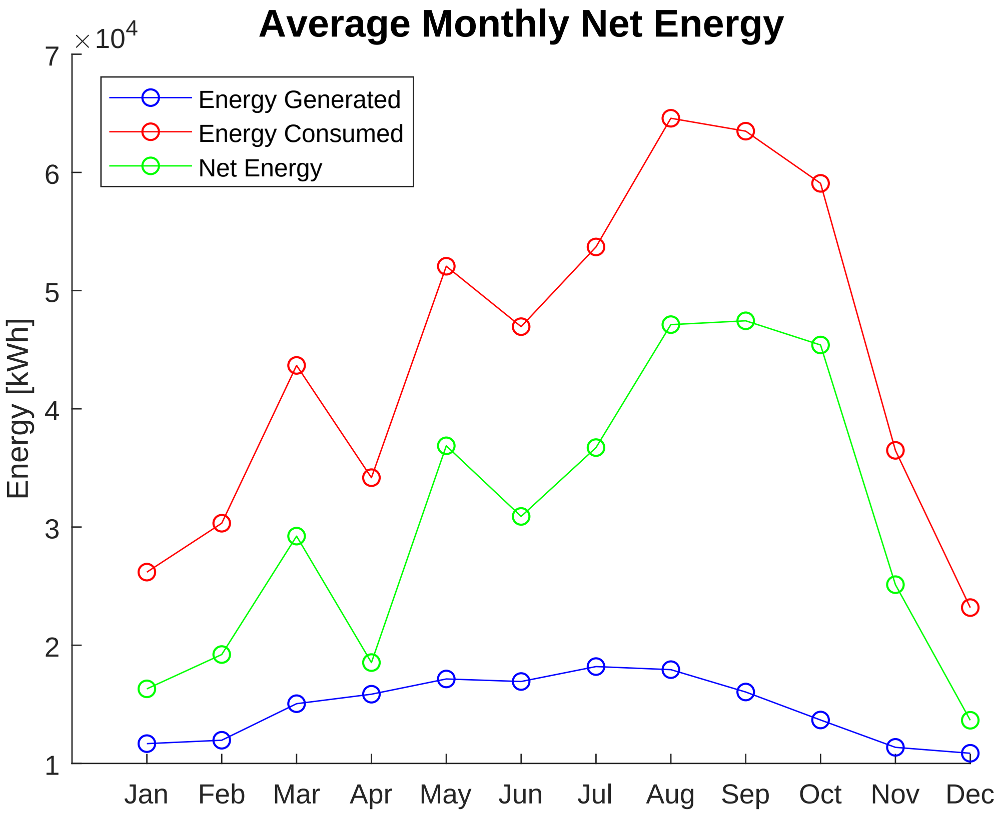

Figure 5.2: Average monthly net energy.

5.2 V2G Discharging

Analysing the data from the previous section, it can be observed that there are some daily periods in which the PV generation is superior to the load demands in most months, except for September, October, and November. This means that we can use this excess generated energy to charge the golf buggies that are not currently being used during these periods and discharge this charged energy during other periods according to the golf course's needs. Figure 5.3 depicts the average daily excess power for the month of May, which is the month with the most significant PV excess generation, Figure 5.4 represents the monthly excess energy generation, and Table 5.1 depicts the daily and monthly excess generation values, and Table 5.2 illustrates the monthly surplus energy by tariff. Figure II.12 through Figure II.22 represent the average daily excess power generated for the remaining months and are displayed in Annex II.

According to the data provided by the golf resort, on average, 21 buggies are being utilised simultaneously per day, meaning that 39 buggies are free to be discharged hourly, at a rate of 0.408 kWh per hour, which adds to a total of 15.912 kWh per hour when considering the whole available fleet. In order to maximise the economic viability of this study, it was assumed that the available buggies would discharge according to the following rules:

- The buggy fleet discharges the energy surplus as a whole and at its maximum rate of 15.8 kWh per hour.
- It is prioritised to discharge this energy on the tariffs with the highest price per kWh, which are in order: Peak, Half Peak, Off-Peak and Super Off-Peak.
- When the energy tariff cannot be prioritised, the discharging occurs in the hours with the highest peak load.

Table 5.2 represents the total monthly V2G discharging, in line with the listed rules and according to each electricity tariff, and Figure 5.5 depicts the total monthly discharging per electricity tariff in percentage.

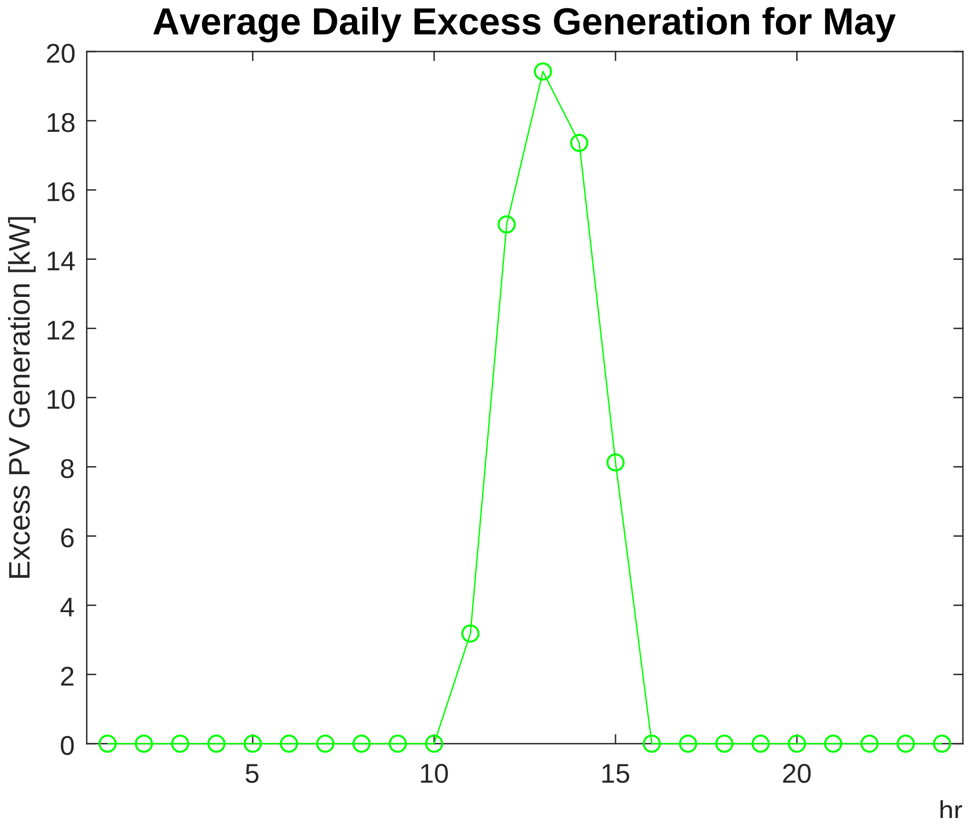

Figure 5.3: Average daily excess generation for the month of May.

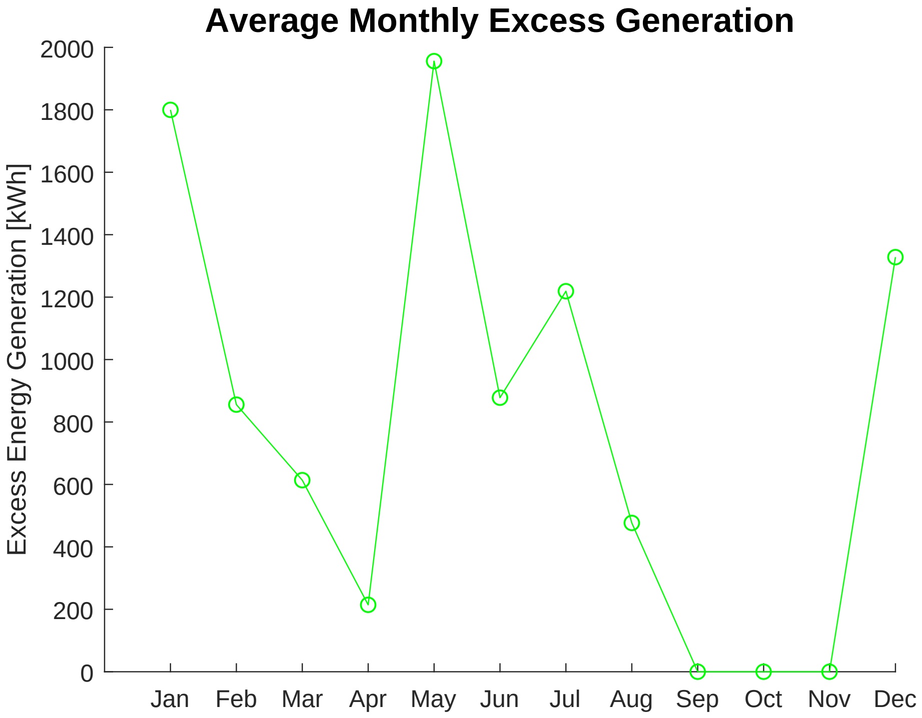

Figure 5.4: Average monthly excess generation.

Table 5.1: Daily and monthly excess energy generation.

	Daily Excess (kWh)	**Monthly Excess (kWh)**
January	58.06	1799.80
February	30.56	855.69
March	19.80	613.66
April	7.14	214.29
May	63.09	1955.92
June	29.26	877.86
July	39.32	1218.94
August	15.38	476.64
September	0	0
October	0	0
November	0	0
December	42.84	1328.09
Total		9340.9

Table 5.2: Monthly V2G discharging per electricity tariff.

	Super Off-Peak Energy Discharged (kWh)	**Off-Peak Energy Discharged** (kWh)	**Half Peak Energy Discharged** (kWh)	**Peak Energy Discharged** (kWh)
January	0	0	319.99	1479.82
February	0	0	0	855.69
March	0	0	0	613.66
April	0	0	0	214.29
May	0	0	969.38	986.54
June	0	0	0	877.86
July	0	0	231.44	986.54
August	0	0	0	476.64
September	0	0	0	0
October	0	0	0	0
November	0	0	0	0
December	0	0	0	1328.09
Total	0	0	1520.81	7819.13

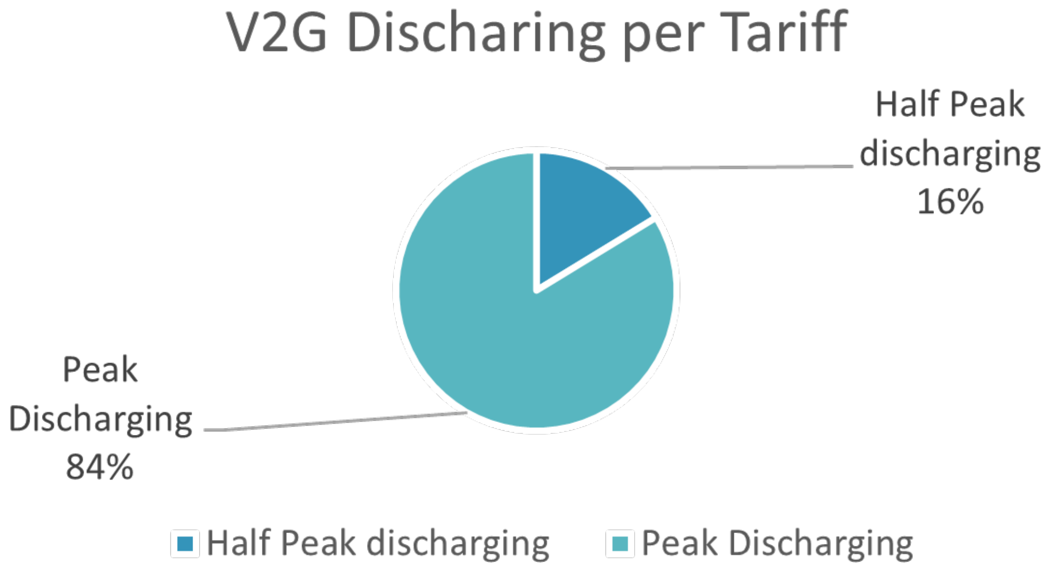

Figure 5.5: V2G discharging per electricity tariff.

5.3 Energy Analysis

Following the rules mentioned above, a new net power is obtained, with the V2G discharging data from table 5.2. This new power represents the previous net power, with the discharging of the surplus generated power. Figure 5.7 illustrates the average daily new net power for the month of May, which is the month with the most prominent discharging windows, Figure 5.8 depicts this charging and discharging process, and Figure 5.9 depicts the average monthly new net energy. Figures II.23 to II.33 represent the average daily new net power for the remaining months and are displayed in Annex II.
Concatenating the data from Tables 4.2, 4.4, 4.7 and 5.2, Table 5.3 is created, which depicts the yearly metrics for each tariff, as well as Figure 5.6.

Table 5.3: Yearly metrics per electricity tariff.

Tariff	**Generation** (kWh)	**Energy Consumption** (kWh)	**V2G Discharging** (kWh)	**Electricity Price** (€/kWh)
Super Off-Peak	0	93934.38	0	0.0812
Off-Peak	2734.85	139779.78	0	0.0923
Half Peak	132555.97	218533.92	1520.81	0.1358
Peak	41407.35	81627.80	7819.13	0.2164

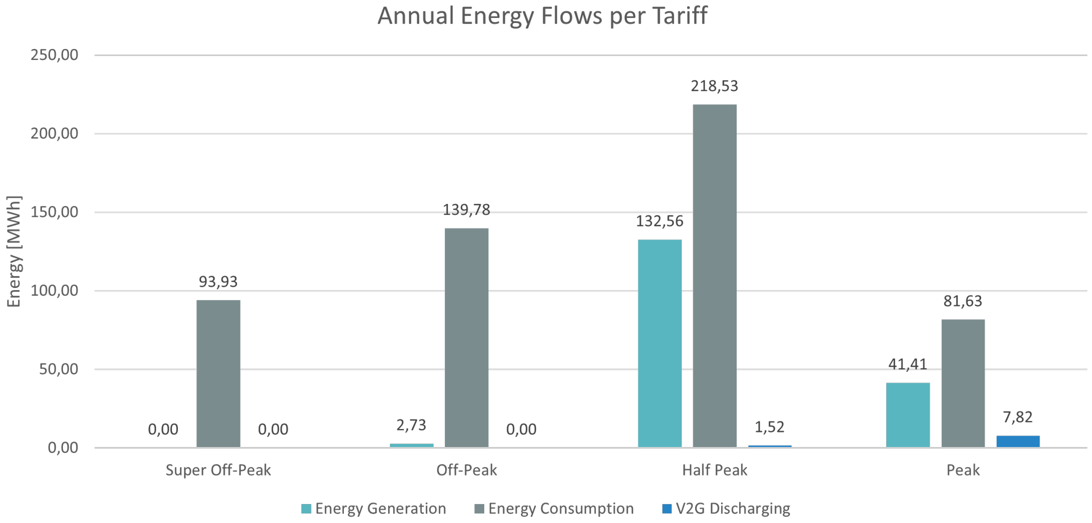

Figure 5.6: Annual energy flows per electricity tariff.

The V2G technology addition to the golf resort buggies allows the discharging of 9340.9 kWh of surplus energy per year, which brings benefits and drawbacks to the golf resort. The main benefit is the reduction of the resort loads during peak hours, which correlates to a decrease in the golf resort electricity bills through the discharging of this energy during higher-priced tariff hours. On the other hand, the main drawback is the increased battery degradation of the golf buggies because of the average yearly charging cycles increment.

The following two sub-sections will analyse these benefits and drawbacks in greater detail.

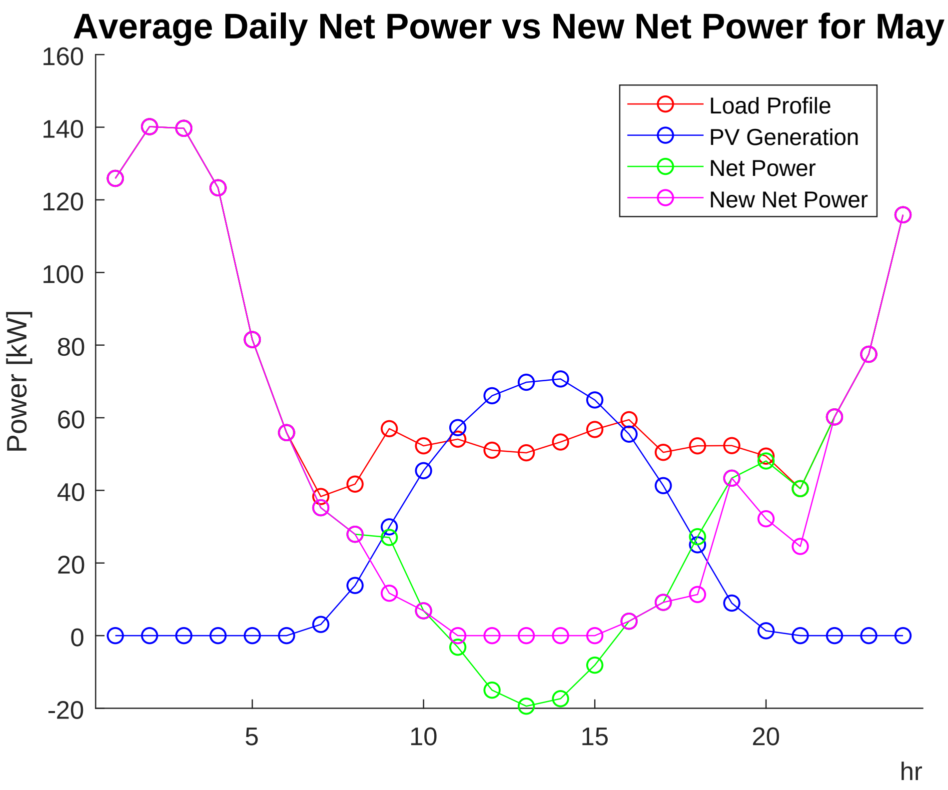

Figure 5.7: Average daily net power vs new net power for the month of May.

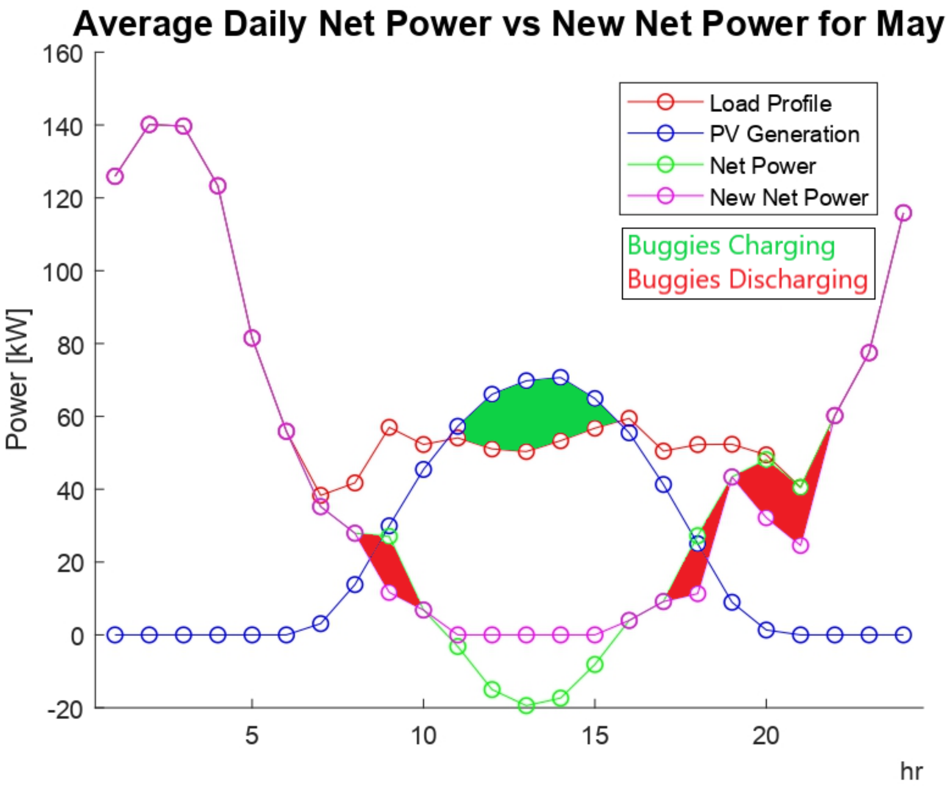

Figure 5.8: Depiction of the charging and discharging process for an average day in May.

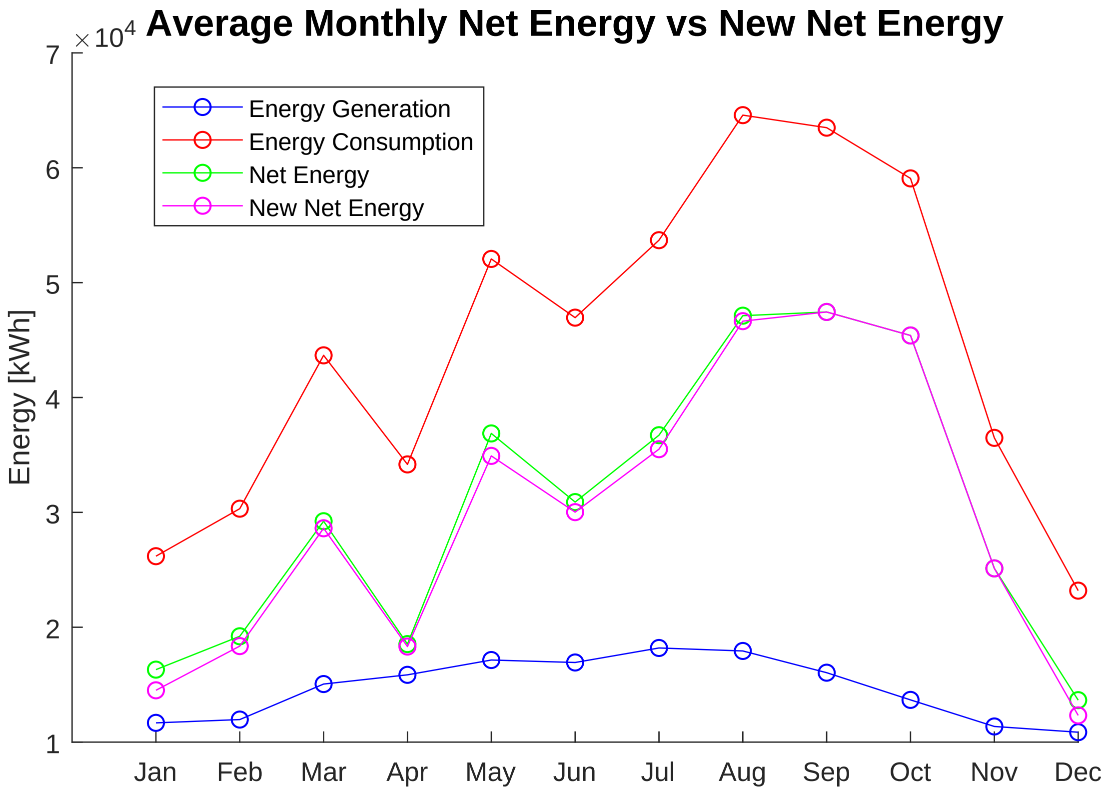

Figure 5.9: Average monthly net energy vs new net energy.

5.4 Battery Degradation

The total yearly excess generated energy that can be discharged through V2G technology is 9340.9 kWh. Dividing this value for the fleet of 60 buggies equates to 155.7 kWh that each buggy has to discharge annually. Assuming that one buggy charging cycle equates to 4.08 kWh for ten hours, dividing the amount of power that each buggy needs to discharge by the average buggy cycle, the V2G technology integration results in 38 additional charging cycles per year.

Contrarily, the total number of yearly buggy utilisation is 7623, resulting in usage of each buggy of 127 times per year, which requires on average 4 kWh per utilisation. Yearly, this corresponds to 508 kWh that each buggy consumes, and dividing this value by the average buggy cycle, results in 125 cycles per year.

Even though battery degradation is not linear, for simplicity, it was assumed that these additional 38 yearly cycles added with the surplus generated energy discharges represent a 30% decrease in each golf buggy's typical battery life. The average buggy battery replacement price for the golf resort is 720€, and assuming it is properly maintained and cleaned, it can last for around ten years. Thus, the 30% battery life reduction means that after seven years, the golf buggy batteries need to be replaced, which, when taking into consideration the buggy fleet and the battery replacement price, equates to an added cost of the V2G technology integration, in the form of an extraordinary expense to the golf resort, of 12,960€.

5.5 Economic Analysis

In order to accomplish an economic analysis, first, the initial investment costs need to be calculated. The total number of PV modules to be installed is 244, alongside a single solar inverter. For the bulk purchase of the panels, the individual price comes down to 323€ per panel, and the solar inverter price is 3,340€.[1]

To simplify this analysis, it was attributed that the expenses for the support structures, solar modules assembly and other equipment, alongside the execution of the electric infrastructure, and others, for the PV installation, would correspond to 80% of the total price of the modules and the solar inverter. Regarding the yearly operation and maintenance (O&M) costs, it was assigned a cost of 1.5% of the total initial investment. Table 5.4 depicts the initial investment costs and the yearly O&M costs.

Table 5.4: Initial investment and yearly O&E costs.

PV modules cost (€)	**Solar inverter cost (€)**	**Support structures & others cost (€)**	**Total initial Investment (€)**	**O&M cost (€)**
78,812	3,340	65,721.60	147,873.60	2,218.10

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[1] Prices retrieved from: https://www.europe-solarstore.com/.

A regular investment period of ten years was assumed, with a discount rate of 6%. In order to increase the verisimilitude of the study, it was also considered yearly PV generation efficiency losses of 1%, and that electricity prices would increase by 2% per year of the study compared to the price of the previous year. The yearly differences in efficiency and electricity costs, compared to the first year of the study, are depicted in Table 5.5.

Table 5.5: Efficiency losses and electricity price increase over the analysis period, when compared to the first year of investment.

Year	Efficiency Losses (%)	Increase of electricity costs (%)
1	0%	0.000
2	1	2.000
3	2	4.040
4	3	6.121
5	4	8.243
6	5	10.408
7	6	12.616
8	7	14.869
9	8	17.166
10	9	19.509

With the data from Table 5.4 and by applying the yearly updated ratios of electricity price and efficiency losses from Table 5.5, the consumption costs for each tariff are calculated for the investment period. Following the same logic, the PV generation and V2G discharging savings are obtained, and the final yearly energy cost is obtained for the golf course by summing the annual costs and savings. Table 5.6 summarises the energy costs and savings for the investment period.

Table 5.6: Yearly energy costs and savings.

Year	Super Off-Peak Consumption Cost (€)	Off-Peak Consumption Cost (€)	Half Peak Consumption Cost (€)	Peak Consumption Cost (€)	PV Generation Savings (€)	V2G Discharging Savings (€)	Final Energy Cost (€)
1	7,627.47	12,901.67	29,676.91	17,664.26	27,214.08	1,898.58	38,757.64
2	7,780.02	13,159.71	30,270.44	18,017.54	27,480.78	1,917.19	39,829.75
3	7,935.62	13,422.90	30,875.85	18,377.89	27,747.26	1,935.78	40,929.23
4	8,094.33	13,691.36	31,493.37	18,745.45	28,013.40	1,954.35	42,056.76
5	8,256.22	13,965.19	32,123.24	19,120.36	28,279.10	1,972.89	43,213.02
6	8,421.35	14,244.49	32,765.70	19,502.77	28,544.21	1,991.38	44,398.71
7	8,589.77	14,529.38	33,421.02	19,892.82	28,808.62	2,009.83	45,614.54
8	8,761.57	14,819.97	34,089.44	20,290.68	29,072.19	2,028.22	46,861.24
9	8,936.80	15,116.37	34,771.23	20,696.49	29,334.78	2,046.53	48,139.57
10	9,115.53	15,418.69	35,466.65	21,110.42	29,596.24	2,064.78	49,450.28

With the data from Table 5.6, the economic analysis was performed for the investment period, with the year zero representing the initial investment as defined from Table 5.4. First, the cash flows with PV generation, and V2G discharging were obtained, corresponding to the subtraction of the final energy cost from Table 5.6 with the O&M costs. Then the cash flows without PV generation and V2G discharging were calculated by summing the electricity tariffs consumption costs. The yearly savings were then calculated by subtracting these two cash flows alongside any extraordinary expense necessary for each investment year. As seen previously, the addition of the V2G technology creates an additional exceptional cost in the eighth year of the investment period. The updated savings were calculated according to the discount rate, and finally, the accumulated updated savings were obtained by summing the updated savings for the current and previous investment years. All of this data is depicted in Table 5.7.

Table 5.7: Cash Flows for the Investment Period.

Year	**Cash Flow With PV & V2G (€)**	**Cash Flow Without PV & V2G (€)**	**Extraordinary Expenses (€)**	**Savings (€)**	**Updated Savings (€)**	**Accumulated Updated Savings (€)**
0	-147,873.60	0.00	0.00	-147,873.60	-147,873.60	-147,873.60
1	-40,975.75	-67,870.31	0.00	26,894.56	25,372.23	-122,501.37
2	-42,047.85	-69,227.71	0.00	27,179.86	24,189.98	-983,113.9
3	-43,147.33	-70,612.27	0.00	27,464.93	23,060.09	-75,251.30
4	-44,274.86	-72,024.51	0.00	27,749.65	21,980.32	-53,270.98
5	-45,431.12	-73,465.00	0.00	28,033.88	20,948.55	-32,322.44
6	-46,616.81	-74,934.30	0.00	28,317.49	19,962.71	-12,359.72
7	-47,832.64	-76,432.99	0.00	28,600.35	19,020.86	6,661.14
8	-49,079.35	-77,961.65	12,960.00	15,922.30	9,989.85	16,650.99
9	-50,357.67	-79,520.88	0.00	29,163.21	17,261.66	33,912.65
10	-51,668.39	-81,111.30	0.00	29,442.91	16,440.77	50,353.42

Figure 5.10 depicts the accumulated present value savings over the investment period. The data in white represents the years for which these savings are negative, and in green, the years in which the savings are positive.

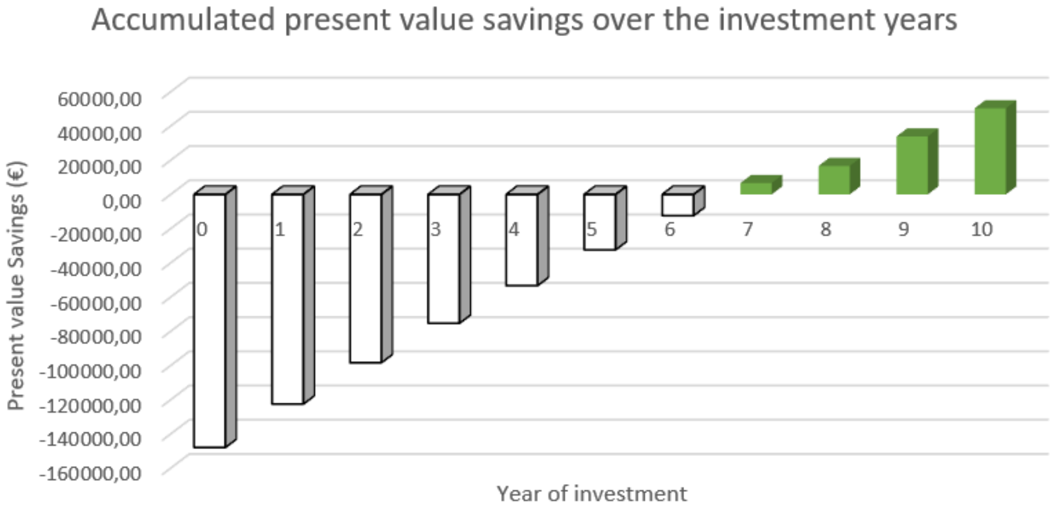

Figure 5.10: Accumulated present value savings over the investment years.

By using Equation 3.14 through Equation 3.17, the results of the economic analysis for the investment period were the following, as depicted in Table 5.8.

Table 5.8: Economic Analysis Results.

Net Present Value (€) NPV	**Internal Return Rate (%)** IRR	**Payback Period (yr.)** PP	**Levelized Cost of Energy (€/kWh)** $LCOE$
50,353.42	13	7	0.1315

In order to further validate the study, three more performance indicators were obtained, for the first year of the PV and V2G installation. These indicators are depicted in Table 5.9, and were obtained through Equation 3.18 to Equation 3.20.

Table 5.9: Performance indicators for first year of the study.

Performance Ratio (%) PR	**Self-Consumption Ratio (%)** SCR	**Self-Sufficiency Ratio (%)** SSR
87	100	35

Finally, to address the feasibility of the V2G technology integration into the Dom Pedro Victoria Golf Course, this technology BCR is calculated for the ten-year investment period through Equation 3.21. Table 5.10 depicts the BCR analysis of the V2G technology.

Table 5.10: BCR of the addition of V2G technology to the PV system.

Present Value Benefits (€)	**Present Value Costs (€)**	**BCR**
14,522.34	81,31.26	1.79

6

CONCLUSIONS AND FUTURE WORK

In this final chapter, the conclusions of the whole thesis and study are assessed, and any possible future work to be implemented is presented.

6.1 Conclusions

As depicted throughout this study, V2G technology has a plethora of benefits, and it can ease the energy transition associated with EVs. The bidirectionality of the technology leads to the creation of new income sources for EV owners and can provide several beneficial services to the grid. The main service this study analysis is the possibility of the buggies of the Dom Pedro Victoria Golf Course acting as distributed energy sources by storing the excessive PV generated energy, to be later discharged to the grid, in the highest price tariff hours, and higher load demand periods.

After finalising the study, the results were quite positive. The addition of a 244 solar panel, 97.6 kWp PV system to the golf course results in the annual generation of 176.70 MWh. For every month, except for September, October and November, there are daily windows in which the energy generation surpasses the energy consumption. Annually this surplus of generated energy equates to 9.34 MWh that the golf buggies can discharge through V2G technology, reducing the power consumed during peak hours, but this charging and discharging process leads to a decrease in the buggies' battery life of about 30%.

The economic analysis assumes an investment period of ten years, a discount rate of 6%, efficiency losses on the solar modules of 1% per year, and an electricity price increase by 2% compared to the previous year's price of the system was calculated. The results were an NPV of 50,353.42€, indicating a more than acceptable investment, an IRR of 13%, which is more than double the discount rate and indicates a viable project, a PP of seven years, meaning that after seven years, the entire investment costs are recovered, and an $LCOE$ of 0.1315 €/kWh, which is lower than the half peak tariff, which is the tariff with the highest annual energy consumption.

By further analysing the PR, SCR and SSR results for the first year of the PV and V2G installation, it can be concluded that the energy produced corresponds to 87% of the possible energy that could be generated in STC conditions, and that 100% of the energy generated is self-consumed, with the surplus generation being later discharged back to the grid, and that this PV and V2G ecosystem produces 35% of the annual energy demand of the Dom Pedro Victoria Golf Course.

Finally, in order to assess the feasibility of the V2G technology, by calculating its BCR for the investment period, it can be concluded that with every 1€ that is spent with this technology, 1.79€ are profited by it, which indicates a feasible project and ratio of benefits over costs.

Not only this, but another exciting takeaway from this study is the fact that the extraordinary expense that comes with the reduction of the golf buggies battery life cycle, because of the addition of V2G technology, only appears on the eighth investment period, which is after the PP occurs, indication robust economic viability and applicability for the whole project.

6.2 Future Work

Technology is constantly evolving and keeps improving and optimising throughout the years. Before practically and physically implementing the concepts of this thesis, it would be best to test it on a smaller scale by adding V2G to a reduced number of buggies at first. Not only this, but for possible future work, the first thing that comes to mind is the replacement of the lead-acid batteries of the golf buggies with lithium batteries or lithium iron batteries. Not only do lithium batteries have lower degradation throughout their lifespan, but they also do not present as much of a challenge regarding their state of discharge as lead-acid batteries, meaning that it is safe to discharge them beyond 50% of their capacity, which in turn increases the amount of energy that can be discharged at one time. Adding more cycles to the golf buggy battery life will increase the BCR and better economic viability.

Another future work to consider is the increase of the number of PV modules that can be implemented, which will increase the maximum peak power of the PV installation. As observed, there are months in which the generation never surpasses the load demands. By increasing the generation, we can overcome this difference, which will increment the amount of V2G energy that can be discharged throughout the years, and further increase the profitability and feasibility of the project.

Besides this, this same study could be performed according to another end-goal like the optimal reduction of CO_2e emissions for the golf resorts, instead of maximising the financial benefits of this system.

BIBLIOGRAPHY

[1] J. M. Lourenço. *The NOVAthesis LaTeX Template User's Manual*. NOVA University Lisbon. 2021. URL: `https://github.com/joaomlourenco/novathesis/raw/master/template.pdf` (cit. on p. iii).

[2] K. Bilen et al. "Energy production, consumption, and environmental pollution for sustainable development: A case study in Turkey". In: *Renewable and Sustainable Energy Reviews* 12.6 (2008), pp. 1529–1561. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2007.03.003`. URL: `https://www.sciencedirect.com/science/article/pii/S136403210700041X` (cit. on p. 1).

[3] Commission Of the European Communities. "An Energy Policy for Europe: Communication from the Commission to the European Council and the European Parliament." In: (2007), pp. 1–28 (cit. on p. 1).

[4] K. J. Dyke, N. Schofield, and M. Barnes. "The Impact of Transport Electrification on Electrical Networks". In: *IEEE Transactions on Industrial Electronics* 57.12 (2010), pp. 3917–3926. DOI: `10.1109/TIE.2010.2040563` (cit. on p. 1).

[5] D. B. Richardson. "Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration". In: *Renewable and Sustainable Energy Reviews* 19 (2013), pp. 247–254. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2012.11.042`. URL: `https://www.sciencedirect.com/science/article/pii/S1364032112006557` (cit. on pp. 1, 6).

[6] P. Siano and K. Jamuna, eds. *Advances in Smart Grid Technology*. Springer, 2020, pp. 397–411. DOI: `10.1007/978-981-15-7245-6`. URL: `https://doi.org/10.1007%5C%2F978-981-15-7245-6` (cit. on p. 1).

[7] T. Yiyun et al. "Research on Vehicle-to-Grid Technology". In: *2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring*. 2011, pp. 1013–1016. DOI: `10.1109/CDCIEM.2011.194` (cit. on p. 1).

[8] J. Tomić and W. Kempton. "Using fleets of electric-drive vehicles for grid support". In: *Journal of Power Sources* 168.2 (2007), pp. 459–468. ISSN: 0378-7753. DOI: `https://doi.org/10.1016/j.jpowsour.2007.03.010`. URL: `https://www.sciencedirect.com/science/article/pii/S0378775307005575` (cit. on pp. 1, 8, 9, 11).

[9] L. Noel et al. *Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility*. English. Energy, Climate and the Environment. Palgrave Macmillan, 2019-01. ISBN: 978-3-030-04863-1. DOI: `10.1007/978-3-030-04864-8` (cit. on pp. 2, 9–11, 13–15, 17, 19, 20, 22, 25–27, 29).

[10] IEA. *Global Energy Review 2020*. OECD Publishing, 2020, p. 56. DOI: `https://doi.org/10.1787/a60abbf2-en`. URL: `https://www.oecd-ilibrary.org/content/publication/a60abbf2-en` (cit. on p. 2).

[11] D. B. Agusdinata et al. "Socio-environmental impacts of lithium mineral extraction: Towards a research agenda". In: *Environmental Research Letters* 13 (2018-12). DOI: `10.1088/1748-9326/aae9b1` (cit. on p. 6).

[12] M. Woodward, B. Walton, and J. Hamilton. *Electric vehicles*. 2020-07. URL: `https://www2.deloitte.com/uk/en/insights/focus/future-of-mobility/electric-vehicle-trends-2030.html` (visited on 2022-03) (cit. on p. 6).

[13] A. Y. Saber and G. K. Venayagamoorthy. "Plug-in Vehicles and Renewable Energy Sources for Cost and Emission Reductions". In: *IEEE Transactions on Industrial Electronics* 58.4 (2011-04), pp. 1229–1238. ISSN: 1557-9948. DOI: `10.1109/TIE.2010.2047828` (cit. on p. 6).

[14] L. Shuguang and Y. Zhenxing. "Progress and Prospect of Electric Vehicle's V2G Technology". In: *2019 6th International Conference on Information Science and Control Engineering (ICISCE)*. 2019-12, pp. 412–416. DOI: `10.1109/ICISCE48695.2019.00089` (cit. on pp. 6, 8).

[15] W. Kempton and S. E. Letendre. "Electric vehicles as a new power source for electric utilities". In: *Transportation Research Part D: Transport and Environment* 2.3 (1997), pp. 157–175. ISSN: 1361-9209. DOI: `https://doi.org/10.1016/S1361-9209(97)00001-1`. URL: `https://www.sciencedirect.com/science/article/pii/S1361920997000011` (cit. on p. 7).

[16] B. Bibak and H. Tekiner-Moğulkoç. "A comprehensive analysis of Vehicle to Grid (V2G) systems and scholarly literature on the application of such systems". In: *Renewable Energy Focus* 36 (2021), pp. 1–20. ISSN: 1755-0084. DOI: `https://doi.org/10.1016/j.ref.2020.10.001`. URL: `https://www.sciencedirect.com/science/article/pii/S1755008420300533` (cit. on pp. 7, 19, 20, 22, 26).

[17] W. Kempton and J. Tomić. "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue". In: *Journal of Power Sources* 144.1 (2005), pp. 268–279. ISSN: 0378-7753. DOI: `https://doi.org/10.1016/j.jpowsour.2004.12.025`. URL: `https://www.sciencedirect.com/science/article/pii/S0378775305000352` (cit. on pp. 8, 15).

[18] U. Datta et al. "A price-regulated electric vehicle charge-discharge strategy for G2V, V2H, and V2G". In: *International Journal of Energy Research* 43.2 (2019), pp. 1032–1042. DOI: `https://doi.org/10.1002/er.4330`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.4330`. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1002/er.4330` (cit. on p. 8).

[19] C. El-Bayeh et al. "Charging and Discharging Strategies of Electric Vehicles: A Survey". In: *World Electric Vehicle Journal* 12 (2021-01), pp. 1–33. DOI: `10.3390/wevj12010011` (cit. on p. 8).

[20] M. Yilmaz and P. T. Krein. "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles". In: *IEEE Transactions on Power Electronics* 28.5 (2013-05), pp. 2151–2169. ISSN: 1941-0107. DOI: `10.1109/TPEL.2012.2212917` (cit. on pp. 9, 10).

[21] C. Guille and G. Gross. "A conceptual framework for the vehicle-to-grid (V2G) implementation". In: *Energy Policy* 37.11 (2009), pp. 4379–4390. ISSN: 0301-4215. DOI: `https://doi.org/10.1016/j.enpol.2009.05.053`. URL: `https://www.sciencedirect.com/science/article/pii/S0301421509003978` (cit. on p. 11).

[22] L. Qiao, X. Liu, and B. Jiang. "Design and implementation of the smart meter in vehicle-to-grid". In: *2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*. 2011-07, pp. 618–621. DOI: `10.1109/DRPT.2011.5993967` (cit. on p. 11).

[23] S. Martinenas et al. "Standards for EV charging and their usability for providing V2G services in the primary reserve market". English. In: *Proceedings of International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium 2016*. International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, EVS29 ; Conference date: 19-06-2016 Through 22-06-2016. 2016. ISBN: 9781510832701 (cit. on pp. 11, 12).

[24] M. Yilmaz and P. T. Krein. "Review of benefits and challenges of vehicle-to-grid technology". In: *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2012-09, pp. 3082–3089. DOI: `10.1109/ECCE.2012.6342356` (cit. on p. 12).

[25] J. Donadee et al. "Potential Benefits of Vehicle-to-Grid Technology in California: High Value for Capabilities Beyond One-Way Managed Charging". In: *IEEE Electrification Magazine* 7.2 (2019), pp. 40–45. DOI: `10.1109/MELE.2019.2908793` (cit. on p. 11).

[26] J. Y. Yong et al. "A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects". In: *Renewable and Sustainable Energy Reviews* 49 (2015), pp. 365–385. ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2015.04.130`. URL: `https://www.sciencedirect.com/science/article/pii/S1364032115004001` (cit. on pp. 13, 14, 16–18).

[27] A. M. Pirbazari. "Ancillary services definitions, markets and practices in the world". In: *2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T D-LA)*. 2010, pp. 32–36. DOI: `10.1109/TDC-LA.2010.5762857` (cit. on p. 15).

[28] K. M. Tan et al. "Minimization of Load Variance in Power Grids—Investigation on Optimal Vehicle-to-Grid Scheduling". In: *Energies* 10.11 (2017). ISSN: 1996-1073. DOI: `10.3390/en10111880`. URL: `https://www.mdpi.com/1996-1073/10/11/1880` (cit. on p. 16).

[29] M. Ehsani, M. Falahi, and S. Lotfifard. "Vehicle to Grid Services: Potential and Applications". In: *Energies* 5.10 (2012), pp. 4076–4090. ISSN: 1996-1073. DOI: `10.3390/en5104076`. URL: `https://www.mdpi.com/1996-1073/5/10/4076` (cit. on pp. 16–19).

[30] J. J. Escudero-Garzas, A. Garcia-Armada, and G. Seco-Granados. "Fair Design of Plug-in Electric Vehicles Aggregator for V2G Regulation". In: *IEEE Transactions on Vehicular Technology* 61.8 (2012), pp. 3406–3419. DOI: `10.1109/TVT.2012.2212218` (cit. on pp. 16, 17).

[31] L. Can, C. Lin, and L. Lin. "Research on Vehicle-to-grid Technology". In: *2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring* (2011), pp. 1013–1016. DOI: `10.1109/CDCIEM.2011.194` (cit. on p. 20).

[32] M. Noori et al. "Light-duty electric vehicles to improve the integrity of the electricity grid through Vehicle-to-Grid technology: Analysis of regional net revenue and emissions savings". In: *Applied Energy* 168 (2016), pp. 146–158. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2016.01.030`. URL: `https://www.sciencedirect.com/science/article/pii/S0306261916300101` (cit. on pp. 20–22).

[33] D. Wang et al. "Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services". In: *Journal of Power Sources* 332 (2016), pp. 193–203. ISSN: 0378-7753. DOI: `https://doi.org/10.1016/j.jpowsour.2016.09.116`. URL: `https://www.sciencedirect.com/science/article/pii/S0378775316313052` (cit. on pp. 22–24).

[34] E. Apostolaki-Iosifidou, P. Codani, and W. Kempton. "Measurement of power loss during electric vehicle charging and discharging". In: *Energy* 127 (2017), pp. 730–742. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2017.03.015`. URL:

`https://www.sciencedirect.com/science/article/pii/S0360544217303730` (cit. on pp. 24, 25).

[35] V. Henze. *Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh.* URL: `https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/` (visited on 2022-03) (cit. on p. 25).

[36] V. V. Viswanathan and M. Kintner-Meyer. "Second Use of Transportation Batteries: Maximizing the Value of Batteries for Transportation and Grid Services". In: *IEEE Transactions on Vehicular Technology* 60.7 (2011-09), pp. 2963–2970. ISSN: 1939-9359. DOI: `10.1109/TVT.2011.2160378` (cit. on p. 26).

[37] B. Schmidt. *Tesla's switch on vehicle-to-grid technology is big news for clean energy shift.* 2020-05. URL: `https://thedriven.io/2020/05/20/teslas-switch-on-vehicle-to-grid-technology-is-big-news-for-clean-energy-shift/` (visited on 2022-03) (cit. on p. 28).

[38] Nissan. *Nissan, Enel and Nuvve operate world's first fully commercial vehicle-to-grid hub in Denmark.* 2016-04. URL: `https://europe.nissannews.com/en-GB/releases/nissan-enel-and-nuvve-operate-world-s-first-fully-commercial-vehicle-to-grid-hub-in-denmark` (visited on 2022-03) (cit. on p. 29).

[39] L. Noel and R. Mccormack. "A cost benefit analysis of a V2G-capable electric school bus compared to a traditional diesel school bus". In: *Applied Energy* 126 (2014-07), pp. 246–255. DOI: `10.1016/j.apenergy.2014.04.009` (cit. on p. 29).

[40] Y. Zhao, M. Noori, and O. Tatari. "Vehicle to Grid regulation services of electric delivery trucks: Economic and environmental benefit analysis". In: *Applied Energy* 170.C (2016), pp. 161–175. DOI: `10.1016/j.apenergy.2016.0`. URL: `https://ideas.repec.org/a/eee/appene/v170y2016icp161-175.html` (cit. on p. 29).

[41] Daehan Park, Seungwook Yoon, and Euiseok Hwang. "Cost benefit analysis of public service electric vehicles with vehicle-to-grid (V2G) capability". In: *2016 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific).* 2016-06, pp. 234–239. DOI: `10.1109/ITEC-AP.2016.7512954` (cit. on p. 29).

[42] X. Zhou, T. Guo, and Y. Ma. "An overview on microgrid technology". In: *2015 IEEE International Conference on Mechatronics and Automation (ICMA).* 2015-08, pp. 76–81. DOI: `10.1109/ICMA.2015.7237460` (cit. on p. 29).

[43] G. M. Masters. "The Solar Resource". In: *Renewable and Efficient Electric Power Systems.* John Wiley & Sons, Ltd, 2004. Chap. 7, pp. 385–443. ISBN: 9780471668824. DOI: `https://doi.org/10.1002/0471668826.ch7`. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1002/0471668826.ch7` (cit. on pp. 34–38).

[44] L. Megre. *Análise de Projetos de Investimento Uma perspetiva económica (2ª Edição revista e corrigida).* 2nd ed. Edições Sílabo, 2018. ISBN: 9789726189701 (cit. on pp. 38–40).

[45] IT4Golf. *Dom Pedro Victoria Golf Course in Vilamoura - Best Golf Courses in Algarve: Dom Pedro Hotels & Golf Collection*. URL: `https://www.dompedrogolf.com/en/courses/dom-pedro-victoria` (visited on 2022-03) (cit. on p. 42).

[46] ERSE. *Erse - Tarifas E preços - eletricidade*. 2022. URL: `https://www.erse.pt/atividade/regulacao/tarifas-e-precos-eletricidade/` (visited on 2022-03) (cit. on pp. 43, 44).

[47] OAL. *Legislação sobre a hora legal: Observatório Astronómico de Lisboa*. 1996-03. URL: `https://oal.ul.pt/hora-legal/legislacao` (visited on 2022-03) (cit. on p. 43).

[48] ERSE. *Quadros de Tarifas e Preços da Energia Elétrica a vigorar a partir de 01/01/2022*. 2022. URL: `https://www.erse.pt/media/1blnwjdh/tarifas-eletricidade-2022.xlsx` (visited on 2022-03) (cit. on p. 44).

I

Annex 1

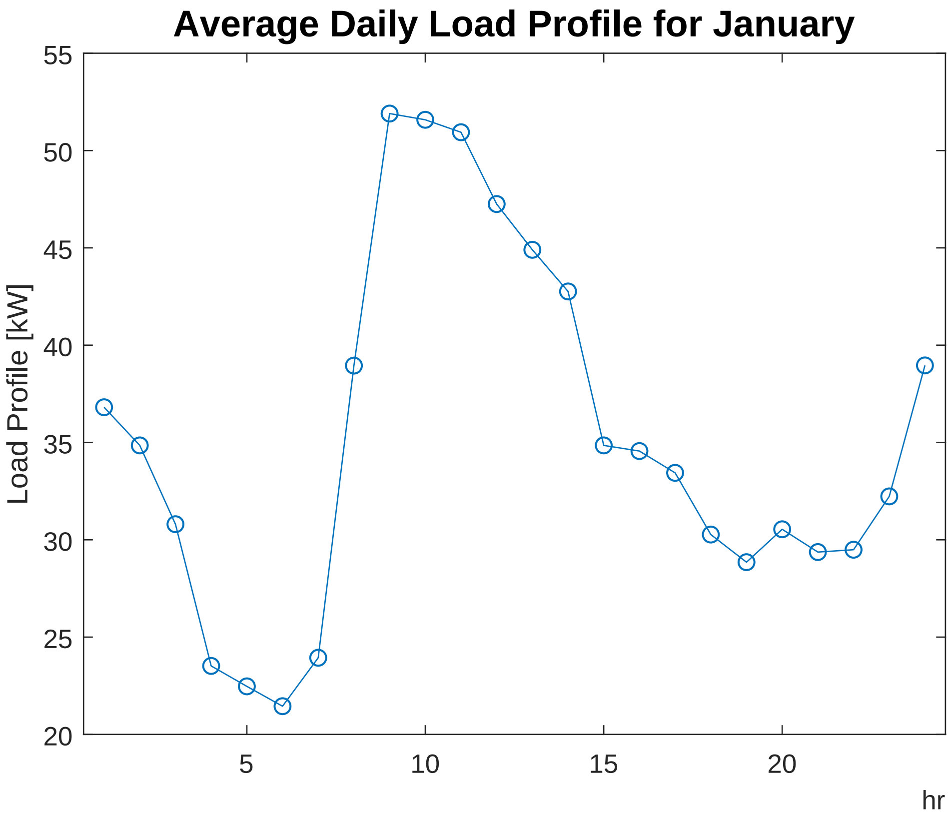

Figure I.1: Average daily load profile for the month of January.

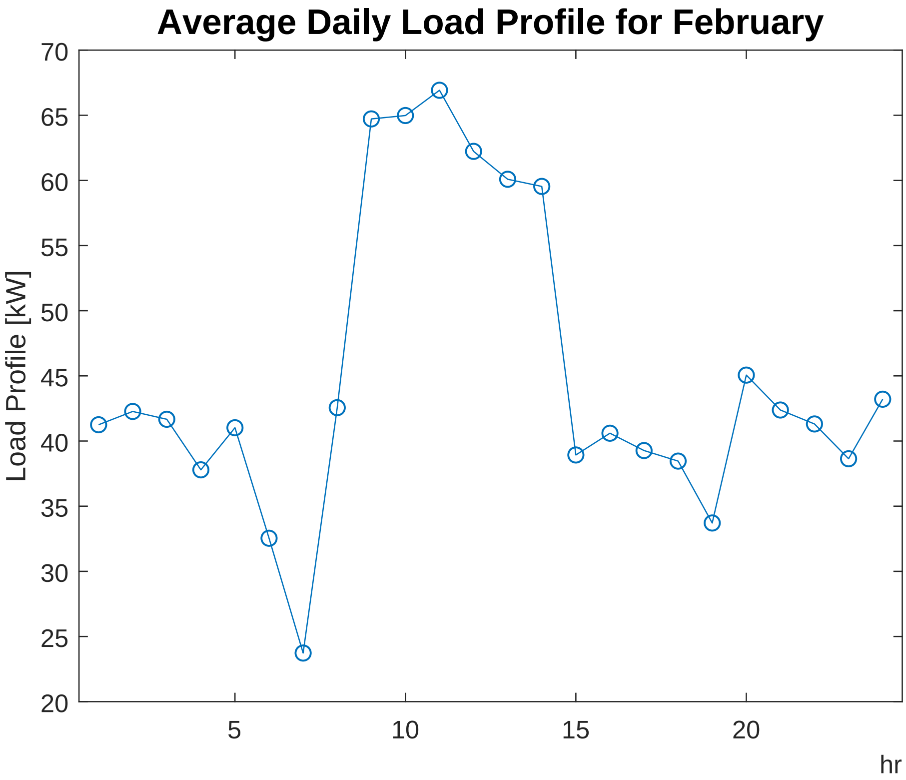

Figure I.2: Average daily load profile for the month of February.

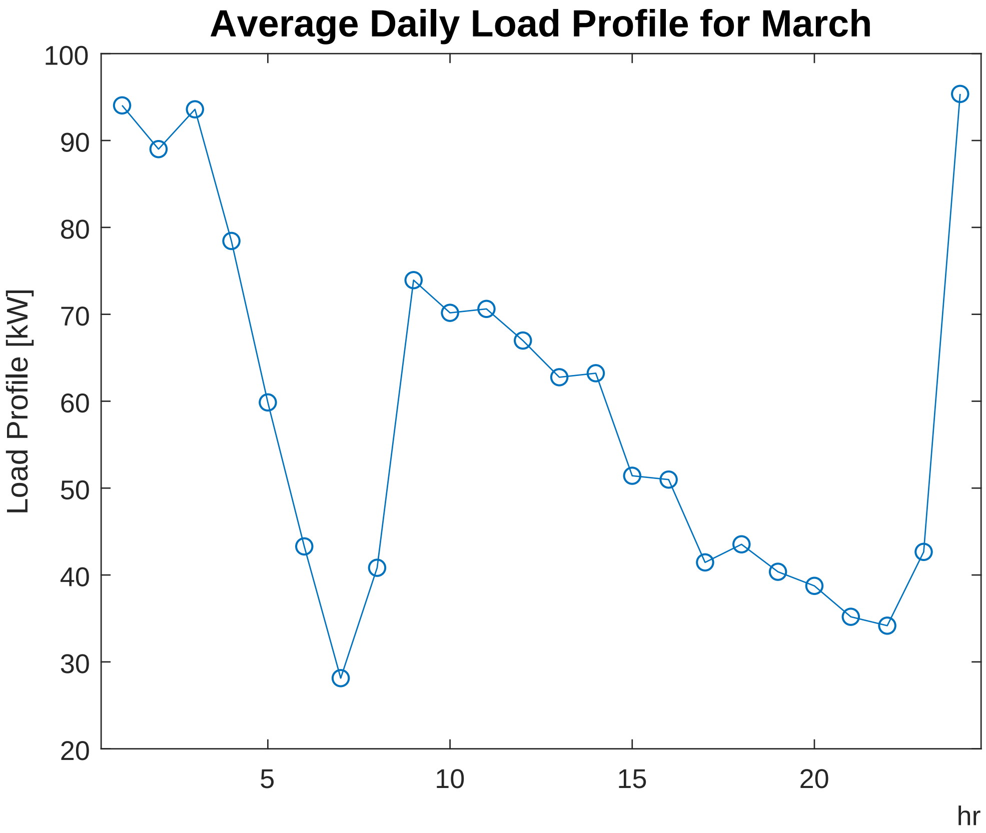

Figure I.3: Average daily load profile for the month of March.

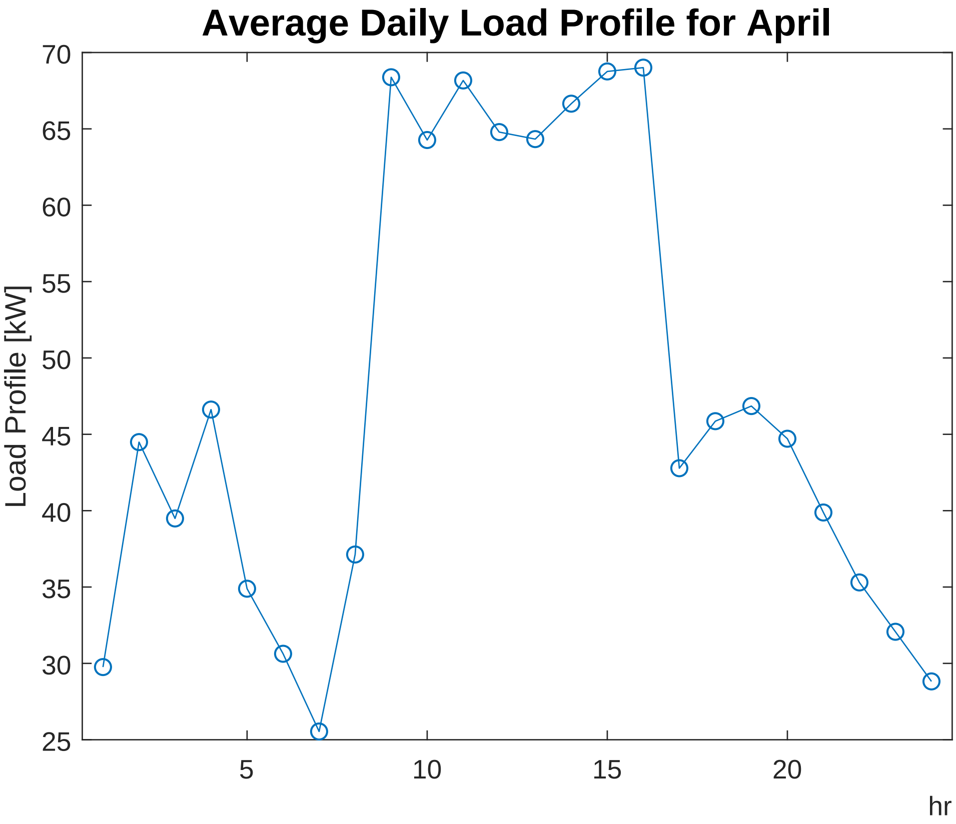

Figure I.4: Average daily load profile for the month of April.

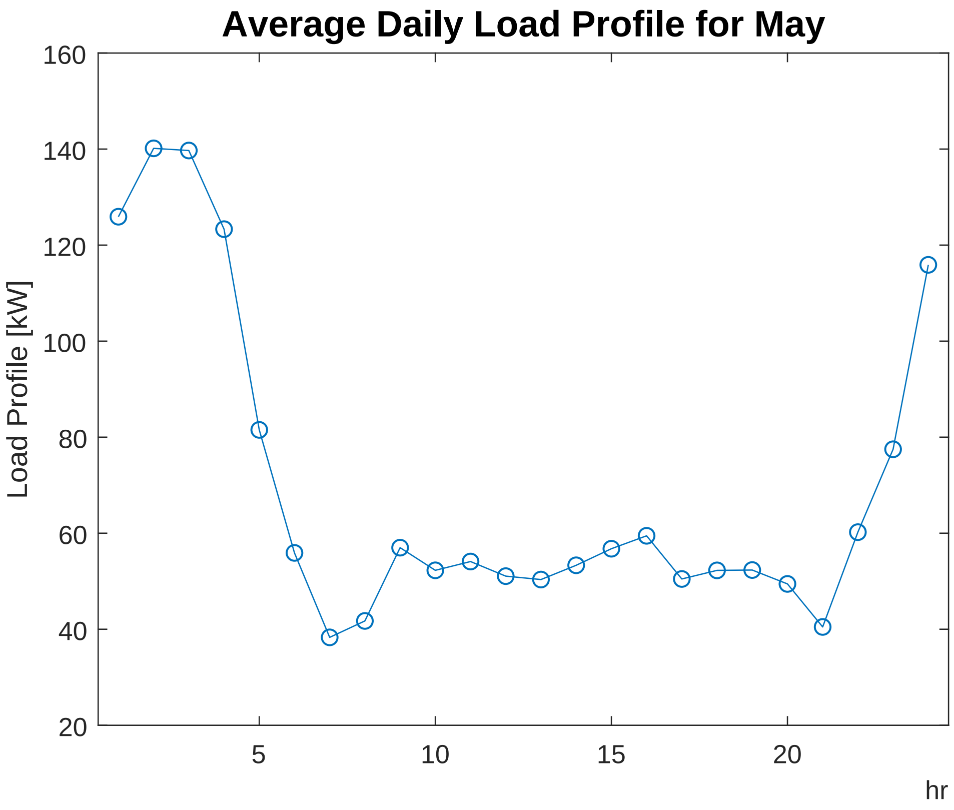

Figure I.5: Average daily load profile for the month of May.

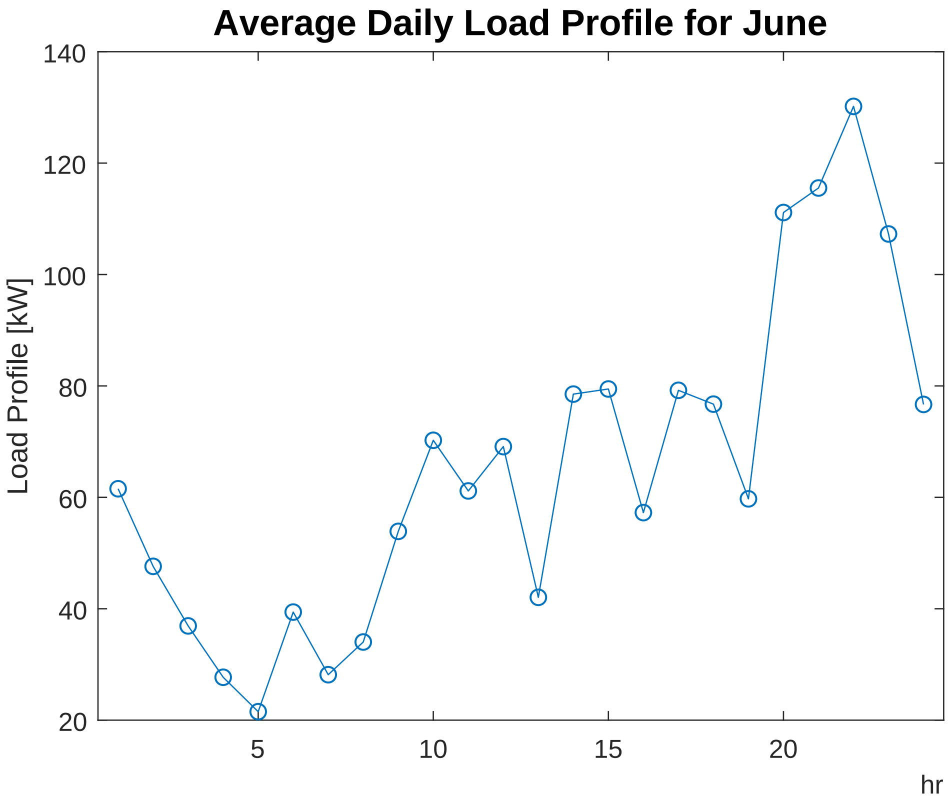

Figure I.6: Average daily load profile for the month of June.

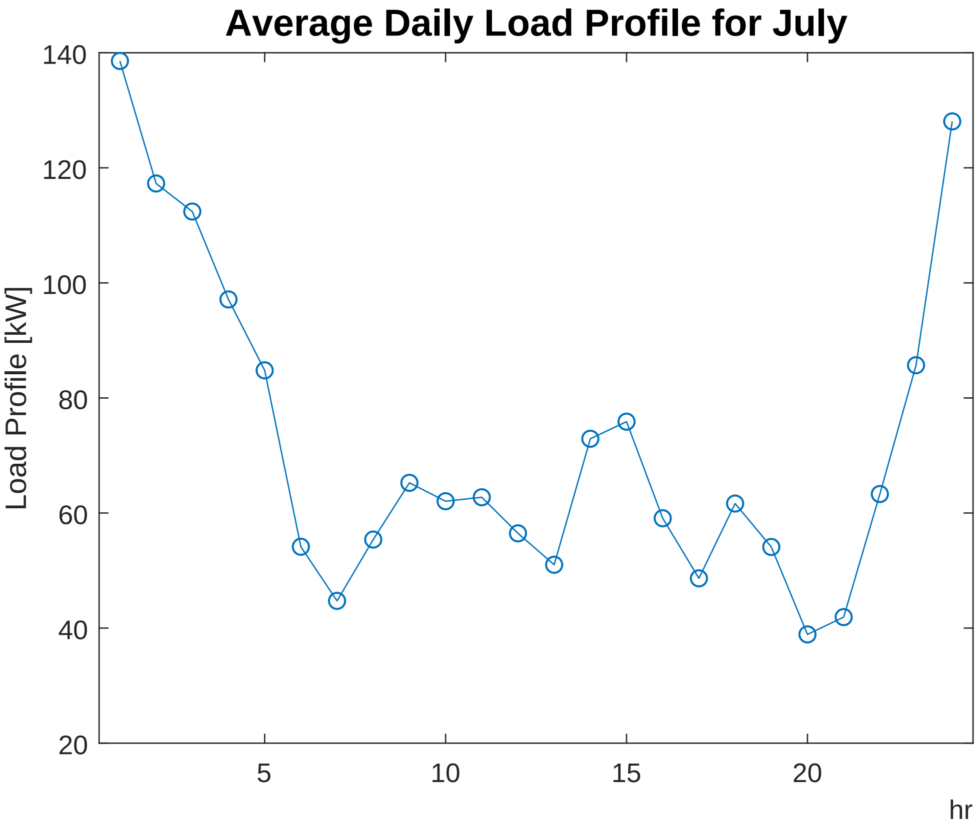

Figure I.7: Average daily load profile for the month of July.

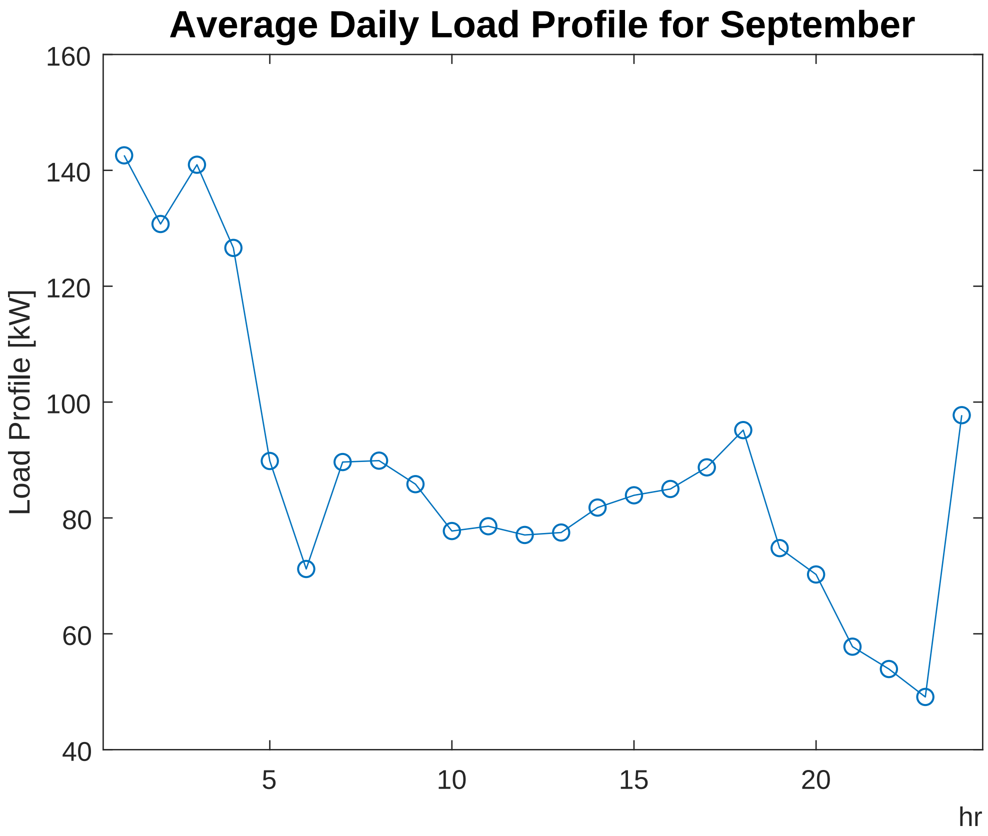

Figure I.8: Average daily load profile for the month of September.

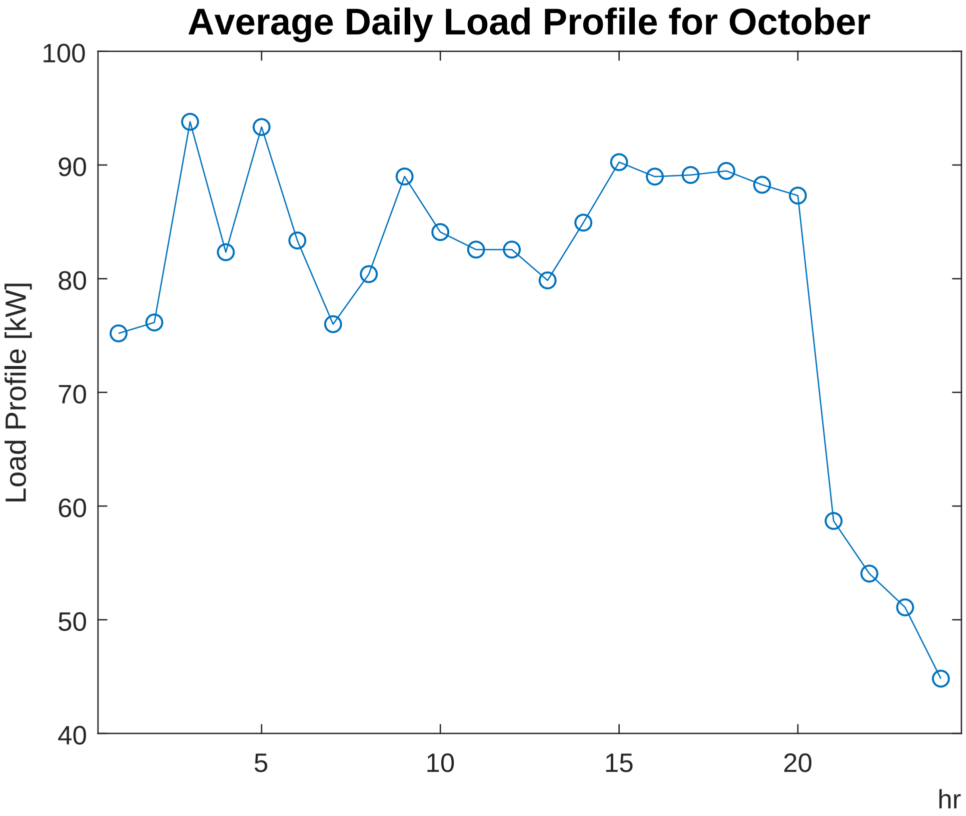

Figure I.9: Average daily load profile for the month of October.

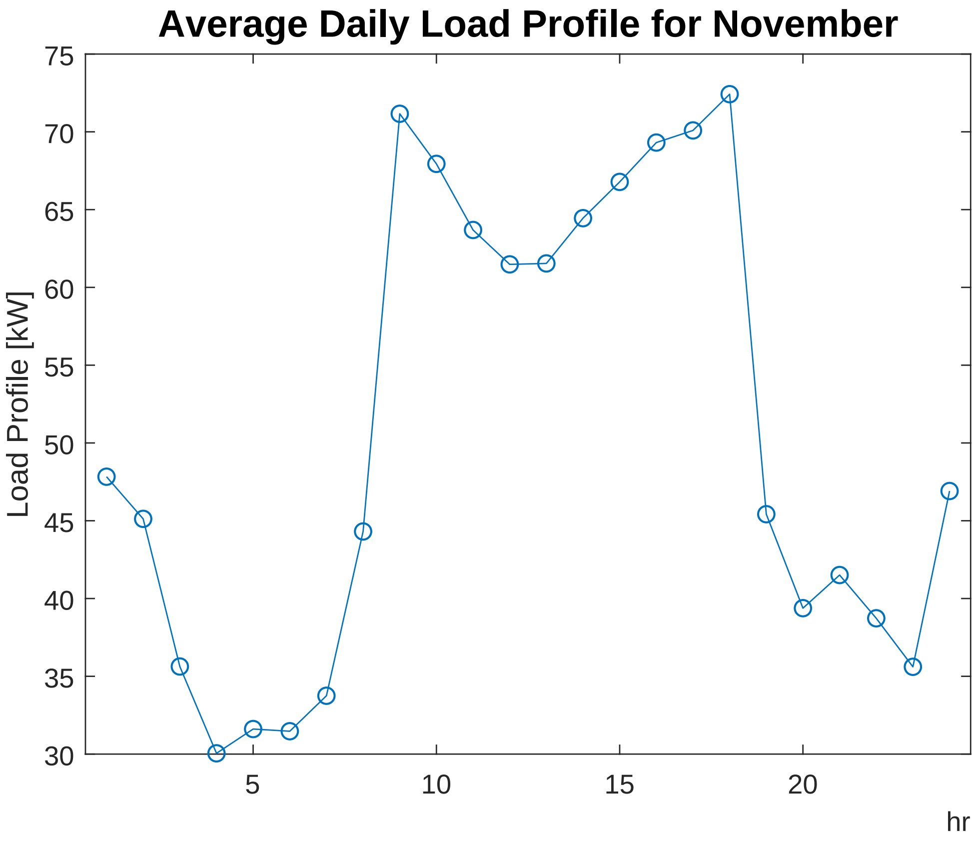

Figure I.10: Average daily load profile for the month of November.

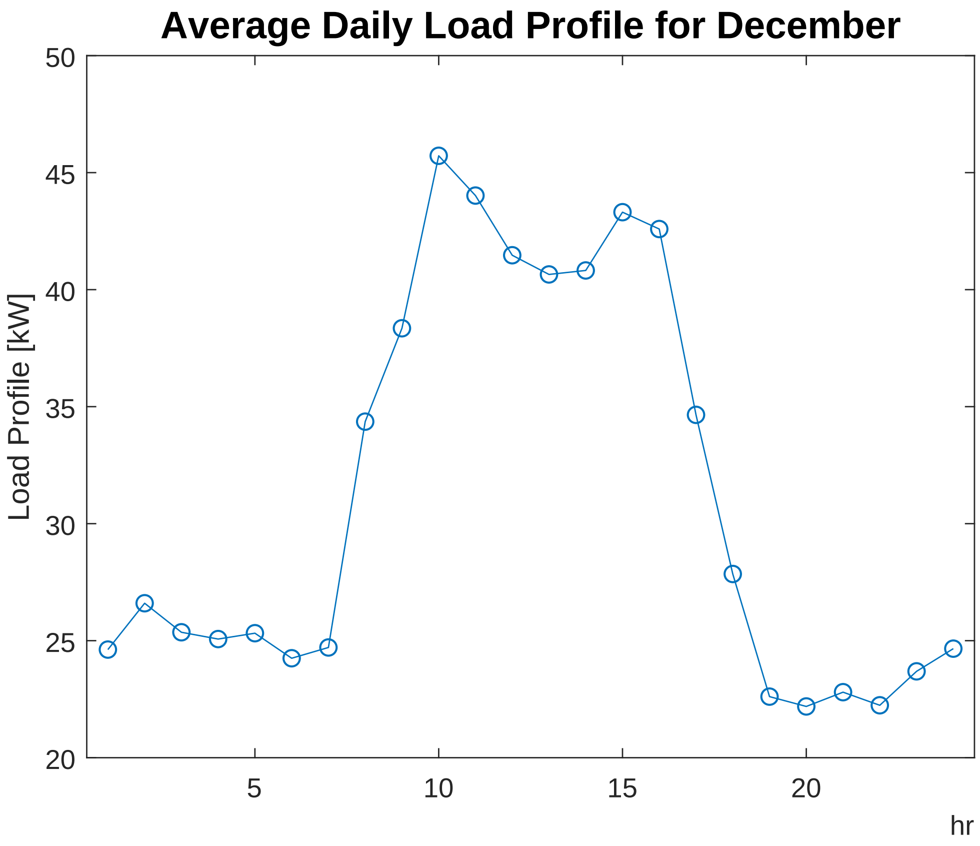

Figure I.11: Average daily load profile for the month of December.

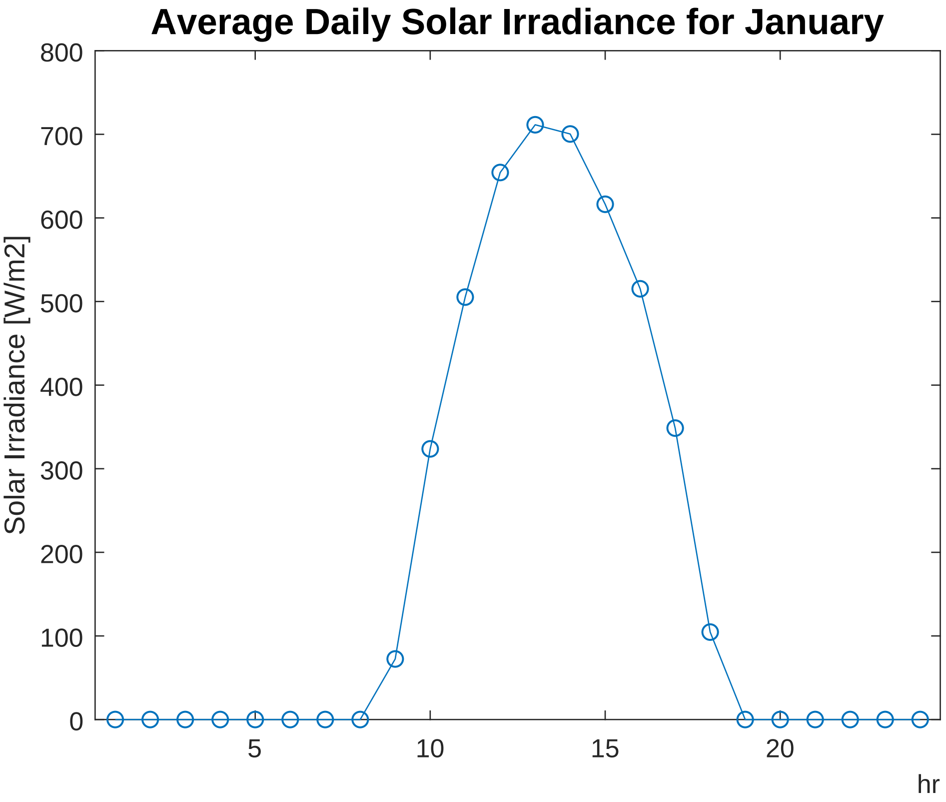

Figure I.12: Average daily solar irradiance for the month of January.

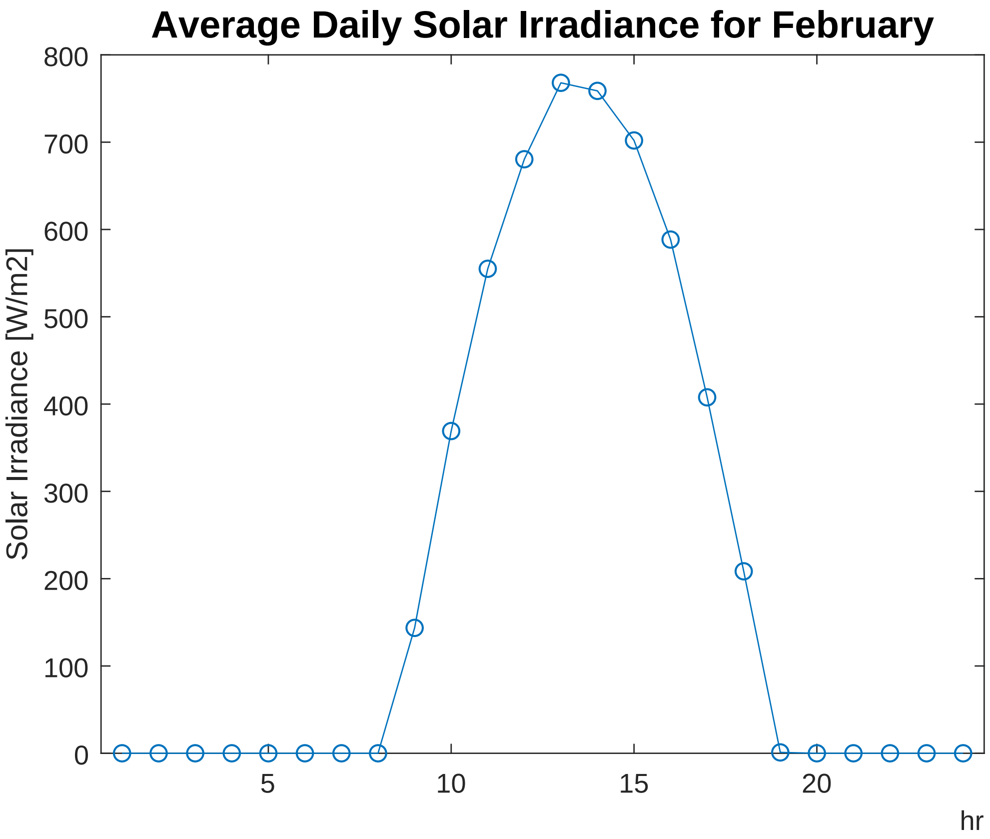

Figure I.13: Average daily solar irradiance for the month of February.

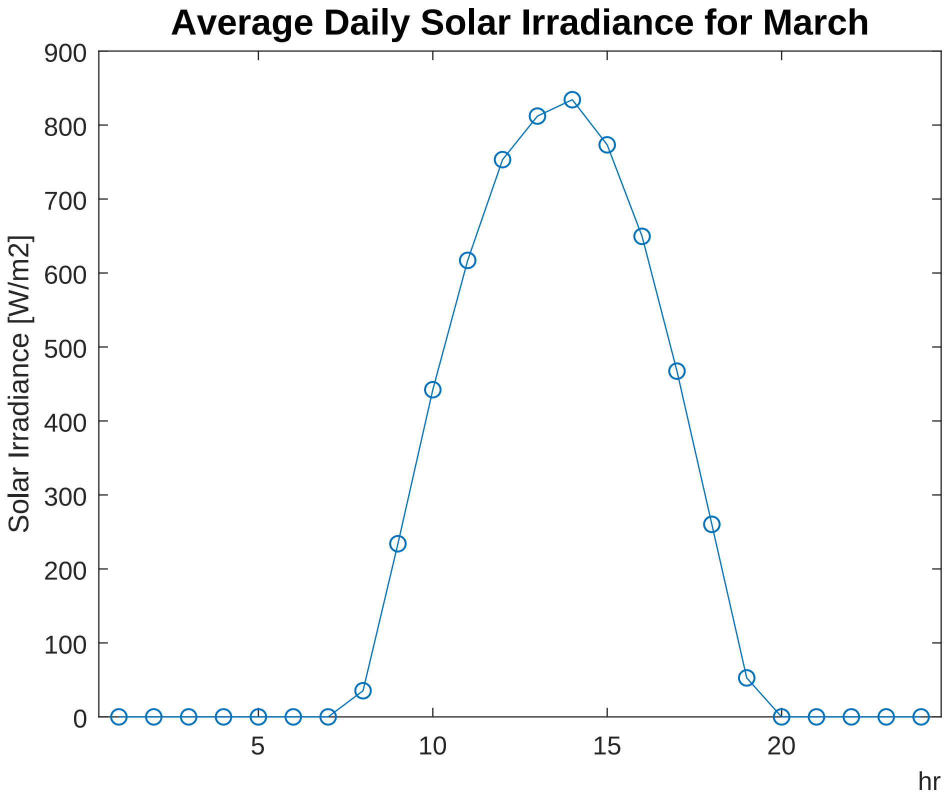

Figure I.14: Average daily solar irradiance for the month of March.

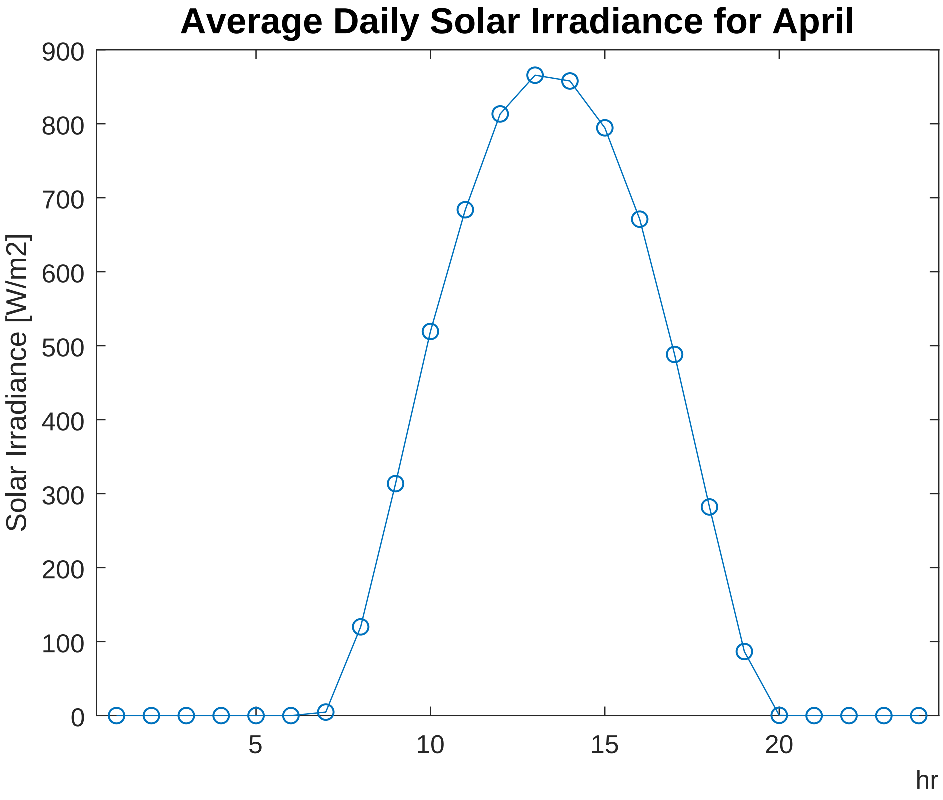

Figure I.15: Average daily solar irradiance for the month of April.

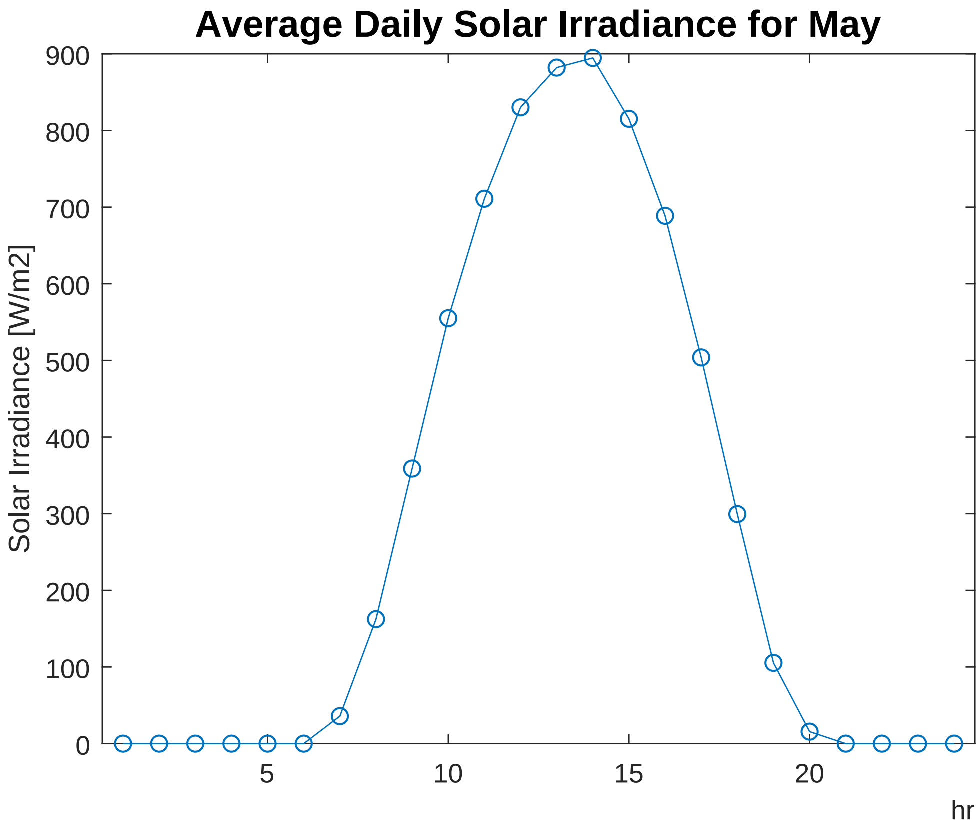

Figure I.16: Average daily solar irradiance for the month of May.

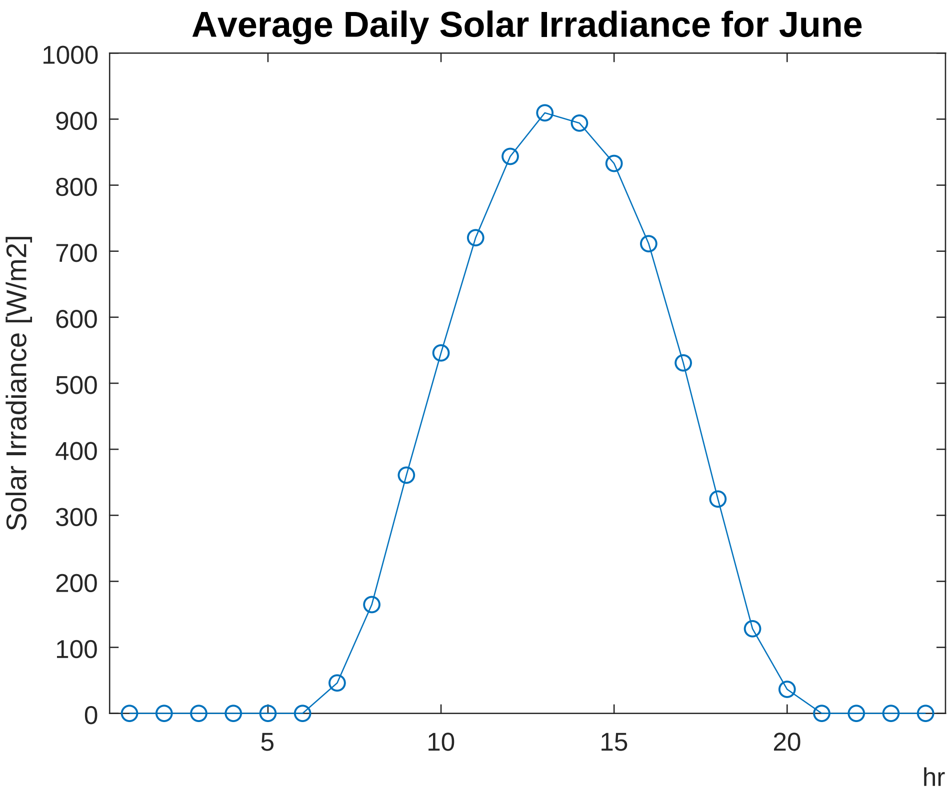

Figure I.17: Average daily solar irradiance for the month of June.

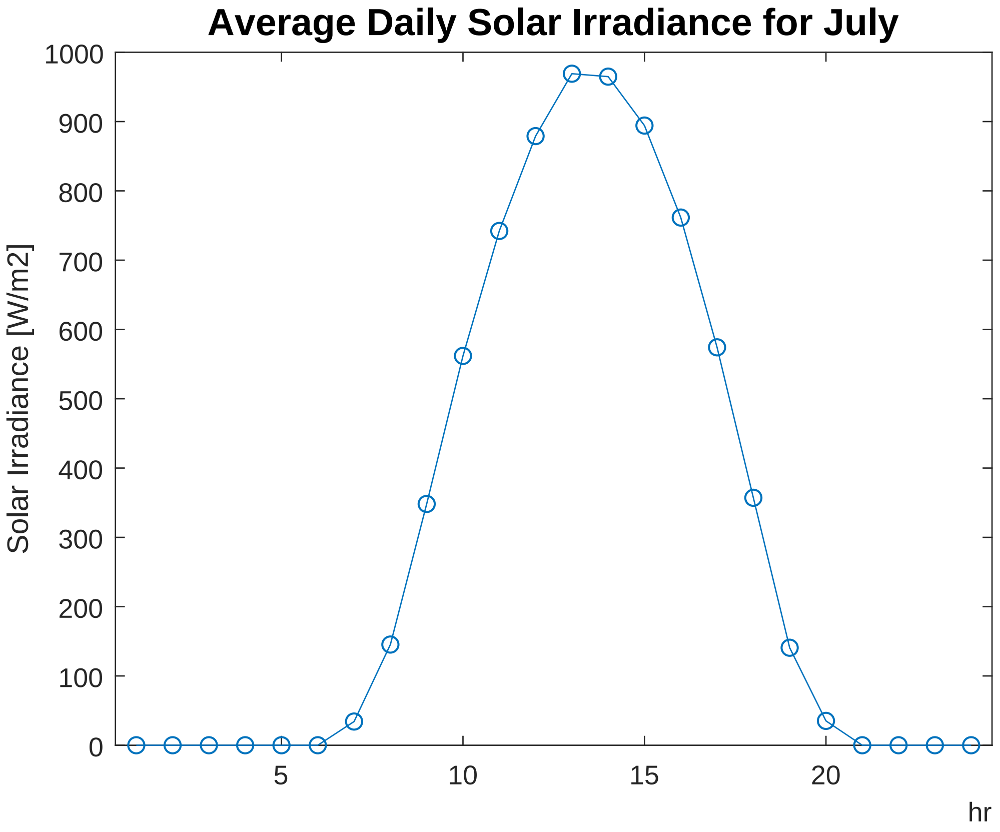

Figure I.18: Average daily solar irradiance for the month of July.

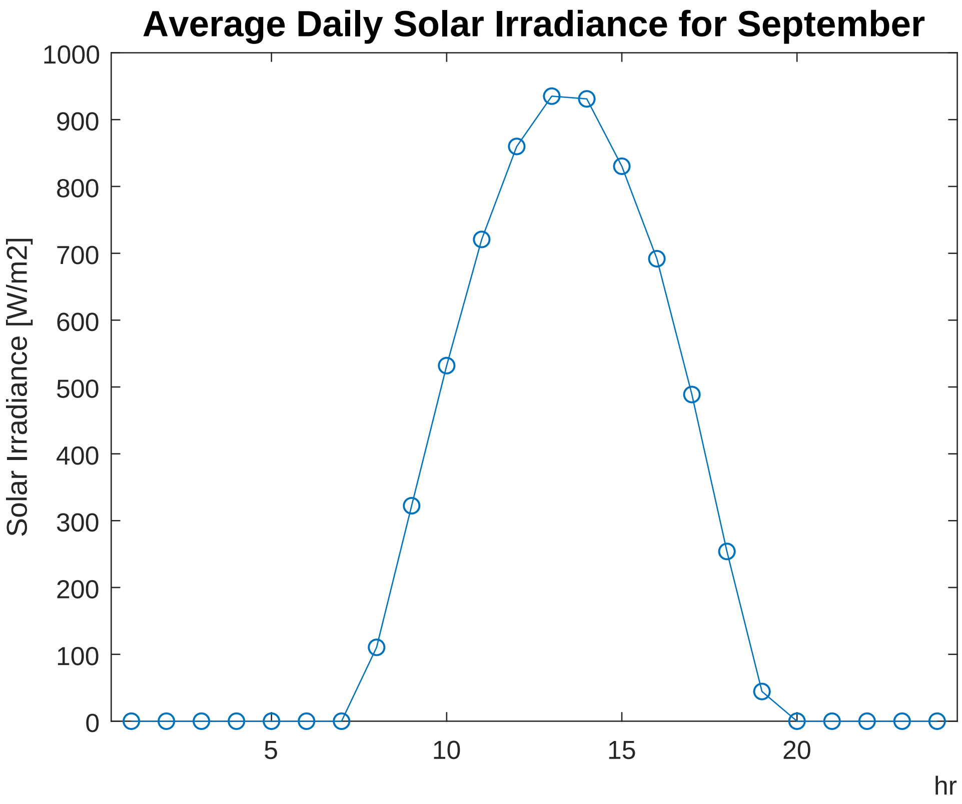

Figure I.19: Average daily solar irradiance for the month of September.

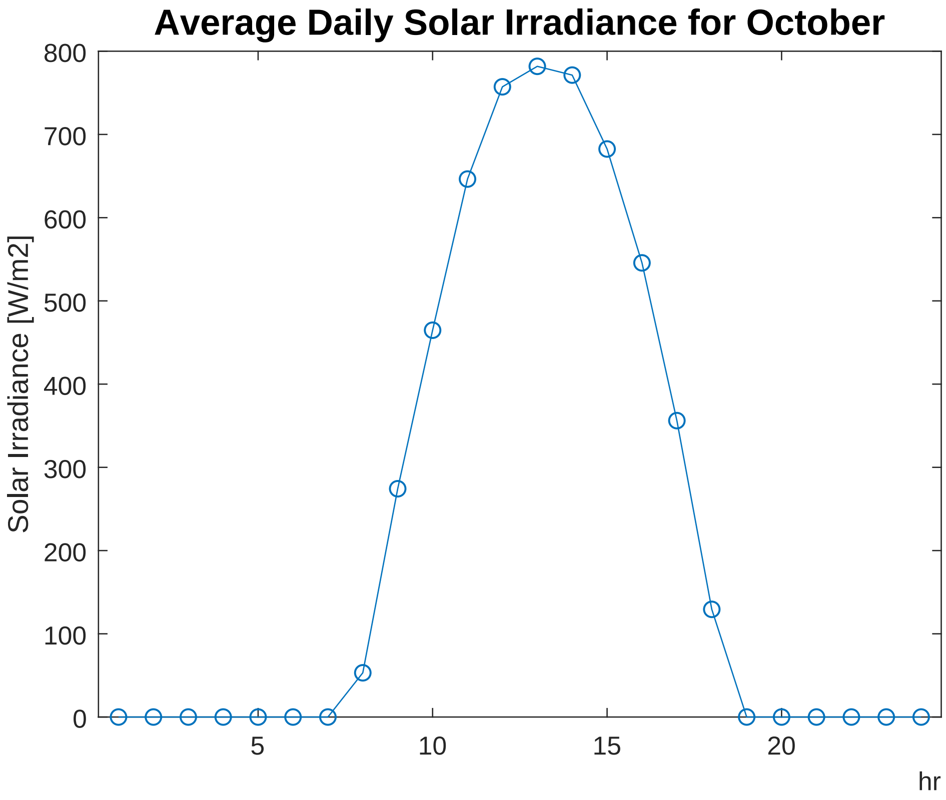

Figure I.20: Average daily solar irradiance for the month of October.

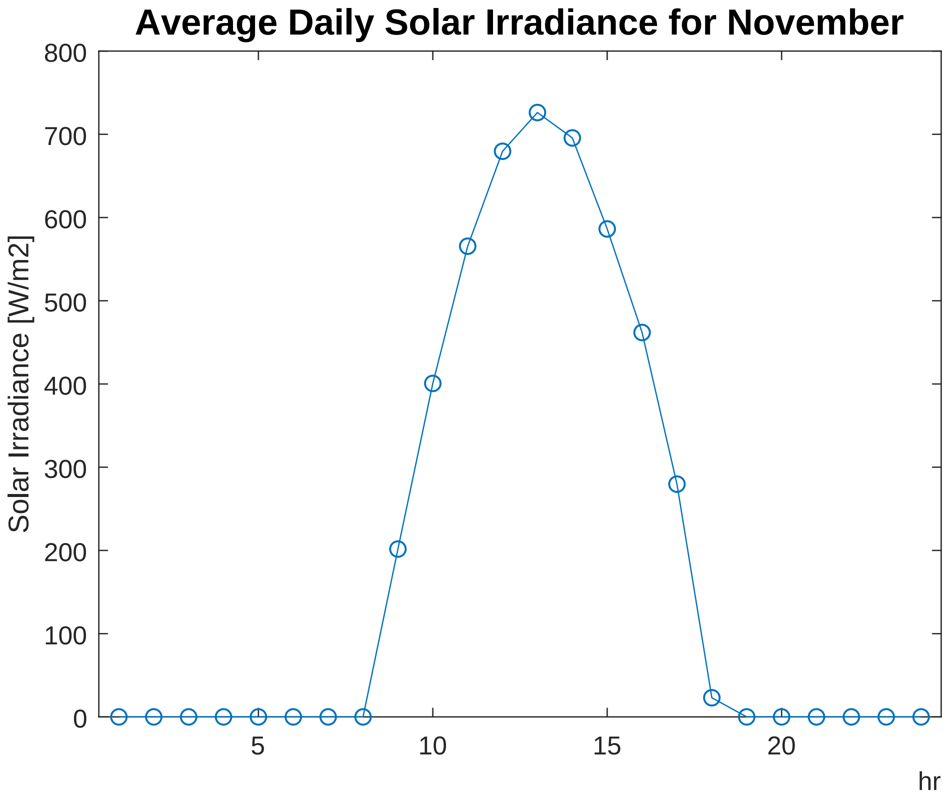

Figure I.21: Average daily solar irradiance for the month of November.

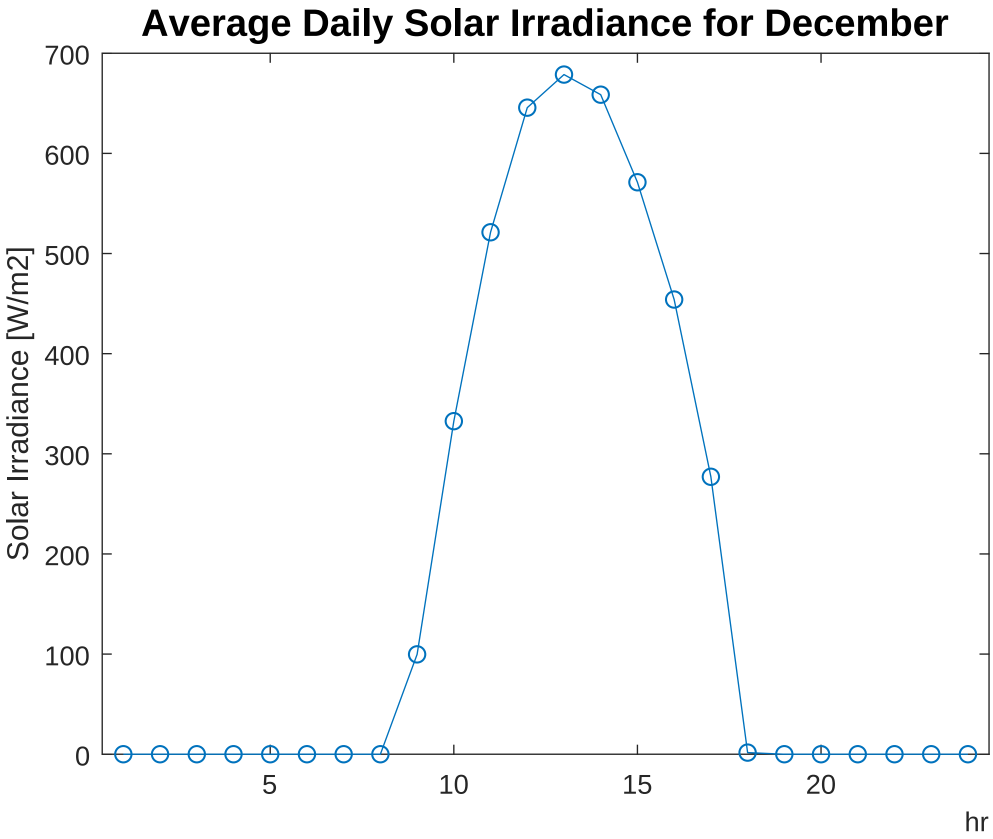

Figure I.22: Average daily solar irradiance for the month of December.

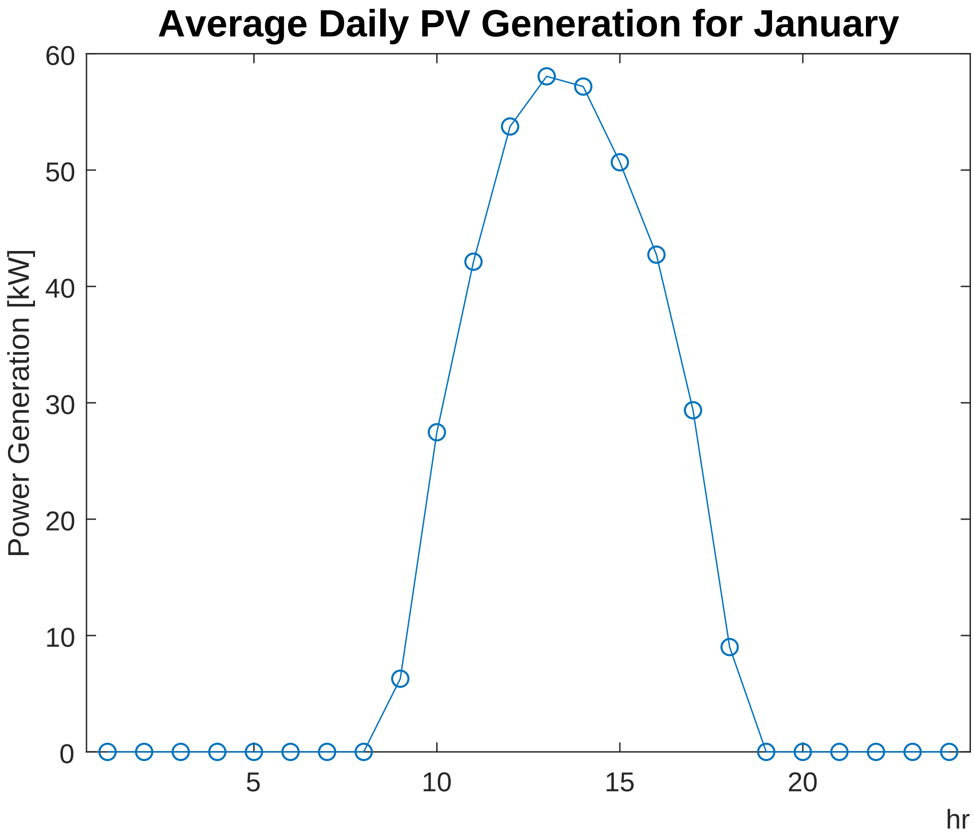

Figure I.23: Average daily PV generation for the month of January.

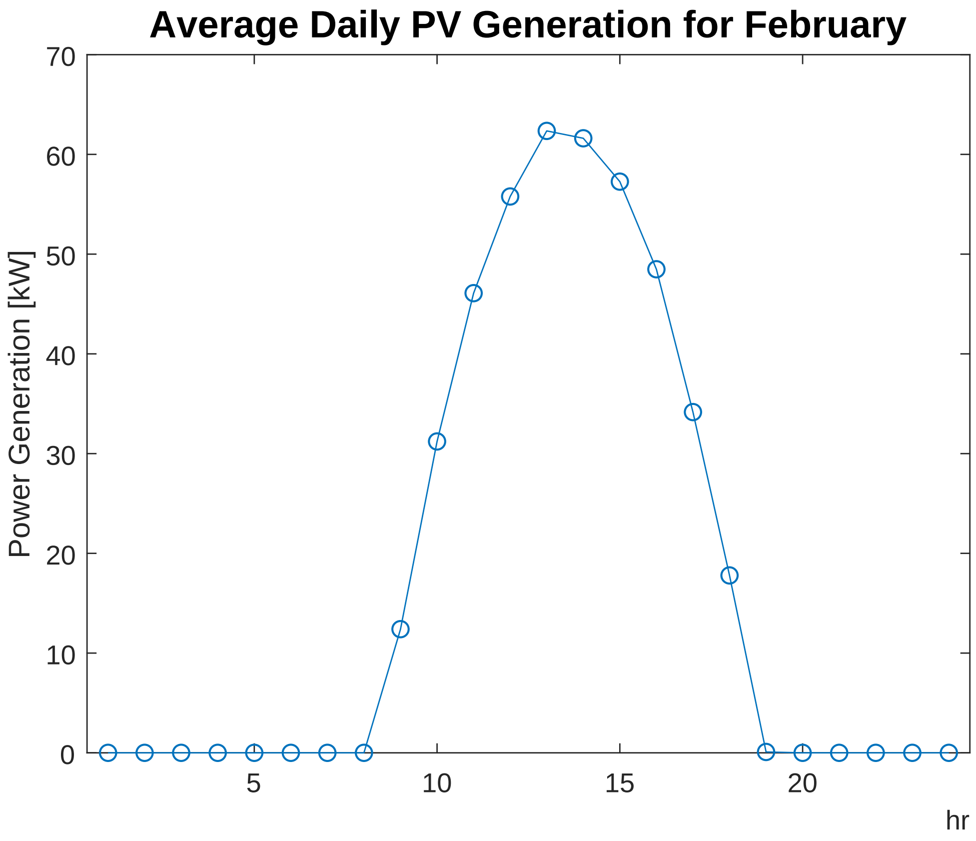

Figure I.24: Average daily PV generation for the month of February.

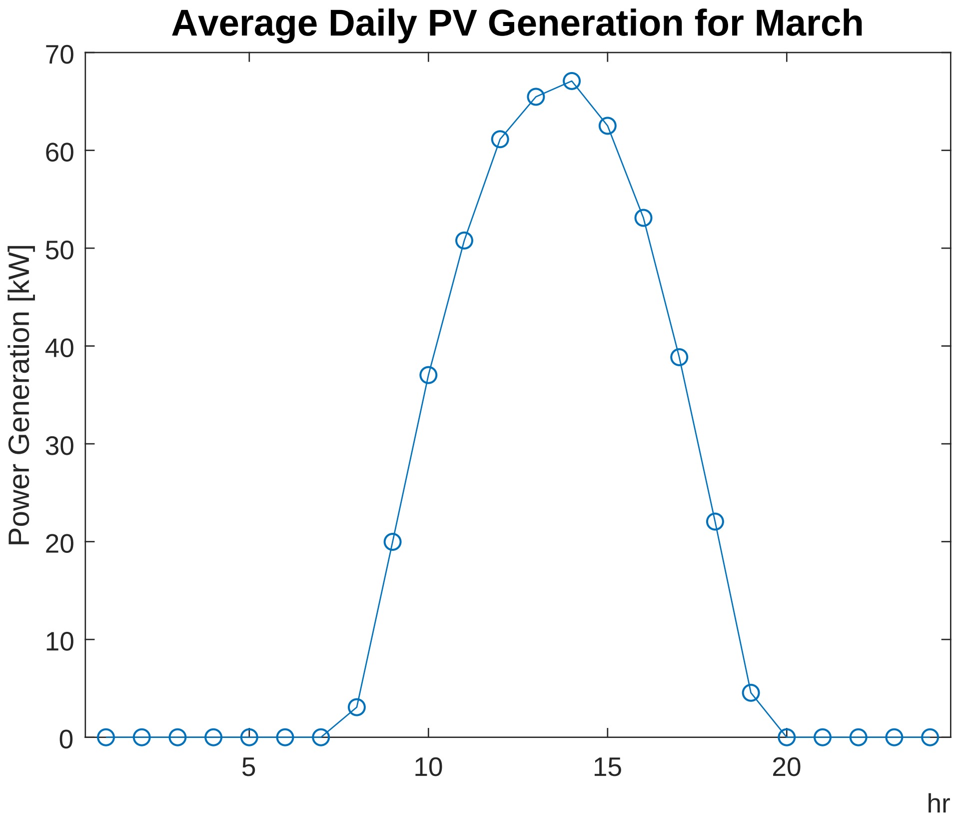

Figure I.25: Average daily PV generation for the month of March.

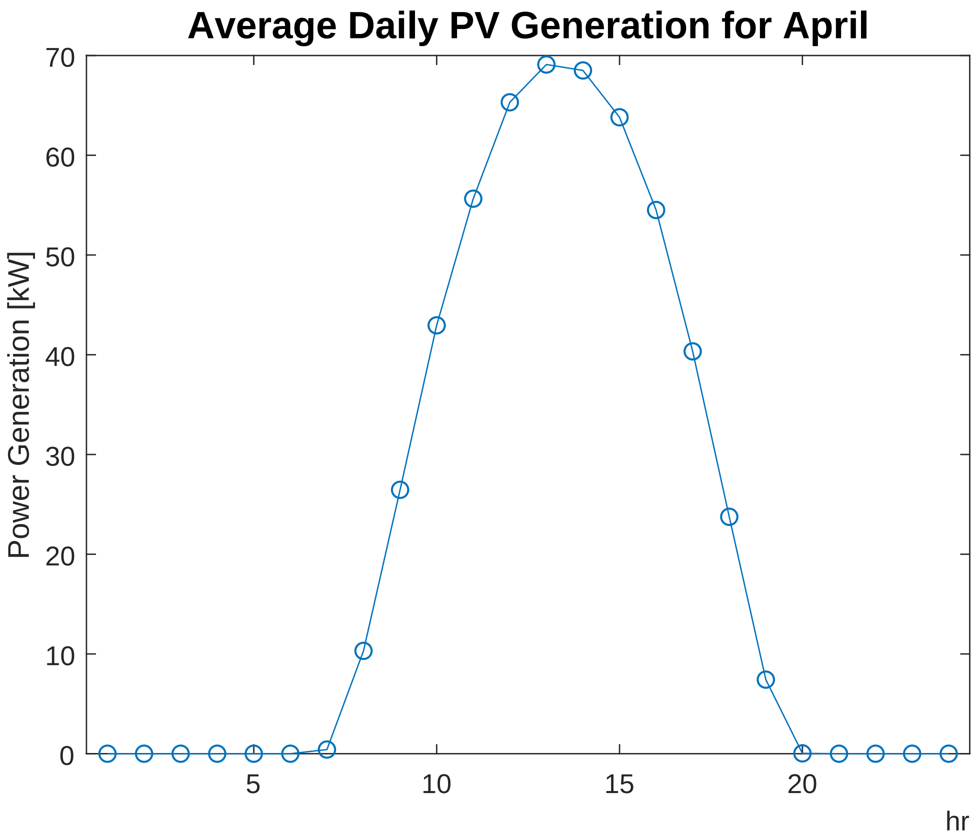

Figure I.26: Average daily PV generation for the month of April.

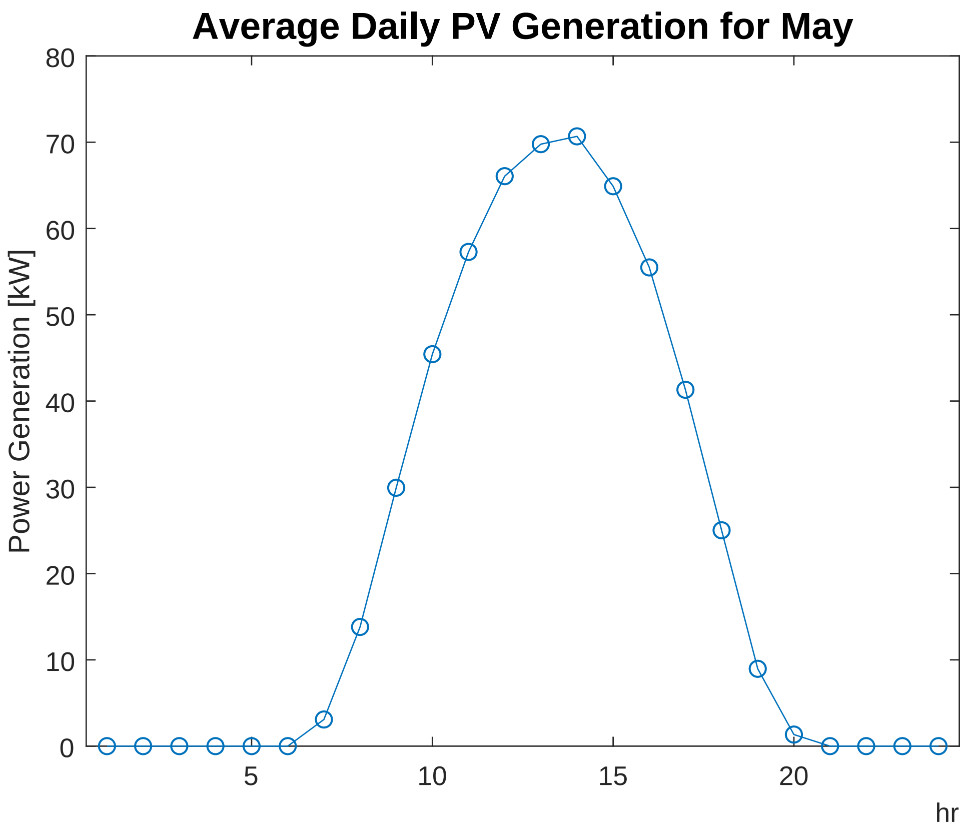

Figure I.27: Average daily PV generation for the month of May.

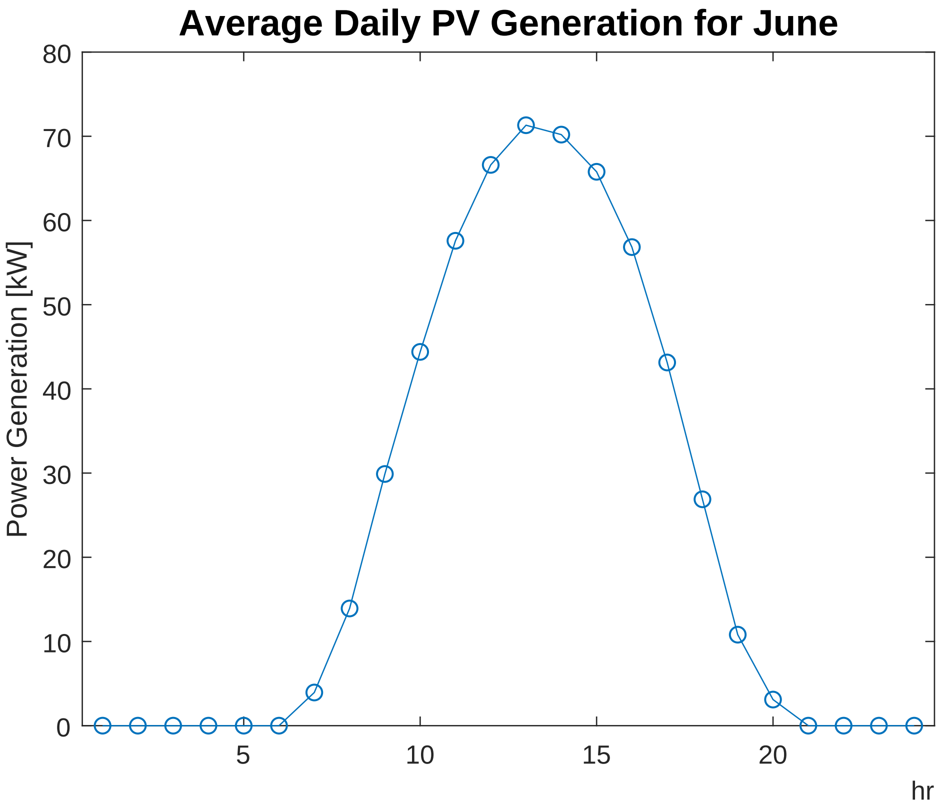

Figure I.28: Average daily PV generation for the month of June.

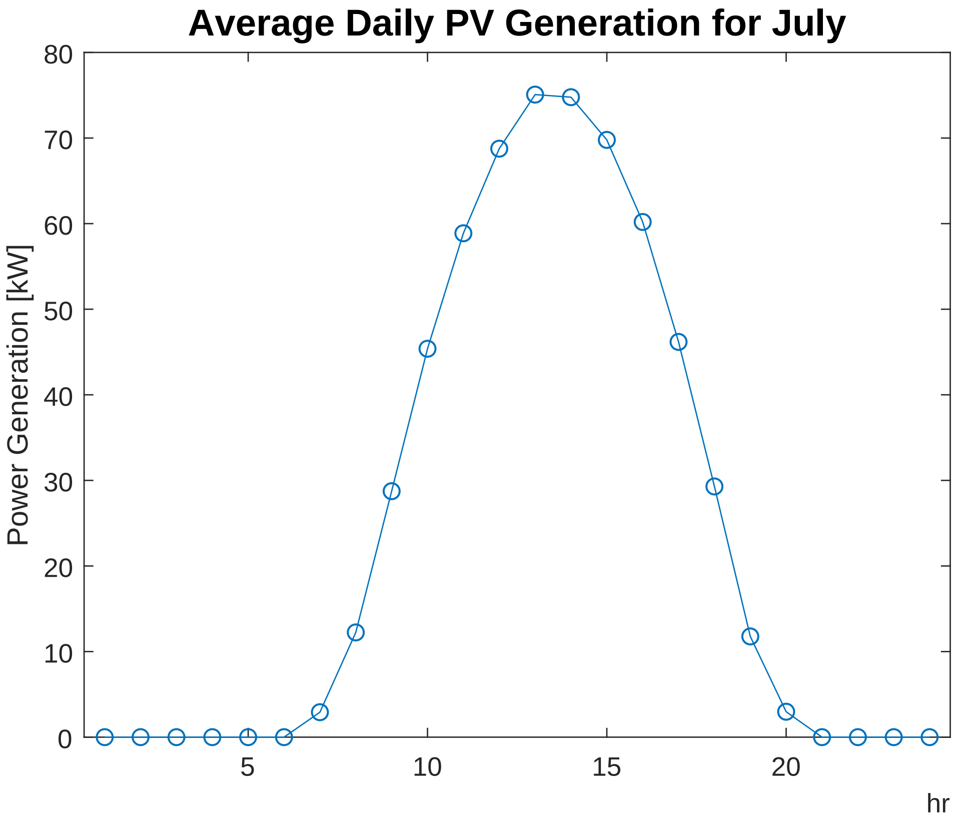

Figure I.29: Average daily PV generation for the month of July.

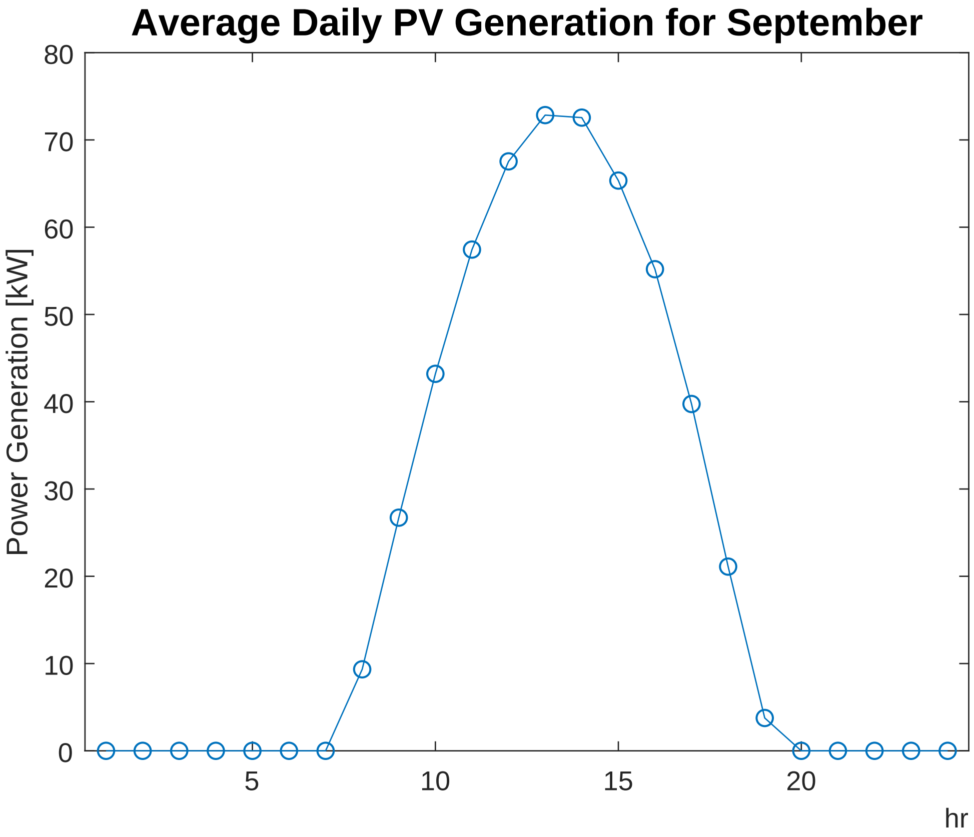

Figure I.30: Average daily PV generation for the month of September.

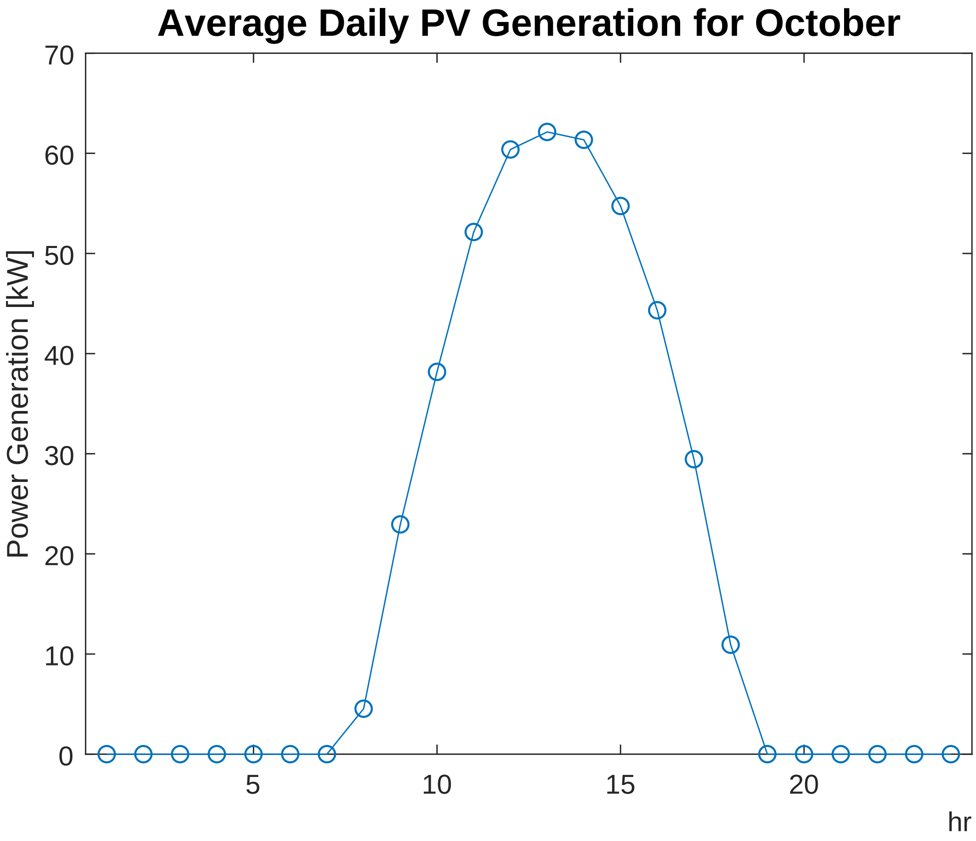

Figure I.31: Average daily PV generation for the month of October.

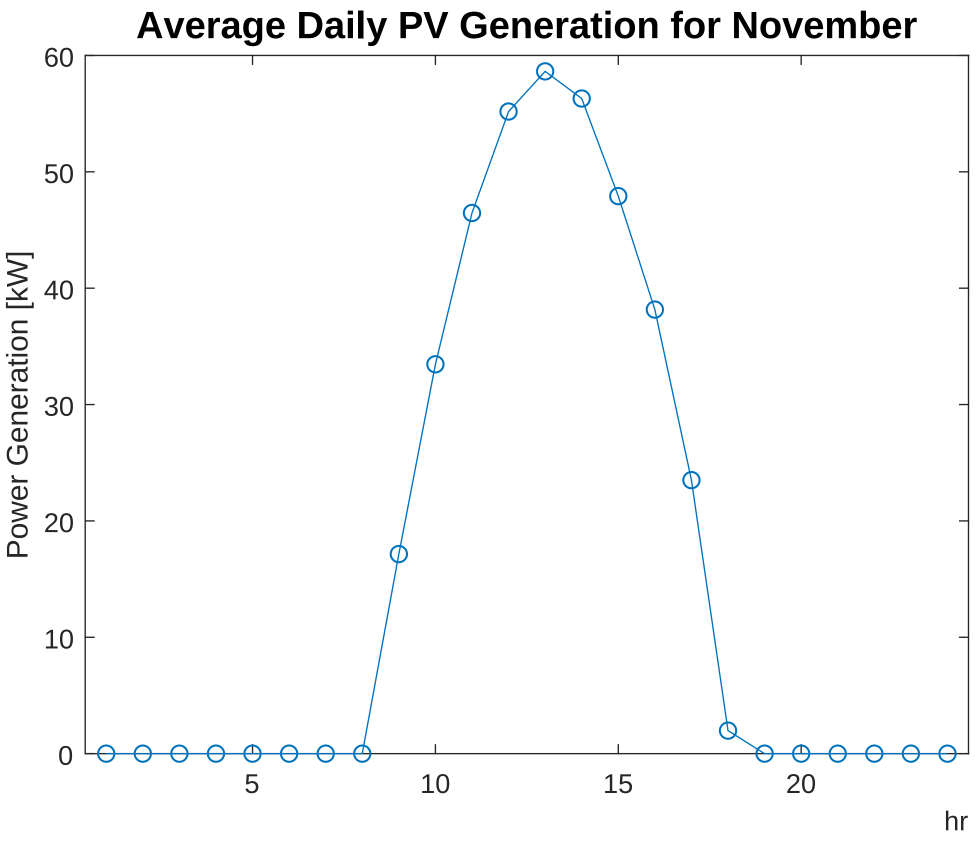

Figure I.32: Average daily PV generation for the month of November.

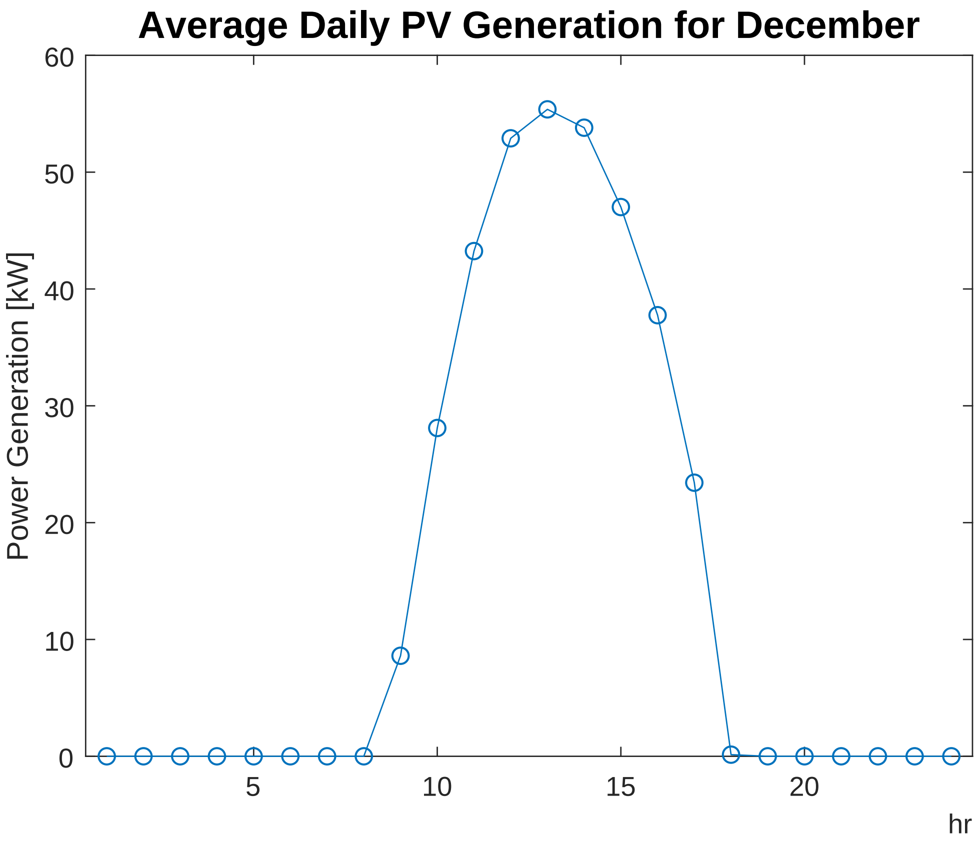

Figure I.33: Average daily PV generation for the month of December.

II

Annex 2

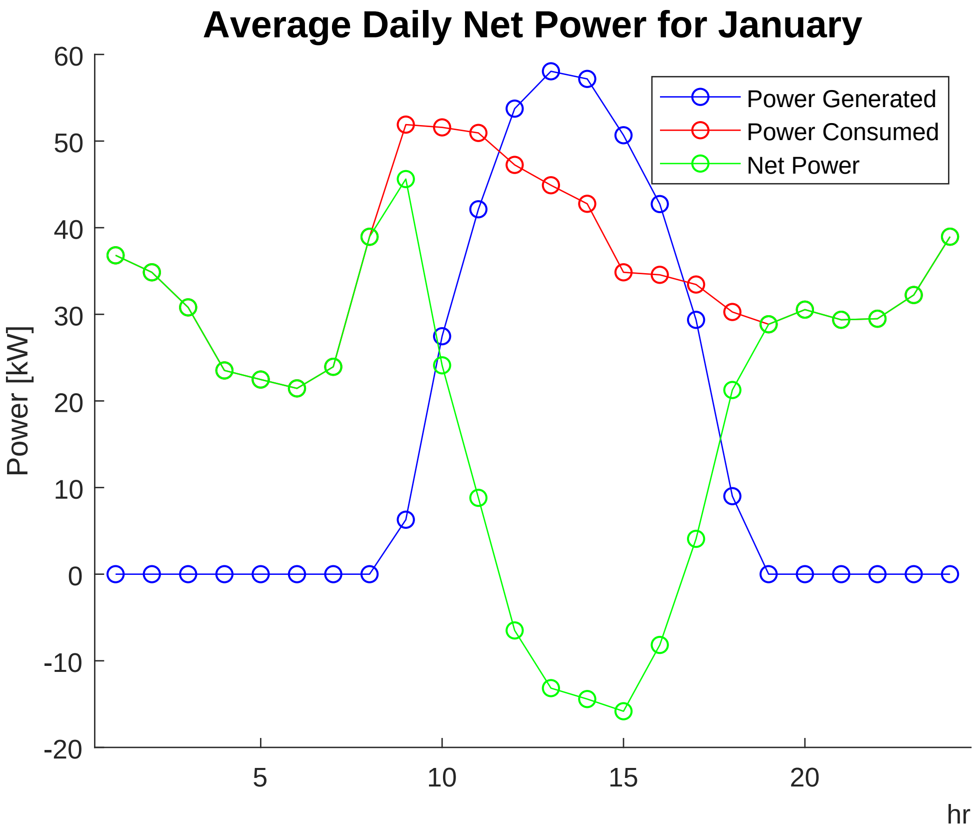

Figure II.1: Average daily net power for the month of January.

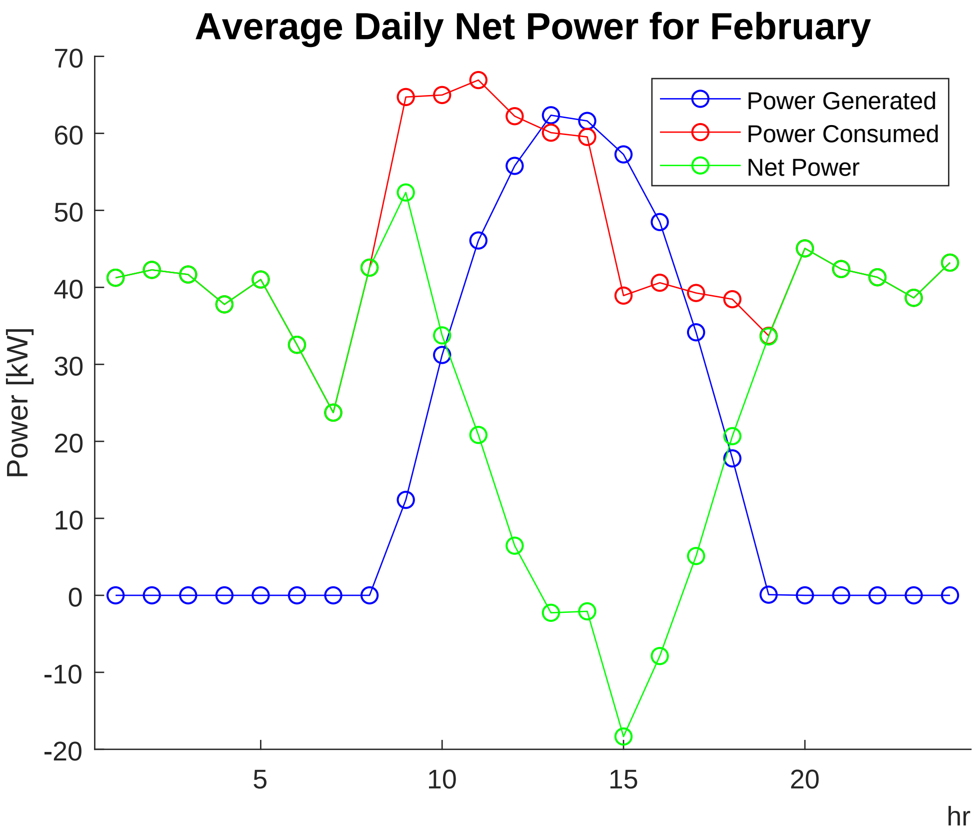

Figure II.2: Average daily net power for the month of February.

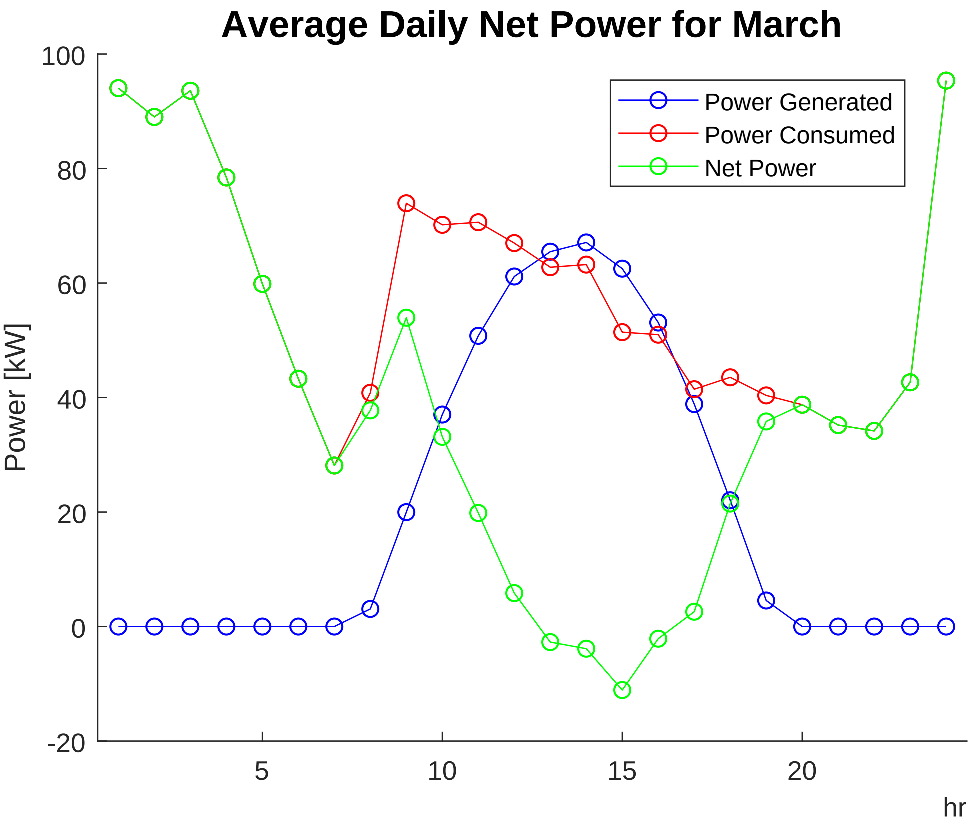

Figure II.3: Average daily net power for the month of March.

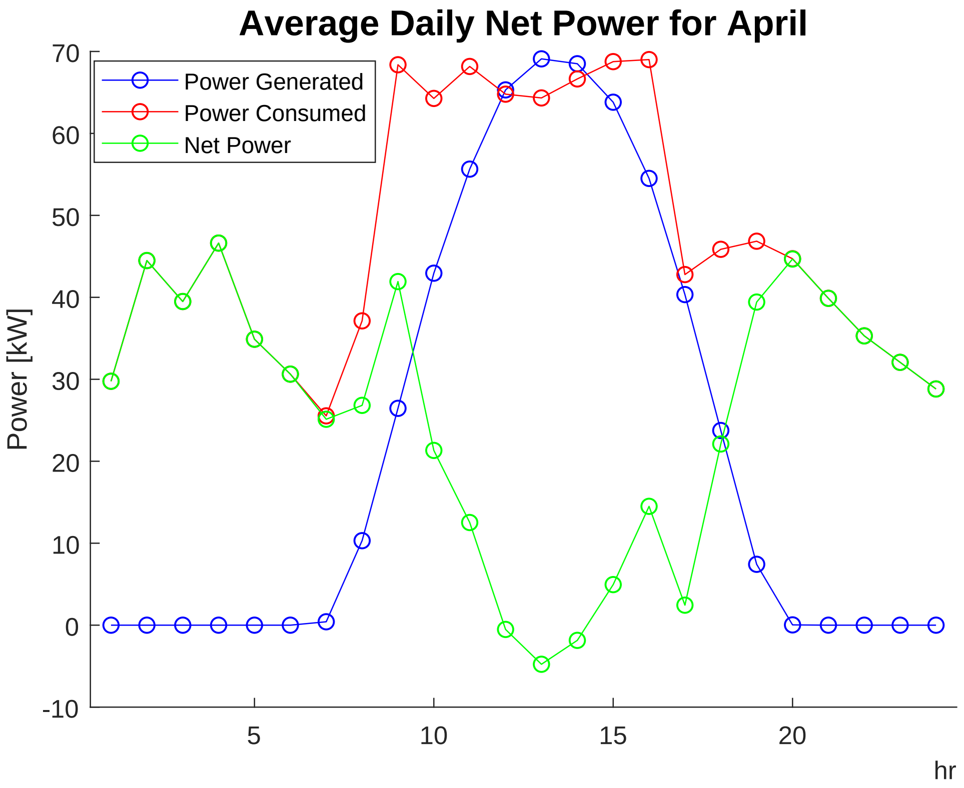

Figure II.4: Average daily net power for the month of April.

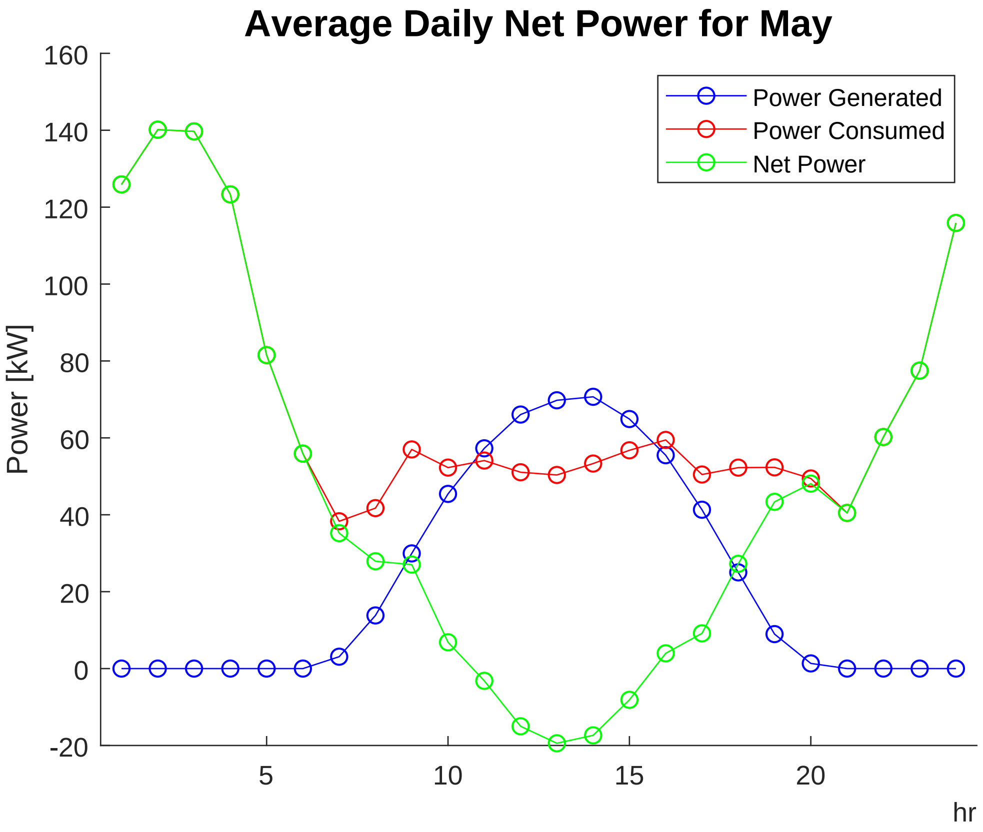

Figure II.5: Average daily net power for the month of May.

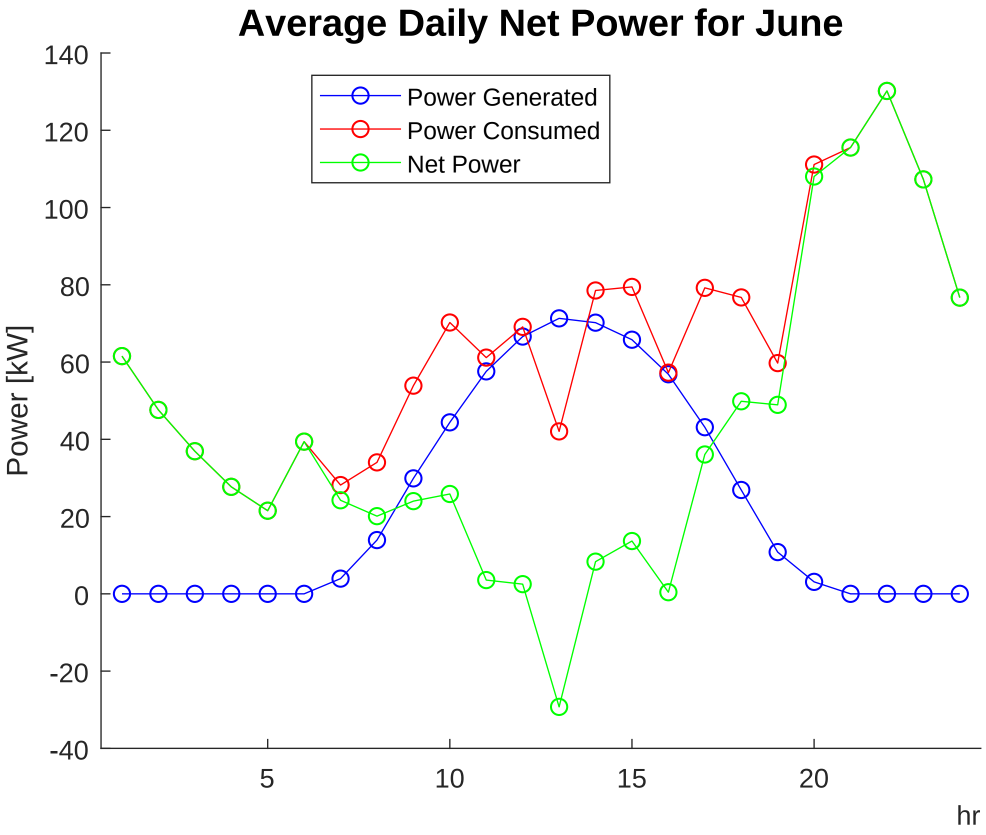

Figure II.6: Average daily net power for the month of June.

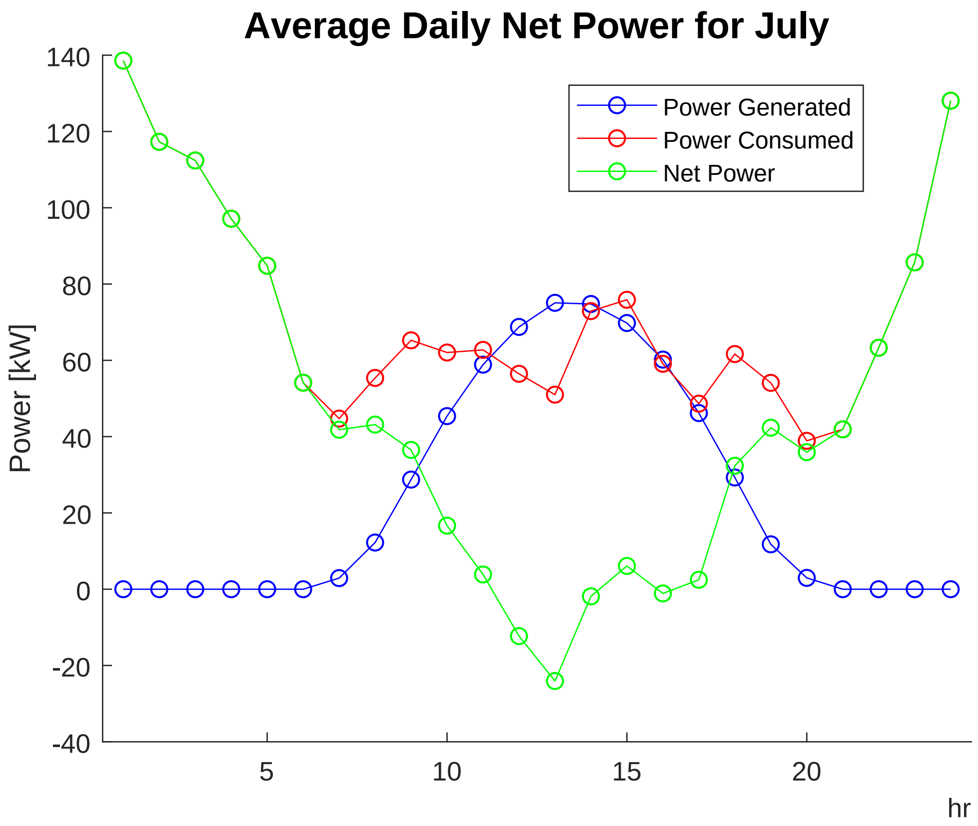

Figure II.7: Average daily net power for the month of July.

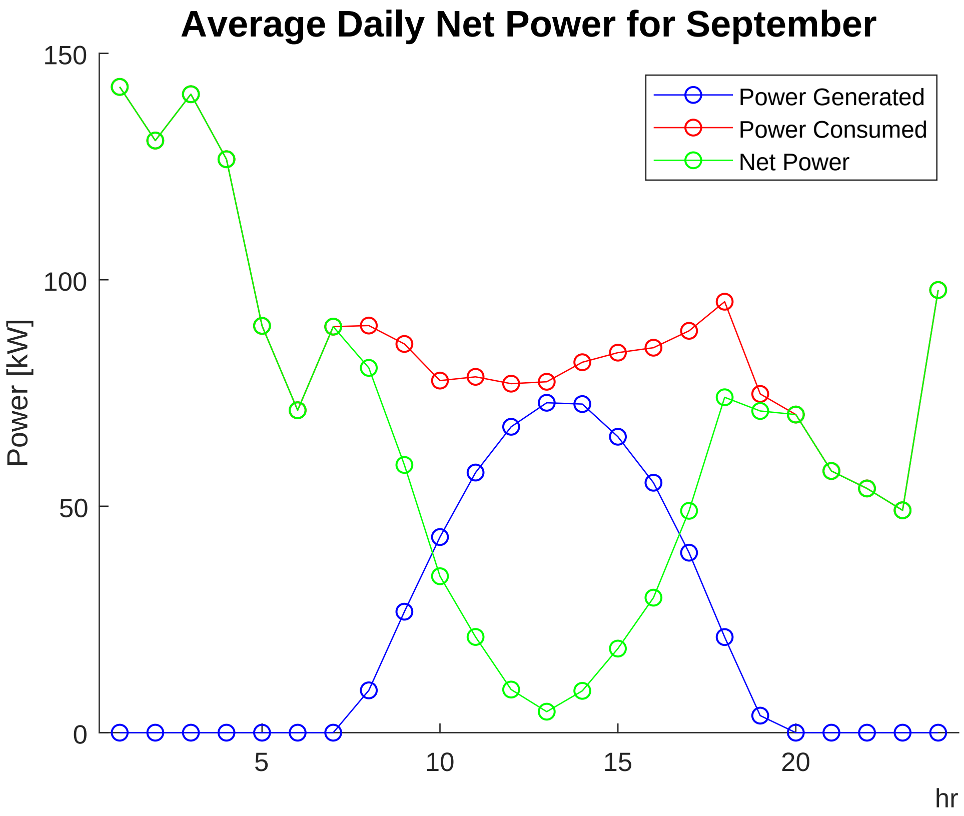

Figure II.8: Average daily net power for the month of September.

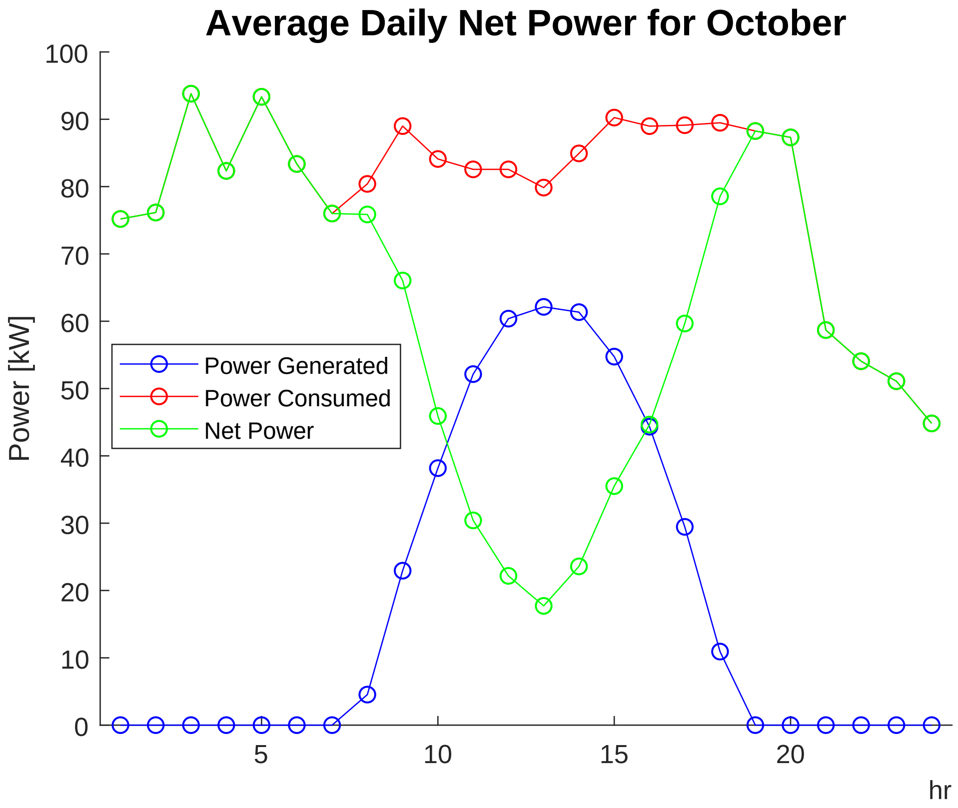

Figure II.9: Average daily net power for the month of October.

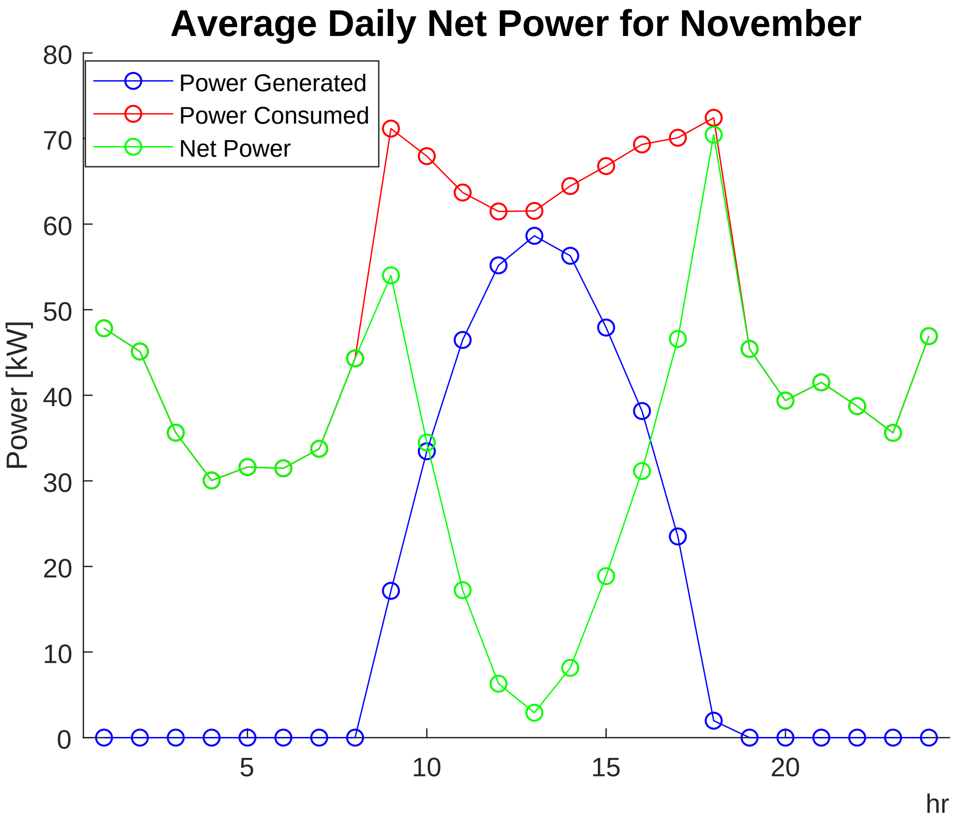

Figure II.10: Average daily net power for the month of November.

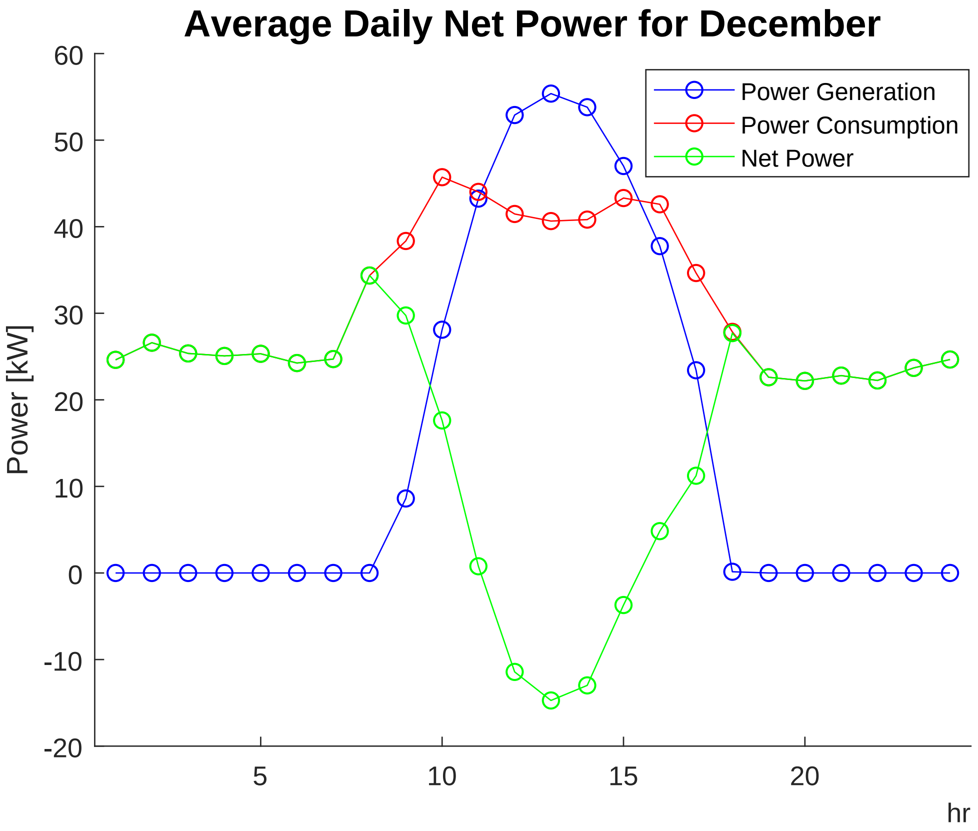

Figure II.11: Average daily net power for the month of December.

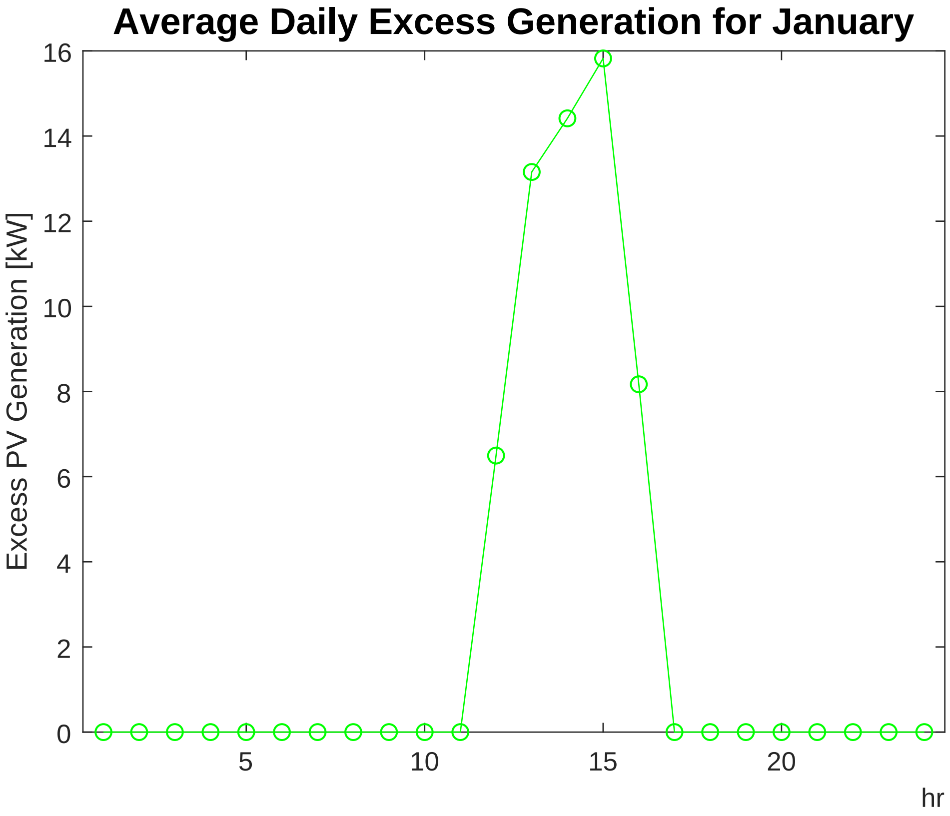

Figure II.12: Average daily excess generation for the month of January.

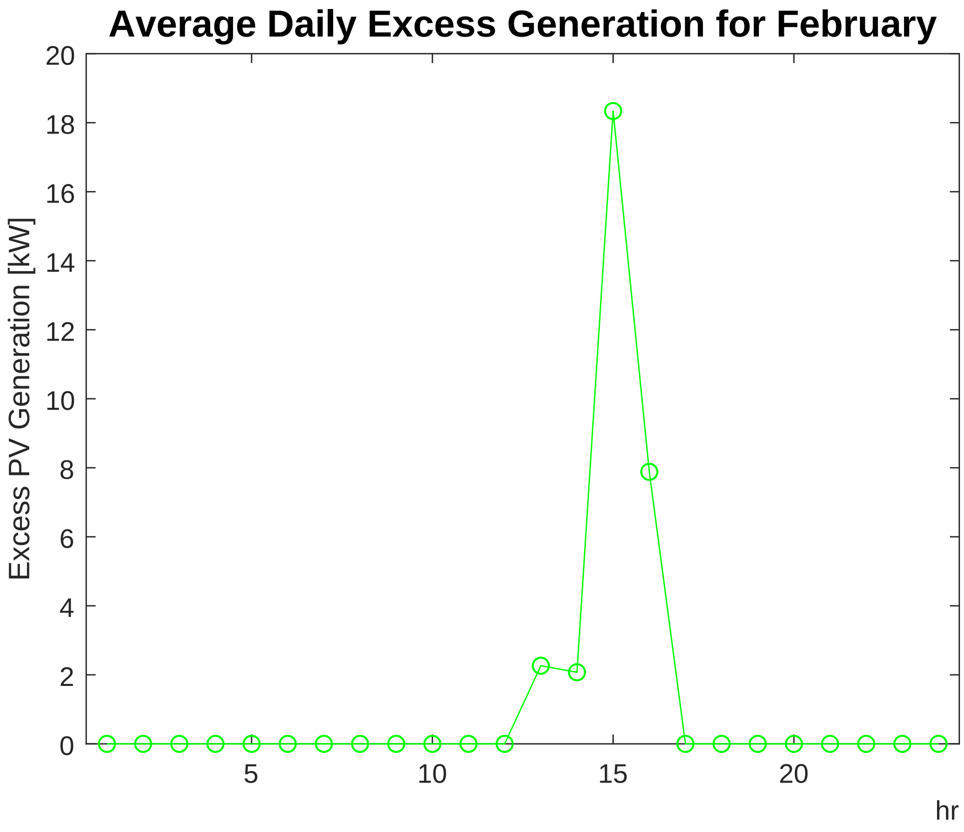

Figure II.13: Average daily excess generation for the month of February.

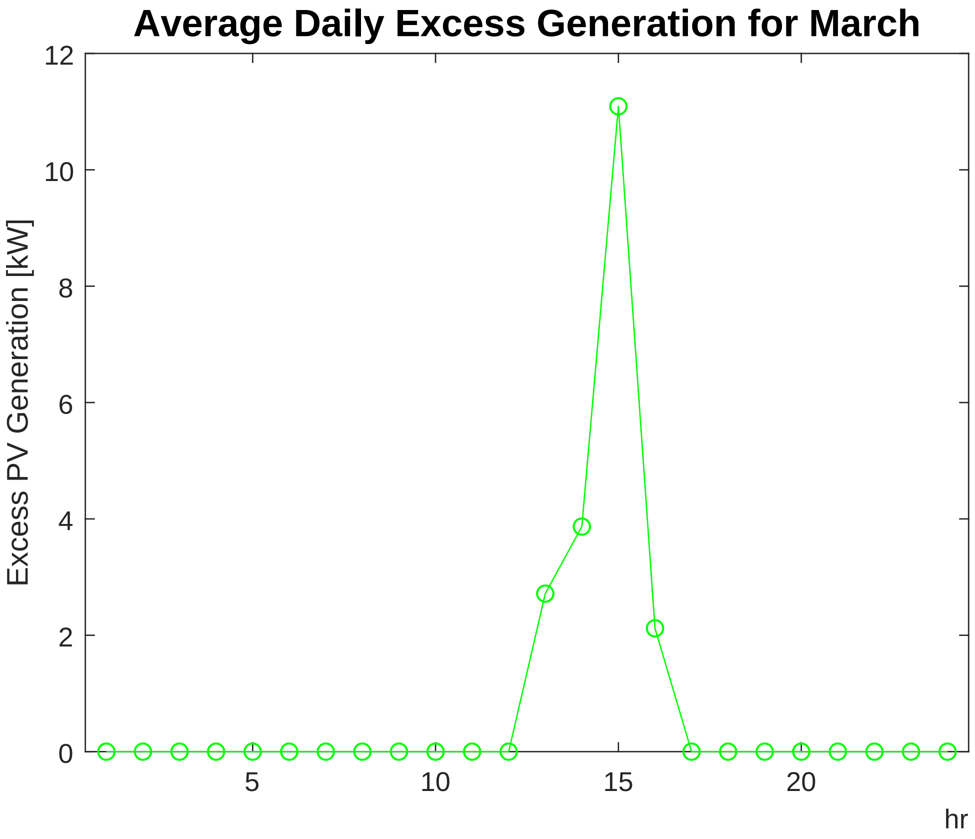

Figure II.14: Average daily excess generation for the month of March.

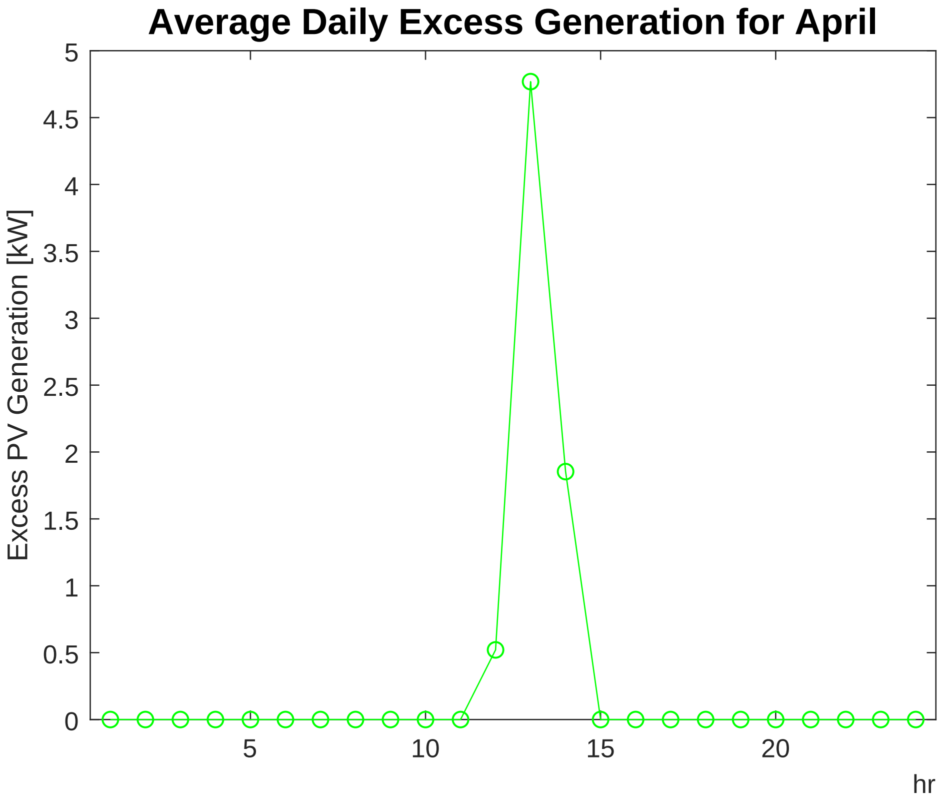

Figure II.15: Average daily excess generation for the month of April.

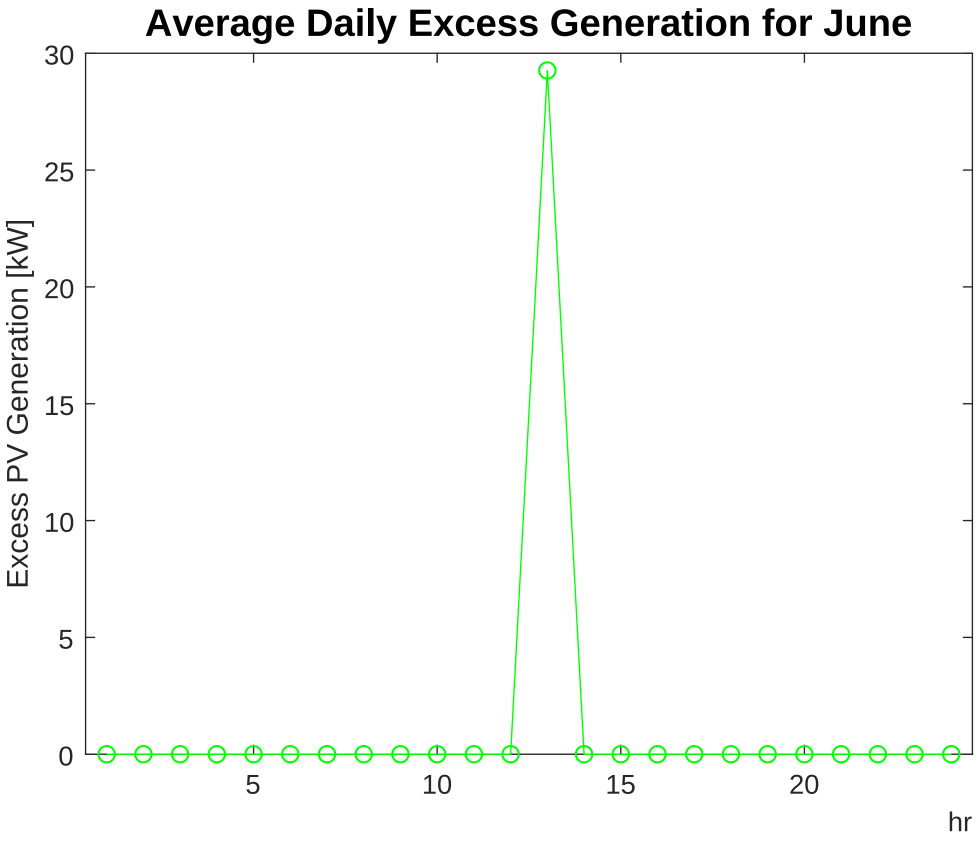

Figure II.16: Average daily excess generation for the month of June.

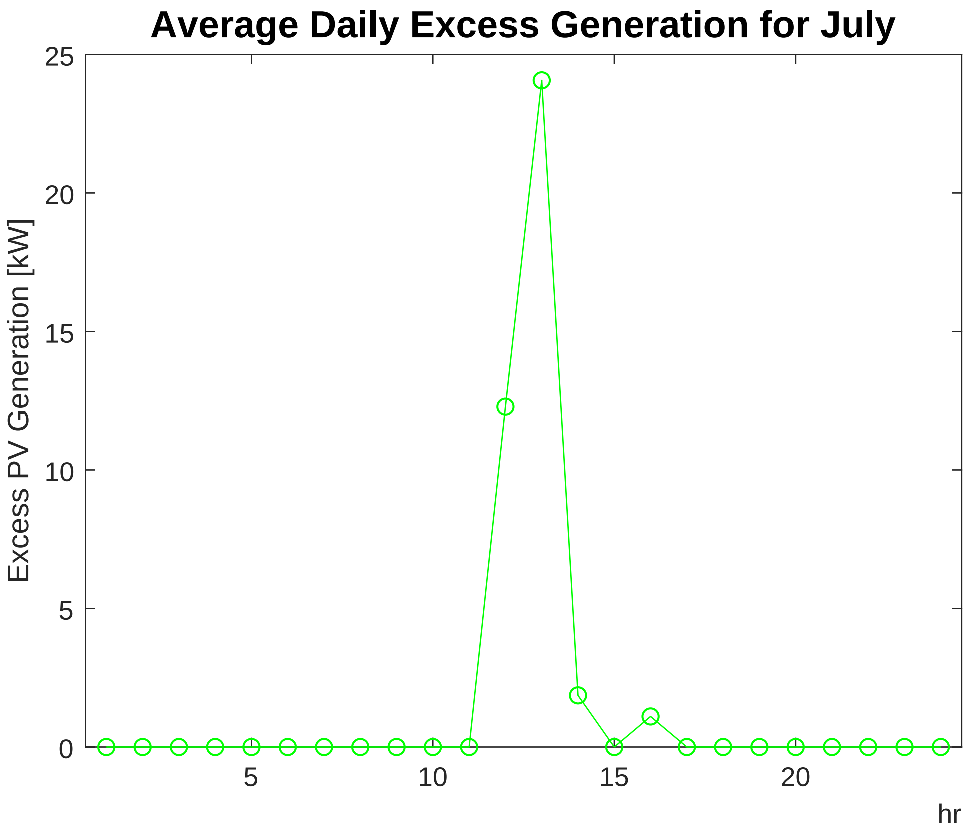

Figure II.17: Aerage daily excess generation for the month of July.

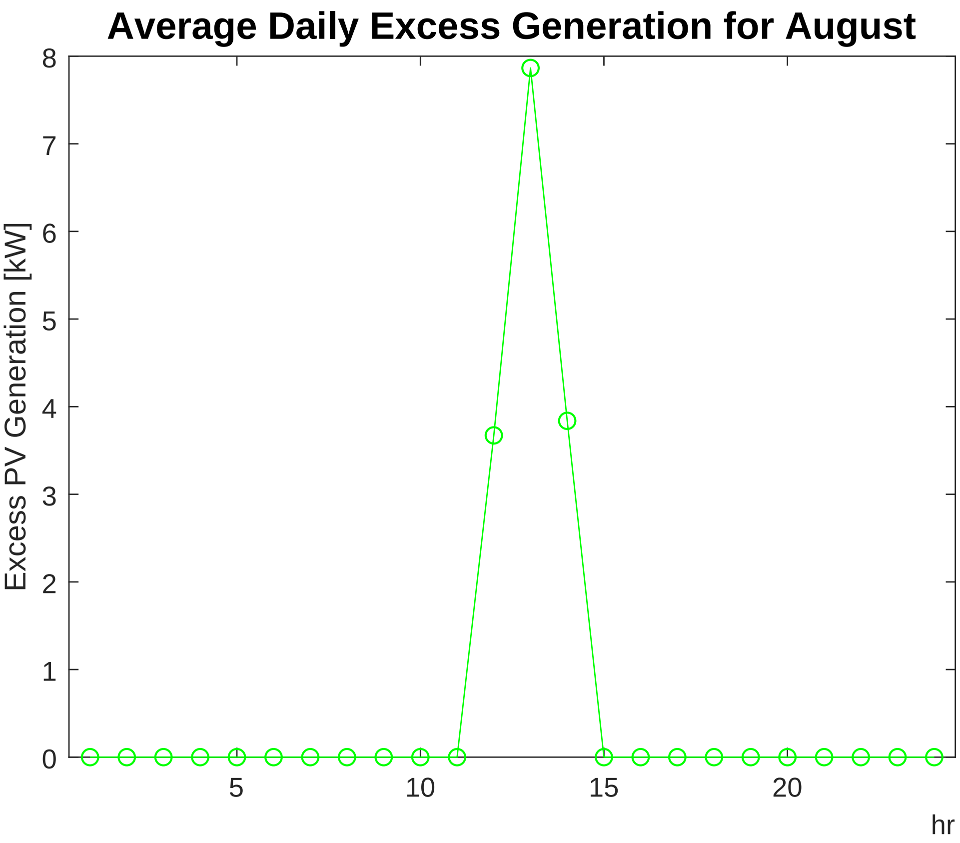

Figure II.18: Average daily excess generation for the month of August.

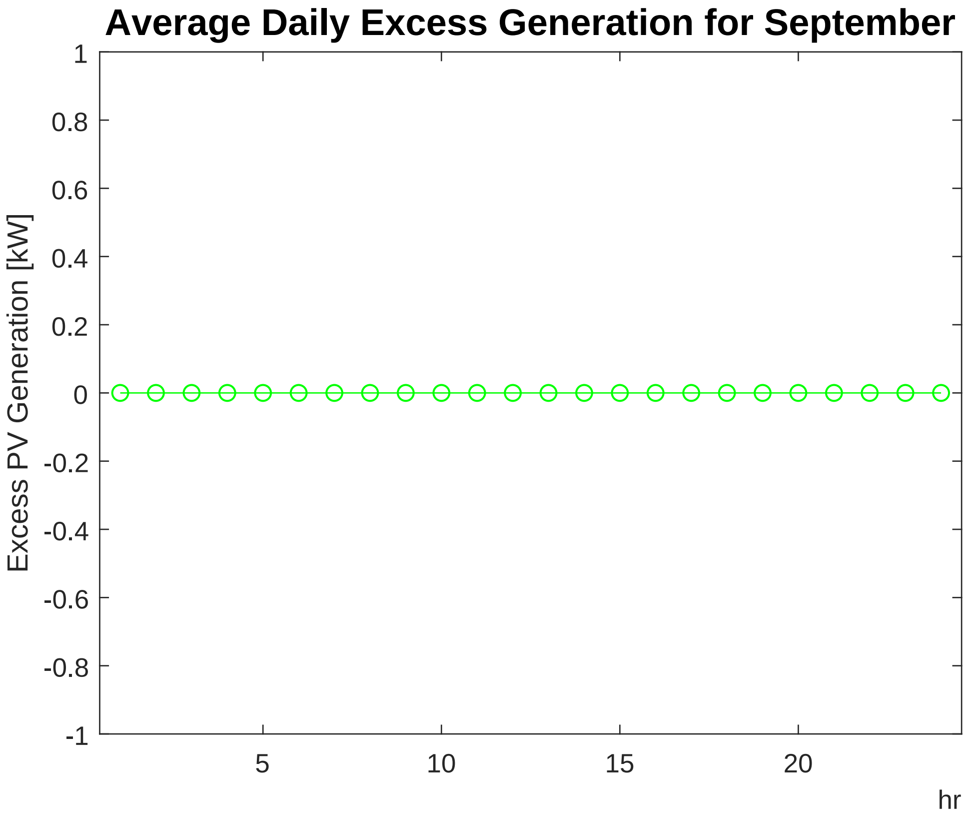

Figure II.19: Average daily excess generation for the month of September.

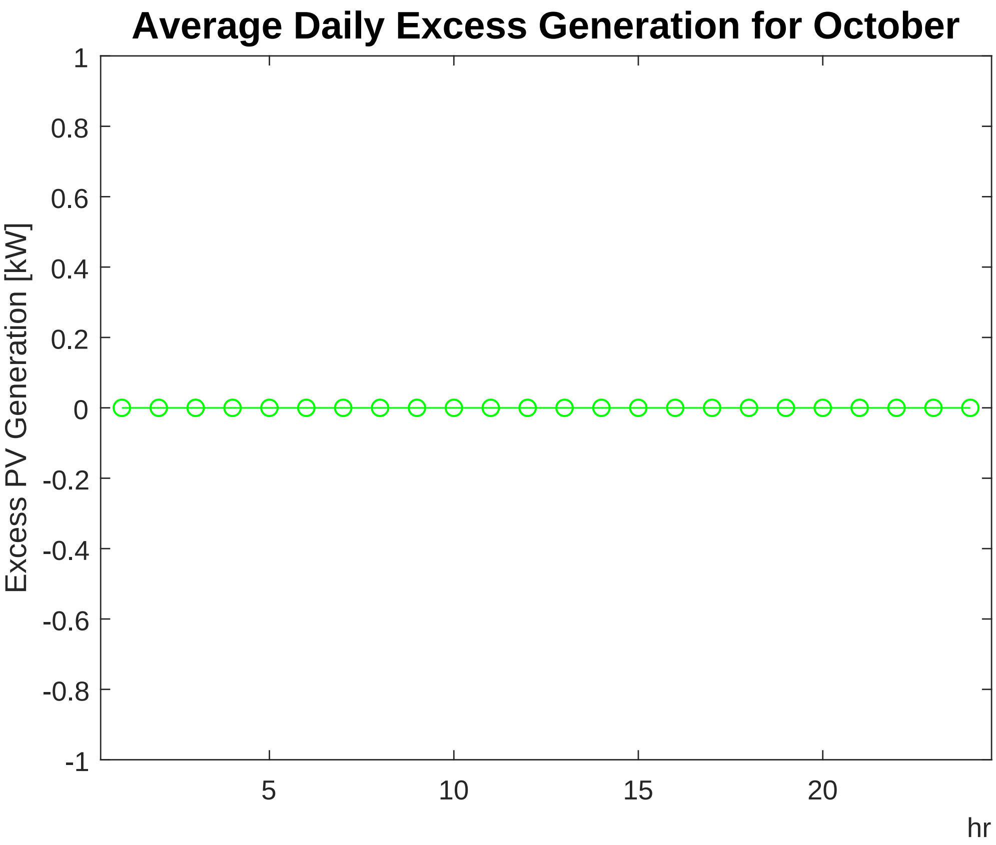

Figure II.20: Average daily excess generation for the month of October.

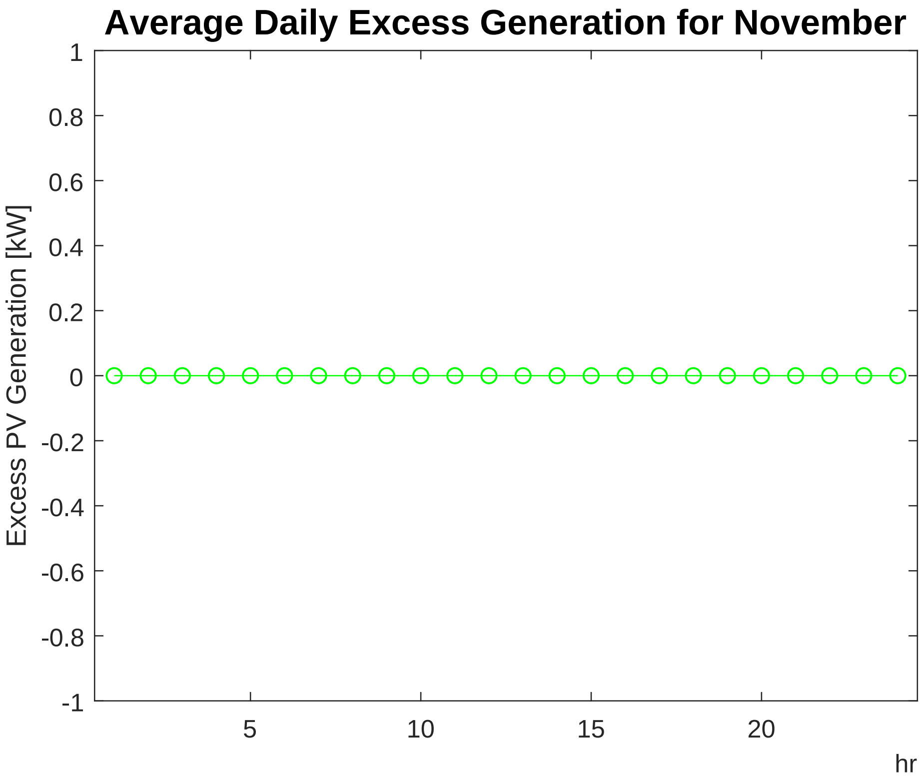

Figure II.21: Average daily excess generation for the month of November.

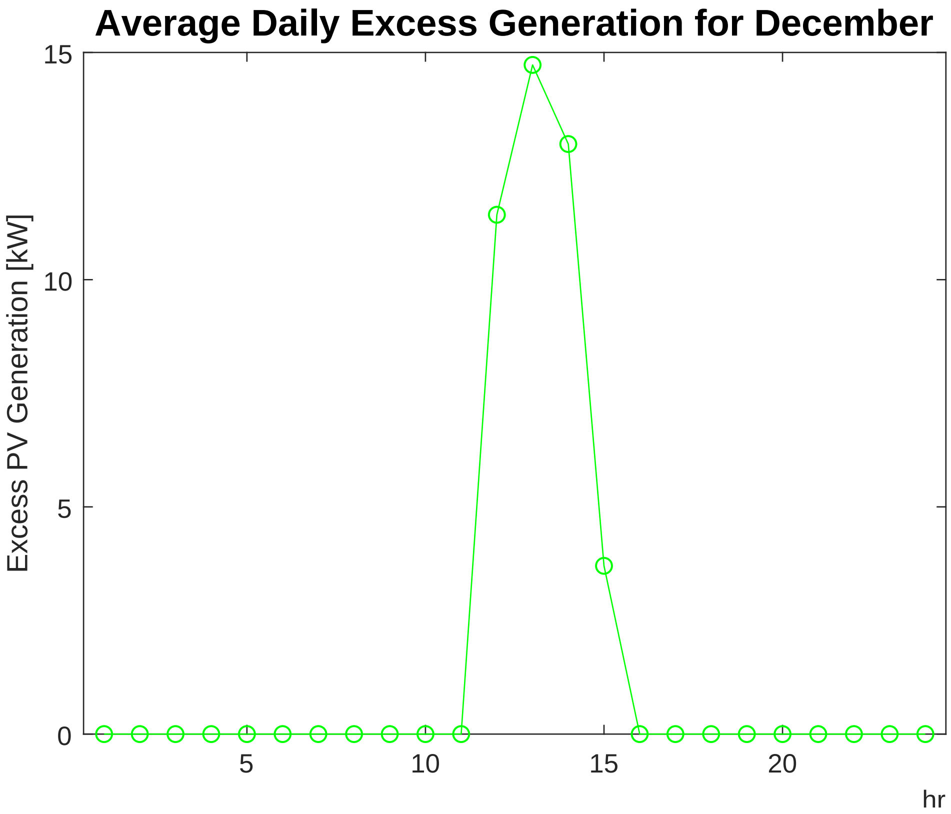

Figure II.22: Average daily excess generation for the month of December.

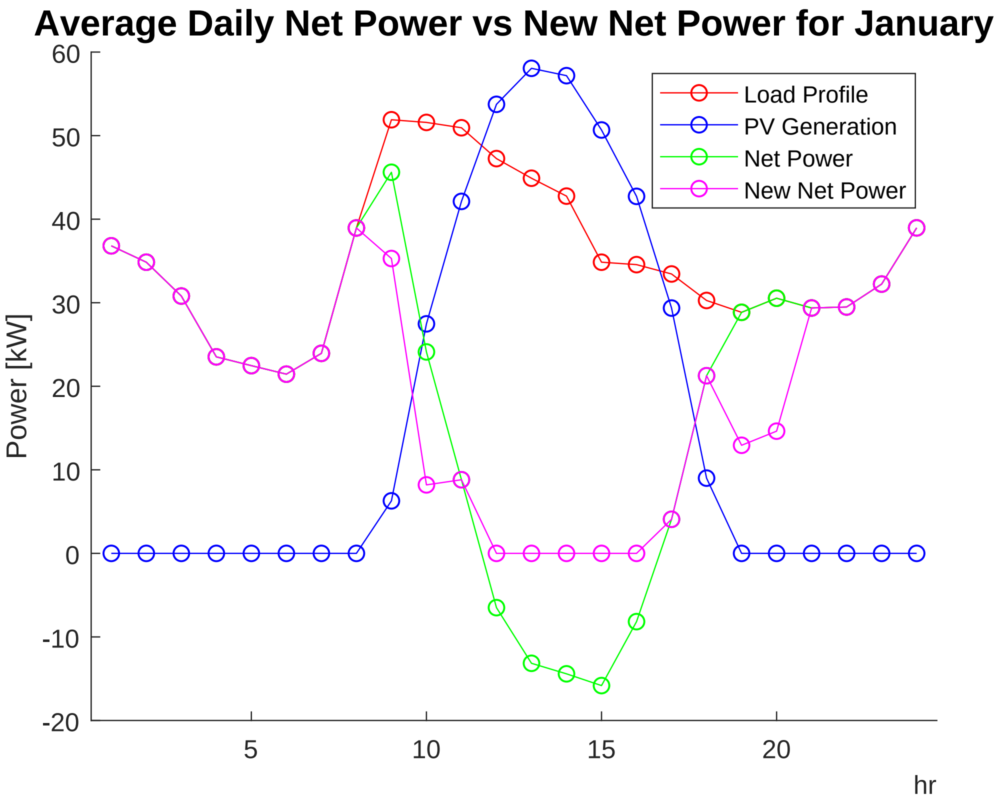

Figure II.23: Average daily net power vs new net power for the month of January.

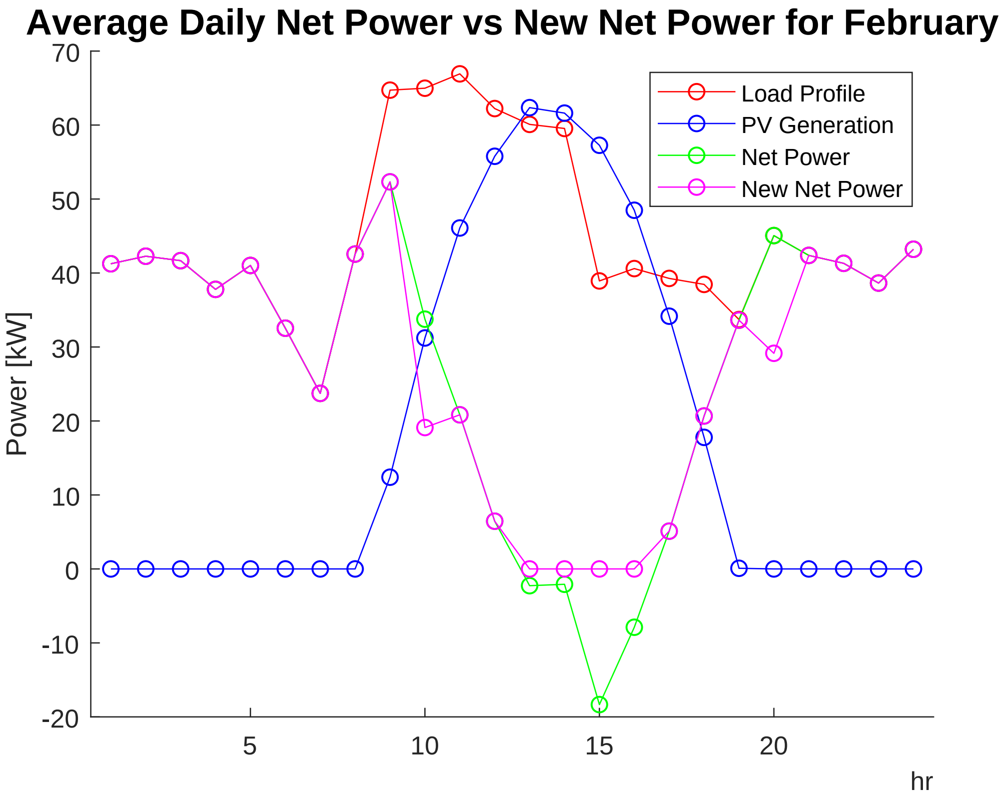

Figure II.24: Average daily net power vs new net power for the month of February.

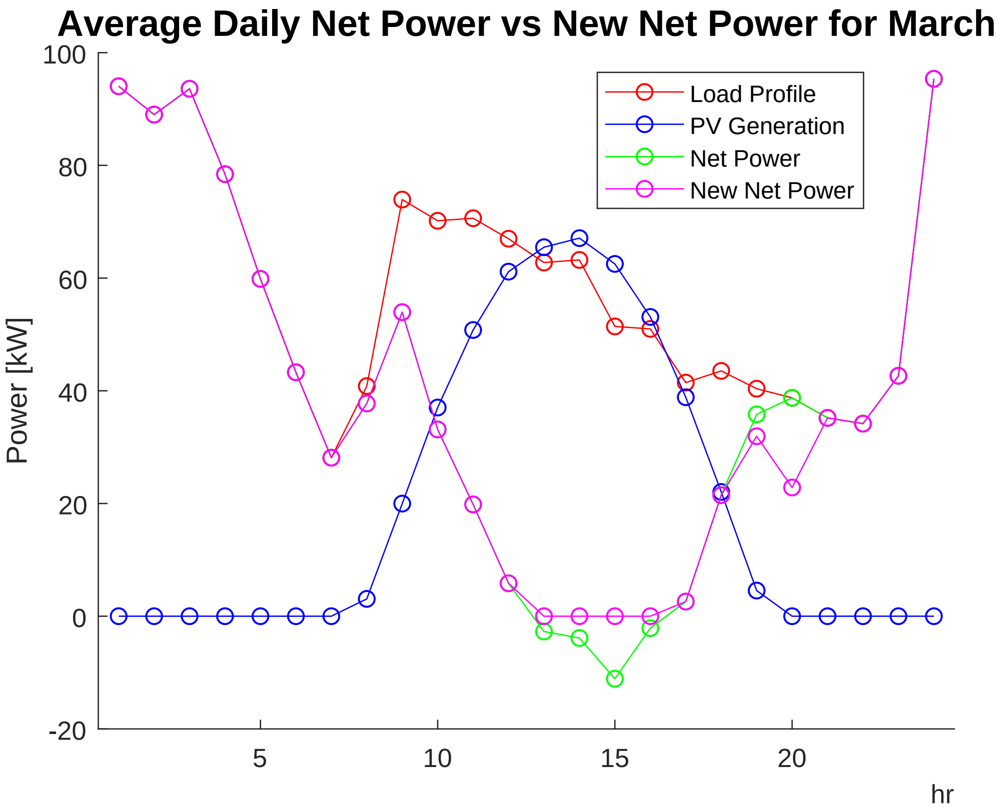

Figure II.25: Average daily net power vs new net power for the month of March.

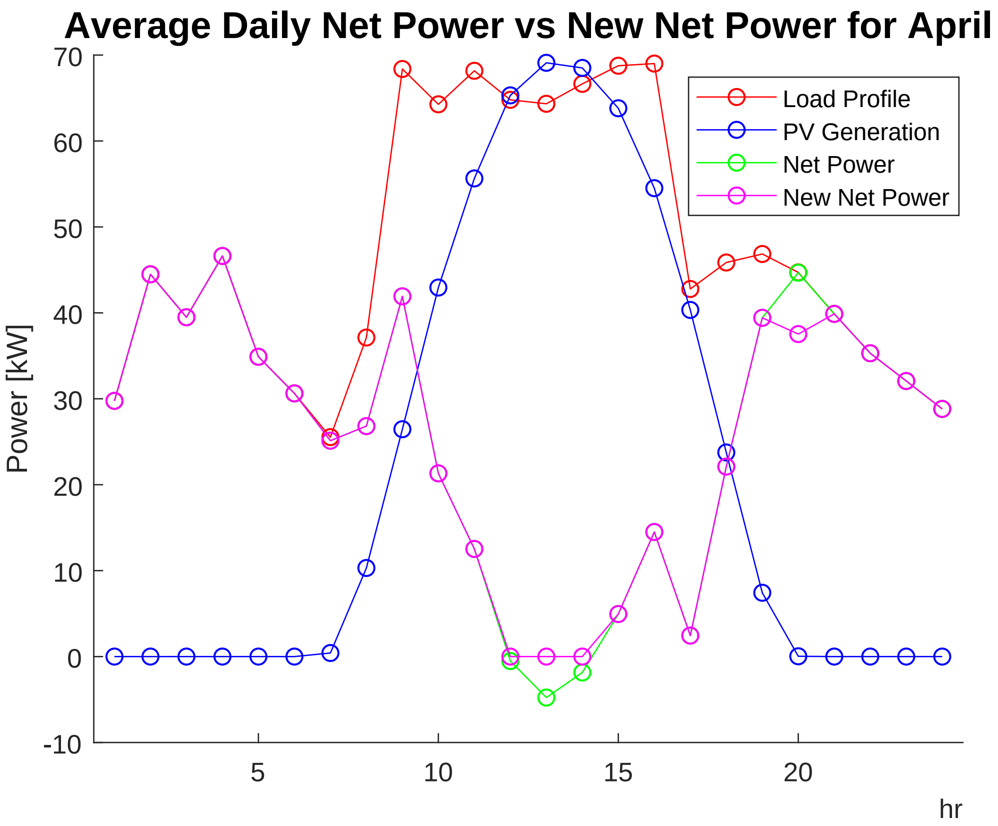

Figure II.26: Average daily net power vs new net power for the month of April.

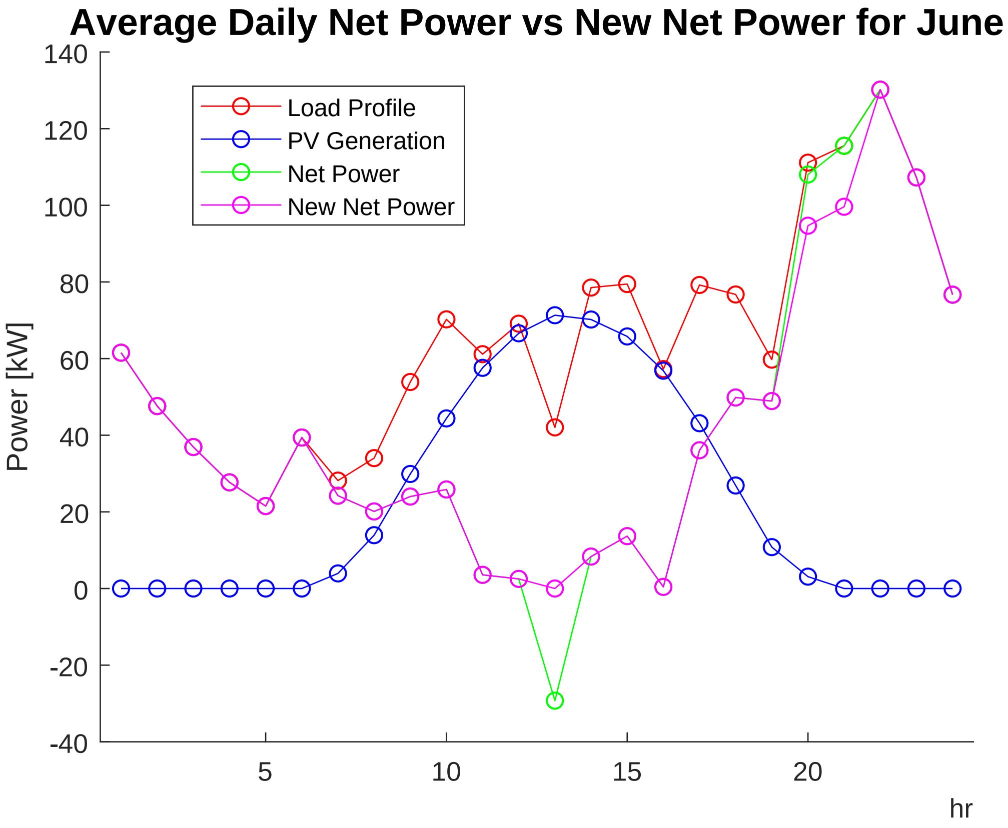

Figure II.27: Average daily net power vs new net power for the month of June.

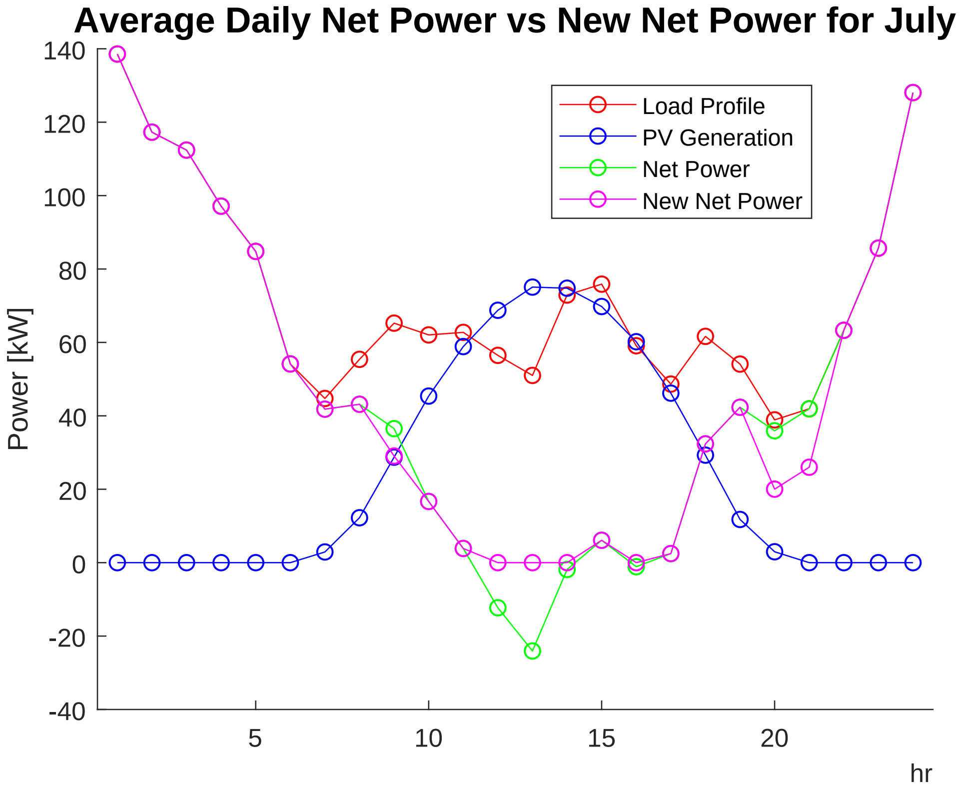

Figure II.28: Average daily net power vs new net power for the month of July.

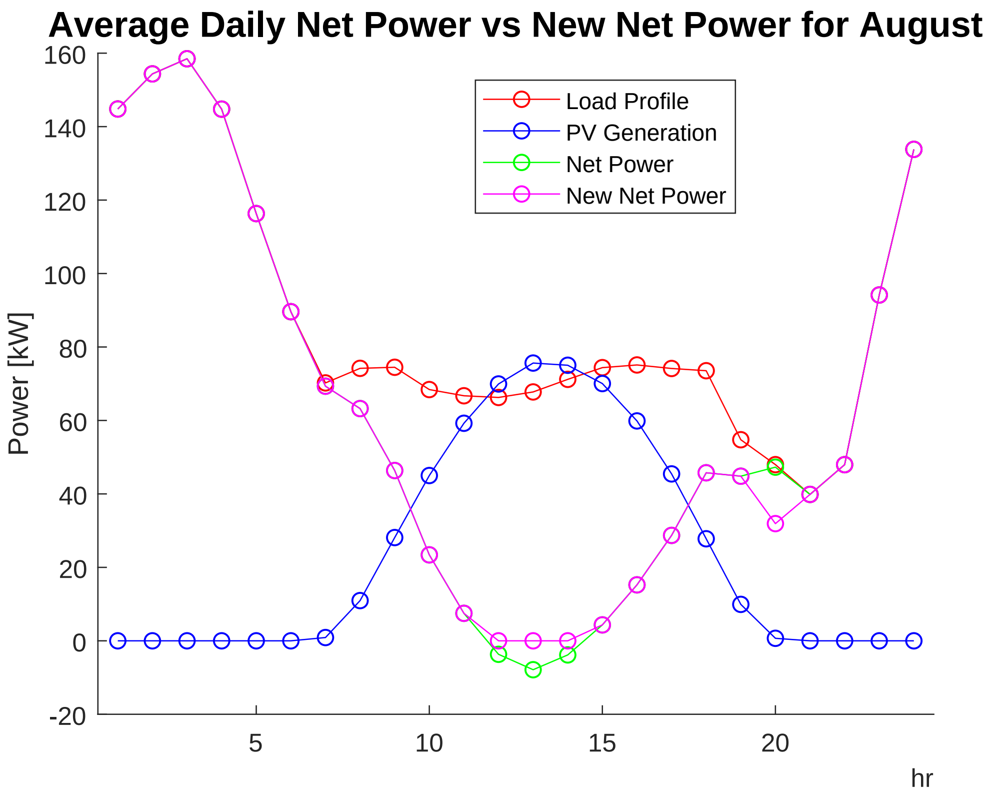

Figure II.29: Average daily net power vs new net power for the month of August.

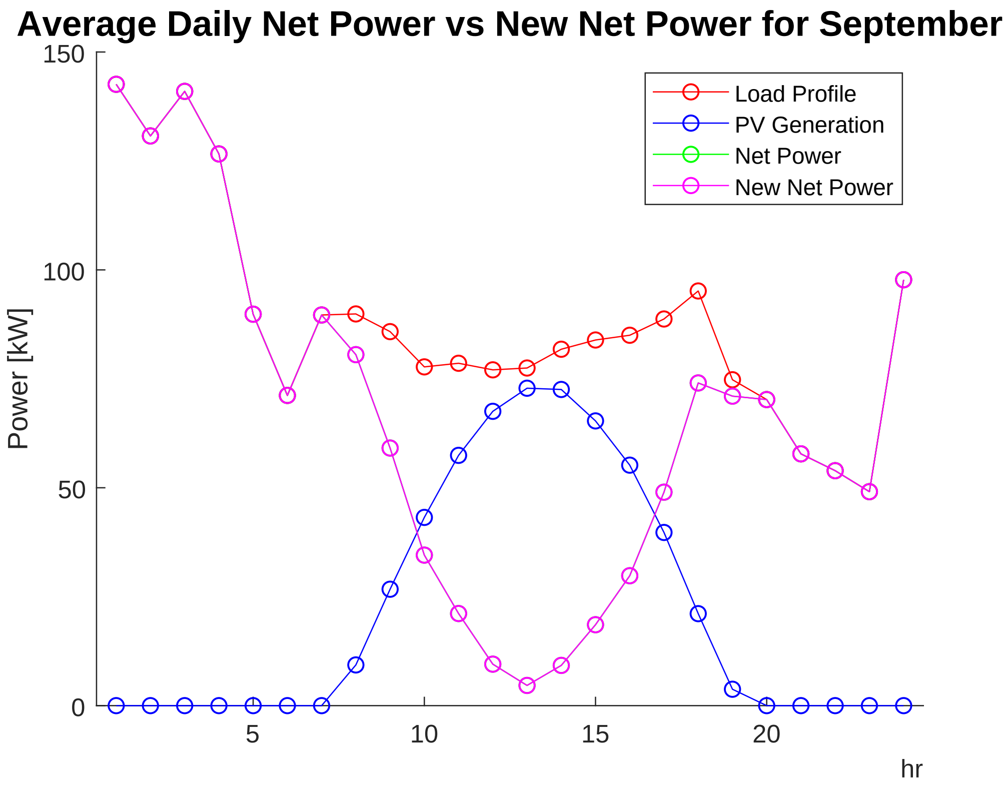

Figure II.30: Average daily net power vs new net power for the month of September.

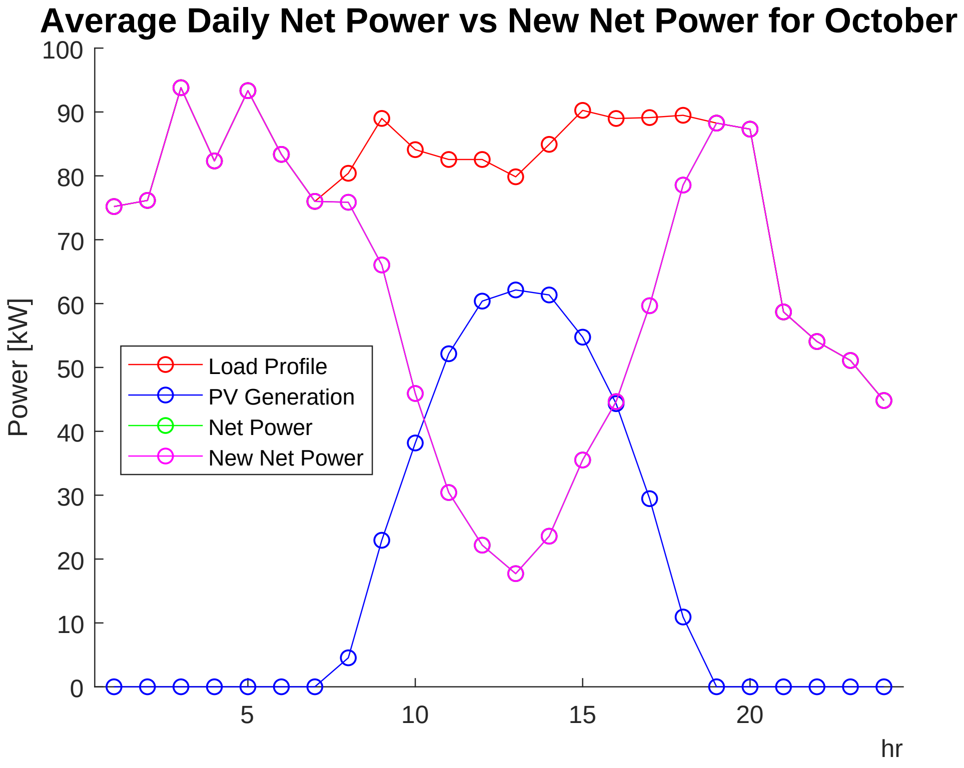

Figure II.31: Average daily net power vs new net power for the month of October.

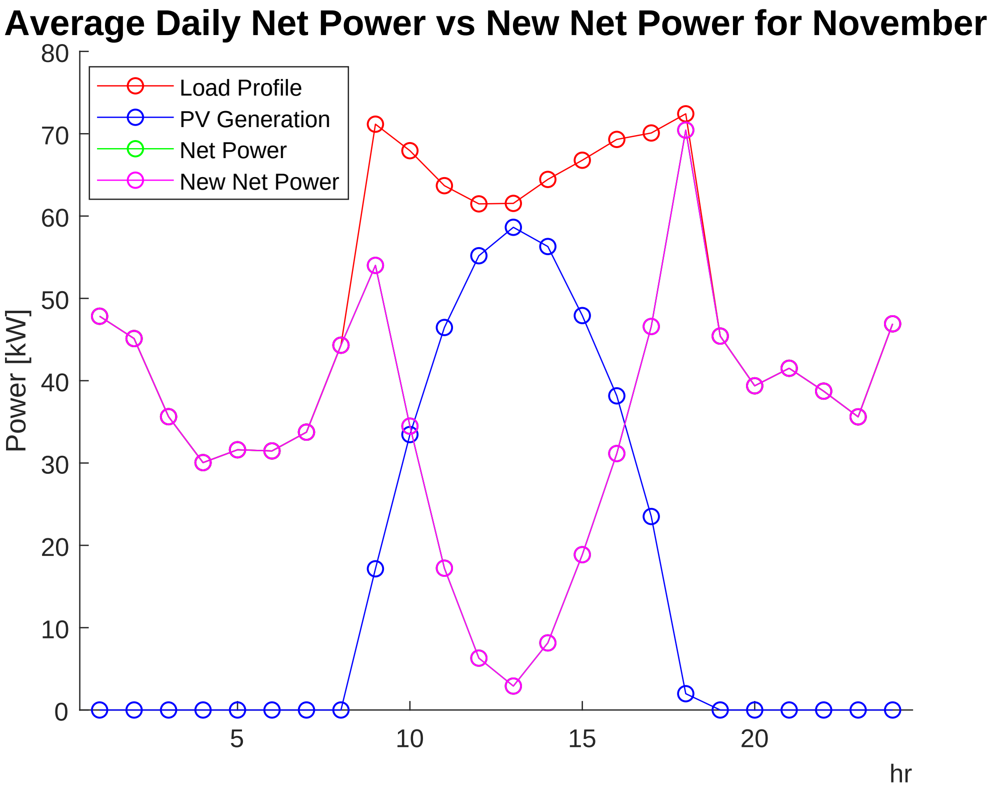

Figure II.32: Average daily net power vs new net power for the month of November.

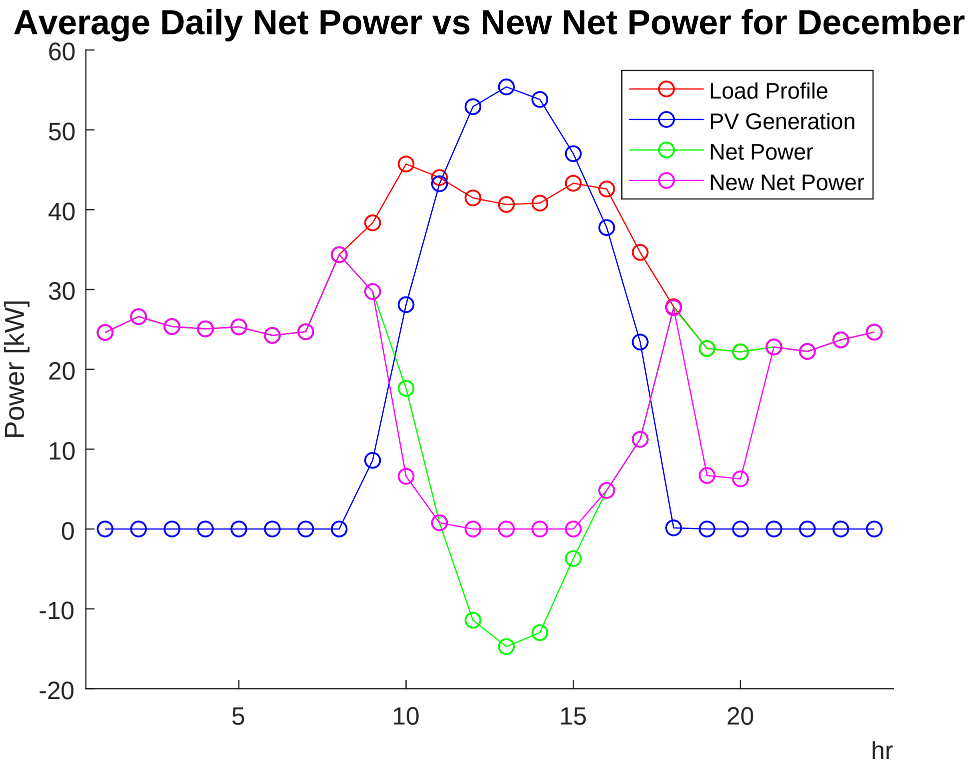

Figure II.33: Average daily net power vs new net power for the month of December.