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# Development principles of Pirkkala airport environment as microgrid solution

Master of Science Thesis
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# ABSTRACT

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The increasing number of airports pursuing sustainability goals through electrification faces challenges when the existing electrical network cannot meet demands. In an effort to reduce the carbon footprint, airports need to take into account the environmental impact of the entire electrification process. It is therefore crucial to consider how electricity is generated. To minimize emissions and reduce the carbon footprint of airport operations, it's important to use renewable energy sources that are compatible with the airport's specific regulations. It might be challenging to meet the demand for electricity at all times when renewable energy sources (RES) like solar or wind power don't supply energy consistently or predictably. Batteries are frequently combined with RES to improve the system's overall efficiency in order to solve this problem. Properly forecasting future load patterns is crucial in determining the appropriate size and capacity of a renewable energy system that combines photovoltaic solar panels with battery energy storage systems.

The present study investigates the feasibility of electrifying an airport using a microgrid solution that includes photovoltaic (PV) solar panels and battery energy storage systems (BESS). The study examines the energy flow of the airport under five different scenarios, which include the existing load, the addition of electric aircraft, the addition of E-bus load, the addition of electric ground handling equipment (GHE) loads, and the addition of electric vehicles. To accomplish this, we provide modeling and simulation to incorporate electrified loads that will be present in the future. Moreover, a pre-built simulator based on cost minimization is used to optimize the sizing of the PV and BESS components of the microgrid solution. Energy flow analysis, which gauges the amount of energy received and given to the network, is the foundation for the economic analysis of the microgrid solution. On the basis of this study, the annual cost of electricity purchase is then determined and compared.

Keywords: Airport electrification, Microgrid, Renewable energy resources (RES), energy flow, load analysis, Electric aircrafts, Electric vehicles, Electric buses, Electric ground handling equipment, cost analysis.

# PREFACE

This Master's thesis was completed as part of the requirements for the Master of Science degree in Electrical Engineering at Tampere University of Technology, under the supervision of Professor Pertti Järventausta.

I would like to express my sincere gratitude to Professor Pertti for his invaluable guidance and support throughout the entire research process. His knowledge, expertise, and insightful feedback have been instrumental in shaping the direction and scope of this research work. I am also grateful to Joni Markkula and Lasse Peltonen for their support and valuable contributions to this research.

I would also like to thank my family and friends for their constant encouragement and support during my academic journey. Their unwavering support has been a constant source of motivation for me, and I am grateful for their presence in my life.

I hope that this research work will contribute to the existing body of knowledge on airport electrification and microgrid solutions, and will provide insights for future research and implementation of sustainable solutions in the aviation industry.

Tampere, 1 May 2023

Majid Kazemi

# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| *AM* | *Air Mass* |
| APU | Auxiliary Power Unit |
| ATC | Air Traffic Control |
| ATM | Automatic Teller Machines |
| BESS | Battery Energy Storage System |
| CHP | Combined Heat and Power |
| C-rate | Charge and Discharge Rate |
| DC | Direct Current |
| DSO | Distribution System Operator |
| e-Aircraft | Electric Aircraft |
| e-GHE | Electric Ground Handling Equipment |
| e-buses | Electric buses BESS |
| e-VTOL | Electric Vertical Take-off and Landing |
| EVs | Electric Vehicles |
| ESS | Energy Storage System |
| FMI | Finish Meteorology Institute |
| GHG | Green House Gas |
| GPU | Ground Power Unit |
| HFAC | High Frequency Alternating Current |
| HVAC | Heating, Ventilation and Airconditioning |
| ICT | Information and Communication Technology |
| LED | Light-Emitted Diode |
| LFP | Lithium iron phosphate |
| Li-ion | Lithium-ion |
| LV | Low Voltage |
| PV | Photovoltaics |
| PCA | Preconditioned Air |
| SAF | Sustainable Aviation Fuel |
| SOC | State Of Charge |
| STC | Standard Test Conditions |
| TOU | Time Of Use |
| VFD | Variable Frequency Drive |
| WTGs | Wind Turbine Generators |

| | |
|---|---|
| *a* | Annual |
| A | Solar Panel Area |
| *Ah* | Ampere hour |
| *B* | *Rated Battery Capacity* |
| *C* | *Battery capacity* |
| *c* | *Cent* |
| *CE* | *Energy Consumption* |
| *D* | *Distance* |
| *E* | *Energy Yield* |
| *ED* | *Electricity Demand* |
| *Ef* | *Energy consumption* |
| *h* | *hour* |
| *H* | *Hourly Solar Radiation Time Series* |

| | |
|---|---|
| *HZ* | *Hertz* |
| *kW* | *Kilowatt* |
| *kWh* | *Kilowatt hour* |
| *kWp* | *Maximum kilowatt Peak Power* |
| *MW* | *Megawatt* |
| *MWh* | *Megawatt hour* |
| *MWp* | *Maximum Megawatt Peak Power* |
| $m^2$ | *Square-meter* |
| *Pc* | *Charging Capacity* |
| *PR* | *Performance Ratio* |
| *r* | *Solar Panel Efficiency* |
| *s* | *Second* |
| *V* | *Voltage* |
| *W* | *Watt* |
| € | Euro |

# 1. INTRODUCTION

The aviation industry is responsible for a significant amount of global greenhouse gas (GHG) emissions, with almost 95% of these emissions associated with jet fuel combustion in aircraft engines. In 2020, global carbon dioxide emissions were approximately 37.9 gigatons [1], with air traffic accounting for 2.1% [2] of the total global CO2 emissions, including 796 million tones.

The table 1-1 depicts the share of world greenhouse gas emissions by different sectors, including the aviation sector, which is the topic of this thesis. According to the table, the aviation sector is responsible for approximately 2.1% of global greenhouse gas emissions. Although this percentage may seem small, it is increasing rapidly, which is a cause for concern. This indicates that while the aviation sector's emissions are relatively low compared to other sectors, such as electricity and heat, buildings, and manufacturing and construction, it still contributes significantly to global greenhouse gas emissions.

***Table 1-1.****Global greenhouse gas emissions by sector* [2]

| Sectors | Share of greenhouse emissions |
|---|---|
| Electricity and Heat | 31.9% |
| Buildings | 5.9% |
| Other fuel combustion | 3% |
| Manufacturing and construction | 12.6% |
| Road | 12.5% |
| Aviation | 2.1% |
| Ship | 1.8% |
| International Bunker | 2.7% |
| Fugitive emissions | 5.9% |
| Industrial processes | 5.9% |
| Agriculture | 11.9% |
| Land use change and forestry | 2.8% |
| Waste | 3.3% |

It is important to note that the share of greenhouse gas emissions for the aviation sector may vary depending on the region and the type of flight. For example, international flights may have a higher carbon footprint compared to domestic flights. Nonetheless, the table provides a general idea of the aviation sector's contribution to global greenhouse gas emissions.

The thesis will use this table as a starting point to discuss the impact of the aviation sector on the environment and the need for the electrification of airports and the aviation industry. The table highlights the importance of addressing the aviation industry's emissions to achieve global climate goals and promote sustainable development.

To combat climate change, the aviation industry needs to reduce its energy consumption and transition to more sustainable energy sources. While Sustainable Aviation Fuel (SAF) is a short-term solution, the electrification of aircraft is the most effective approach to eliminating CO2 emissions in the air transport sector in the long term. In addition to electrifying airport-related operations, such as ground handling equipment and electric charging stations for private vehicles and e-buses travelling to airports, the use of microgrids in airports can help further reduce GHG emissions. In other words, electrifying airports and implementing microgrids offer promising solutions to reduce energy consumption, lower costs, and decrease GHG emissions.

Small electric aircraft are already available and offer a promising solution to reducing GHG emissions in the short term. By powering these aircraft with electricity from renewable resources, such as wind and solar power, they can eliminate GHG emissions altogether. The potential impact of electrification, both in the short and long term, on reducing GHG emissions is significant, as evidenced by the elimination of 720,000,000 and 2,780,000 tons of CO2 in the world and Finland, respectively [3] [4]. However, the electrification of larger commercial aircraft is still in its early stages, and there are many technological and logistical challenges that need to be addressed before they become a viable and widespread option for air travel.

One potential solution for reducing GHG emissions in the aviation sector is the use of microgrids at airports. A microgrid is a small-scale energy system that can operate independently or in parallel with the main power grid, using a combination of renewable and non-renewable energy sources. By implementing microgrids at airports, they can generate their own electricity, reduce their reliance on the main grid, and increase their use of renewable energy sources. This can help reduce GHG emissions, lower energy costs, and improve the resiliency of airport operations.

This thesis aims to investigate the feasibility of microgrids and electrification in airport operations by performing energy flow analysis at Pirkkala airport. The research seeks to provide a comprehensive analysis of the potential for these technologies to reduce the environmental impact of the aviation sector and contribute to global efforts to combat climate change.

## 1.1 Objectives and research questions

The thesis aims to achieve the following objectives:

1. Modeling and Simulation of a Photovoltaics (PV) and Battery System for a Grid-Connected Airport: This thesis would involve developing a simulation model of a solar panel and battery system for an airport that operates connected to the grid. The project would involve simulating the system's performance under different energy demand scenarios.
2. Modeling and Simulation of new electrified loads including electric aircraft, E-buses, electric ground handling equipment (E-GHE) and electric vehicles (EVs).
3. Design and Optimization of a PV and Battery System for a Grid-Connected Airport utilizing a pre-built simulator created for Sizing of battery and photovoltaic panels based on electricity cost optimization [5]: This thesis would involve designing and optimizing a solar panel and battery system that is connected to the power grid ,specifically tailored for Finland's specific geographic area and market conditions.
4. The project implements energy flow analysis, investigating the annual energy received from and delivered to the grid under various consumption scenarios. The project would also involve electricity cost estimation.

Further, research questions are as follows:

1. What is the optimal configuration of a renewable energy system that can meet the energy demand of an electrified airport? How can the renewable energy system be designed to accommodate the increasing electrification of airport operations, including electric aircrafts, e-buses, electric ground handling equipment and electric cars?
2. How much electricity can be produced locally at the airport and how much needs to be obtained from the grid? Additionally, what are the expected costs of electricity consumption under various demand scenarios?

3. What are the factors that affect the performance of the renewable energy system, including solar panel and battery capacity, charging infrastructure, and energy management strategies?

## 1.2 Scope

The scope of the thesis is to design and optimize a microgrid for Pirkkala Airport located in Tampere Finland that operates connected to the grid. The microgrid includes a solar panel and battery system, and the project involves analyzing the energy consumption patterns and demand tariff to determine the appropriate size of the system. The focus of the project is on the technical  aspects of the microgrid related to the airport, and the evaluation of the environmental and economic impact of the renewable energy system compared to a traditional fossil fuel-based system is not within the scope of the thesis. The simulation model of the solar panel and battery system and airport-related demands for the microgrid is designed to be extendable and flexible for future studies. While the electricity cost calculation is implemented, the monetary evaluation of various scenarios is also not within the scope of the thesis.

## 1.3 Tasks

In order to achieve the objectives and answer the research questions mentioned earlier, the following tasks must be completed:

● Investigation of airport electrification trend

● Providing a broad perspective about microgrid technologies

● Analyzing the load types and patterns in the airport environment

● Investigation of installation of possible renewable resources in the airport environment

● Modelling a microgrid in order to implement the energy flow analysis

● Implementation of energy flow analysis to determine the required supply resources

● The implementation of an economic analysis, which will take into account factors such as energy consumption, and market prices, will be used to determine the annual payment owed to the energy supplier for the energy received from the network.

- Recommendations for how renewable energy systems can be designed to accommodate the increasing electrification of airport operations.

## 1.4 Structure of the thesis

Chapter 2 presents Air traffic electrification and microgrid technologies in the airport environment. Airport load analysis and selection of suitable microgrid is implemented in chapter 3. The details related to modeling and simulations are conducted in chapter 4. The simulation results are presented in chapter 5. Chapter 6 is dedicated to discussion. Finally, conclusion is presented in chapter 7.

# 2. AIR TRAFFIC ELECTRIFICATION AND MICROGRID TECHNOLOGIES IN THE AIRPORT ENVIRONMENT

The electrification of the aviation sector is an emerging trend that has gained significant attention in recent years, particularly with the aim of reducing carbon emissions and increasing the sustainability of air travel. While the technology and infrastructure to fully electrify commercial passenger aircraft is still in the early stages of development, there have been some notable advancements and initiatives in this area.

While air traffic generates 8 percent of GHG in the transportation sector after private vehicles and commercial cars account for 41 and 22 percent respectively [6], it releases 2.1% of world GHG emissions. It is also worth mentioning that a large part of the air traffic related GHG emissions are associated with aircraft, and indirect airport consumption make up only a small portion of aviation GHG emissions. Thus, electrification of aircraft has a crucial role in carbon neutrality. Although the last decade has witnessed a trend towards electrification of aircraft and many game-changing achievements obtained for small aircraft, large aircraft electrification has a long way ahead, as a consequence, these days sustainable aviation fuel (SAF) has attracted all concentration.

## 2.1 Electrification of small-sized aircraft

One available fully electric aircraft for short-haul flights is VELIS Electro manufactured by Pipistrel. It is two-seater pilot training aircraft that can fly for 50 minutes. The figure 2-1 shows the VELIS Electro which is powered by an electric motor that is fueled by lithium-ion batteries, which can be recharged within an hour. The aircraft can fly for up to 50 minutes on a single charge, with a top speed of 140 km/h (75 knots).


***Figure 2-1.****VELIS Electro, world's first electric powered airplane to receive Certificate* [7]*.*

The VELIS Electro is equipped with modern avionics, including a glass cockpit, and has a range of safety features, such as a ballistic parachute system, electronic flight control system, and a redundant battery management system. It also features a quiet electric propulsion system, making it an eco-friendly and low-noise aircraft. The aircraft's lightweight design and low energy consumption make it a cost-effective and environmentally-friendly option for short-haul flights. It is an excellent training platform for new pilots, allowing them to gain experience with electric aircraft and preparing them for a future where electric aircraft are more prevalent. By and large, the VELIS Electro represents a significant step forward in the development of electric aircraft and highlights the potential for electric aviation in the future.

Currently, the most prominent use of electric technology in aviation is in small electric aircraft designed for short flights or aerial surveillance. These electric aircraft typically have a limited range and payload capacity, making them suitable for applications such as urban air mobility, air taxis, and package delivery. Apart from small fully electric aircraft, e-VTOL (electric vertical take-off and landing) aircraft which is considered as air taxi is ready to be commercialized. Joby's piloted five-seat e-VTOL can carry four passengers at speeds of up to 200 mph, with a maximum range of 150 miles on a single charge. The figure 2-2 illustrates Joby's all-electric vertical takeoff and landing (e-VTOL) aircraft for urban air mobility. Their piloted e-VTOL aircraft is designed to be a safe, efficient, and sustainable mode of transportation for short trips within cities.


***Figure 2-2.****Joby receives part 135 certificate from the FAA which allows to operate aircraft commercially* [8].

The e-VTOL is equipped with advanced avionics and a fly-by-wire flight control system, which allows for precise and efficient control of the aircraft. It also features redundant systems to ensure safe operation, including multiple batteries and motors, as well as a parachute for emergency situations. Joby aims to launch commercial operations in the near future. The company believes that e-VTOL aircraft will revolutionize urban transportation, reducing congestion and providing a faster and more convenient way to travel within cities. In terms of larger aircraft, several companies and organizations are working on developing electric and hybrid-electric propulsion systems for commercial passenger planes. Another approach to electric aviation is the development of electric propulsion systems for small planes that can be used for short-range flights. These planes, often referred to as electric regional aircraft, could provide a more sustainable alternative to conventional regional planes that currently rely on fossil fuels.

## 2.2 Electrification of ground handling equipment

Electrification of airports has already started in many nations. While electric shuttle buses are mainly electrified in modern airports, other vehicles are started to be electrified such as cargo platform vehicles, conveyor belt leaders etc. Although there is a tendency to change all vehicles and devices to electrified ones, airports often have limited spare electric capacity. This is where efficient charging solutions become significant. The valley filling approach is one of the best ways to address the problem. In this way, the capacity needed for these new electric loads can be freed up. By ensuring the completion of charge of the devices and vehicles when the electricity prices are cheaper, usually during the night, more capacity will be available for newly added loads during the day. A decent instance of ground handling electrification is the electric aircraft tug utilized to move aircraft from one place to another for various purposes.

The figure 2-3 illustrates a pushback tug manufactured by MOTOTOK company. A pushback tug is a type of vehicle used to move aircraft on the ground. It is specifically designed to push an aircraft away from a gate or parking stand and position it for take-off or taxiing.

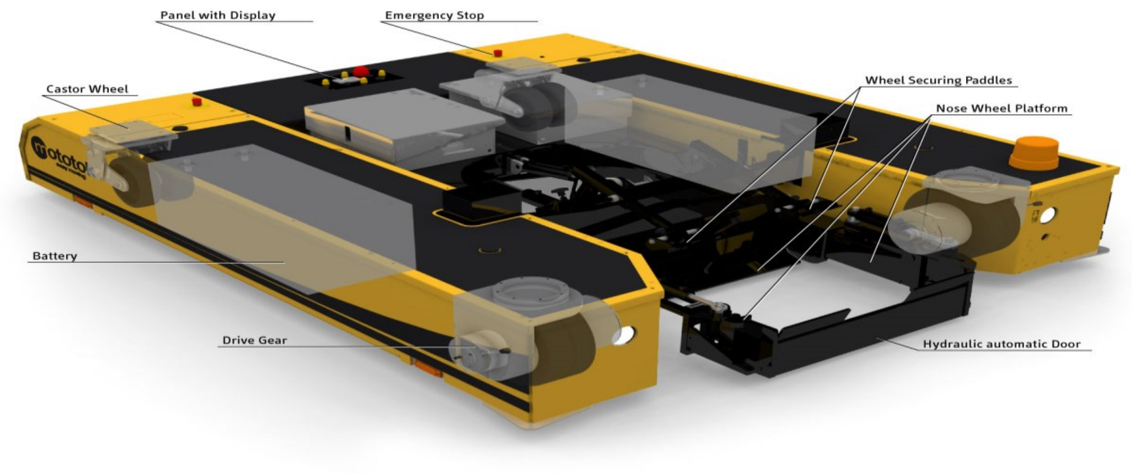


***Figure 2-3.****Pushback tug manufactured by MOTOTOK company* [9]

The table 2-1 also demonstrates information related to pushback tug’s battery including the battery's energy capacity, voltage, recharging time, and operating range.

***Table 2-1.****Pushback tug manufactured by MOTOTOK company* [9].

| Battery characteristics (maintenance-free, deep cycle gel batteries) armor plate with electrolyte recirculation | |
|---|---|
| **Parameters** | **Values** |
| Energy capacity | 300 Ah |
| Voltage | 80 v |
| Recharging time | 3 h |
| Range (depending on workload, distance to push/move, engines of the aircraft on/off) | 3-4 days of hanger operations up to 30 pushbacks |

The characteristics of batteries used in ground handling equipment, such as pushback tugs, are important for several reasons. Firstly, the battery's capacity and voltage determine the amount of electrical energy it can store and deliver, which in turn affects the power output and operational performance of the equipment. Secondly, battery characteristics such as charging time, cycle life, and safety features also play a crucial role in determining the overall efficiency, reliability, and sustainability of the equipment. To calculate the energy consumption of ground handling equipment, such as a pushback tug, we can use the battery characteristics to estimate the amount of electrical energy used per unit of time. Formula (1) can be used to perform this calculation.

$$Ef = \frac{(C \times V)}{1000} \tag{1}$$

where Ef is the energy consumption, C is the capacity of the battery in ampere hours (Ah), and V is the voltage of the battery in volts (V). As an example, if a pushback tug has a battery with capacity of 300 Ah and a voltage of 80 V, its energy consumption can be calculated as:

$$Ef = \frac{(300\ Ah \times 80\ V)}{1000} = 24 \text{ kWh}$$

This means that the pushback tug is equipped with a 24 kWh battery capacity. By knowing the energy consumption of the equipment, it becomes possible to estimate the battery runtime and to plan for the charging and maintenance of the battery. Overall, understanding the battery characteristics of ground handling equipment such as pushback tugs is crucial for ensuring efficient and sustainable operations at airports. By calculating the energy consumption of the equipment based on its battery characteristics, operators can optimize their use of resources, reduce their carbon footprint, and improve their overall performance and reliability.

Gate electrification has been witnessed in most modern airports. Electric equipment, comprised of a preconditioned air (PCA) unit and a 400 Hz ground power frequency converter, can be installed to electrify the gate. Large aircraft conventionally use on-board auxiliary power units (APU) located in the tail of the aircraft to provide power for gate operations, however small aircraft use ground power units (GPU) to provide electricity and cabin climate control while an aircraft is parked at the gate. In some airports, the solar-at-gate project has implemented. A photovoltaic solar power facility was installed at Airport, sized to supply the power demand to operate the gate electrification equipment in order to supply renewable electricity to an aircraft during gate operations [10]. The figure 2-4 demonstrates gate electrification in airports which refers to the provision of ground power to aircraft parked at the gate, allowing them to operate their on-board systems without the need to use their engines or auxiliary power units (APUs) for electrical power.

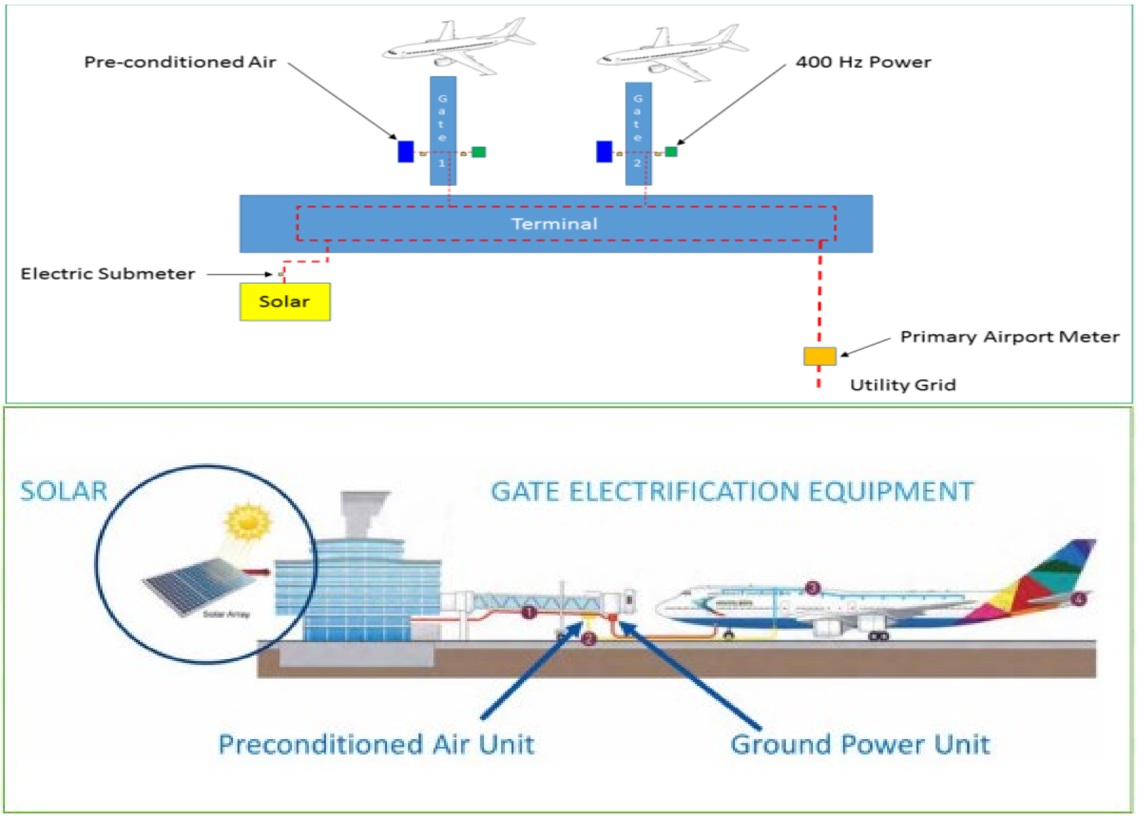


***Figure 2-4.****Gate electrification equipment* [10]

The use of gate electrification can reduce aircraft emissions, improve air quality around the airport, and save fuel by reducing the need for the aircraft to operate their engines or APUs while parked at the gate. Additionally, gate electrification can reduce noise pollution by reducing the need for engines to run while the aircraft is at the gate. Gate electrification is increasingly being adopted by airports around the world as a part of their sustainability efforts and to comply with local regulations on air pollution and noise. In the grand scheme of things, the electrification of the aviation sector is still in the early stages of development, but it has become an area of significant interest and investment as the aviation industry strives to reduce its carbon footprint and move towards a more sustainable future.

## 2.3 Microgrid solutions for electrification of airports

This trend of electrification of aircraft requires proper electrical infrastructure and charging facilities. Since the consumption increases, the electrical structure needs to become strengthened. To have more efficient and reliable electrical systems, on-site power generation is decent alternative. On-site power production eliminates the power transmission losses and can prepare condition for airports in such a way to act as microgrid.

Resiliency, efficiency, and sustainability are three main reasons that encourage airports to utilize the microgrid. Microgrid could guarantee uninterrupted 24/7 power with required quality as it enables the airport to operate in an island mode in the case of outages and disturbances [11]. Different end-users have different requirements from their power supply system. Although education campuses and apartment buildings might concentrate more on sustainability and carbon neutrality, airports and high technology industries require absolute reliability. Microgrid sophisticated control also enables the airport to optimize power usage based on demand, energy price, and other factors. While using renewable energy resources, microgrid support carbon neutrality and help to decrease GHG emissions.

The air traffic energy demand is classified as the figure 2-5, and airports may consider implementing microgrids to provide electricity. Using a Combined Heat and Power (CHP) system could increase efficiency as well. In Finland, as one of the primary renewable resources is biogas-powered generator sets, CHP is the most suitable alternative.

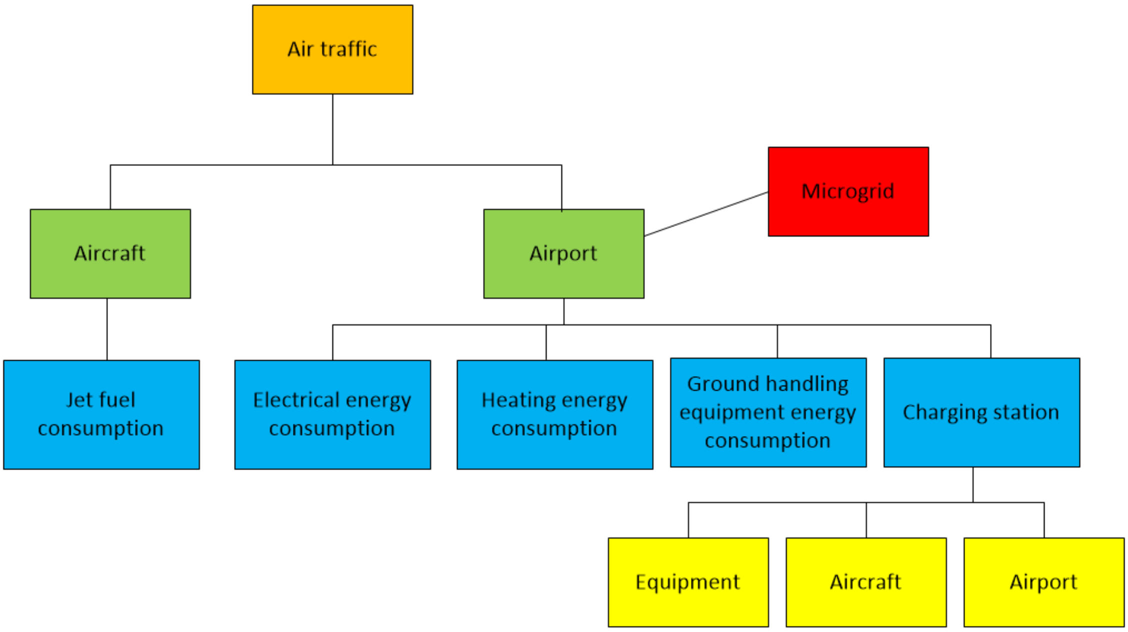


***Figure 2-5.****Classification of air traffic energy demand* [12]

Air traffic energy demand can be divided into two main categories: aircraft demand and airport demand. Aircraft demand refers to the energy required for the operation of the aircraft itself, primarily in the form of jet fuel consumption. On the other hand, airport demand encompasses a range of energy needs, including electrical energy consumption, heating energy consumption, ground handling equipment energy consumption, and charging stations [12].

In recent years, there has been growing interest in the electrification of aviation, including the use of electric and hybrid-electric aircraft. This trend is likely to increase the demand for electrical energy at airports, particularly for charging stations used to recharge electric aircraft, ground handling equipment, and electric vehicles. Overall, the classification of air traffic energy demand into aircraft and airport demand provides a useful framework for understanding the energy needs of the aviation industry and developing strategies to reduce its environmental impact. As it is illustrated in figure 2-6, a microgrid incorporates four key components generation, energy storages, control system and load [13]. The ability of a microgrid to maintain a supply-demand balance is a key attribute. Each type of supply, demand and storage can be categorized on the basis of its controllability and dependability.

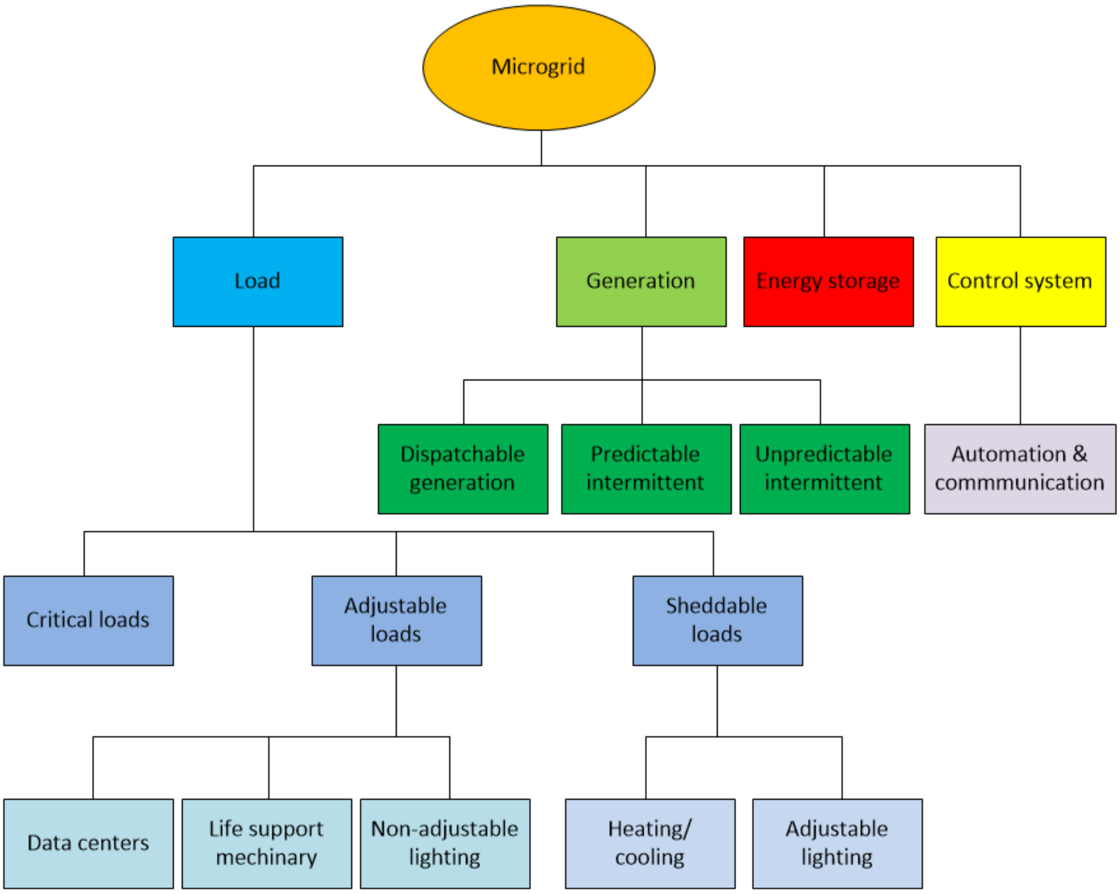


***Figure 2-6.*** *Main components of a microgrid and their categorization*

Energy supply constitutes categories ranging from controlled, intermittent, and not controllable. Dispatchable generation includes diesel generators and fuel cells. PV is referred as predictable intermittent supply and wind power is considered as less predictable intermittent supply. Load has a range of controllability characteristics ranging from critical loads such as data systems or life support machinery at one end of the scale, to adjustable loads such as heating/ cooling, lighting, or grid dispatch at the other. The extent to which the loads can be modulated as well as the time period over which they can be changed are key characteristics. Some loads may also be temporarily curtailed where necessary [14]. It is worth mentioning that depending on the situation load characteristics differ from what was categorized earlier. For instance, the lighting is typically referred to as an adjustable load, however in some airport applications such as runway and taxiway areas, lighting is accounted as critical load.

Microgrids could be AC (Alternating Current), DC (Direct Current), and hybrid systems, and each of them has benefits and drawbacks. AC systems are the most common, followed by DC, while High frequency AC (HFAC) applications tend to be found in aircraft or similar applications, but are beginning to enter the mainstream. Since the AC distribution system is used for a long time, well-developed interconnection, products, standards, and codes are available. However, there is a lack of approved standards and codes for Low Voltage DC (LV DC) equipment, distribution systems, and microgrids. One advantages of AC system is familiarity with design of LV AC electrical systems.

Regarding DC system, there is a lack of familiarity with the design of LV DC distribution systems due to the absence of approved or recognized LV DC system architectures. Moreover, DC systems are required different safety and protection practices compared with LV AC distribution systems and infrastructure upgrades needed from AC to DC systems. In terms of the hybrid microgrid, control of the system is a challenge. Otherwise, the combination of feeding DC loads from DC sources such as photovoltaics reduces conversion losses, as does the local use of energy and reduced distribution network losses. Using DC microgrid brings benefits of lower conversion requirements, reduction in the number of required devices, and improvement in reliability. The reliability can be improved as there are fewer points of failure. Another salient point is AC to DC conversion is easier and cheaper than DC to AC [15].

## 2.4 Considerations for selecting generation resources in airports and microgrids

To select appropriate Generation for microgrid, consideration of many aspects is necessary. One primary aspect is the availability and price of fuels. A good example for availability of fuel is the microgrid project conducted by Siemens in the Galapagos Islands in Ecuador where the generator sets consume natural oil produced on the Ecuadorian mainland instead of diesel, therefore eliminating all the costs related to the fuel provision [16]. Th figure 2-7 illustrates the microgrid project carried out by Siemens in the Galapagos Islands in Ecuador. Another salient point is the price of fuel. The cost of one particular fuel might increase for any reason for some time, therefore consideration of alternative is essential. For example, the price of biofuel might rise due to high demand. One approach to address the issue is to select the generator sets operating based on two fuels. Hydrogen can be a suitable alternative for biofuel. Companies manufacturing gensets has started to produce dual fuel gensets running on both biogas and hydrogen and mixture of them.

***Figure 2-7.****The implemented hybrid power plant on Isabela Island with a power output of 1.2 MW comprises 3,024 solar panels, five generators, and 84 battery modules* [16]

When selecting resources for electricity generation, it is important to consider compatibility with the rules and regulations of the airport. This includes not only technical compatibility, but also compliance with safety and environmental standards, and any other requirements that may be in place. By carefully assessing the compatibility of different generation resources, it is possible to identify the most suitable options that meet both the airport's needs and regulatory requirements.

**Wind Turbine Generators** (WTGs) are not ideal for use in airports due to the need to install tall structures to obtain an adequate amount of wind, which could cause a physical obstruction and not comply with airport protection regulations. Hence, only a few WTGs, ranging from 35 to 50 meters in height above the ground, have been installed in some airports to meet energy requirements while adhering to safety regulations. This is in contrast to typical onshore WTGs, which rise to 160 meters above the ground to generate sufficient power. [10].

**Solar power** is considered the most suitable renewable energy source for airports due to its economic viability and compatibility with the airport's infrastructure, which requires substantial electricity consumption. This is because airports are part of the permanent national infrastructure and require a significant amount of electricity to operate. Solar power is particularly beneficial because it has a low profile and can easily integrate into existing airport facilities without causing any physical obstruction. There are three types of solar PV designs available for airports, which are ground-mounted, roof-mounted, and canopy-supported. Figure 2-8 illustrates these options visually. All of these designs have been implemented in various airports over the years, and they provide an effective way to generate renewable energy while maintaining the functionality of the airport [10].


***Figure 2-8.****Instances of solar PV configurations in airport environment* [10]

However, certain regions prohibit the placement of solar panels due to their close proximity to airport runways. These areas are known as runway strips and are situated alongside runways, extending from the runway ends and laterally from the sides of runways. The strip typically extends 60 meters from the end of most runways and either 75 meters (in code 1 or 2 airports) or 150 meters (in code 3 or 4 airports) from the side of the runway, measured from each side of the runway center line. Figure 2-9 depicts a diagram illustrating the dimensions of the runway strip.

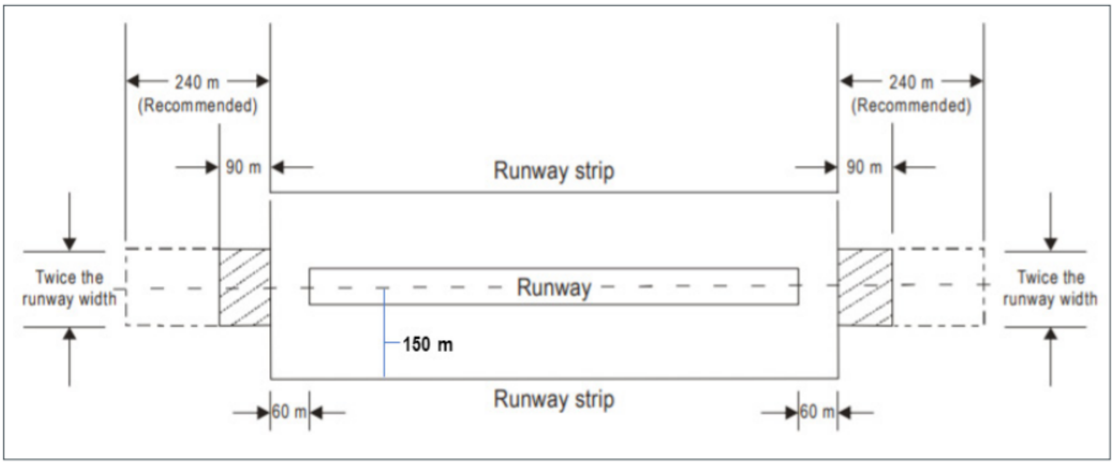


***Figure 2-9.****Characteristics of the Runway Strip* [17]

Objects cannot be situated within a runway strip unless it is crucial for air navigation or aircraft safety. This region is also identified as the "Object-Free Area." Additionally, a runway safety area, extending 90 meters beyond the runway end and associated runway strip, is mandated. However, it is suggested that this area should extend up to 240 meters, as illustrated in Figure 2-9. The runway safety area is likewise regarded as an object-free area. A distance from the taxiway is also advised, which is designated by the taxiway strip. No objects should be placed in this area.

A transitional surface starts from the border of the runway strip and stretches up to the inner horizontal surface, which is situated 45 meters above the ground level. The gradient from the edge of the runway strip at ground level upwards is 33 percent for larger airports and 40 percent for smaller ones. A diagram outlining the transitional surface can be found in Figure 2-10.

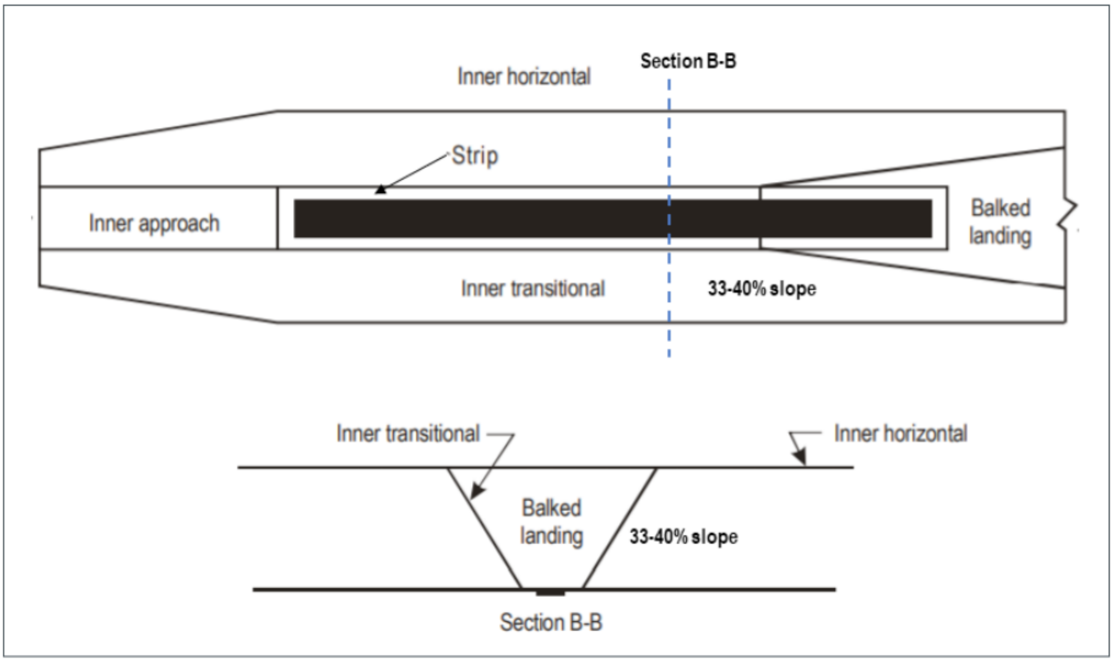


***Figure 2-10.****Characteristics of the Inner Transitional Area* [17]

Certain regions in proximity to runways may not be suitable for installing solar panels due to these limitations [17]. There is a possibility of glare and its impact on approaching aircraft and air traffic control towers with solar photovoltaic (PV) systems. The smooth and reflective surface of solar panels may generate glare, especially when the sun is positioned low in the sky and produces a glancing reflection. Figure 2-11 provides a visual demonstration of how glare caused by reflected sunlight can affect surroundings. Hence, a glare analysis following established procedures is necessary while installing solar modules in the airport.

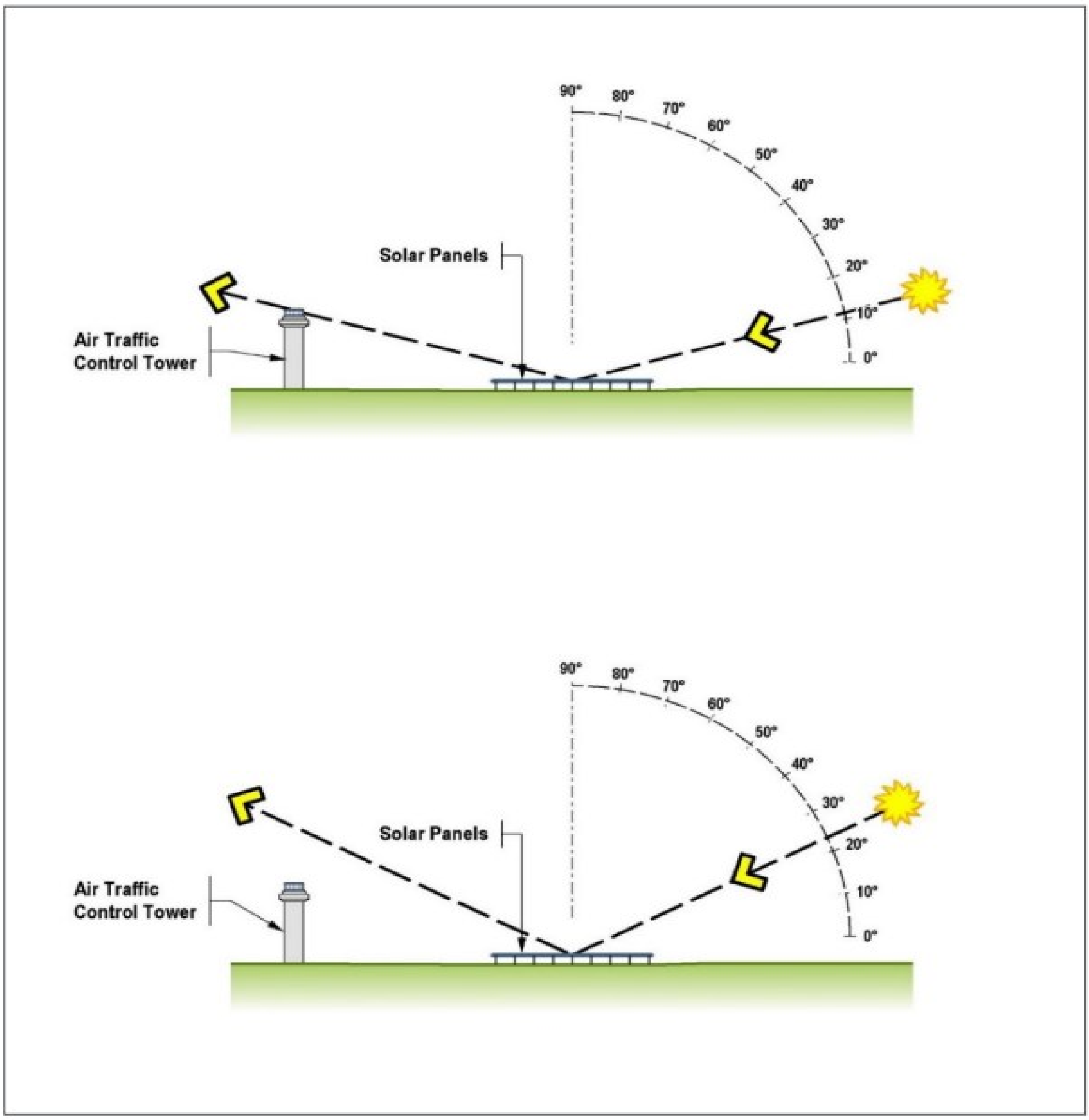


***Figure 2-11.****The effects of reflected sunlight causing glare* [17]

The utilization of fuel cells and microgrids together has become increasingly popular because they share similar objectives of providing affordable, reliable, environmentally friendly, and community-oriented energy solutions [18]. This collaboration is essential because a microgrid can have multiple energy sources, some of which may not be consistent, such as solar power or energy storage. On the other hand, a fuel cell can run continuously as long as it has a fuel supply, usually natural or biogas. This makes the fuel cell a reliable source of power in situations where other energy sources are unavailable. Additionally, microgrids and fuel cells frequently use combined heat and power (CHP) technology, which recovers waste heat generated during power production and repurposes it to provide heating and cooling for buildings or to produce steam and hot water.

Fuel cells advantages are as follow:

- Modular and scalable: Fuel cells can be easily added or removed as per the energy demand, making them a flexible solution for microgrid applications.
- Easy to site: Fuel cells are versatile in terms of their installation location, as they can be installed both indoors and outdoors, making them a community-friendly option. Also, they require less space compared to other renewable energy solutions such as solar or wind farms.
- Fewer regulatory hurdles: Fuel cells are typically exempt from the strict regulatory requirements that other energy solutions may face due to their clean emissions profile.
- Quiet operation: Fuel cells have few moving parts, making them much quieter compared to other forms of energy generation.

Fuel cells are a viable and effective technology for microgrids especially in applications where resiliency and reliability matters. In DC microgrid, fuel cells, solar plants and batteries could generate DC power without power conversion which causes energy losses. Fuel cells, solar plants, and batteries can all be used to generate and store DC power, which can then be distributed within the microgrid without undergoing power conversion. This allows the microgrid to operate more efficiently and can result in cost savings over time.

**Fuel-agnostic microgrids** have become possible utilizing a linear generator which converts motion along a straight line into electricity using chemical or thermal energy. The generator can serve as backup, as a main generator or to help firm renewable energy resources. Linear generator is a new clean power technology that can utilize numerous fuels — including ammonia, hydrogen, biogas and natural gas — with the same hardware [19].

# 3. AIRPORT LOAD ANALYSIS AND SELECTION OF SUITABLE MICROGRID ARCHITECTURE

When designing and planning an electrical installation, it is essential to conduct load analysis, and this applies to microgrids as well. By modeling energy consumption, it is possible to determine the base load and peak load, which are important factors for selecting generation resources. The load profile model is useful in load shifting and demand forecasting, which helps maintain the stability of the entire system. Through active load shifting, the controller can balance the demand for each load. Additionally, the load profile model allows for the forecasting of load demand in advance, which helps utilize excess energy resources or purchase electricity when consumption is predicted to be higher than production [20]. Load profile modeling involves qualifying energy consumption based on input data, forecasting load demand, characterizing influential factors, and predicting the impact of new technologies. This type of modeling can be done through calculation-based approaches or measurement-based approaches, as illustrated in Figure 3-1.

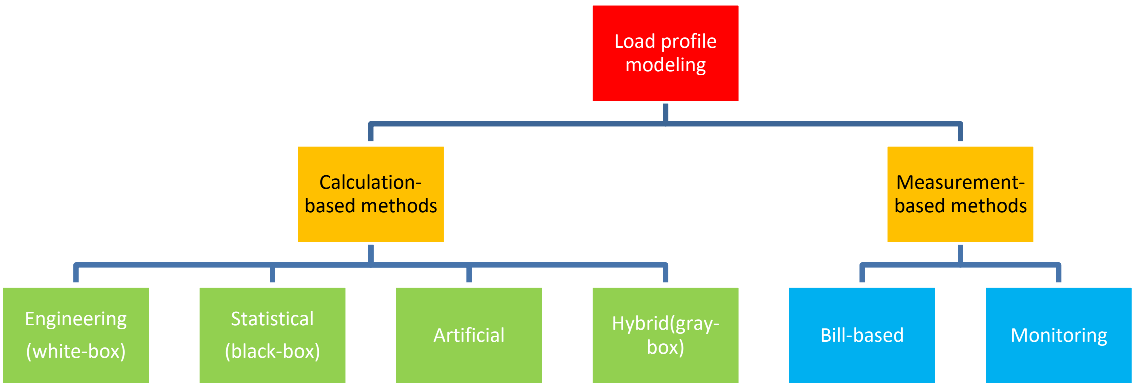


***Figure 3-1.****Schematic diagram that outlines the load modeling approach* [20]

Calculation-based approaches involve using mathematical equations and theoretical assumptions to estimate energy consumption and load demand. These methods are typically based on historical data or industry-standard models and may involve factors such as weather, occupancy patterns, and equipment efficiency. Calculation-based approaches are generally less expensive and time-consuming than measurement-based approaches, but they may be less accurate since they rely on assumptions and estimates. Measurement-based approaches, on the other hand, involve directly measuring energy consumption and load demand using sensors, meters, and other monitoring equipment. These methods provide more accurate data since they are based on actual measurements, but they are generally more expensive and time-consuming than calculation-based approaches. Measurement-based approaches may be necessary in cases where accuracy is critical, such as in large or complex electrical installations.

In summary, calculation-based approaches rely on theoretical models and historical data to estimate energy consumption and load demand, while measurement-based approaches involve directly measuring energy consumption and load demand using monitoring equipment. In this thesis, the calculation-based approach is utilized for modeling load profile. In terms of future planning, calculation-based is a suitable method to be used. The current electrification trend requires the prediction of energy consumption and load profile, as ground handling equipment, gates, and aircraft are becoming increasingly electrified. Furthermore, electrification of private vehicles dictates charging stations in airport parking lots which need to be analyzed.

## 3.1 Classification of airport loads

To classify the loads in small and medium-sized airports, a common approach is to sort them into three categories based on their mode of operation. These categories are fixed loads, opening loads, and variable loads. Fixed-loads are those electric loads that operate continuously 24/7 and generate a minimum base energy demand required to keep critical airport facilities operational. Opening loads are those electric charges that operate only during the airport's opening hours, but are essential to start the passenger and aircraft attention processes. These loads are independent of the number of passengers or air operations taking place. Variable-loads are electric charges that operate variably during the airport's opening hours, depending on the number of passengers or aircraft operations. These loads fluctuate according to the airport's demand and may require adjustments to accommodate varying loads. Overall, categorizing loads in this way enables a better understanding of the energy demands of small and medium-sized airports and helps develop appropriate strategies for managing their energy usage.

Examples of fixed-loads could mainly be the data center, security, radio navigation and meteorological systems. However, there are other types of facilities that primarily consist of opening loads but also include several fixed loads that remain switched on continuously. For instance, the Information and Communication Technologies (ICTs) facility comprises fixed loads associated with network communication devices and certain computer systems. The signaling and information facility includes fixed loads connected to specific signaling and information computer systems. The equipment various facility consists of fixed loads linked to devices such as refrigerators, automatic teller machines (ATMs), and similar equipment. An instance of opening loads could include a range of equipment such as HVAC systems, lighting fixtures, communication and information devices, ICT tools, and various other types of equipment. Also, variable loads refer to electromechanical equipment for transporting luggage and passengers, as well as airfield lighting. The operation of both types of equipment is dependent on the schedules of departing and arriving flights. Additionally, the airfield lighting's usage is also contingent on the requirements set forth by the Air Traffic Control (ATC) service [21].

The investigation of airport loads has revealed that a considerable percentage of them are direct current (DC) loads. Among these loads are terminal and airfield lighting which predominantly use LED technology and therefore operate on DC power. It is worth noting that several conventional alternating current (AC) loads, such as HVAC systems, are now being substituted with more efficient technologies that utilize variable speed drives (VFDs) powered by an internal DC bus. This makes them "camouflaged" DC loads. While data centers, ITC, signaling, and information and radio navigation loads are originally DC loads, they usually undergo conversion to AC before being transmitted through the grid.

## 3.2 Advantages and challenges of DC microgrids for airports: a hybrid solution approach

Further, as we mentioned earlier, fuel cells, solar plants, and batteries generate DC power, and a DC microgrid can be a good option for airports where resiliency is important. In fact, the loads at airports are increasingly becoming DC-based, which makes a DC microgrid an even more attractive option. Integrating renewable energy sources like fuel cells and solar plants into a DC microgrid can help reduce energy losses that occur during the AC/DC conversion process, which is necessary when using traditional AC power sources. Additionally, while using DC loads, the need for AC/DC conversion is reduced, which can lead to further energy savings and improved efficiency. By leveraging the fact that airport loads are predominantly DC, airports can reduce their dependence on traditional power sources and increase their resiliency during power outages or other disruptions. This can help ensure that critical airport operations, such as air traffic control and emergency response, can continue even in challenging circumstances. The figure 3-2 illustrates a schematic diagram of DC microgrid in the airport environment. While the current dominance of AC load means that DC microgrids are not yet widely used, advancements in power electronics and the replacement of DC load with AC load could make DC microgrids the optimal choice for airports in the future.

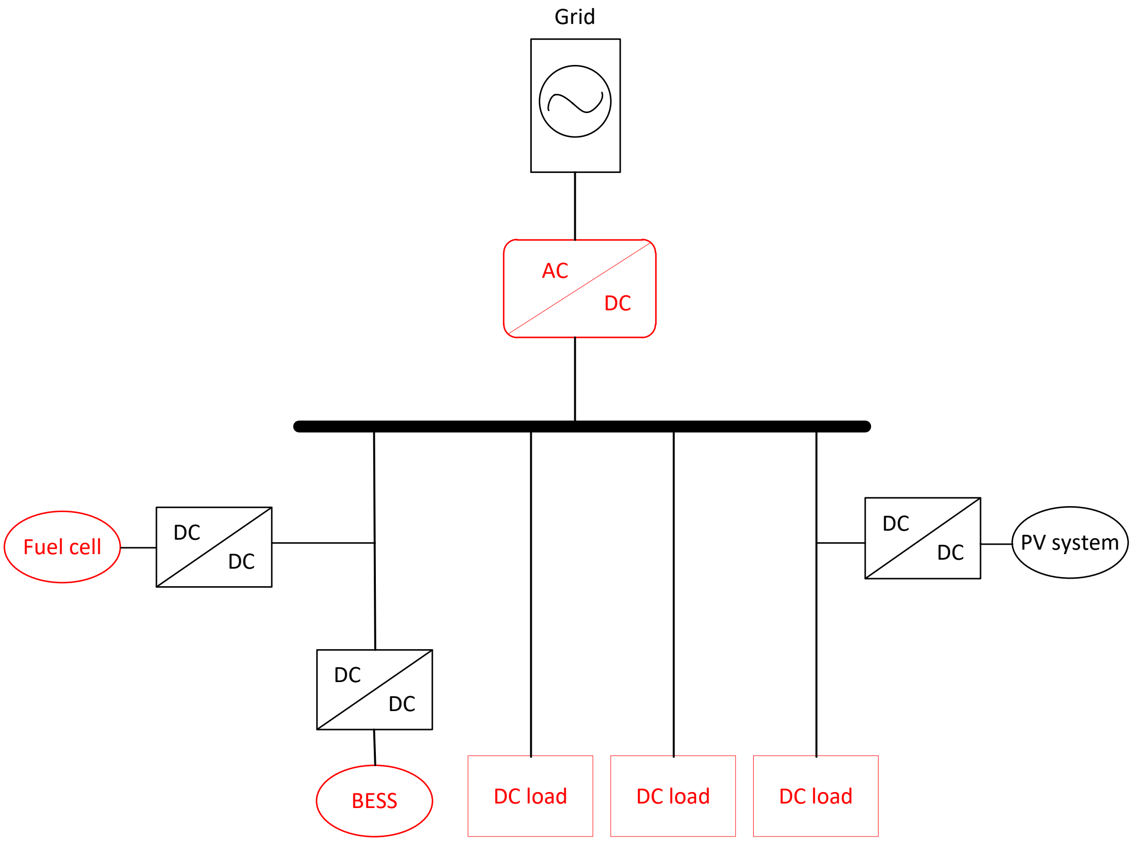


***Figure 3-2.****Schematic diagram of a DC microgrid in airport*

The advantages of using a DC microgrid are numerous. Firstly, it is a simpler and less expensive option compared to an AC microgrid, as it does not have issues with synchronization, reactive power control, and frequency control. Additionally, there is no need for a separate wired or wireless communication between components, since synchronization is not required. Instead, a DC/AC grid inverter can be used to interconnect with the grid, sized based on the export and import of energy, rather than the total microgrid storage and generation assets. Moreover, with local sources and loads increasingly becoming predominantly DC, there is less need for AC/DC conversions, which boosts efficiency. Finally, DC microgrids are more resilient than AC microgrids, as they are decoupled from the AC Grid.

Despite the advantages of DC microgrids, there are still some challenges that need to be addressed, which is why a hybrid solution may be more appropriate. One of the main challenges is the lack of approved standards and codes for low voltage DC (LV

DC) equipment, distribution systems, and microgrids. This can create uncertainty and safety concerns around the use of DC microgrids, as well as limit the range of equipment and components available. Additionally, the electricity market is not yet fully prepared for adopting DC microgrids, which can limit their economic viability and hinder their integration into existing power systems. While it is true that the mentioned challenges could also apply to AC microgrids, as both AC and DC microgrids face integration challenges into existing power systems. However, it is worth noting that DC microgrids can face additional challenges related to the availability and cost of DC devices and equipment, as AC technology has been more widely adopted and developed over the years.

While these challenges can be addressed over time, a hybrid solution that combines DC and AC technologies may be more practical and efficient in the near term. There are three distinct designs for hybrid microgrid, which are illustrated in the accompanying figures. Each of these designs possesses its own set of advantages and disadvantages. Nevertheless, the hybrid microgrid shown in figure 3-3 may be the superior choice for several reasons.

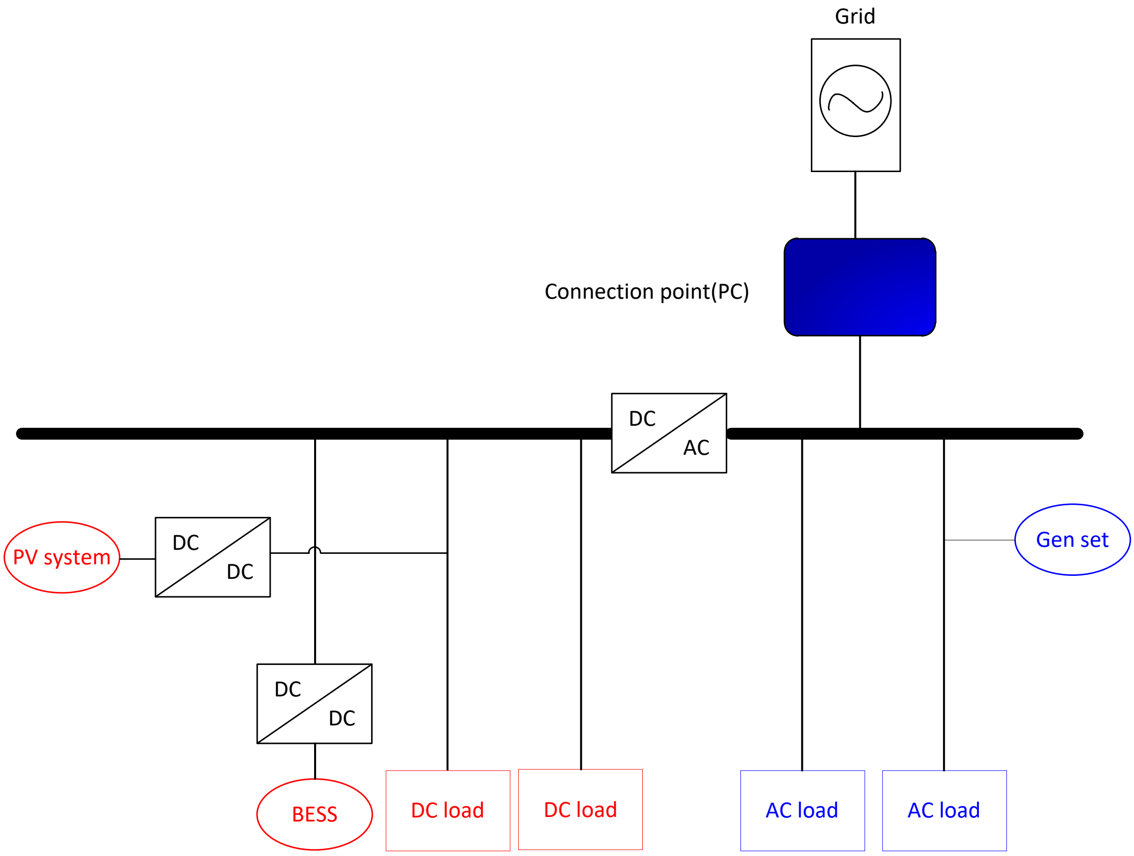


***Figure 3-3.****Schematic diagram of a hybrid microgrid in airport*

Initially, AC microgrid technology has become matured and many projects have already been carried out successfully using this technology. Instances of this can be seen in the AC microgrid implemented in Finland, such as the LEMENE project located in the Marjamäki industrial area [22]. Additionally, a project for an AC microgrid at an airport was carried out in the US, namely the Pittsburgh International Airport Microgrid [23]. Therefore, the architecture shown in Figure 3-3 could be a better choice compared to the architecture in Figure 3-4, where an AC/DC converter is used instead of static switches at the connection point.

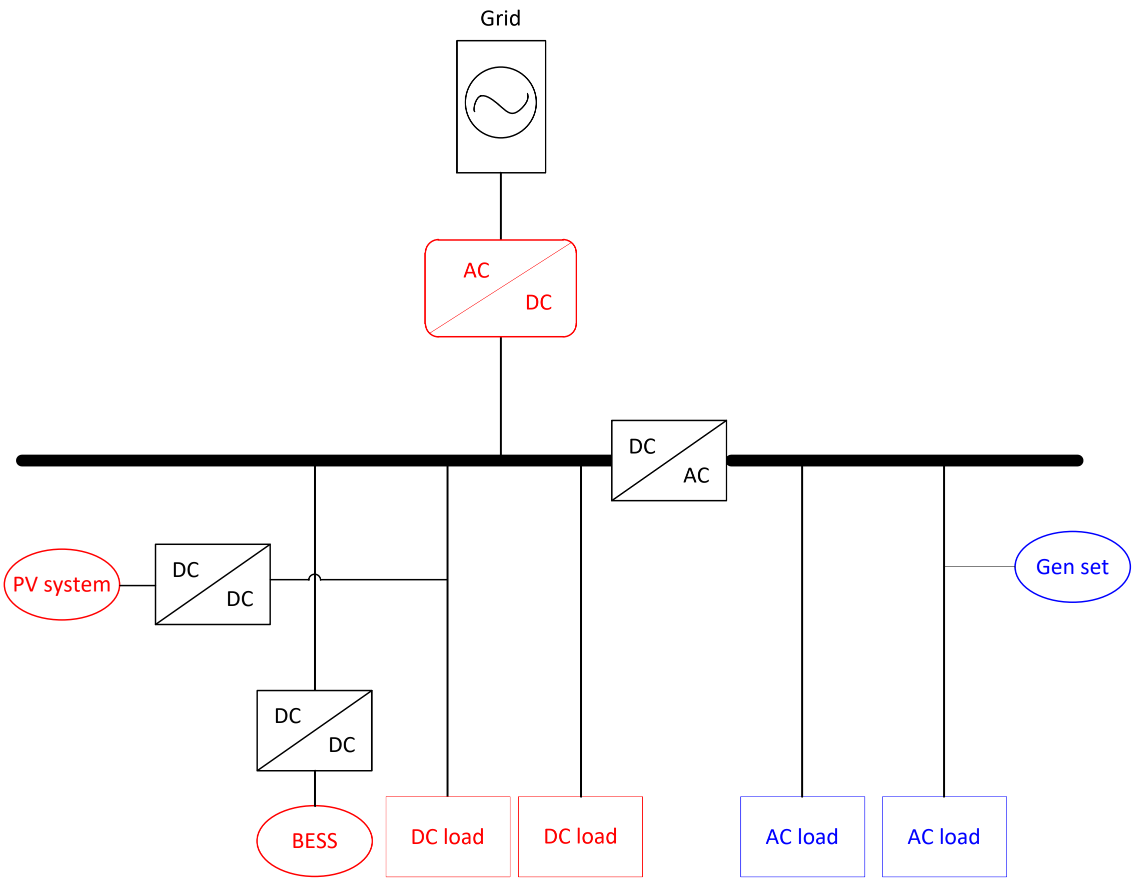


***Figure 3-4.****Schematic diagram of a Hybrid microgrid in airport*

Moreover, there are benefits to the figure 3-3 design over the architecture depicted in figure 3-5. The design in figure 3-5 is more costly since it necessitates the use of two distinct control systems, resulting in less flexibility when compared to a single control system that can manage all power generation and loads. In the case of separate control systems, where there is no communication between them, the system becomes less efficient.

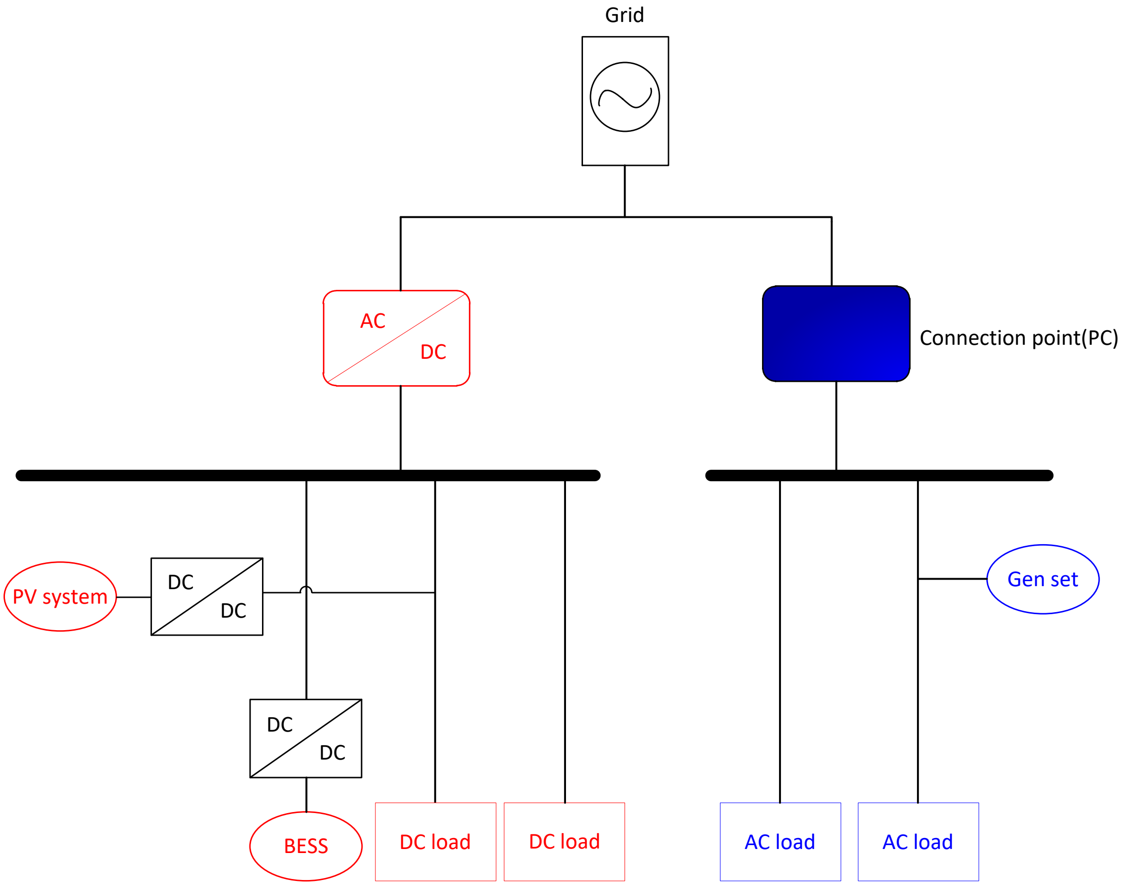


***Figure 3-5.****Schematic diagram of a Hybrid microgrid in airport*

If we take into account the addition of new loads such as electric air crafts, electric ground handling equipment, electric private cars, e-buses, and hybrid microgrid, it is possible to create a diagram that depicts the proposed connections, as shown in the figure 3-6.

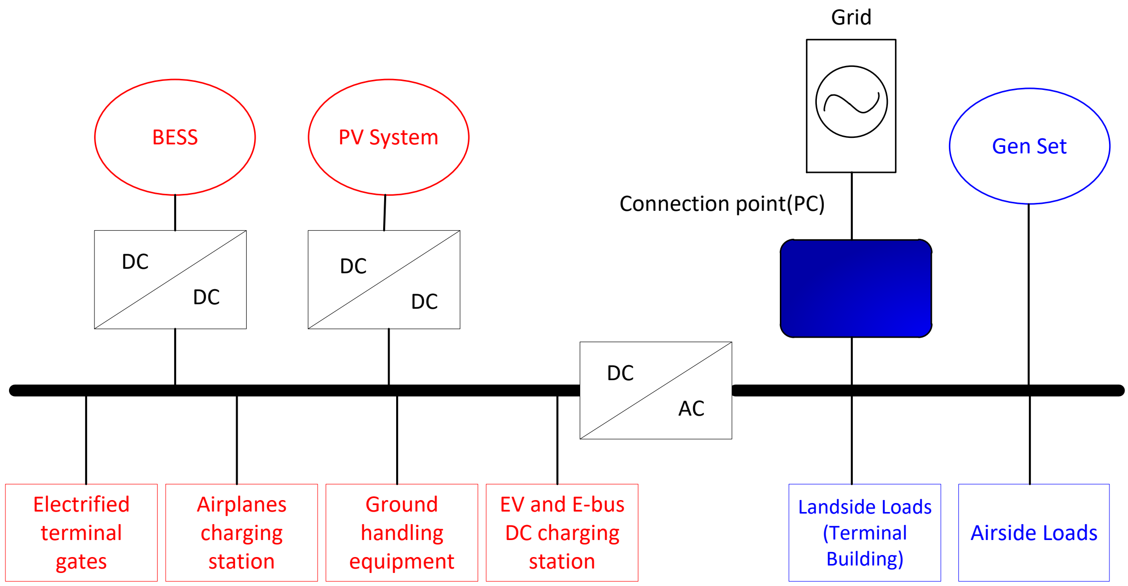


***Figure 3-6.****Schematic diagram of a Hybrid microgrid in airport including predicted new loads*

In the coming times, additional DC loads like LED lighting and concealed DC loads like HVAC and data centers can be linked to the DC bus. The diagram 3-7 presents a visual representation of this concept.

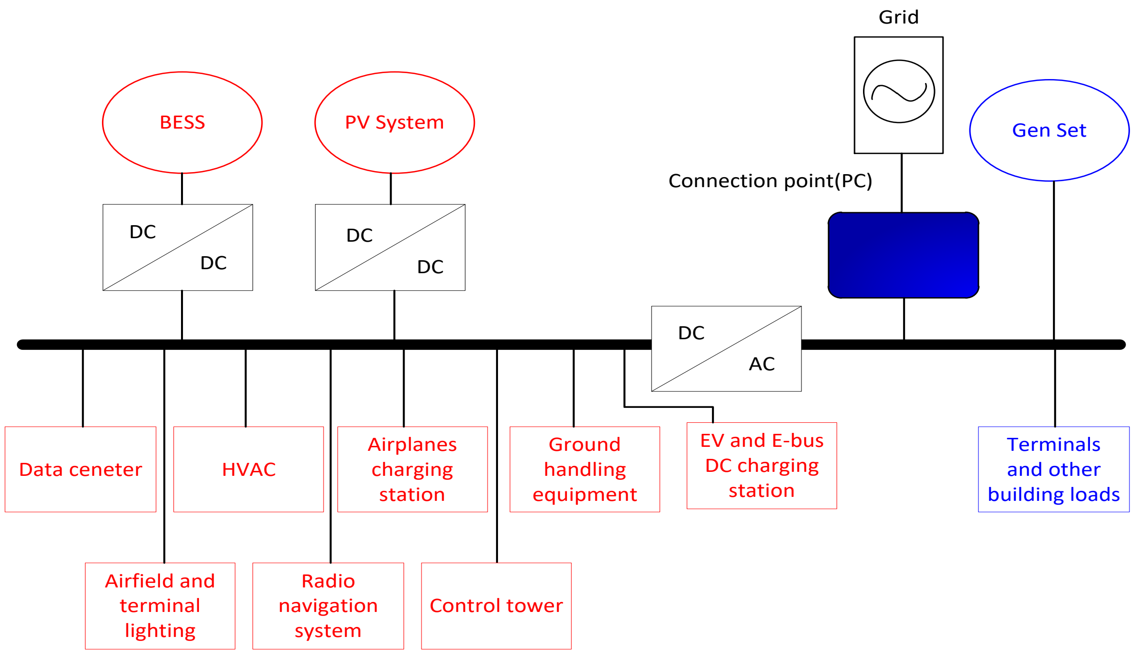


***Figure 3-7.****Schematic diagram of a Hybrid microgrid in airport including predicted new loads and existing DC loads*

## 3.3 Electrotechnical requirements for operation in microgrid

According to the specifications outlined in the grid code, power generating facilities, energy storage systems, and AC loads participating in demand response programs must fulfill certain requirements to ensure the safe and reliable operation of the microgrid. These requirements vary depending on the type and capacity of the facility.

For power generating facilities, such as PV plants, it is critical that they are able to respond quickly to voltage and frequency fluctuations to ensure stable operation, particularly during islanding [24]. To achieve this, they must be designed with dynamic characteristics that allow them to regulate their output in response to changes in grid conditions. In addition, when renewable energy sources are used to replace traditional methods of generating electricity, such as with PV systems, there is a reduction in the power system's ability to maintain its frequency during disturbances due to the absence of rotating masses that provide inertia [25]. Therefore, power generating facilities must have the ability to emulate virtual inertia to improve stability, particularly during island operation.

For Type B power generating facilities (those with a capacity above 1 MW and less than 10 MW), specific requirements include operating within certain voltage and frequency limits, with the facility able to function within a frequency range of 49.0 to 51.0 Hz. The facility must be capable of continuing to operate normally when the rate of change of frequency is less than 2.0 Hz/s and must have appropriate synchronization equipment to maintain normal operation frequency and voltage during synchronization with the grid. Additionally, power generating facilities must be able to maintain the active power at the target value despite frequency changes, except when a frequency control mode is active, and must have fault-ride-through capability to withstand momentary voltage fluctuations without getting disconnected from the grid. They must also have remote control capability to reduce active power production according to a given setpoint and recover active power after a voltage disturbance within a specific time frame. The fault ride-through requirements for power generating facilities are illustrated in Figure 3-8.

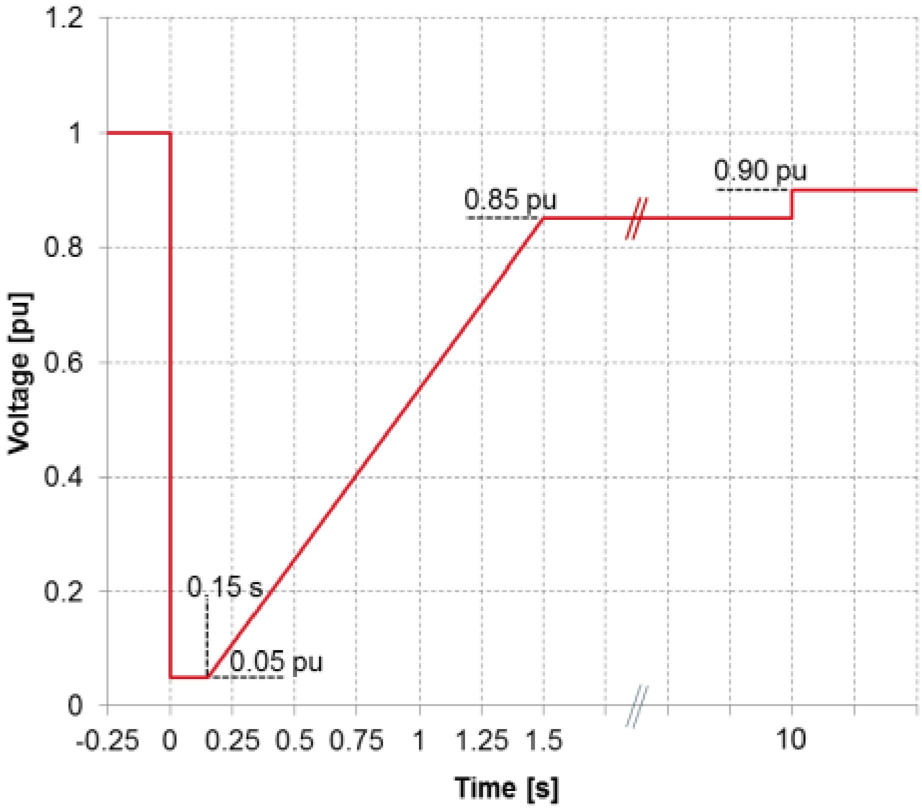


***Figure 3-8.*** *Voltage profile during fault-ride-through event* [24]

Other requirements for power generating facilities include protection settings designed to enable the facility to remain connected to the grid during disturbances, as well as the capability to inject fault current rapidly, and the ability to operate at a power factor of 1.0 or provide support to the voltage of the connection point.

For energy storage systems, they must be able to respond quickly to changes in the grid and regulate their output to maintain grid stability. They must also be able to remain connected to the grid during faults and disturbances [26].

Finally, for AC loads participating in demand response programs, they must be able to reduce their power consumption during periods of high demand and return to normal operation quickly once the demand response event is over. Figure 3-9 illustrates the operating voltage and frequency range for the load. They must also be able to remain connected to the grid during faults and disturbances [27].

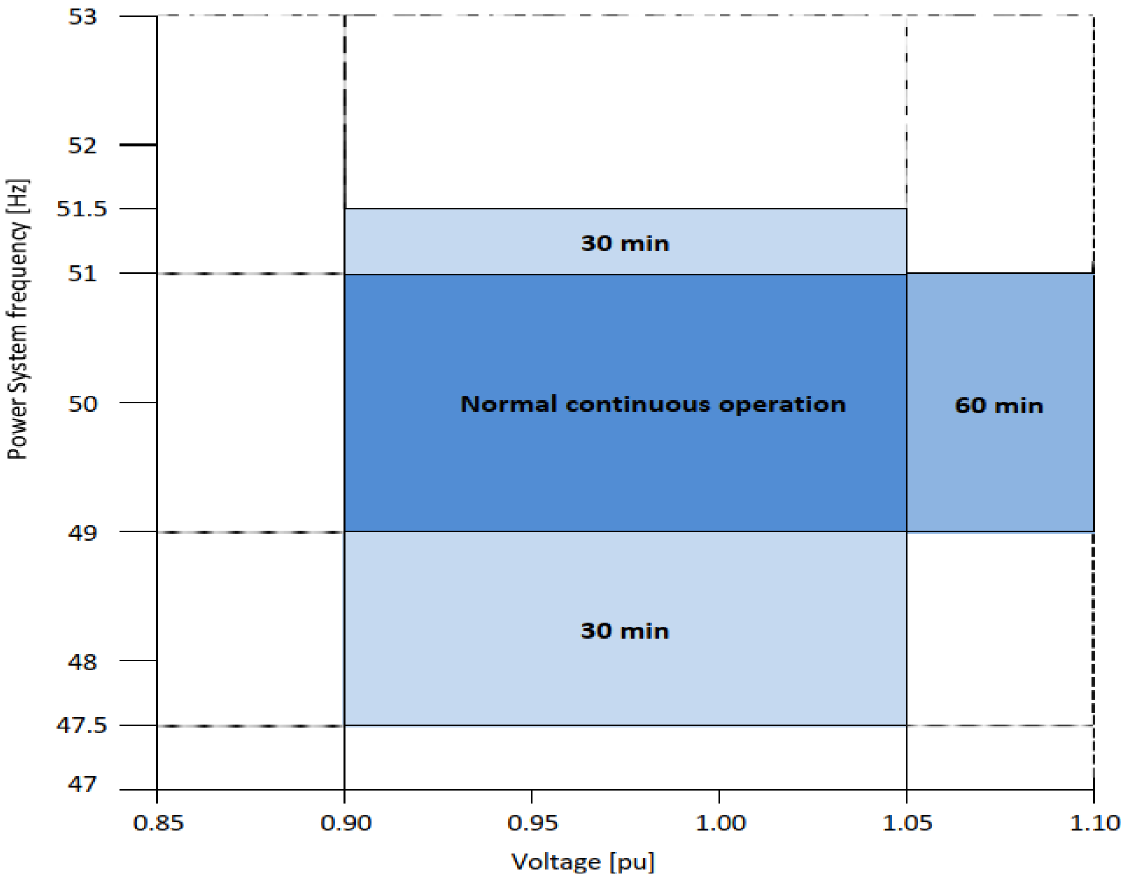


***Figure 3-9.****Operating voltage and frequency range for load* [27]

Overall, meeting these electrotechnical requirements is crucial for ensuring the safe and reliable operation of microgrids, particularly as the use of renewable energy sources and demand response programs continue to increase.

# 4. SIMULATION MODELS

The research questions and goals outlined in the introduction chapter must be tackled. Consequently, this chapter aims to construct a simulation environment that allows us to address these research questions and examine five different scenarios. By doing so, we hope to enhance our knowledge of the supply resources requirements necessary in airport settings. Renewable energy sources, such as solar power, have gained increasing attention as a promising solution to mitigate the environmental impact of energy generation and reduce dependence on fossil fuels. In particular, the aviation industry has been exploring the use of renewable energy sources to reduce its carbon footprint and achieve sustainability goals. One promising application is the use of solar panels to generate electricity to power airports. Solar energy production is subject to fluctuations due to weather conditions and time of day, which can result in imbalances between energy supply and demand. To address this challenge, energy storage systems, such as batteries, can be used to store excess solar energy during periods of high solar generation and release it during periods of low solar generation or high energy demand. The figure 4-1 indicates airport microgrid structure.

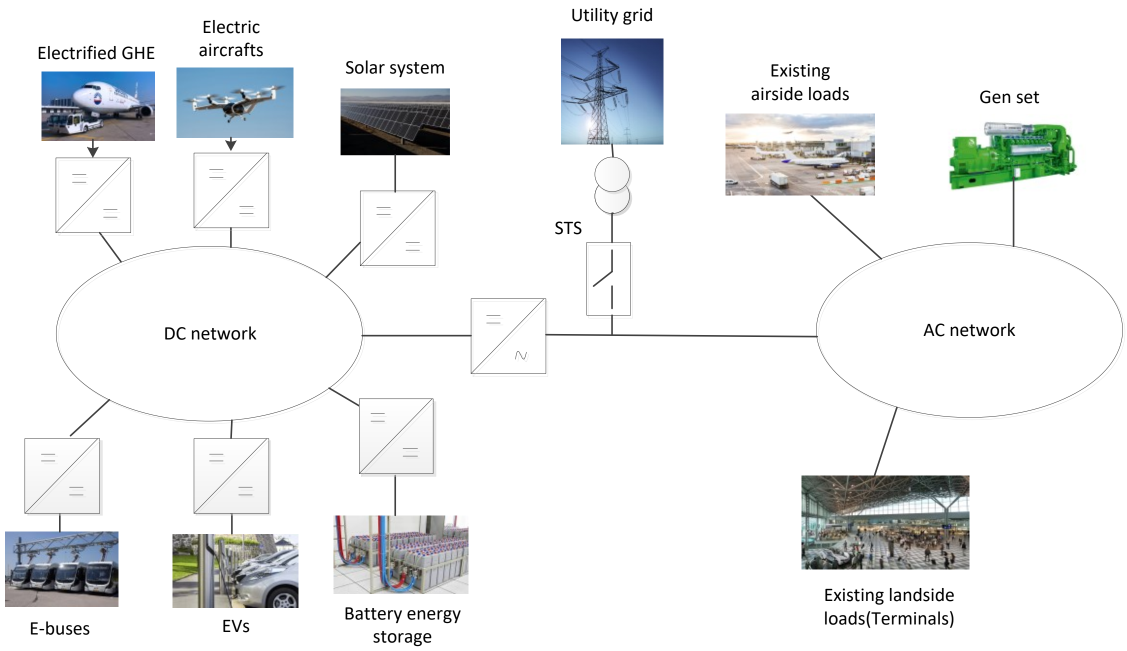


***Figure 4-1.****Airport microgrid architecture*

This chapter focuses on the simulation and analysis of a microgrid system incorporating solar power and battery energy storage at Pirkkala airport in Finland. The first part of the chapter describes the calculation of the hourly yield of a solar panel system and the factors that affect it, including solar panel area, efficiency, solar radiation, and environmental conditions. The second part discusses the battery storage system and its ability to provide energy storage for excess solar energy and meet energy demand during periods of low solar generation or high energy demand. The third to sixth parts examine the load simulation of electric aircraft and electric vehicles and their impact on the microgrid system. The overall objective is to assess the feasibility and effectiveness of the microgrid system and provide recommendations for improving its performance. The flowchart for simulating the behavior of the system under different scenarios, providing a visual representation of the simulation process is depicted in figure 4-2 to 4-4. Part 7 explains how economic analysis is modeled and simulated to determine the monetary benefits of introducing a microgrid. Eventually, a ready-to-use simulation is introduced in part 8 to determine the appropriate size of solar generator and battery energy storage system (BESS) based on cost minimization.

In conclusion, the chapter provides a comprehensive analysis of the microgrid system incorporating solar power and battery energy storage at Pirkkala airport in Finland. The simulation model developed using Matlab provides valuable insights into the technical characteristics of the solar panels and battery, as well as the energy demand profile of the airport. The load simulation of electrified transportation demand provides a realistic assessment of the impact of these technologies on the microgrid system. The recommendations provided for improving the performance of the microgrid system can be used to guide future research and development in this area.

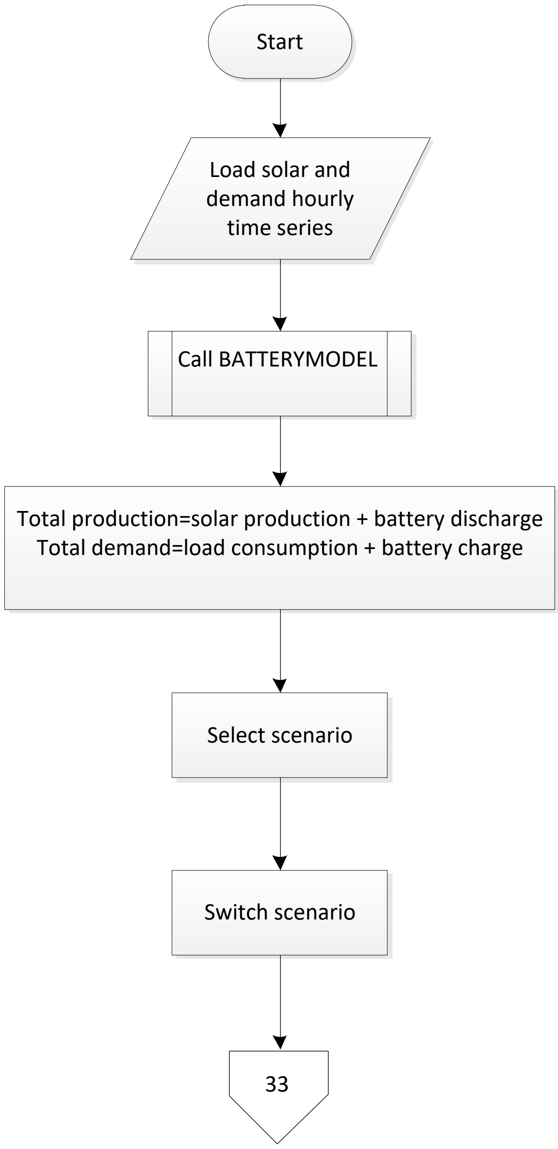


***Figure 4-2.****Simulation process flowchart*

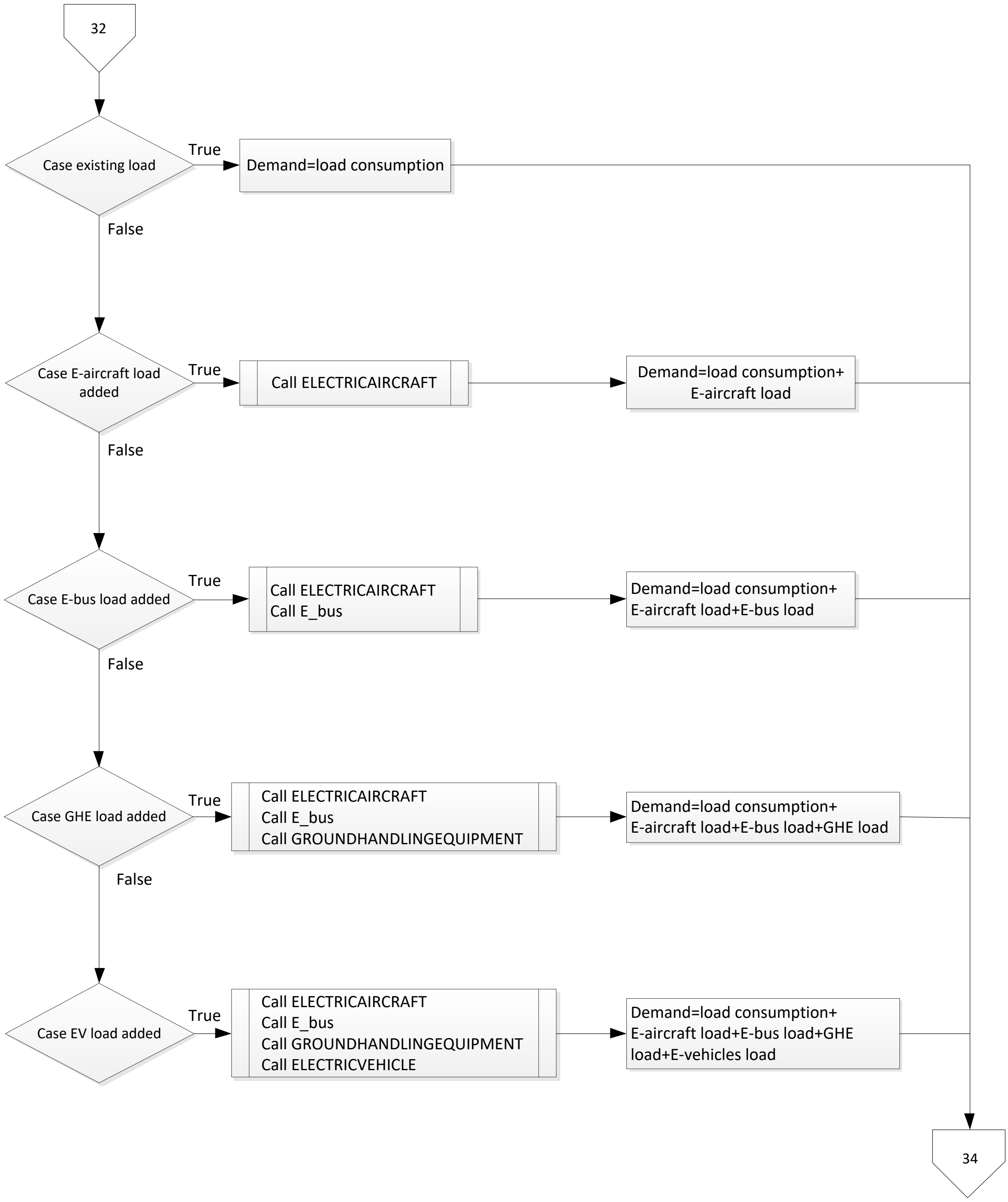


***Figure 4-3.****Simulation process flowchart*

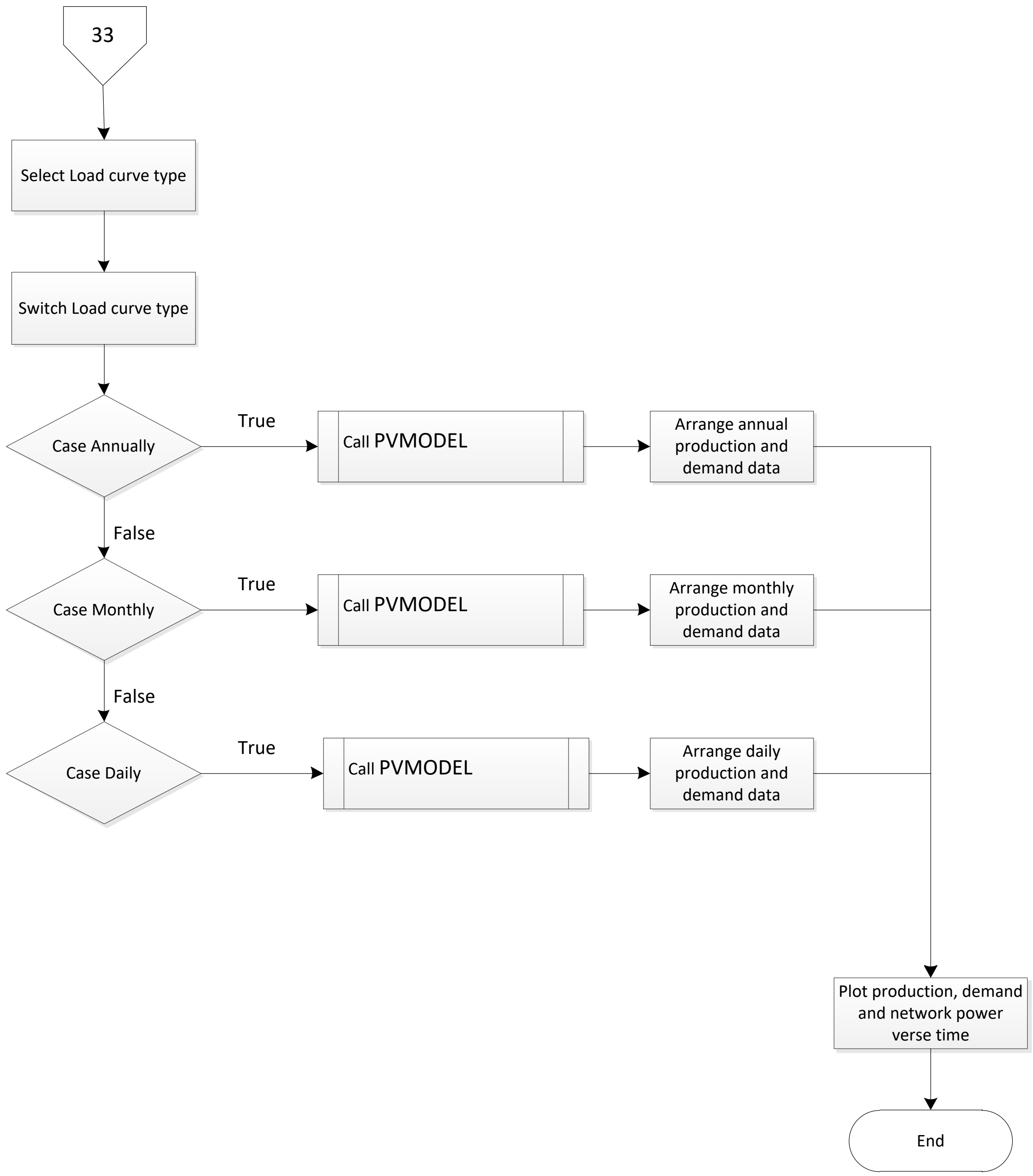


***Figure 4-4.****Simulation process flowchart*

## 4.1 Solar power and load consumption

To determine the hourly yield of a solar panel system, an equation is used that takes into account several important factors. These factors include the total area of the solar panel, the efficiency of the panel, and the hourly solar radiation on tilted panels. It's important to note that this equation assumes that the solar panel is installed at an optimal angle and orientation to receive maximum solar radiation. The solar irradiance data is selected at an hourly resolution, thus the impact of clouds or weather patterns on solar energy production is not captured. However, factors such as shading and environmental conditions can also impact the energy output of the system. Therefore, it's crucial to consider local weather patterns and shading when designing and installing a solar panel system. The equation (2) is used to calculate the energy yield of a solar panel system [28].

$$E = A \times r \times H \times PR \tag{2}$$

where E represents the energy yield in kilowatt-hours (kWh), A is the total solar panel area in square meters (m2), r is the solar panel efficiency or yield as a percentage, H is the hourly solar radiation time series on tilted panels (without shading), and PR is the performance ratio or coefficient for losses. For this study, the solar panel is assumed to have characteristics presented in table 4-1.

***Table 4-1.****Solar panel characteristics*

| | |
|---|---|
| STC Power Rating | 275 W |
| Panel area | 1.65 $m^2$ |
| Solar panel efficiency | 16.67% |
| Performance ratio | 1 |

In Table 4-1, STC Power Rating refers to the maximum power output that a solar panel can produce under Standard Test Conditions (STC), which are defined as a solar irradiance of 1000 W/m2, a cell temperature of 25 degrees Celsius, a wind speed of 1 m/s, and an AM (Air Mass) value of 1.5. The solar panel efficiency is obtained utilizing the formula (3) where kWp is maximum peak power and A is panel area.

$$r = \frac{kWp}{A} \times 100 \tag{3}$$

Using these values, the solar panel yield or efficiency is approximately 16.67%.

$$r = \frac{kWp}{A} \times 100 = \frac{0.275}{1.65} \times 100 \approx 16.67\%$$

It is important to note that this nominal ratio is given for standard test conditions (STC). However, this study does not consider local weather patterns or shading. Further, a PR value of 1 is assumed to represent the performance of the photovoltaic system under standard test conditions.

Based on the descriptions provided above, the Matlab code is employed to simulate the power output of the solar panel system. Solar irradiance hourly time series are obtained from Finish meteorology institute (FMI) [29]. Since the solar irradiance measurement is not available in Pirkkala airport, the closest observation station, Jokioinen Ilmala observation station, is selected. In addition, hourly time series data on electricity consumption at Pirkkala airport was obtained from a relevant organization, but due to confidentiality, the data was scaled.

The figure 4-5 displays the curve for the solar output power and load demand, indicating that the load consumption remains almost constant throughout the year. Additionally, it is evident that weather has an impact, as the solar power production drops significantly during the winter months.

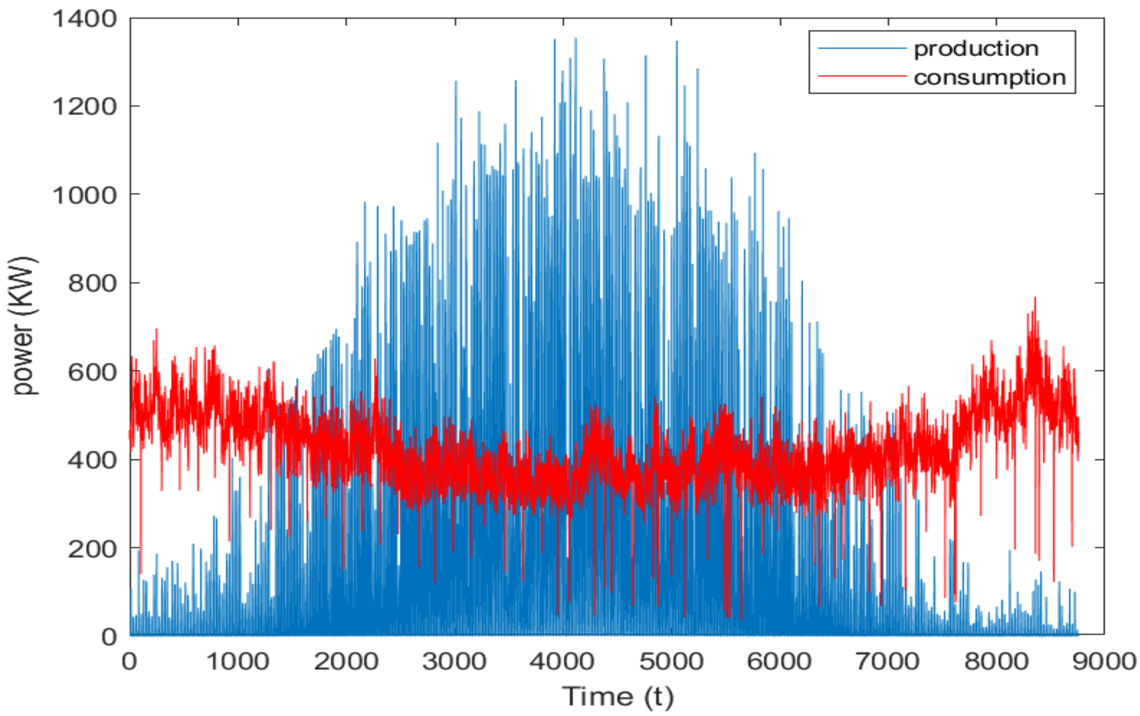


***Figure 4-5.****Airport solar output power and load demand curve over the course of year*

## 4.2 Battery storage system

The objective of this section is to simulate the performance of a battery used in conjunction with solar panels to form a microgrid at Pirkkala airport. Specifically, we aim to investigate the battery's ability to provide energy storage for excess solar energy and its effectiveness in meeting energy demand during periods of low solar generation or high energy demand.

To achieve this objective, we developed a simulation model using Matlab, which will take into account the technical characteristics of the solar panels and battery, as well as the energy demand profile of Pirkkala airport. We will analyze the simulation results to draw conclusions about the feasibility and effectiveness of the microgrid system and provide recommendations for improving its performance.

In order to determine the appropriate battery size for the microgrid project, it is recommended to conduct a feasibility study which includes a load analysis of the airport's energy demand, a site analysis of the solar resource availability, and an evaluation of the energy storage requirements. The load analysis involves reviewing historical energy consumption data to estimate the size of the battery required to meet the airport's energy needs during periods of low solar energy generation or high energy demand. The site analysis involves evaluating the solar resource availability at the airport to estimate the amount of excess solar energy that can be stored in the battery during periods of high solar energy generation. Based on the load analysis and site analysis, the energy storage requirements can be determined, which will inform the decision of energy capacity which is suitable for this project. Additionally, taking into account the desired level of energy independence, it may be necessary to install a large battery with large energy storage capacity to ensure that critical loads at the airport can be covered by its own resources during power outages or periods of low solar energy generation.

It's worth noting that while energy storage capacity is an important factor to consider for the airport project, cost minimization is also a critical consideration. A larger battery with greater energy storage capacity may provide greater energy independence and resilience, but it may also come with a higher price tag. Therefore, in selecting the battery capacity, a balance needs to be struck between the desired level of energy independence, resilience, and cost-effectiveness. The weight of cost as a factor may be higher in some cases, but ultimately the final decision will depend on the combination of all factors. By way of conclusion, it is important to note that in normal situations, some portion of the airport's energy needs may still be sourced from the grid.

The flowchart presented in Figure 4-7 depicts the programming sequence for battery charging and discharging in accordance with the objectives of this study. The system works by first calculating the net power, which is the difference between the power generated by the PV system and the power consumed by the load. If the net power is positive (i.e., excess PV production), the battery is charged by converting the net power into energy received (in kWh) with the battery efficiency taken into account. The energy received is then limited to the maximum battery capacity, and the state of charge (SOC) is updated accordingly. On the other hand, if the net power is negative (i.e., insufficient PV production), the battery is discharged by converting the net power into energy delivered (in kWh) with the battery efficiency taken into account. The energy delivered is then limited to the minimum battery capacity, and the SOC is updated accordingly. Finally, the energy received and delivered are tracked and stored as charge and discharge values, respectively. The charge and discharge output power values are then tracked and plotted, as shown in the figure 4-6.

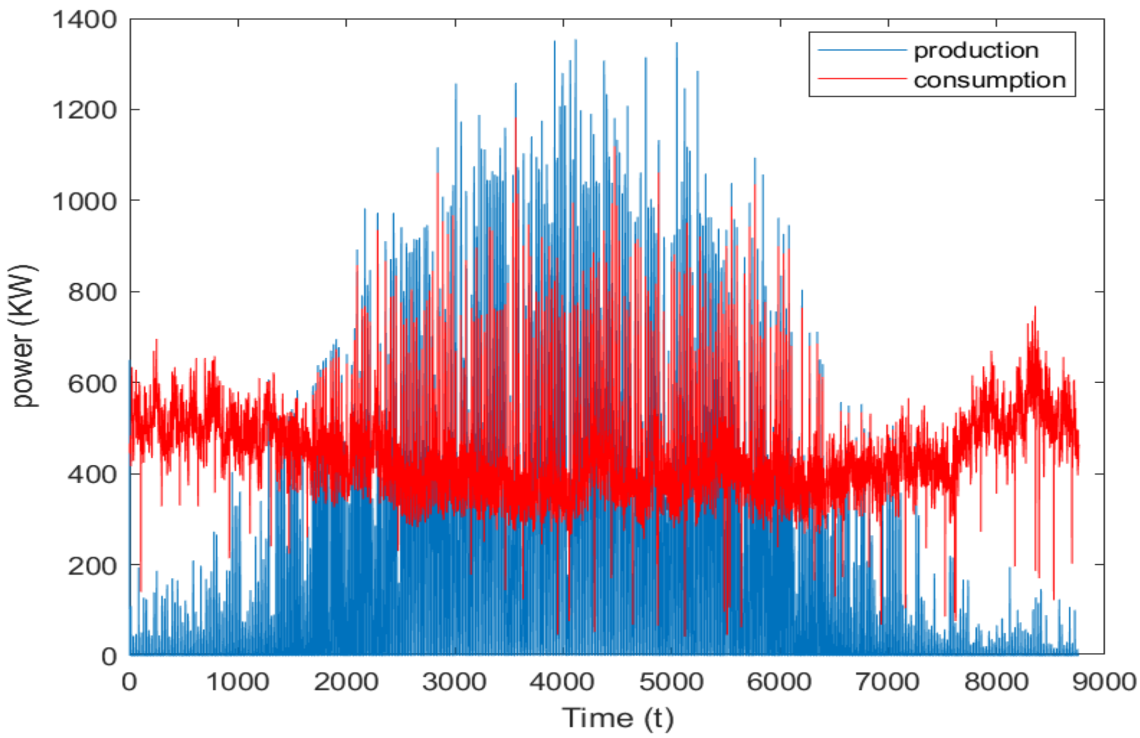


***Figure 4-6.*** *.Airport solar output power and load demand curve including battery charge and discharge Output Power*

The initial values assumed in the Matlab program are according to Table 4-2.

***Table 4-2.****Initial values used in the battery model*

| | |
|---|---|
| Battery capacity | 1000 kWh |
| Battery efficiency | 92 % |
| Initial SOC | 50 % |

It should be noted that in this study, the analysis of energy flow in the network was conducted by considering only the battery capacity and initial state of charge (SOC) of the battery, without taking into account the battery power capability. It's also worth noting that, the maximum power rating of the battery system is determined based on cost minimization. As a result, there may be certain periods where the battery system is unable to meet the peak energy demand.

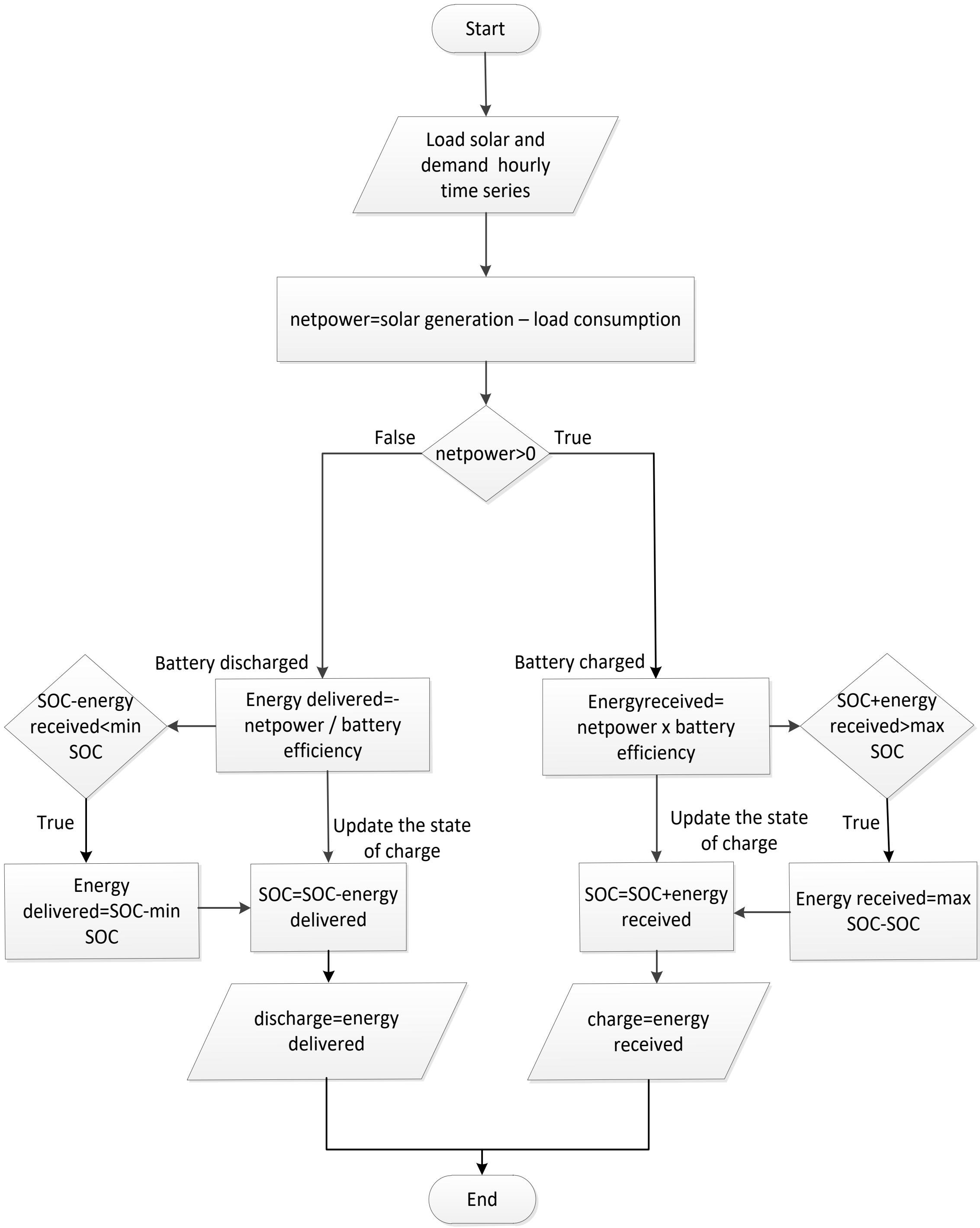


***Figure 4-7.****Battery charge and discharge programing flowchart*

## 4.3 Electric aircraft load simulation

One of the scenarios being considered involves introducing electric aircrafts. To calculate the electricity demand at specific times, the aircraft arrival times are extracted from the table 4-3, and their electricity consumption is calculated accordingly. This provides a clear picture of the amount of demand that is added to the electricity network at each specific time. The provided Matlab function demonstrates how the electric aircraft are charged and how the total energy consumption is computed.

***Table 4-3.****Aircraft arrival time schedules*

| Flight number | Arrival time |
|---|---|
| Flight 1 | 15:10 |
| Flight 2 | 15:20 |
| Flight 3 | 16:00 |
| Flight 4 | 16:30 |
| Flight 5 | 17:20 |
| Flight 6 | 19:40 |
| Flight 7 | 19:45 |
| Flight 8 | 20:35 |
| Flight 9 | 20:45 |
| Flight 10 | 21:00 |

The figure 4-8 shows a trend line that represents how the charging power of an electric aircraft varies as the State of Charge (SOC) of the battery changes [30]. The x-axis represents the SOC percentage, while the y-axis represents the charging power in kW (kilowatts), which is the rate at which the electric aircraft is charged.

The trend line on the figure is not a straight line, which means that the charging power is not constant for all SOC values. Instead, the trend line has four distinct segments, which correspond to four different ranges of SOC values. Each segment has a different slope, indicating that the charging power changes at a different rate for each segment.

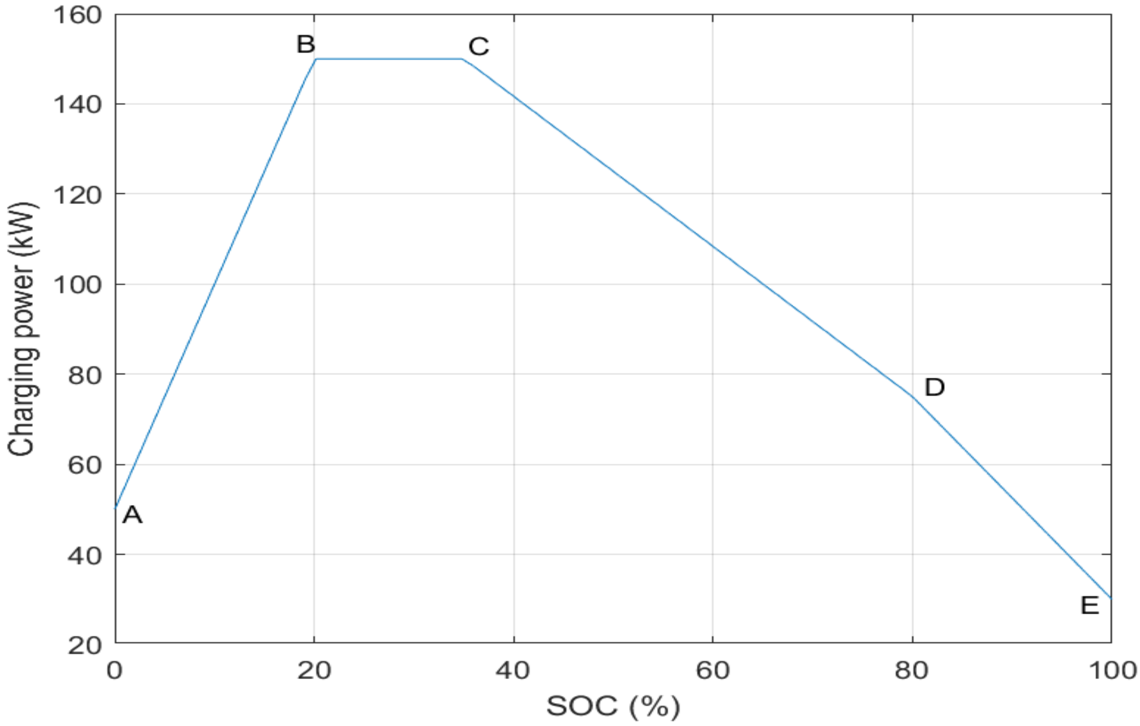


***Figure 4-8.****Charging Power Trend versus State of Charge for Electric Aircraft*

The segments are divided by three points on the x-axis: B, C, and D, which correspond to the SOC values of 20%, 35%, and 80%, respectively. The first segment (A ≤ SOC ≤ B) starts at a charging power of VA, which is 1/3 of the charger's nominal speed and linearly increases to VB, which is the charger's nominal speed. The second segment (B < SOC ≤ C) has a constant charging power of VB. The third segment (C < SOC ≤ D) has a decreasing charging power that starts at VC, which is the charger's nominal speed, and decreases to VD, which is 1/2 of the charger's nominal speed. The fourth segment (D < SOC ≤ E) also has a decreasing charging power that starts at VD and decreases to VE, which is 1/5 of the charger's nominal speed. Moreover, the initial values used to model the electric aircraft are shown in Table 4-4.

***Table 4-4.****Electric aircraft battery characteristics*

| | |
|---|---|
| Battery capacity | 200 kWh |
| Nominal battery speed charger | 150 kW |
| Battery efficiency | 90% |
| Maximum SOC | 100% |

There is also a Matlab function that models the energy consumption of electric aircraft at different charging speeds based on the arrival time of the aircraft. The simulation runs for 24 hours (60*24 minutes). The energy storage system (ESS) has a capacity of

200 kWh and initial state of charge (SOC) of 20%. The minimum and maximum SOC values are set to 10% and 100% respectively. The charger efficiency is 90%. The code calculates the energy stored in the battery, the energy consumption, the SOC, and the charging speed of the aircraft at each time step of the simulation.

The code simulates the charging of electric aircraft based on their arrival time schedule. The arrival times are converted to minutes and the electricity consumption of each aircraft is calculated using a separate function. The consumption values are stored in a cell array for each aircraft, which is later summed up to obtain the total hourly and annual energy consumption of the electric aircraft.

## 4.4 Electric bus load simulation

In the third scenario, the impact of E-bus load is analyzed, and two charging strategies were evaluated: relay charging and opportunity charging. The study focused solely on E-buses, as they have a consistent pattern and clear data, unlike electric vehicles (EVs), which vary in vehicle models. The best charging capacity to increase the lifetime of a battery depends on various factors such as the battery chemistry, operating conditions, and manufacturer's recommendations. However, there are some general guidelines that can be followed.

For lithium-ion batteries, which are commonly used in electric vehicles including E-buses, it is recommended to charge them at a lower rate ($P_c$/2 or less) to increase their lifespan. $P_c$ represents the battery's capacity, so a charging rate of $P_c$ /2 for a 470 kWh battery would be 235 kW. In addition, it is also recommended to avoid charging the battery to its full capacity or discharging it completely. Instead, it is best to keep the battery's state of charge (SOC) within a certain range (usually between 20% and 80%) to reduce stress on the battery and extend its life. Therefore, a charging capacity of 235 kW or lower and keeping the battery's SOC between 20% and 80% would be the best way to increase the lifetime of a 470 kWh lithium-ion battery in an E-bus. To estimate the energy consumption of the E-bus load, we utilize the initial values provided in table 4-5.

***Table 4-5.****Input parameters for E-bus load energy consumption estimation*

| | |
|---|---|
| Energy capacity | 470 kWh |
| Operating range | 200 km |
| Energy consumption | 2.35 kWh/km |
| Charging capacity | 235 kW |
| Charging efficiency | 90% |
| Maximum SOC | 80% |
| Distance | 20 km |

To fulfil the above-mentioned requirement, relay charging strategy can be employed. In relay charging, two or more E-buses are operated in a relay or shift system, where one E-bus is in operation while the other is charging. This allows the bus service to continue without interruption, while also providing sufficient time for the batteries to be charged. To ensure continuous transfer of passengers between the airport and the city center while also increasing the lifespan of the E-bus batteries, a strategy that involves two E-buses can be implemented. Each E-bus is capable of performing three round trips per charge, where each round trip consists of a half-hour journey from the airport to the city center, followed by a half-hour return journey to the airport. After completing three round trips, the E-bus needs to be charged for approximately one and a half hours, taking into account its charging capacity of 235 kW, with the charging time increasing proportionally as the charging capacity decreases. By alternating the use of the two E-buses, one E-bus can cover the transfer while the other charges. This way, the batteries of both E-buses are subjected to less stress, leading to a longer lifespan.

Another charging strategy could be opportunity charging strategy. To effectively implement an opportunity charging strategy for E-buses in a small-sized airport, various factors should be taken into consideration. These include analyzing the bus route and schedule to identify optimal charging locations, selecting appropriate charging infrastructure based on operational requirements and electrical grid capacity, choosing the appropriate battery capacity to cover the longest route on the schedule, and designing a charging strategy that optimizes charging schedules while minimizing the impact on the airport's electrical grid. For a small-sized airport with a distance of approximately 20 km from the city center, the ideal E-bus characteristics would depend on several factors. Since it is assumed the round trip is 40 km and one bus leaves the airport to the city center every hour, the E-bus would need to have a battery capacity that can cover at least 40 km on a single charge. However, it is advisable to choose an E-bus with a battery capacity that is higher than the required minimum to allow for unexpected changes in the bus schedule or route.

Energy consumption of EV-buses is 200-400 kWh per 100 km. Thus, the energy consumption in this study is considered to be 2.35 kWh/km. Using 20 % safety margin considering non-ideal conditions such as the route and the driving style of the operator and driving up hills, carrying a full passenger load, the energy capacity of E-bus should be somewhere around 120 kWh to cover the route on the schedule. Further, in order to use the battery in range of 20 to 80 %, the energy capacity is selected 150 kWh. Considering the charging capacity of 350 kW, the battery can be charged to 80% capacity in less than 25 minutes. The Matlab function simulates the electricity consumption of electric buses (E-buses) over a year. The function takes into account various parameters such as the E-bus energy capacity, charging efficiency, operating range, distance traveled, charging strategy, and working hours, among others. The two charging strategies implemented are the relay strategy and the opportunity strategy.

In the relay strategy, the E-bus is charged at a certain location in the airport after several round trips when the battery's SOC is close to 20% which in this case is after three round trips. The charging hours are determined based on the airport working hours and the time required to charge the battery. The charging hours are sorted in descending order, and the electricity consumption load curve is calculated for each hour based on the number of E-buses that get charged. In the opportunity strategy, the E-bus is charged whenever there is an opportunity which is in this case during the waiting time at the airport . The electricity consumption load curve is calculated based on the number of trips per hour and the energy consumption per trip.

## 4.5 Ground handling equipment load simulation

The fourth scenario involves the addition of ground handling equipment (GHE) load. To accurately calculate the power consumption of GHE loads, we need to make some assumptions regarding the power consumption of each GHE and the number of hours each GHE operates per flight. It is assumed that ground handling equipment are utilized immediately after aircraft landing and the consumption of all GHE are estimated according to aircraft arrival time schedule. For the small-sized airport assumptions shown in table 4-6 are considered.

***Table 4-6.****GHE power consumption and number of hours utilization assumption*

| GHE | power consumption | number of hours used per flight |
|---|---|---|
| Pushback tug | 20 kW | 0.25 h |
| Baggage tractor | 15 kW | 0.3 h |
| Passenger bridge | 30 kW | 0.4 h |
| Ground power unit | 40 kW | 0.5 h |
| Airfield maintenance vehicle | 25 kW | 0.25 h |

A Matlab code using a function calculates the total energy consumption of various pieces of ground handling equipment used at an airport. The function uses pre-defined values for the power consumption of each piece of equipment in kilowatts and the number of hours each piece of equipment is used per flight. It also creates arrays to store the power consumption for each piece of equipment at each time interval (in this case, hourly intervals for a full day), and calculates the energy consumption for each piece of equipment at each time interval based on when it is used. Finally, the function calculates the total energy consumption for each time interval by summing the energy consumption for all pieces of equipment, and generates a time series of the total energy consumption over a full year.

The function assumes that the equipment usage hours are according to the aircraft arrival time schedule and power consumption values are accurate and that they will remain constant over the entire year. Additionally, it assumes that the energy consumption can be calculated by simply multiplying the power consumption by the number of hours each piece of equipment is used. However, there may be other factors that affect the energy consumption of this equipment, such as temperature and humidity, that are not accounted for in this study.

## 4.6 Electric vehicle load simulation

In the final scenario, electric vehicle load is introduced, and a set of six common vehicle models in Finland, including Nissan Leaf, Tesla Model 3, Hyundai Kona Electric, Mitsubishi Outlander PHEV, Toyota Prius PHEV, and Volvo XC40 Recharge T5 PHEV are selected. Using the “randperm” function, a random model is selected each time, reflecting real-world scenarios. In addition, we assumed an initial state-of-charge (SOC) value of 20% for vehicles at the beginning of the charging process.

The Matlab code used to simulate the electricity consumption of a fleet of electric vehicles (EVs) charging during the day. The simulation is done for 365 days, and 20 EVs are randomly selected to charge at each time step. The code generates random charging start times for each vehicle. The EV models are also randomly assigned based on a given list of models. Using the model, the code selects the daily distance travelled by each EV, as well as their energy consumption, charging efficiency, and battery capacity, before calculating the overall electricity consumption. In this study, Table 4-7 is utilized to illustrate the technical characteristics of the vehicles.

***Table 4-7.****EV characteristics*

| Vehicle models | Energy Consumption (kWh/km) | Battery Capacity(kWh) | Charging Efficiency(%) |
|---|---|---|---|
| Nissan Leaf | 0.2 | 40 | 90 |
| Tesla Model 3 | 0.16 | 50 | 90 |
| Hyundai Kona Electric | 0.147 | 64 | 90 |
| Mitsubishi Outlander PHEV | 0.135 | 13.8 | 85 |
| Toyota Prius PHEV | 0.039 | 8.8 | 85 |
| Volvo XC40 Recharge T5 PHEV | 0.208 | 10.7 | 85 |

The Matlab code defines a class for electric vehicle load analysis. The class has five properties including the distance traveled by the electric vehicle, the energy consumption of the electric vehicle per kilometer, the charging efficiency of the electric vehicle, the rated capacity of the electric vehicle battery and the charging capacity of the electric vehicle charger. An object is created for each EV, and electricity demand is calculated for each vehicle using the object's function. The electricity demand is then aggregated for all the EVs charging during each hour of the day. Finally, the total electricity demand for each hour of the 365-day simulation is calculated and stored in a matrix. To calculate the electricity demand and charging time, the initial values for the charging capacity and distance are assumed as table 4-8.

***Table 4-8.****Initial values for electricity demand and charging time calculation*

| | Fully electric vehicle(EV) | Plug-in Hybrid Electric Vehicle (PHEV) |
|---|---|---|
| Distance | 12600 km per year | 18200 km per year |
| charging capacity | 7 kW | 7 kW |

The program provided simulates the charging load of electric vehicles over a period of time, taking into account the time needed to fully charge each vehicle. It dissects the charging load in each hour into two parts: the load that comes online in that hour and the load that was initiated in previous hours but continues into the current hour because the underlying electric vehicles are yet to be fully charged. The number of hours where there are overlapping charging loads depends on the amount of time needed to fully charge individual electric vehicles. The program takes this into account and calculates the charging load for each hour, factoring in both the new load and the continuing load from previous hours. The formula (4) calculates electricity demand for each vehicle [31].

$$ED = \frac{EC \times D}{CE} \tag{4}$$

where ED is electricity demand (kWh/day), EC is energy consumption per km (kWh/km) D is total distance per day and CE is charging efficiency. Moreover, the time needed to charge battery is calculated using the formula (5).

$$t = \frac{B(1-SOC)}{Pc} \tag{5}$$

where B is rated battery capacity, SOC is state of charge and Pc is charging capacity.

## 4.7 Electricity consumption cost modelling and simulation

The cost of electricity consumption is modeled based on two components: distribution tariff and energy retailer tariff. The pricing structure of distribution tariff for electricity consumption cost calculation in this study was obtained from Elenia, a distribution system operator (DSO) located in Tampere. This particular pricing structure was chosen because of its relevance to the specific geographic area and market conditions under investigation [32]. Table 4-9 shows the components of distribution tariff prices and their corresponding unit prices.

***Table 4-9.****Elenia Demand tariff 3 (20 kV delivery)*

| Distribution | Winter weekdays 1 Nov-31 Mar Mon-Sat 7-22 | All other times | Basic fee | Demand fee |
|---|---|---|---|---|
| **Tax class 1** | 51.31 €/MWh | 36.68 €/MWh | 315.85 €/month | 2.44 €/kW ,month |

The distribution tariff, which includes taxes, is determined by demand tariff 3 of Elenia distribution system operator (DSO), using the average of the two highest monthly demands in electricity consumption to calculate the demand component. However, in this study, due to a lack of access to consumption time series data, the demand fee was calculated using the average of the two highest monthly demands from the most recent period of available electricity consumption data, instead of the average of the two highest monthly demands in the previous 12 months. As for the energy retailer component, the hourly market price of 2019 has been selected, where the market price was normal with an energy retailer margin of 0.25 c/kWh which is typical in Finland [5]. The day-ahead market hourly time series prices are obtained from Nord pool market data [33].

## 4.8 Pre-built modelling and simulation

The study utilizes a ready-to-use simulator utilized in the paper called "Using electrical energy storage in residential buildings – Sizing of battery and photovoltaic panels based on electricity cost optimization" [5]. The optimization of the photovoltaic system size and battery energy storage is based on the load profile and electricity pricing structure, with the load profile given greater consideration than the electricity pricing structure. The goal is to determine the most cost-effective combination of PV size and battery storage to maximize profitability, taking into account the energy needs of the airport.

The ready-to-use simulator is comprised of a PV model, a battery model, and a control system. The schematic of the pre-built simulation model is depicted in figure 4-9. The PV model incorporates the direct beam, diffuse, and reflected components of global solar irradiance. The diffuse solar irradiance is modeled using the Reindl model, with the simulator utilizing a cloudiness probability model specific to Finland. The Battery Energy Storage System (BESS) utilized in the model is a Lithium-ion battery (Li-ion battery) that employs a lithium iron phosphate (LFP or LiFePO4) cell type with a graphite negative electrode. This specific battery type is well-suited for the intended application due to its extended cycle and calendar lifespan, as well as its robust safety characteristics. To maintain consistent battery losses, the battery's state of charge (SOC) limits was established at 25-95%. Also, the charge and discharge rate (C-rate) which reflects the maximum power of battery is 0.7 in this model. It is worth mentioning that battery round trip efficiency is approximately 92% [5].

The control system for the BESS is designed to reduce electricity costs through economic incentives. The primary incentive is the difference between the purchase price and the grid supply price, and the control system's main goal is to avoid supplying electricity to the grid whenever possible. Another incentive is the power-based price component of the distribution tariff, which is managed using a control strategy to decrease the maximum hourly average power. The third incentive is the Time-of-Use (TOU) pricing, where the energy retailer's tariff is similar to real-time pricing that changes hourly based on day-ahead market prices [5].

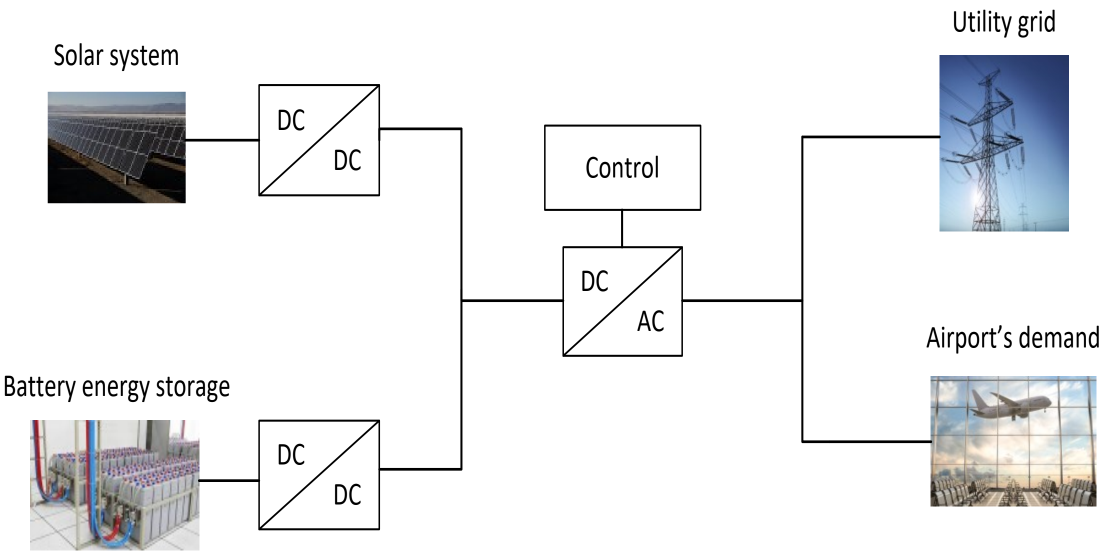


***Figure 4-9.****Schematic of pre-built simulation model*

# 5. SIMULATION RESULTS

This chapter explores five different scenarios involving the addition of new simulated loads to an airport with the aim of identifying the optimal size of a photovoltaic (PV) system and potential battery energy storage that could maximize profitability. By analyzing these scenarios, this study aims to provide insights into the most efficient and cost-effective renewable energy solutions for airports, while also examining the potential impacts of future load increases on the electrical network. It is also crucial to consider self-consumption and resiliency as these factors are important for the airport's overall sustainability. Specifically, the investigation will assess the amount of electricity that needs to be supplied by the network versus the amount that can be generated locally at the airport. Moreover, the economic effects of PV and BESS installation have been investigated in this chapter. Specifically, the electricity costs before and after PV and BESS installation have been calculated and compared for each scenario.

To analyze the economic viability and optimal sizing of a photovoltaic system with associated electrical energy storage, the ready-to-use simulator is utilized. The study found that the same optimal size of PV and BESS is suitable for all scenarios. The results show that the optimal PV size without BESS ranges between 1.3 to 1.6 MWp, while the economically optimal PV size with battery ranges between 1.5 to 1.8 MWp. Additionally, the optimal battery size is 1 MWh. Based on these findings, a PV size of 1.3 MWp may be selected for cases without a battery, while a PV size of 1.5 MWp and a battery size of 1 MWh may be optimal for cases with a solar PV and battery combination. We also found that a PV system without a battery is more profitable than one with a battery. However, Because in airport in addition to cost minimization, self-consumption and resiliency is important, PV and BESS combination will be utilized for analysis.

## 5.1 Scenario 1

In this scenario, the existing load of the airport is investigated. Using the provided simulator, the amount of energy consumed from the grid and fed back to the grid is calculated. Additionally, the amount of money that needs to be paid in cases with PV and BESS, and without them, is calculated and compared. Using ready-to-use simulation, it is found that a PV size of 1.5 MWp and a battery size of 1 MWh would be appropriate for a solar PV and battery combination. The figure 5-1 illustrates airport production and consumption curves in the case of utilization of a combination of solar PV panels with a capacity of 1.3 MWp and a BESS with a capacity of 1 MWh.

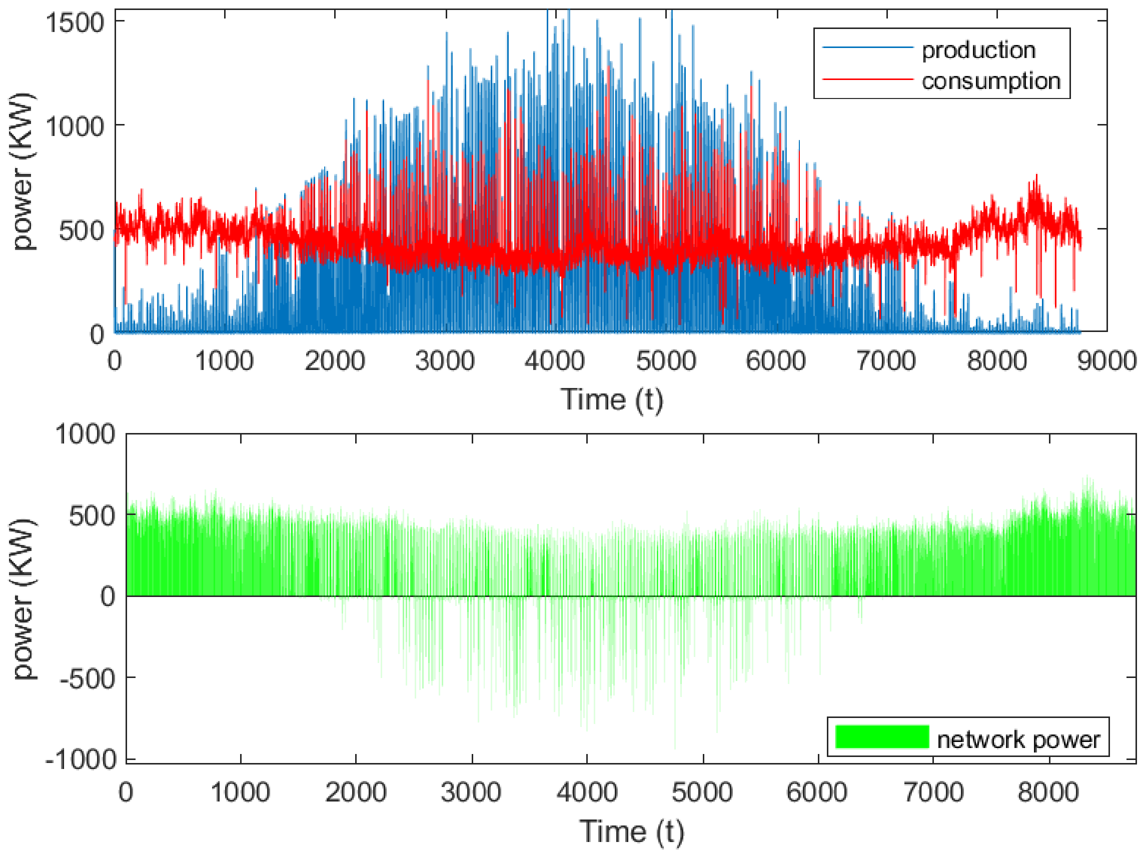


***Figure 5-1.****The energy production and consumption at the airport, as well as the energy received from and delivered to the network*

As it can be seen in figure 5-1, the airport might receives approximately 2 558 MWh energy from grid annually while it could deliver nearly 404 MWh energy to the network. Therefore the average hourly energy received from the grid is around 246 kWh. Positive power indicates the amount of energy received from the electrical grid, while negative power indicates the energy delivered back to the grid. In other words, the positive y-axis represents the energy received from the grid, whereas the energy delivered to the grid is shown on the negative y-axis. It is worth mentioning that without PV and BESS the airport receives 3 686 MWh annually from the grid.

Total annual cost and its components including annual distribution and retailer cost for both cases, without PV and battery energy storage, and with combination of PV and BESS are provided in Table 5-1. From the perspective of electricity consumption cost, the total annual electricity cost shows that installation of PV and BESS is able to bring 93 446 €/a cost saving as the annual cost without PV and BESS is 343 270 €/a, while the annual cost for the combination of PV and BESS is 249 824 €/a.

***Table 5-1.*** *Total annual electricity cost and its components*

| | Without PV & BESS | With PV &BESS |
|---|---|---|
| Annual distribution cost | 171 326 €/a | 131 372 €/a |
| Annual retailer cost | 171 945 €/a | 118 452 €/a |
| Total annual cost | 343 270 €/a | 249 824 €/a |

To analyze the worst-case scenarios, this study investigates the maximum energy received from and delivered to the grid. The PV and BESS system received the most energy from the grid, approximately 768 kWh, on December 15th when the load was highest and there was no production from the PV system. Figure 5-2 provides a visual representation of the energy production, consumption, and the energy received and delivered to the grid throughout the day.

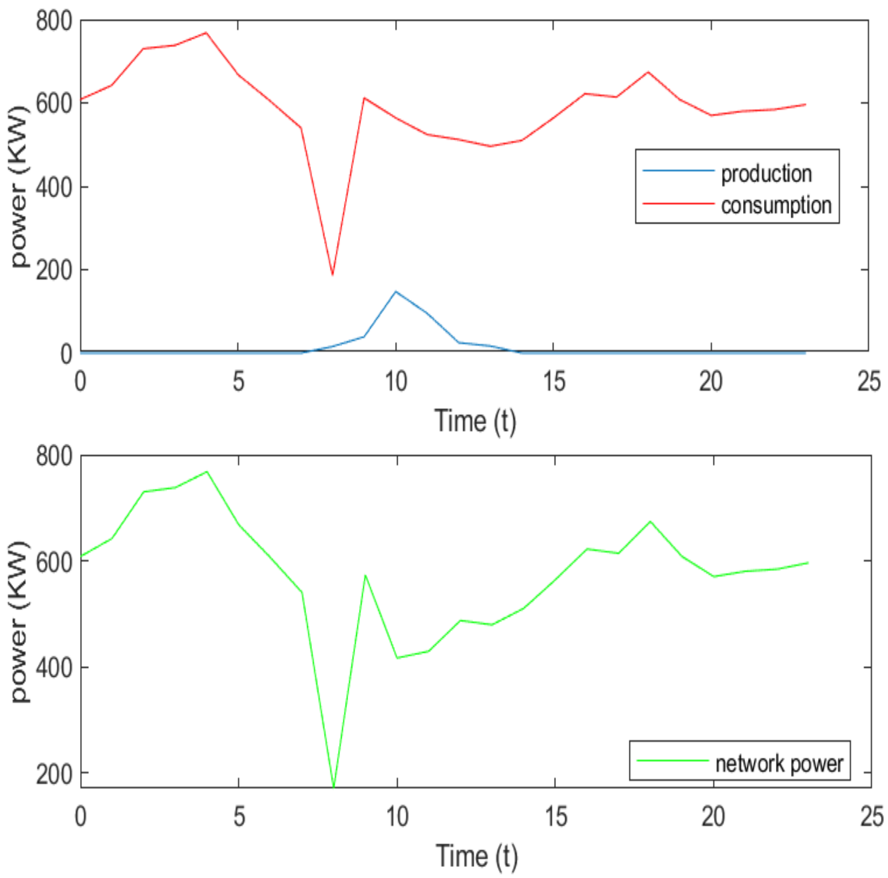


***Figure 5-2.*** *Energy production, consumption, and the energy received from and delivered to the grid in the case of receiving the most energy from the grid on December 15th*

Furthermore, the maximum energy delivered to the grid was nearly 1.238 MWh, which occurred on June 19th when PV production was at a high level. Figure 5-3 shows the energy production, consumption, and the energy received from and delivered to the grid over the course of the day. The salient point is that since the optimization of the battery capacity is based on cost minimization, the battery capacity is low, which means that it cannot store enough energy to be used later at night or in the morning, resulting in limited ability to increase self-consumption.

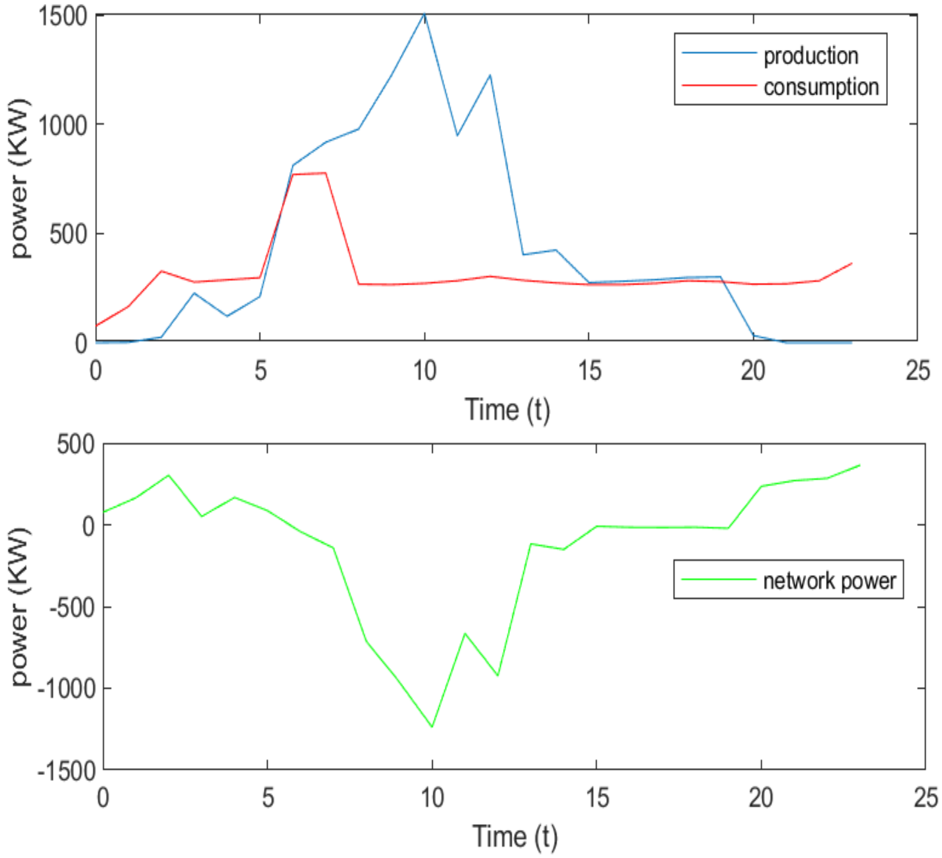


***Figure 5-3.****Energy production, consumption, and the energy received from and delivered to the grid in the case of delivering the most energy to the grid on June 19th*

## 5.2 Scenario 2

The electric aircraft load is added to the current existing load of the airport in this scenario in order to examine the amount of energy supplied from and delivered to the grid . The illustration labeled 5-4 shows the amount of extra weight that can be added to the current load at the airport, as well as the potential pattern of that load. In order to make the possible pattern of added load more clear, only the load profile for January 1st is displayed as a sample in this paper.

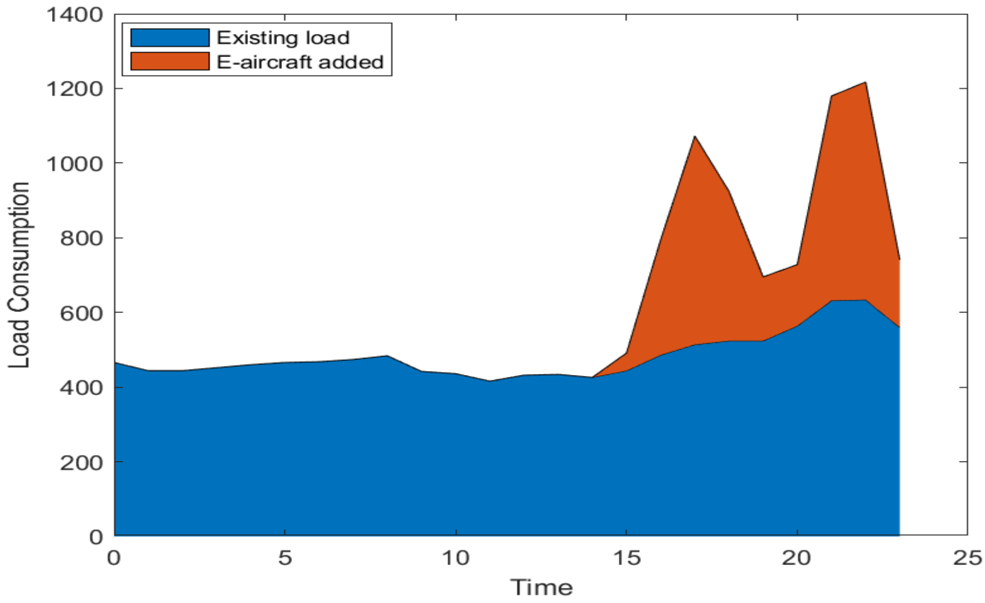


***Figure 5-4.****Electric aircraft load added to the existing airport load at first day of January*

The load profile shows an increase in peak load, which is primarily attributed to the flight time schedule introduced in chapter 4. This schedule caused several aircraft to land within a short period, requiring charging and resulting in a peak in demand. Thus, effective management of the flight time schedule is critical to prevent peak demand in the airport's load profile.

The production and consumption as well as energy flow curves of the airport when using combination of 1.3 MWp of solar PV panels and 1 MWh of BESS capacity are displayed in figure 5-5. This scenario exhibits a marked increase in load profile volatility.

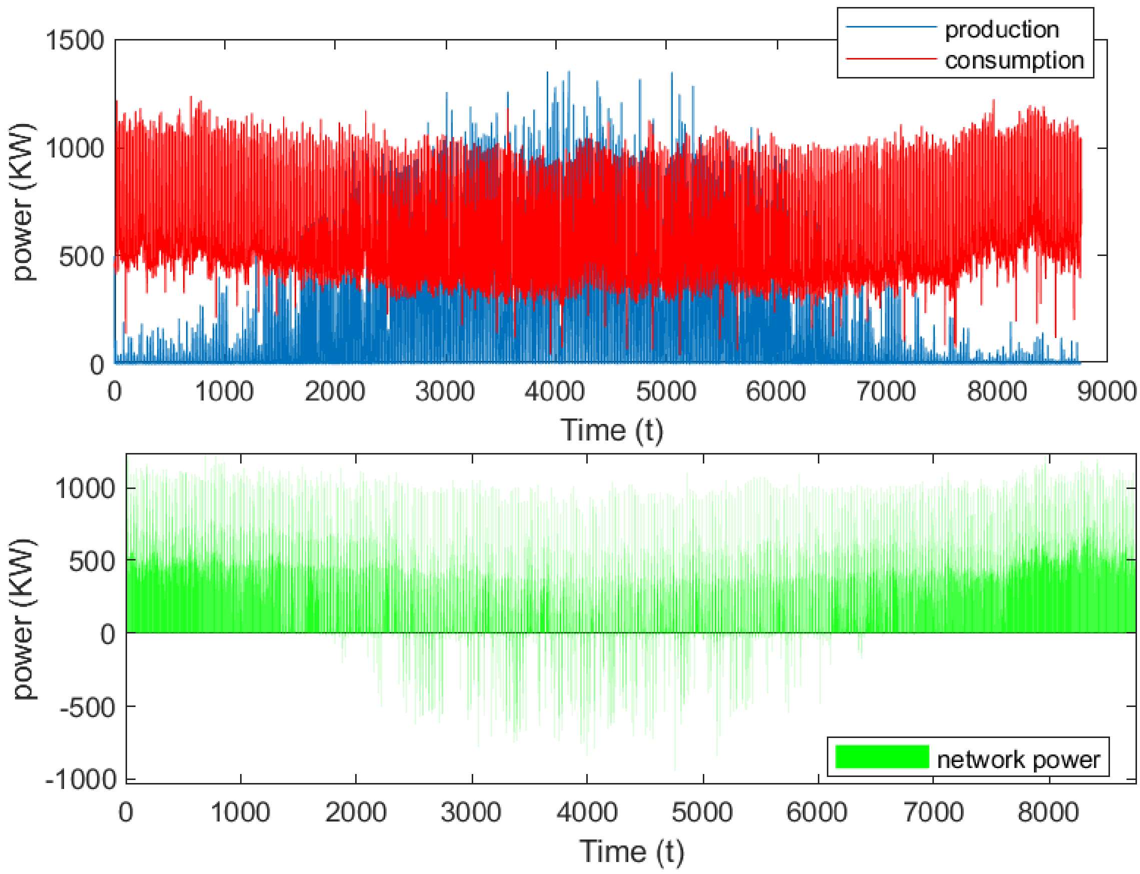


***Figure 5-5.****The energy production and consumption at the airport, as well as the energy received from and delivered to the network after adding electric aircraft load*

According to figure 5-5, this scenario involves the airport receiving approximately 3 685 MWh of energy from the grid per year, while delivering about 246 MWh of energy back to the network. As a result, the average hourly energy received from the grid is roughly 393 kWh. Adding electric aircraft load without changing PV sizing resulted in an increase in energy received from the grid, while the energy delivered to the network decreased, as predicted.

Table 5-2 provides information on the total annual cost and its different components, including the annual costs paid for distribution and to the retailer, for both cases. Installation of PV and BESS can lead to cost saving of 94 307 €/a where the total annual electricity cost for the case with the combination of PV and BESS is 354 743 €/a, while before installation the electricity cost was 449 050 €/a.

***Table 5-2.****Total annual electricity cost and its components*

| | Without PV & BESS | With PV &BESS |
|---|---|---|
| Annual distribution cost | 226 799 €/a | 186 683 €/a |
| Annual retailer cost | 222 251 €/a | 168 061€/a |
| Total annual cost | 449 050 €/a | 354 743 €/a |

## 5.3 Scenario 3

The scenario under consideration involves adding the load of E-buses to the existing load, along with electric aircraft. Two different cases are studied in this scenario. The first case is a relay charging strategy where one E-bus gets charged while another E-bus runs as its battery capacity allows it to travel multiple round trips. The second case is an opportunity charging strategy where the E-buses get charged each time they arrive at the airport. The potential load patterns for both cases are shown in figures 5-6 and 5-7.

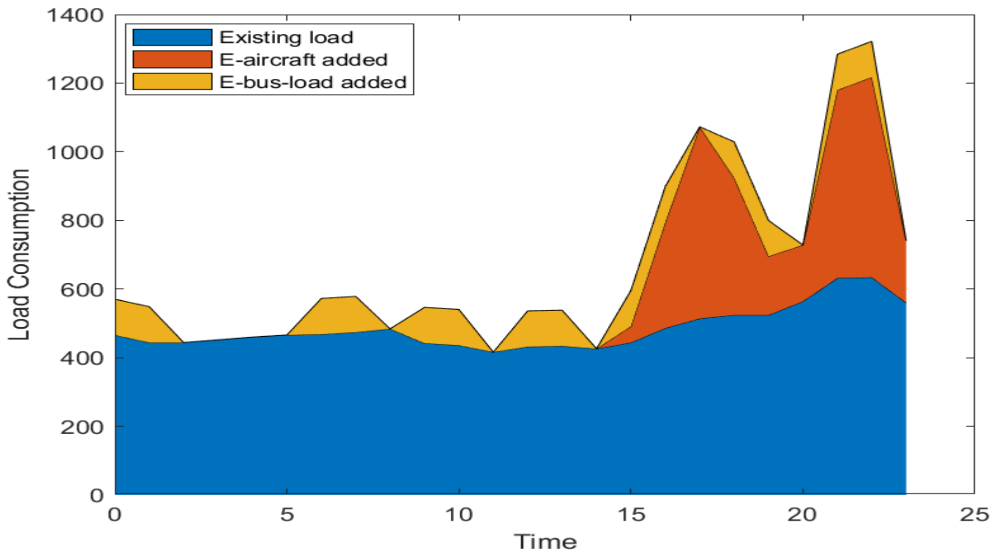


***Figure 5-6.****E-bus load with relay charging strategy added to the airport load at first day of January*

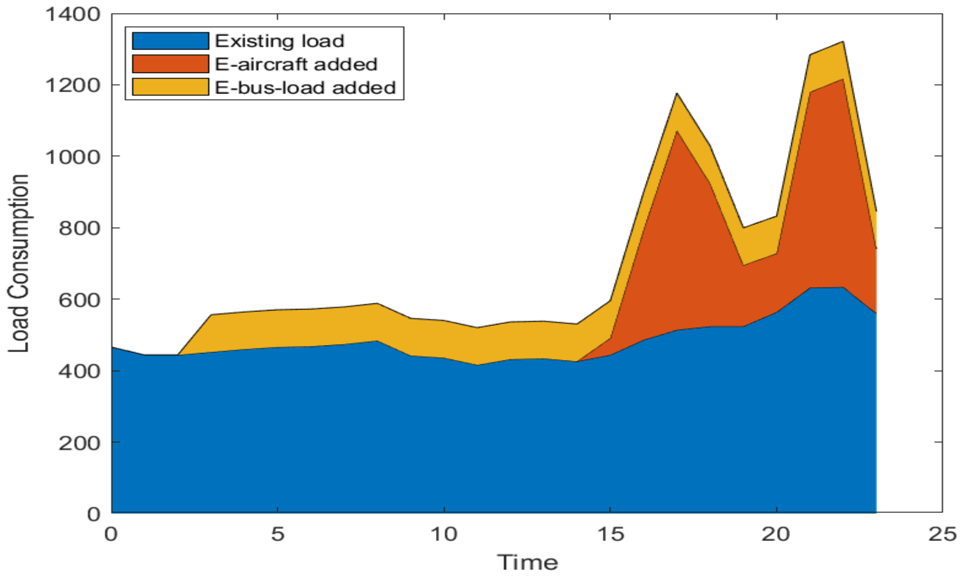


***Figure 5-7.****E-bus load with opportunity charging strategy added to the airport load at first day of January*

Figure 5-8 demonstrates the production and consumption curves of the airport load, including the E-bus load with a relay charging strategy after installation of PV and BESS. The figure also illustrates the energy received from and delivered to the grid, which reflects an increase in annual energy received from the grid and a decrease in energy delivered to the grid.

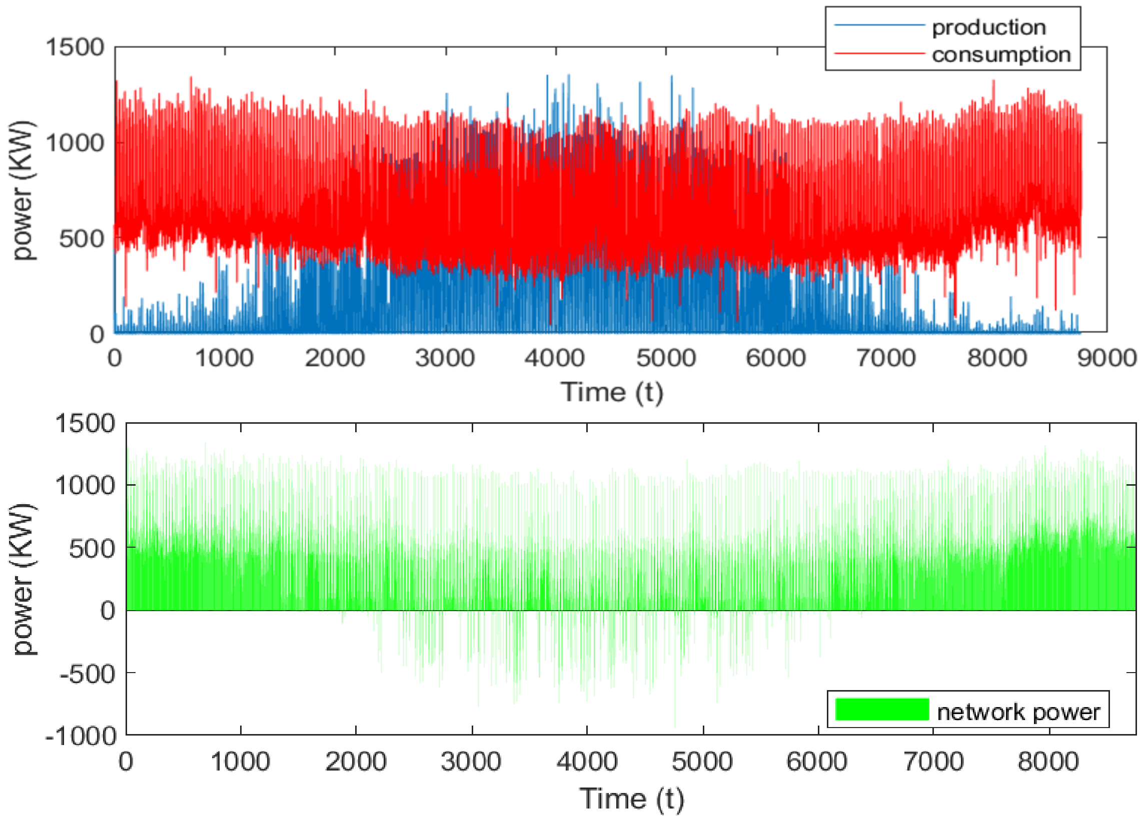


***Figure 5-8.****The energy production and consumption at the airport, as well as the energy received from and delivered to the network after adding e-bus load*

There is not much difference between the production and load patterns when comparing the two cases of relay and opportunity charging strategies. However, the energy received from the network is higher for the opportunity charging strategy at 4 538 MWh compared to 4 315 MWh, while the energy delivered to the grid is lower in the opportunity charging strategy at 298 MWh compared to 342 MWh. Furthermore, the average hourly energy received from the grid is approximately 484 kWh and 453 kWh for the opportunity and relay charging strategies, respectively.

Table 5-3 and Table 5-4 provide information on the total annual cost and its different components, such as annual distribution and retailer cost, for two various cases including relay charging strategies and opportunity charging strategies. There is opportunity for cost saving of 98 743 and 101 035 €/a respectively.

***Table 5-3.****Total annual electricity cost and its components in the case of relay charging strategies*

| | Without PV & BESS | With PV & BESS |
|---|---|---|
| Annual distribution cost | 250 479 €/a | 208 511 €/a |
| Annual retailer cost | 247 858 €/a | 191 084 €/a |
| Total annual cost | 498 337 €/a | 399 594 €/a |

***Table 5-4.****Total annual electricity cost and its components in the case of opportunity charging strategies*

| | Without PV & BESS | With PV & BESS |
|---|---|---|
| Annual distribution cost | 260 889 €/a | 217 970 €/a |
| Annual retailer cost | 260 841 €/a | 202 726 €/a |
| Total annual cost | 521 731 €/a | 420 696 €/a |

## 5.4 Scenario 4

In this scenario, an investigation is conducted on the energy required from and delivered to the grid after adding the GHE load to the previous airport demand . Figure 5-9 provides a visual representation of the GHE demand added to the previous airport consumption during the first day of January, as an example of how adding GHE load affects the airport's overall load pattern.

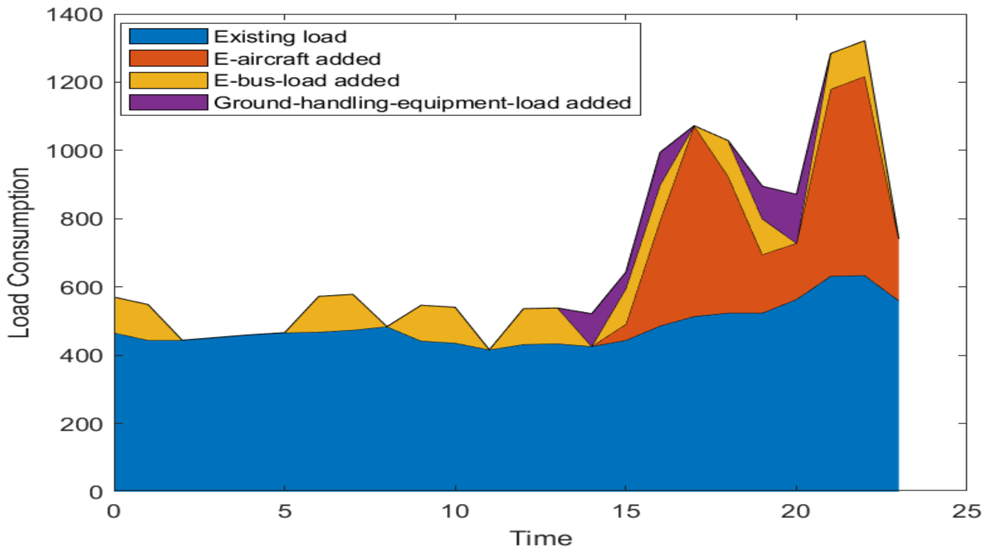


***Figure 5-9.****GHE load added to the airport consumption at first day of January*

As with scenario 2, the GHE load at the airport is affected by the flight time schedule outlined in Chapter 4. Therefore, it is essential to manage the flight time schedule effectively to optimize the airport's load profile.

When adding GHE load to the airport demand, the amount of energy we receive from the grid increases to 4 576 MWh while the amount of energy we deliver to the grid decreases to 162 MWh. The average hourly energy received from the grid is 504 kWh as well. The energy production and consumption at the airport, as well as the energy received from and delivered to the network are depicted in Figure 5-10.

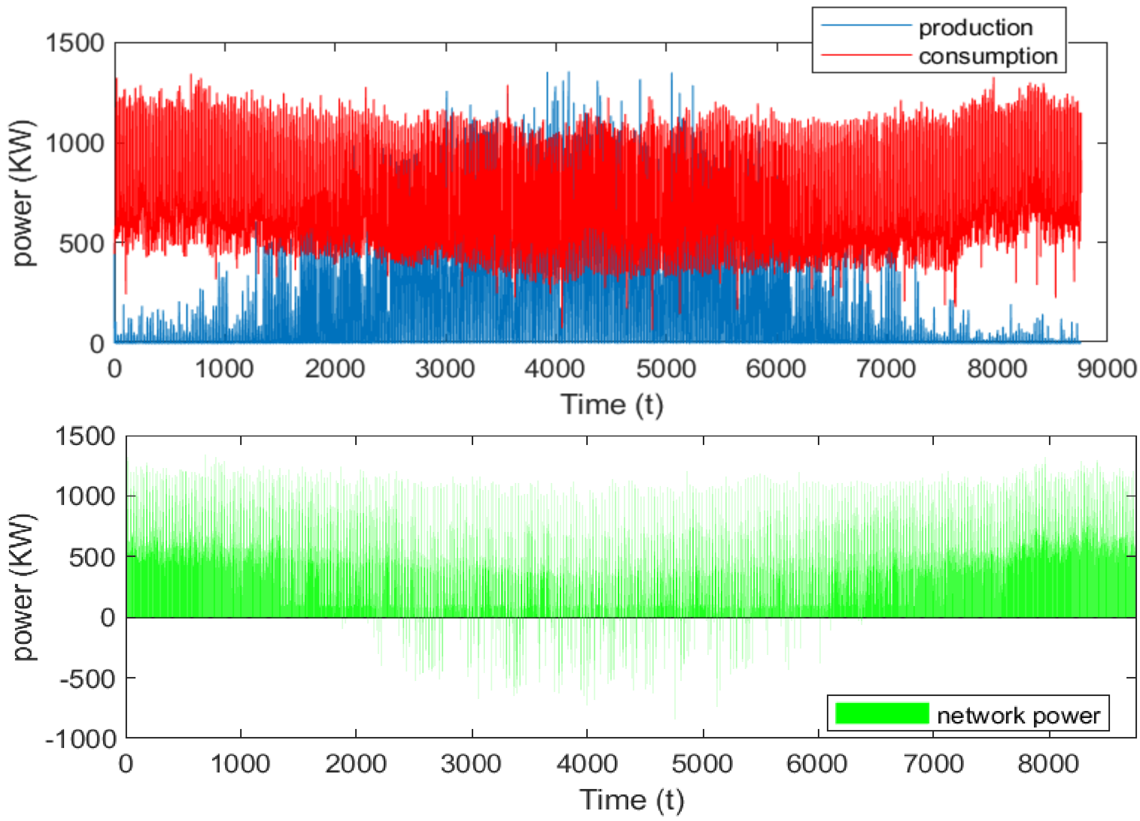


***Figure 5-10.****The energy production and consumption at the airport, as well as the energy received from and delivered to the network after adding GHE load*

Table 5-5 gives details about the complete yearly cost and its various parts for both situations, before and after installation of a combination of PV and BESS. The yearly cost of electricity before installation is 513 213 €/a, while after installation of PV and BESS, it is 413 654 €/a which provides 99 559 €/a cost saving.

***Table 5-5.****Total annual electricity cost and its components*

| | Without PV & BESS | With PV &BESS |
|---|---|---|
| Annual distribution cost | 257 019 €/a | 214 675 €/a |
| Annual retailer cost | 256 195 €/a | 198 979 €/a |
| Total annual cost | 513 213 €/a | 413 654 €/a |

## 5.5 Scenario 5

To examine the potential load profile, the electric vehicle load is added to the airport consumption. Figure 5-11 displays the resulting load pattern. To model the worst-case scenario, the Hyundai Kona Electric, which has the highest consumption, is selected. Since EV load modelling involves several random parameters, including the charging time and car model, the Hyundai Kona Electric model is used to examine the maximum possible load. The figure 5-11 illustrates how EV load management could be utilized to fill in the lower energy demand periods (valleys) and create a more consistent load profile for the airport.

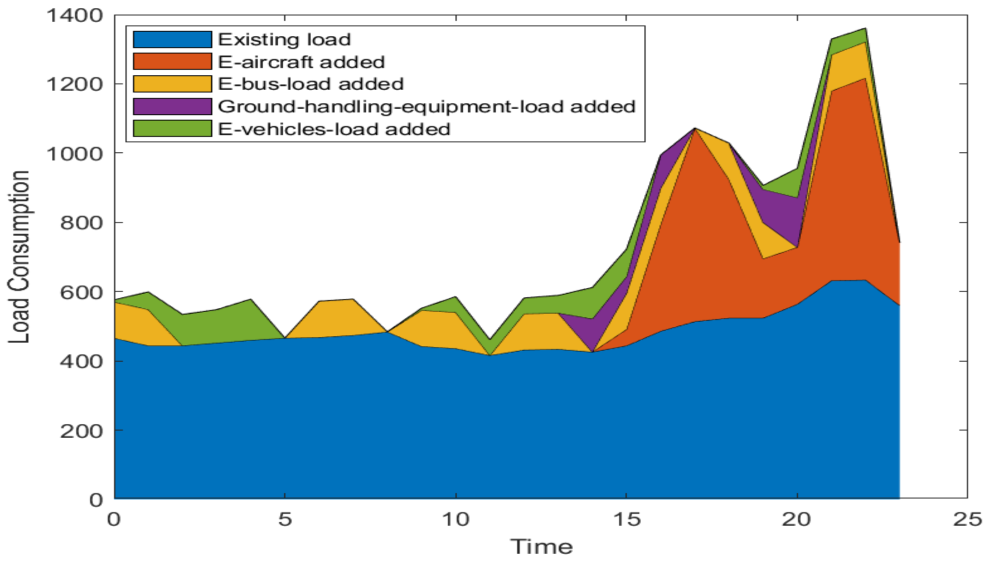


***Figure 5-11.****EV load added to the airport consumption*

Figure 5-12 illustrates the energy production, consumption, as well as the amount of energy received from and supplied back to the grid at the airport. If EV load is added to the airport's electricity demand, the amount of energy obtained from the grid over the course of year increases to 4 883 MWh, while the amount of energy supplied back to the grid decreases to 140 MWh. The average amount of energy received from the grid per hour is 541 kWh.

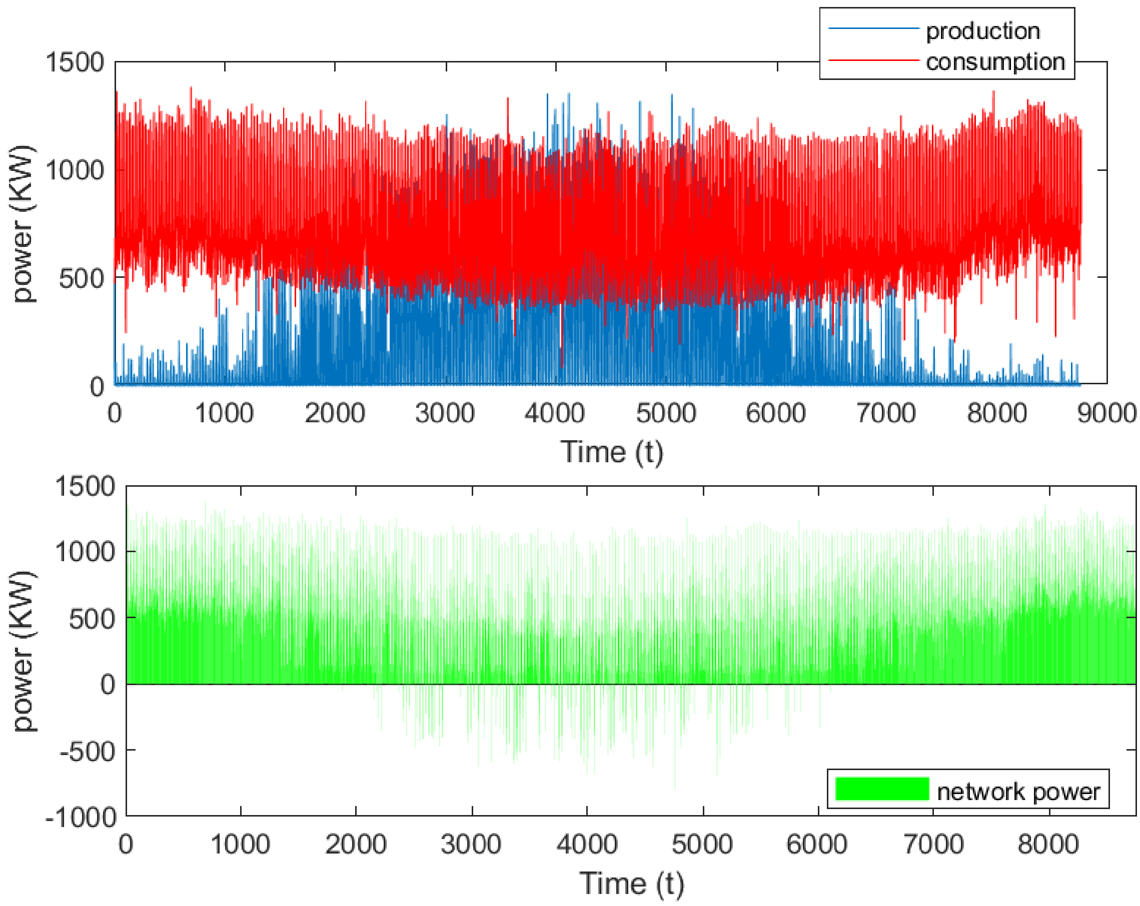


***Figure 5-12.****The energy production and consumption at the airport, as well as the energy received from and delivered to the network after adding EV load*

Table 5-6 provides information on the overall annual cost and its different components for both cases. The annual cost of electricity before PV and BESS installation is 541 582 €/a, whereas after installation, it is 439 842 €/a which result in the cost saving of 101 740 €/a.

***Table 5-6.****Total annual electricity cost and its components*

| | Without PV & BESS | With PV &BESS |
|---|---|---|
| Annual distribution cost | 271 216 €/a | 227 939 €/a |
| Annual retailer cost | 270 366 €/a | 211 904 €/a |
| Total annual cost | 541 582 €/a | 439 842 €/a |

# 6. DISCUSSION

The objective of this thesis was to investigate the amount of energy received from and delivered to the grid through modelling and simulation of a PV and battery system and the potential predicted load added to the current existing load due to electrification. Therefore, a simplified model of the solar system was used to simulate a PV generator and determine the amount of energy delivered to consumption and the grid. Unlike prebuilt simulators used for PV and BESS sizing, the global solar irradiance components including the direct beam, diffuse, and reflected components were not modeled separately. Additionally, solar panel temperature was not considered in the modeling. Instead, the global solar irradiance time series from the Finnish Meteorological Institute (FRI) was utilized. Similarly, the battery model used in this thesis does not consider the battery chemistry (NMC or LFP), internal serial resistance, or C-rate or the control system of the battery, and is simplified for the purpose of energy flow analysis.

The advantage of using a simplified model in PV and battery system analysis is that it can provide a quicker and more straightforward analysis, requiring less time and computational resources. Simplified models can be useful for initial feasibility studies and to gain a basic understanding of the energy flow and performance of the system. shading and temperature analysis are typically considered in the detailed modeling and simulation of PV systems, which are often used for design, optimization, and performance analysis purposes. Also, separate modeling of the global solar irradiance components is typically used for more detailed and accurate simulations of PV systems, such as in design and optimization studies, where precise energy output predictions are required. similarly, consideration of the battery chemistry (NMC or LFP), internal serial resistance, C-rate, and the control system of the battery is typically required in detailed modeling and simulation of battery systems for design, optimization, and performance analysis purposes. As the research question do not require a high level of detail in the battery system analysis, simplified models that neglect some of these factors can still provide useful insights into the system's performance and behavior. Simplified models can be used to provide a quick and straightforward analysis of the battery system, especially in cases where the focus is on system-level performance and energy flow.

Regarding modeling and simulation of electric aircraft, it is assumed for the sake of simplicity that battery capacity and initial state of charge (SOC) are constant, even though in practice they can vary depending on factors such as the aircraft model and distance traveled. In terms of battery capacity, the future potential capacity is selected while the worst case is opted for SOC as the aim is estimation of future demand. However, it's important to recognize that charging stations have varying levels of charging speed, which can affect the period of peak power demand of the aircraft's consumption and therefore the overall load profile. In this study, the variable charging speed is utilized to examine more accurate representation of the real-world conditions of the aircraft's consumption. Another important factor to consider when modeling and simulating electric aircraft is the aircraft arrival time schedules. Typically, a common schedule for a small-sized airport might be selected, such as arrivals from 15:00 to 21:00. This can have a significant impact on the overall load profile, as it affects the timing of charging and the amount of power required from the charging station.

It's worth noting that similar assumptions are made when modeling and simulating electric vehicles (EVs) and electric buses (E-buses). For EVs, it's generally not possible to accurately predict the charging time, as it can vary significantly depending on the time the EV arrives at the parking lot and plugs into the charging station. This can lead to a more unpredictable and variable load profile. Conversely, E-buses tend to have a more constant and predefined charging time, as they often follow a set route with scheduled stops and charging breaks. This means that the charging time and amount of energy required can be more accurately estimated and modeled, leading to a more consistent load profile. Further, in this study, the constant charging speed is used for EVs. The reason for using smart charging for electric aircrafts but not for EVs is primarily due to the higher charging capacity of electric aircrafts, which can lead to relatively higher peak demand compared to EVs.

## 6.1 Future work

The results of this thesis provide a foundation for further development of microgrids in airport areas, particularly in relation to modelling and managing increased electrified loads. There are several avenues for future research that could build on this work.

Firstly, the addition of modelling and simulation of fuel cells could enable the sizing of a fuel cell system that would allow the airport to operate in isolation mode for resiliency and increase in self-consumption purposes. This would be an important step towards ensuring that the airport can continue to function in the event of a power outage or other disruption.

Secondly, modelling and simulation of battery control could allow for the implementation of energy management strategies that would optimize the use of renewable energy sources and minimize reliance on grid power. This could involve exploring different charging and discharging strategies.

Thirdly, since carbon neutrality is a crucial aim for the airport, future research could incorporate optimization that includes two objective functions: cost minimization and $CO_2$ reduction. This would enable decision-makers to make informed choices about the trade-offs between economic and environmental considerations.

Fourthly, an analysis could be performed to determine which charging strategy is the most cost-efficient for electric buses. This could involve exploring different charging rates, times, and locations, as well as assessing the impact of different charging strategies on the overall performance of the microgrid.

Finally, a survey could be conducted to gather data on random parameters of EVs, such as the initial state of charge (SOC), time of charging, and electric model of cars that might enter the airport parking lot. This would help to identify the distribution function of initial SOC, which is a fuzzy behavior, and could inform decisions about the optimal design and operation of the microgrid.

# 7. CONCLUSION

This thesis has modeled and simulated future potential demand and used this data to optimize a PV and battery system for a grid-connected airport in Finland's specific geographic area and market conditions, using a pre-built simulator. Through the simulation and optimization process, several key findings were discovered.

Firstly, While the main objective of the installation of RES at the airport is to achieve a reduction in CO2 emissions, it will also result in significant cost savings of 101 740 €/year.

Secondly, it was found that the PV and battery sizes for different cases were very close to each other and that the differences were within the error margin. As a result, the same PV size and battery size were chosen for all cases. In other words, it was found that the airport had no incentive to increase PV and BESS sizing as a result of added demand caused by electrification in all scenarios.

Thirdly, the results show that the optimal PV size without BESS ranges between 1.3 to 1.6 MWp, while the economically optimal PV size with battery ranges between 1.5 to 1.8 MWp with the optimal battery size of 1 MWh. The optimal sizing for the PV system was found to be the lowest in the range for 2019 electricity prices which are normal low prices. If the electricity price is higher such as in 2022 electricity prices, the PV size could be higher. Based on these findings, a PV size of 1.3 MWp is selected for cases without a battery, while a PV size of 1.5 MWp and a battery size of 1 MWh are optimal for cases with a solar PV and battery combination.

Fourthly, the simulation revealed that a PV system without a battery would be more profitable than a PV system with a battery. However, considering the need for self-consumption and resiliency in the airport, a 1.5 MWp PV system with a 1 MWh battery was ultimately selected.

Fifthly, increasing the battery size beyond 1 MWh in order to increase the self-consumption did not lead to a significant increase in economic benefits, while investment costs increased, resulting in a decrease in profitability.

Based on our research, we discovered that the performance of the renewable energy system, including solar panel and battery capacity can be impacted by the cost minimization strategy employed. This is because reducing costs could result in a smaller battery capacity, which might not be able to provide sufficient power during periods of low solar irradiance or high demand, particularly in regions such as Finland where there is no correlation between solar production and demand. Further, relying on a PV system alone due to cost optimization may result in excess power being fed back into the grid during times of low demand, causing distribution congestion problems as the grid may not be able to handle the excess electricity.

Through modelling and simulation of new electrically-powered equipment at the airport, the study uncovered significant findings regarding the energy management of the airport. The suitable flight schedule and EV loads management have great potential as energy management strategies for reducing peak demand and the need for additional charging station infrastructure. By effectively managing the flight schedule, the airport can spread out the demand for electricity from electric aircraft and GHE over time, preventing peak demand spikes. Additionally, by utilizing EV load management, the airport can take advantage of the flexibility of EV charging to smooth out the load profile and fill in valleys, reducing the need for additional charging infrastructure. These strategies not only help to ensure a consistent and reliable supply of electricity but can also help to reduce the overall energy consumption and carbon footprint of the airport.

There are several important considerations to keep in mind when designing and sizing renewable energy resources (RES) for a microgrid in an airport area and Finland. The installation of wind turbines may be restricted in airport areas. Also, there is no direct correlation between maximum solar generation and periods of high demand, making it challenging to achieve an isolated operating mode. Large-scale BESS solutions can be expensive and require a significant amount of space. One alternative solution might be to use fuel cells, which can provide continuous power as long as there is a fuel supply, enhancing the resiliency and reliability of the airport.

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# APPENDIX A: MATLAB PROGRAM

```
function [En,t_charge] = AIRCRAFTBATTERY()

time_simulation=60*24;                 % time simulation (in minutes)
time=zeros(time_simulation,1);       % minutes

En=zeros(time_simulation,1);         % kWh energy stored in battery
DE=zeros(time_simulation,1);         % kWh
SOC=zeros(time_simulation,1);        % State Of Charge ESS (%)
Vreal=zeros(time_simulation,1);      % kW aircraft charging speed

%%% Energy storage system parameters

Pnom=200;                        % in kWh     Energy sotrage system capacity

SOC0=20;              % Initial SOC
SOCmin=10;            % Minimum SOC
SOCmax=100;           % Maximum SOC

%%% Charger parameters (You can change this values)

Vcha=150;                                 % KW          Nominal speed charger

A=0;      % Inferior
B=20;     % A-B Increase
C=35;     % B-C Flat
D=80;     % C-D Decrease 1
E=100;    % D-E Decrease 2

VA=Vcha/3;
VB=Vcha;
VC=VB;
VD=Vcha/2;
VE=Vcha/5;

nCAC=0.9;             % Charger efficiency

%%% Simulation

for t=1:time_simulation
    time(t)=t;
    if t==1                                               % Initialisation
        En(t)=SOC(t)*Pnom/100;
        Vreal(t)=VA;
        DE(t)=Vreal(t)/60*nCAC;
    else                                                         % from t=2
        SOC(t)=min(SOC(t-1)+DE(t-1)*100/Pnom,SOCmax);
      if SOC(t)>A && SOC(t)<=B                                          % 1
        Vreal(t)=VA+((VB-VA)/(B-A)*(SOC(t)-A));
      elseif SOC(t)>B && SOC(t)<=C                                      % 2
        Vreal(t)=VB;
      elseif SOC(t)>C && SOC(t)<=D                                      % 3
        Vreal(t)=VC+((VD-VC)/(D-C)*(SOC(t)-C));
      elseif SOC(t)>D && SOC(1)<=E                                      % 4
```

```
            Vreal(t)=VD+((VE-VD)/(E-D)*(SOC(t)-D));

          end                                                           % 4
                                                                        % 3
                                                                     % 2end
          if SOC(t)<SOCmax                                       % Charging
              En(t)=SOC(t)*Pnom/100;
              DE(t)=Vreal(t)/60*nCAC;
          end
        end
        if SOC(t)==SOCmax && SOC(t-1)<SOCmax
            t_charge=time(t);       % It's the time in minute to charge the ESS
        end
    end
```

**Program1**. Matlab Code that models electricity consumption of electric aircraft

```
function [annual_EV_consumption] = ELECTRICVEHICLE()

    time_resolution=24;
    day=364;
    c=1;
    annual_EV_consumption=zeros(day*time_resolution,1);
    for year=0:24:day*time_resolution
        car_num=20;
        % Generate the random time that EV start getting charged
        charging_times =randi([0, 23], 1, car_num)';

        % Generate the random initial SOC using weibull distribytion function
        init_soc = 0.2 + 0.1*wblrnd(0.1,0.14,car_num,1);
        for i=1:car_num
            if init_soc(i,1)>0.8
               init_soc(i,1)=0.8;
            end
        end

        % Generate the random initial SOC using uniform distribytion function
        % initial_soc = 0.2 + 0.1*rand(car_num,1);

        % Create a cell array of model car names
        car_names = {'Nissan Leaf','Tesla Model 3','Hyundai Kona Elec-
tric','Mitsubishi Outlander PHEV','Toyota Prius PHEV','Volvo XC40 Recharge T5
PHEV'};
        % Loop to create random orders of the model technology
        flag=cell(1,length(car_names));
        vehicle_model=cell(1,car_num);
        for j = 1:car_num
            % Generate a random permutation of the numbers 1 to 4
            rand_order = randperm(length(car_names));
            for i = 1:length(car_names)
                flag{i}=car_names{rand_order(i)};
            end
            vehicle_model{j,1}=flag{1,1};
        end
```

```
                                        % energy consumption        %
charging efficiency     % Battery capacity
        technolo-
gy_characteristcs=[0.2,0.16,0.147,0.135,0.039,0.208;0.9,0.9,0.9,0.85,0.85,0.8
5;40,50,64,13.8,8.8,10.7];

        charging_capacity=7; % in kw

        % define the number of EVs pluged to get charged at each hour
        time_resolution=24;
        car_num_hourly_charged=zeros(time_resolution,1);
        for i=1:24
            counter=0;
            for j=1:car_num
                if charging_times(j,1)==i-1
                    counter=counter+1;
                end
            end
            car_num_hourly_charged(i,1)=counter;
        end


max_charging_time=ceil(max(technology_characteristcs(3,:))/charging_capacity)
;
        EV_consumption=zeros(time_resolution+1,max_charging_time+1);
        count=1;
        for i=1:time_resolution                                   % loop through
each hour of day
            for j=1:car_num_hourly_charged(i,1)                   % loop based on
the number of EVs get started charging at each hour

                model=vehicle_model{count,1};                     % define the model
of vehicle
                count=count+1;
                if model=="Nissan Leaf"
                   m=1;
                elseif model=="Tesla Model 3"
                   m=2;
                elseif  model=="Hyundai Kona Electric"
                   m=3;
                elseif model=="Mitsubishi Outlander PHEV"
                    m=4;
                elseif model=="Toyota Prius PHEV"
                    m=5;
                elseif model=="Volvo XC40 Recharge T5 PHEV"
                    m=6;
                end
                if m==1 || m==2 || m==3                         % define daily dis-
tance travelled by EVs based on model
                    distance=12600/365;
                else
                    distance=18200/365;
                end
                energy_consumption=technology_characteristcs(1,m);
% define energy consumption based on the model
                charging_efficiency=technology_characteristcs(2,m);
% define charging efficiency based on the model
                battery_capacity=technology_characteristcs(3,m);
% define battery capacity based on the model
```

```
EV_demand=Ev_load(distance,energy_consumption,charging_efficiency,battery_cap
acity,charging_capacity);    % create an object of EV
                [electricity_demand,t] = EV_demand.DEMANDCALCULATION;
% define electricity demand of EV using object function
                for n=1:t
% loop through

EV_consumption(i,n)=EV_consumption(i,n)+electricity_demand;

                end
            end
        end

        for i=1:max_charging_time
            for j=1:time_resolution+1
                if j==1
                    EV_consumption(j,i)=EV_consumption(j,i);
                elseif j==time_resolution+1
                    EV_consumption(1,i)=EV_consumption(1,i)+EV_consumption(j-
1,i+1);
                else
                    EV_consumption(j,i)=EV_consumption(j,i)+EV_consumption(j-
1,i+1);
                end
            end
            for n=1:time_resolution
                EV_consumption(n,i+1)=EV_consumption(n,i);
                if i==max_charging_time
                    break
               else
                EV_consumption(n,i)=0;
                end
            end
        end

        total_EV_consumption=zeros(time_resolution,1);
        for i=1:time_resolution
            total_EV_consumption(i,1)=EV_consumption(i,max_charging_time);
            EV_consumption(i,max_charging_time)=0;
        end

    annual_EV_consumption(c:year+24,1)=total_EV_consumption;
    c=c+24;
    end

end
```

**Program2**. Matlab Code that models electricity consumption of EV