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وزارة التعليم العالي والبحث العلمي
Ministère de l’Enseignement Supérieure et de la Recherche Scientifique

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معهد الصيانة و الأمن الصناعي
Institut de Maintenance et de Sécurité Industrielle

Département de Maintenance en Instrumentation

MÉMOIRE

Pour l’obtention du diplôme de Master

Filière: Génie industriel

Spécialité: Génie industriel

Thème

Gestion intelligente des microgrids en présence des sources d’énergie renouvelable et nucléaire.

Présenté et soutenu publiquement par:

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معهد الصيانة و الأمن الصناعي
Institute of Maintenance and Industrial Safety

Department of Instrumentation Maintenance

Thesis

For the attainment of the Master's degree.

Sector: Industrial Engineering

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Theme

Energy Management for Microgrids with Small Modular Reactor, Renewable energy, and Energy storage systems using *DigSilent PowerFactory*

Presented and publicly supported by:

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Dedication

To my parents and my brother Dr. Benmoumene Taha Elamine, thank you for always believing in me and supporting me throughout my studies.

To all my family, friends, and colleagues at the Institute of Industrial Maintenance and Safety, your encouragement and presence have meant a everything to me.

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To staff of workers at IMSI and CRNB.

ملخص: هذا العمل يركز على تطوير استراتيجية تنسيق مناسبة لشبكة متعددة المصادر تتكون من مفاعل صغير قابل للتجميع (SMR) ومصادر الطاقة المتجددة (RES) وأنظمة تخزين الطاقة (ESS). يتم استخدام برنامج Digsilent PowerFactory، جنبًا إلى جنب مع البيانات الحقيقية لخصائص مصادر الطاقة والحمل للمحاكاة شبه الديناميكية في ثلاثة سيناريوهات مختلفة. يتم الأخذ في الاعتبار القيود مثل معدل الارتفاع التدريجي للمفاعل الصغير وحالة شحن نظام تخزين الطاقة (BESS) أثناء التحليل. تهدف الاستراتيجية المقترحة إلى تحسين تشغيل الشبكة المصغرة، وضمان استخدام فعال لمصادر الطاقة المتاحة مع الحفاظ على استقرار النظام وتلبية الطاقة المطلوبة.

كلمات مفتاحية: **Microgrid, SMR, RES, ESS, BESS, Quasi-dynamic, PowerFactory.**

Abstract: This work focuses on the development of a suitable management and coordination strategy for a multi-source microgrid comprising a Small Modular Reactor (SMR), Renewable Energy Sources (RES), and Energy Storage Systems (ESS). The Digsilent PowerFactory software is utilized, along with real data for the characteristics of the energy sources and the load for quasi-dynamic simulation in three different scenarios. Constraints such as SMR ramping rate and Battery Energy Storage System (BESS) state of charge are considered during the analysis. The proposed strategy aims to optimize the operation of the microgrid, ensuring efficient utilization of the available energy sources while maintaining system stability and meeting the required energy demands.

Keywords: Microgrid, SMR, RES, ESS, BESS, Quasi-dynamic, PowerFactory.

Resumé: Ce travail se concentre sur le développement d'une stratégie de gestion et de coordination appropriée pour une microgrid multi-source comprenant un Réacteur Modulaire de Petite Taille (SMR), des Sources d'Énergie Renouvelable (RES) et des Systèmes de Stockage d'Énergie (ESS). Le logiciel Digsilent PowerFactory est utilisé, ainsi que des données réelles pour définir les caractéristiques des sources d'énergie et de la charge pour une simulation quasi-dynamique dans trois scénarios différents. Des contraintes telles que le taux d'augmentation du SMR et l'état de charge du système de stockage d'énergie (BESS) sont prises en compte lors de l'analyse. La stratégie proposée vise à optimiser le fonctionnement de la microgrid, en veillant à une utilisation efficace des sources d'énergie disponibles tout en maintenant la stabilité du système et en répondant aux demandes énergétiques requises.

Môts clés: Microgrid, SMR, RES, ESS, BESS, Quasi-dynamic, PowerFactory.

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List of Abbreviations

BESS:	Battery Energy Storage System.
CSP:	Concentrated Solar Power.
DOD:	Depth of Discharge.
DPL:	DigSilent Programming Language.
DSL:	Dynamic Simulation Model.
DQSL:	Quasi-Dynamic Simulation Model.
EEC:	European Utility Requirements.
ESS:	Energy Storage System.
EUR:	European Utility Requirements.
GHG:	Greenhouse Gas.
HES:	Hybrid Energy Source.
IAEA:	International Atomic Energy Agency.
IEA:	International Energy Agency.
NPP:	Nuclear Power Plant.
PF:	PowerFactory.
PSH:	Pumped Storage Hydropower.
PV:	Photovoltaic.
RES:	Renewable Energy Source.
SMR:	Small Modular Reactor.
SOC:	State of Charge.

General introduction

In recent years, the global energy system has been going through a significant transformation, driven by the urgent need to transition to more sustainable energy sources. Fossil fuel dependency and the environmental challenges posed by climate change have pushed researchers, policymakers, and industries to explore alternative solutions that can mitigate the effects of traditional energy generation. In this context, the integration of renewable energy sources (RES) and energy storage systems (ESS) into microgrid systems has emerged as a promising avenue for achieving efficient and sustainable energy management.

This thesis presents a comprehensive analysis of multi-source microgrid modeling and coordination using Digsilent PowerFactory software. The microgrid consists of renewable energy sources (RES), a small modular reactor (SMR), and energy storage systems (ESS). The objective was to develop an energy management methodology that effectively balances generation and demand while considering the constraints of the SMR ramping limit and battery state of charge (SOC).

The structure of this thesis is as follows:

Chapter One provides a comprehensive literature review, exploring the current state of the world's energy system and highlighting the critical importance of transitioning to sustainable energy sources.

Chapter Two focuses on a technical review of the energy sources integrated within the microgrid. A mathematical modeling approach is presented to characterize the behavior of the energy sources.

Chapter Three introduces the software utilized for simulation and analysis (Digsilent PowerFactory). A detailed description of the software, its features, and highlights the significance of employing such a tool in microgrid design and analysis.

Chapter four presents the simulation methodology employed in this thesis, focusing on the quasi-dynamic simulation carried out in PowerFactory. The chapter discusses the simulation results, observes and interprets the results. The approach adopted in this chapter follows the IMRAD (Introduction, Methods, Results, and Discussion) structure to provide a coherent an understandable flow of information.

Chapter 1

Energy system structure, challenges, and transition

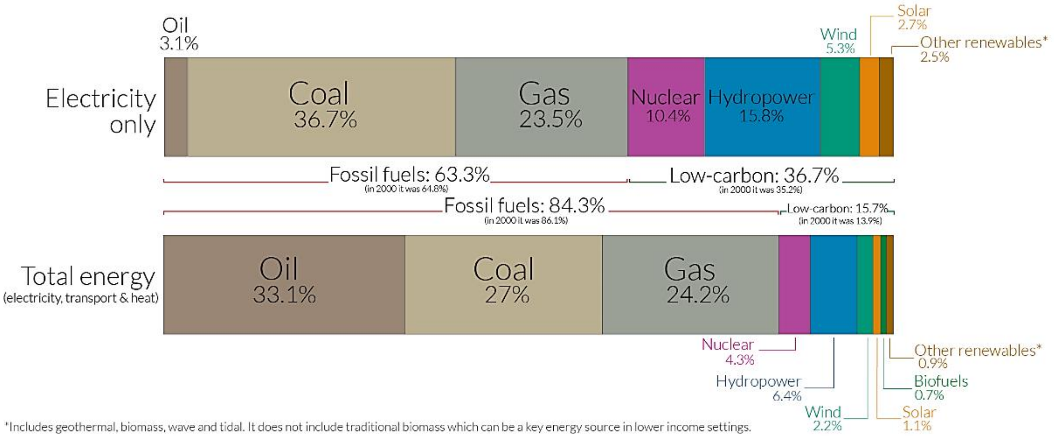
1.1. Introduction

The energy system is the backbone of modern society, powering homes, businesses, and industry. Over the course of history, the world's energy mix has evolved, with fossil fuels dominating for much of the 20th century. However, in recent years, renewable energy sources such as wind and solar have gained traction, along with nuclear power. The structure of the global energy system is complex and varies from region to region, with developed countries leading the way in energy transition. This chapter presents an overview of energy system considering, the role of fossil fuels and renewable sources, the state of nuclear energy, and the structure of energy systems locally and in some developed countries.

1.2. Energy system structure

1.2.1 Historical overview

The global energy system's structure has undergone a dramatic transformation over the last two centuries. According to Our World in Data [1], until the mid-19th century, most of the world's energy came from traditional biomass, means the burning of solid fuels such as wood, crop waste, or charcoal. With the industrial revolution came the rise of coal, which became the dominant energy source by the turn of the 20th century, until now the coal is the dominant electricity source with 36.7%, Figure 1.1 shows that more than one-third of global electricity comes from low-carbon sources. Throughout the 1900s, the world varied its energy sources by adding oil, gas, hydropower and nuclear energy [2]. However, fossil fuels still accounted for more than 80% of the global energy consumption by 2020. Only in recent decades have modern renewables, solar and wind, emerged as notable contributors to the global energy mix [1].



*Includes geothermal, biomass, wave and tidal. It does not include traditional biomass which can be a key energy source in lower income settings.

Figure 1.1: Global energy mix [2].

The historical development of the global energy system shows that energy transitions have been slow in the past, but they do not have to be in the future. Some countries have achieved rapid shifts away from fossil fuels towards low-carbon energy sources in recent years. For example, in the UK, coal power dropped from nearly two-thirds of electricity generation in 1990 to around 1% in 2020 [1]. To mitigate climate change and its impacts, it is essential that the world's energy transition must be based on more sustainable and diverse energy system.

1.2.2 Fossil Fuels

Fossil fuels are the main source of energy in the global energy system today. According to the International Energy Agency (IEA) [3], the world energy structure in 2020 was dominated by fossil fuels, which accounted for more than 80% of the global primary energy supply. Fossil fuels are also the main source of electricity generation, with a share of 63% in 2019 [3]. Oil was the largest source of energy, with a share of 31.6%, followed by coal with 26.9% and natural gas with 22.8%. Nuclear energy contributed with 4.9% and hydroelectricity with 2.5%. The remaining 11.3% came from biofuels and waste with 9.3% and other renewables with 2% [3]. Fossil fuels are widely used because they are efficient, reliable and versatile. However, they also have significant negative impacts on the environment and human health. When burned, they produce carbon dioxide (CO_2) and other pollutants that contribute to global warming, air pollution and acid rain. Fossil fuels are also non-renewable, meaning they will eventually run out or become too expensive to extract. Therefore, there is a need to reduce the dependence on fossil fuels and transit to cleaner and more sustainable sources of energy. The world energy structure is also changing over time, as new technologies emerge, costs decline, and environmental concerns increase.

1.2.3 Renewable sources

Renewable energy supply from solar, wind, hydro, geothermal and ocean increased by almost 7% in 2021, but their share in the global energy supply only rose by 0.1 percentage points to reach 5.2%. Modern bioenergy's share reached 6.7% with a similar, slight increase. This slow growth in renewables' share was due to the high absolute increase in global energy demand caused by the post-Covid-19 economic rebound, which was the highest in history [4].

1.2.3.1 Solar Energy

Solar energy is one of the fastest-growing renewable energy sources in the world. According to the International Energy Agency (IEA) [5], solar PV accounted for 3.6% of global electricity generation in 2021, and it remains the third largest renewable electricity technology behind hydropower and wind. China was responsible for about 38% of solar PV generation growth in 2021, thanks to large capacity additions in 2020 and 2021. Other countries with high solar PV shares include Australia (12%), Viet Nam (10%), Spain (10%) and the Netherlands (10%).

1.2.3.2 Wind energy

Wind energy is the second-largest renewable electricity technology after hydropower, generating 1870 TWh in 2021, almost as much as all the other non-hydro renewables combined. Wind electricity generation increased by 273 TWh in 2021 (17%), the largest of all power generation technologies. China was responsible for almost 70% of wind generation growth in 2021, followed by the United States at 14% and Brazil at 7%. The European Union, despite the notable capacity growth in 2020 and 2021, saw wind power generation fall by 3% in 2021 due to unusually long periods of low wind conditions [6].

1.2.4 Nuclear energy

Nuclear energy is one of our oldest low-carbon energy technologies. It provides about 19% of the world’s energy from about 440 power reactors [7]. It has several advantages, including low greenhouse gas (GHG) emissions, high energy density, reliability, energy security, cost-effectiveness, and job creation. It provides a clean and constant base load energy, which renewables may struggle to offer. Nuclear energy has the potential to be a valuable tool for reducing carbon emissions and combating climate change, while also providing countries with energy security and creating employment opportunities. Despite the high initial capital costs of building nuclear power plants, they are cost-effective over the long term because the cost of fuel is relatively low.

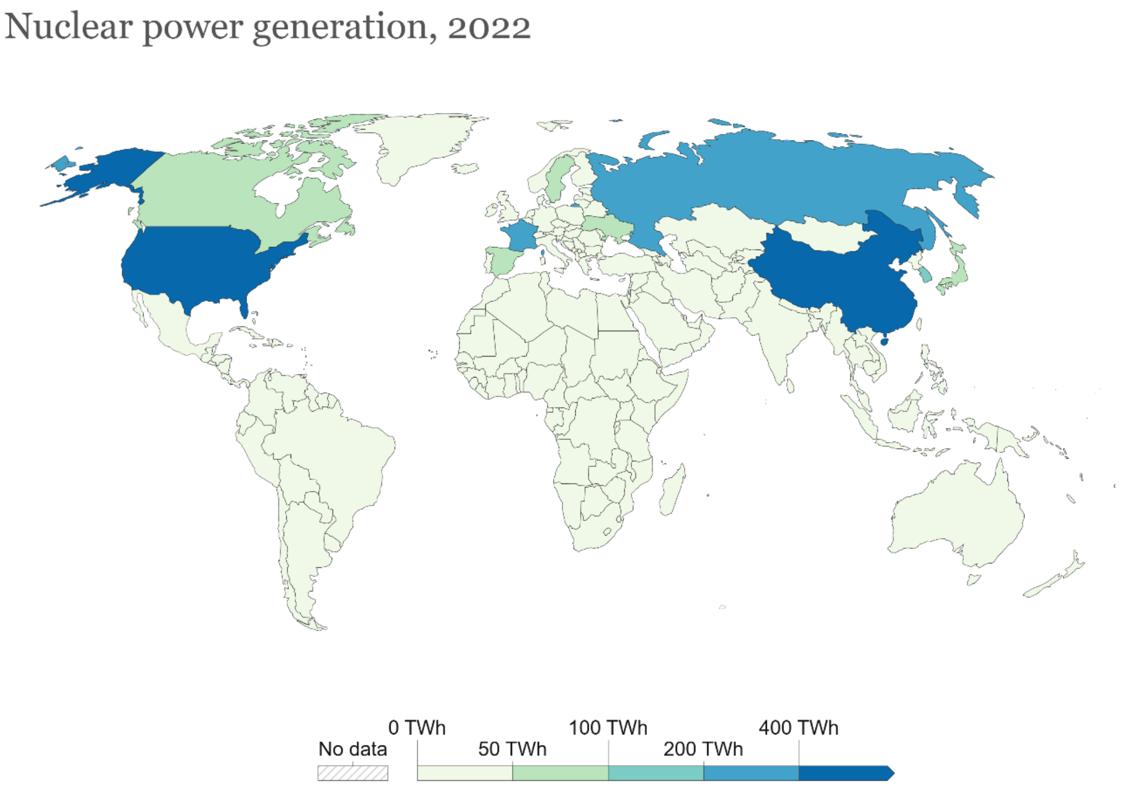


Figure 1. 2: Nuclear energy generation [33].

The implementation of a nuclear power plant requires rigorous planning, preparation, and investment in sustainable infrastructure. It typically takes 10 to 15 years before a nuclear power plant becomes operational. During this period, the state is responsible for building human capacity, ensuring safety and security, managing waste, and decommissioning the plant. Preparatory actions include capacity building, upgrading existing facilities, site exploration, regulatory strengthening, and studying existing and future technologies [34].

1.3. Examples of countries energy mix

1.3.1 Algeria energy system

Algeria's energy system is largely based on fossil fuels. In 2012, Algeria has a total installed capacity of 26 GW. The dominant energy sources are fossil fuels with 99% the rest 1% comes from renewable sources, including solar, hydro, and wind [8].

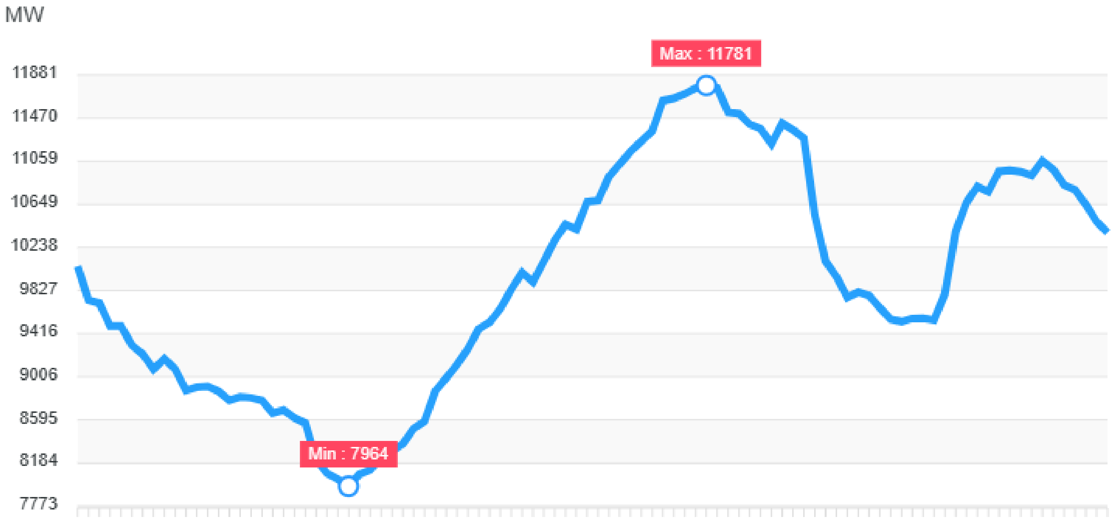


Figure 1. 3 Algeria daily load profile June 2023 (Source: Os.dz).

In Algeria, Sonelgaz, is responsible for managing the distribution of energy. It is a state-owned company that was established in 1969 and has a monopoly over the distribution of electricity and gas in the country. The company is also responsible for the generation and transmission of electricity, as well as the import and export of energy. Sonelgaz operates a network of transmission and distribution lines, as well as substations and other infrastructure, to deliver electricity and gas to customers throughout Algeria.

Despite Algeria's reliance on fossil resources for power generation, the country has gradually increased its renewable energy potential in recent years. The Algerian government has set ambitious renewable targets. In 2015, Algeria adopted an updated Renewable Energy and Energy Efficiency Development Plan until 2030. The Plan aims to increase each capacity of the solar PV at 13 GW, wind at 5 GW, solar thermal at 2 GW, biomass at 1 GW, cogeneration at 400

MW, and geothermal at 15 MW. The targeted capacity for renewable energy generation is set at 22,000 MW until 2030, with a 40% share in total power generation in Algeria [7].

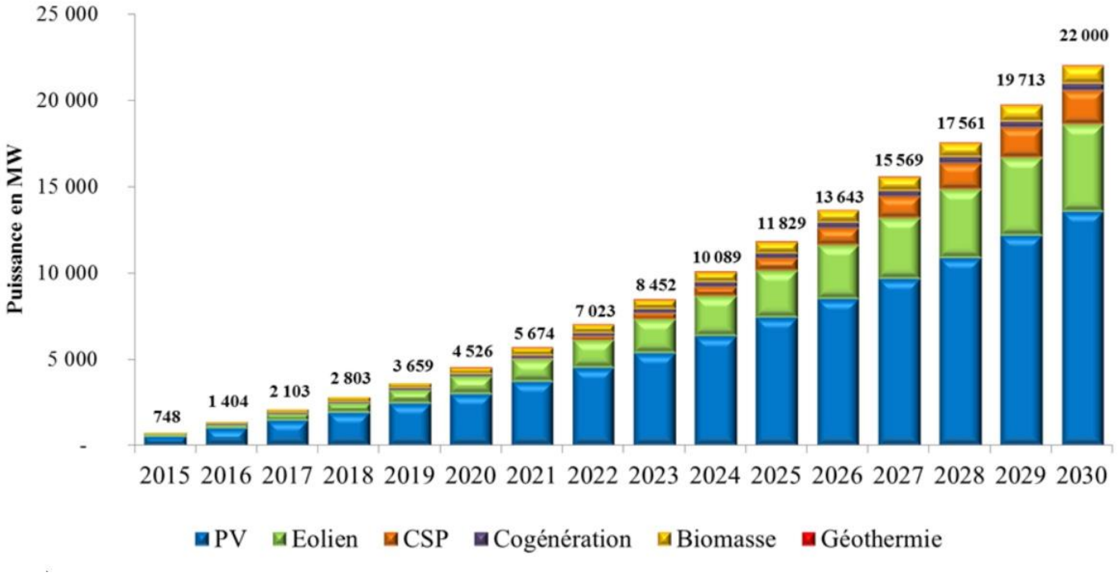


Figure 1. 4 Renewable Energy Development program 2015-2030 [61].

The updated Renewable Energy and Energy Efficiency Development Plan until 2030 is a significant step towards reducing Algeria's dependence on natural gas and increasing renewable energy generation. The renewable energy targets will result in savings of up to 3 hundreds of billion m3 of natural gas consumption [8]. It is crucial for Algeria to continue its efforts in implementing this plan to achieve its renewable energy goals and contribute to global efforts to combat climate change.

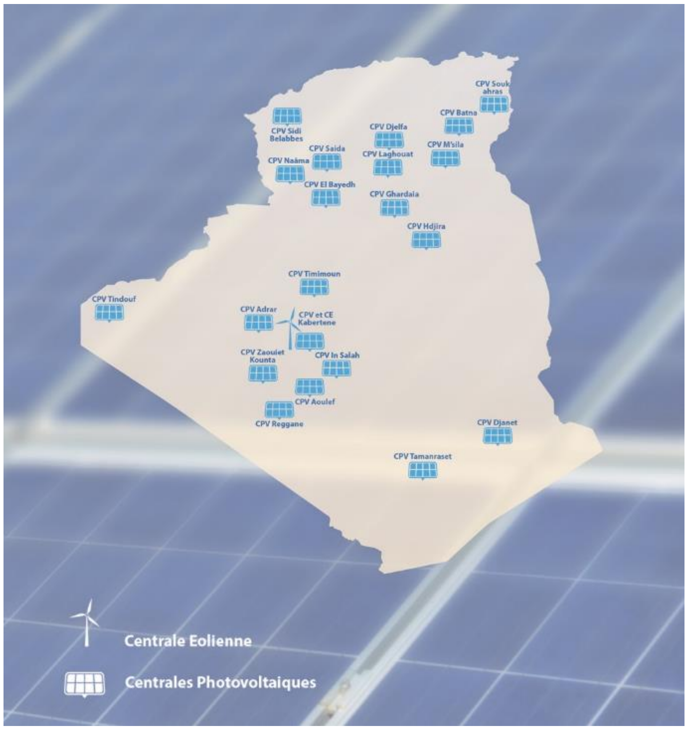


Figure 1. 5 Algeria Renewable energy stations map [Sonelgaz.dz].

Algeria does not have any nuclear generation capabilities; and it is member state of the International Atomic Energy Agency (IAEA) since December 1963 [9].

1.3.2 Belgium energy system

Belgium's energy system is structured around a combination of various sources, including nuclear power, renewables, and natural gas. The country's electricity sector is divided into four major players: Elia, the transmission system operator responsible for ensuring the security and reliability of the electricity grid; other regional distribution system operators responsible for distributing electricity to consumers; and a number of electricity producers, which include nuclear power plants, natural gas-fired power plants, and renewable energy producers

Electricity consumption in Belgium has grown from 5800 kWh per capita in 1990 to about 7094 kWh in 2022. Total installed capacity at the start of 2022 was 25.4 GW [10].

Nuclear power has historically been a significant contributor to Belgium's energy mix, with 5 active nuclear power plants providing around 40% (34.4 TWh) of the country's electricity production [10]. However, in recent years, there has been growing concern about the safety and environmental impact of nuclear power, and the Belgian government has announced plans to phase out nuclear power completely by 2025. But Belgium has plans to invest 100 million euros in nuclear power new technology research over the next four years, with a focus on Small Modular Reactors (SMRs) [11]. As SMRs offer savings in cost and construction time, and they can be deployed incrementally to match increasing energy demand [12].

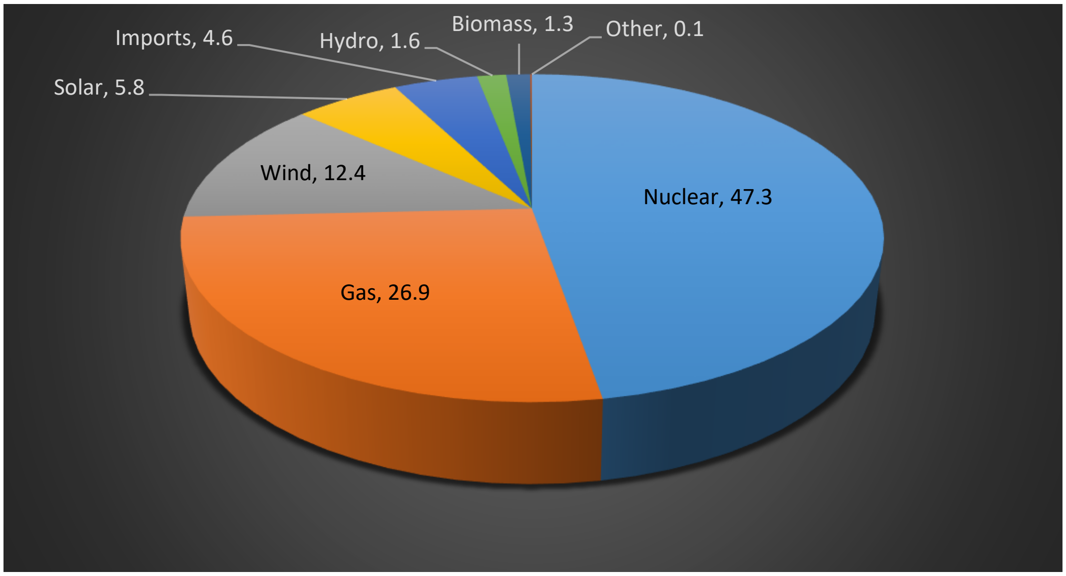


Figure 1. 6 Belgium's electricity mix 2021 (source: Elia.be).

1.3.3 Germany energy system

Germany's energy policy is defined by its "Energiewende" plan, which has been in place for nearly a decade. The Energiewende is a major plan for transforming the country's energy system to make it more efficient and supplied mainly by renewable sources [13].

Germany has been at the forefront of utilizing renewable energy and environmental technologies for many years. In 2019, nearly half 46% of the country's electricity mix was generated from sources such as wind, solar, biomass, and hydropower, indicating an increase of 5.6% from the previous year (2018). Wind energy made up the majority 24.4% of the clean power, followed by solar energy 9% and biomass 8.7%. The remaining power was generated from hydropower [14].

The country aims to fulfill all its electricity needs with supplies from renewable sources by 2035, compared to its previous target to abandon fossil fuels "well before 2040". The corresponding amendment to the country's Renewable Energy Sources Act (EEG) is ready and its share should reach 80% by 2030 [15].

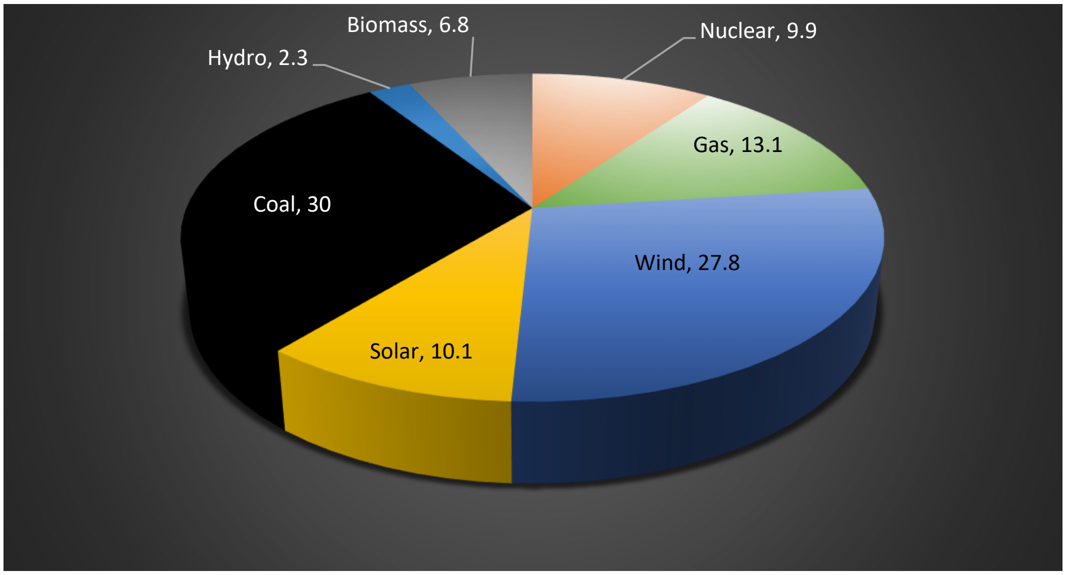


Figure 1. 7 Germany's electricity mix 2022 (source: statista.com).

1.4. Review of energy sources: Advantages and drawbacks

The energy management is a process that optimize and combine various energy sources with different features and behaviors to satisfy a short or a long-term energy demand considering various technical, economic and political constraints. Therefore, it is important to present, in the following subsections, different aspects of energy sources to be considered in their coordination procedure in the following chapters.

1.4.1 Economics

When comparing energy sources from an economic perspective, several factors must be considered, including the cost of building and maintaining infrastructure, fuel costs, and environmental impacts. Fossil fuels are traditionally cheap in terms of their market prices, but they have many hidden costs that are not reflected in their prices, such as the environmental and health impacts of their emissions [16]. Nuclear Power Plants (NPPs) requires significant upfront investment in infrastructure and safety measures, along with ongoing maintenance and fuel costs. However, the electricity cost of NPP is relatively low ranging from 0.027 to 0.098 per kWh [17]. Renewable sources have become increasingly competitive with fossil fuels, but costs can vary widely depending on location, weather patterns, and backup costs. Ultimately, the economic comparison of energy sources depends on specific circumstances and requires considering direct and indirect costs, as well as environmental and social impacts.

1.4.2 Green House Gas (GHG) emission

Greenhouse gas (GHG) emissions are a key factor to consider when comparing energy sources, as they contribute to climate change. Fossil fuels are the largest source of GHG emissions globally, nuclear energy is considered a low-carbon energy source since it produces no direct GHG emissions during electricity generation, but still has indirect emissions related with its construction, fuel production, and waste management. Renewable energy sources have the lowest GHG emissions of any energy source, with wind and solar having no direct GHG emissions during operation, and hydroelectric and geothermal sources having very low emissions. Although some indirect emissions can occur during the production and transport of materials used in renewable energy infrastructure, the comparison of GHG emissions shows that fossil fuels and have the highest emissions, it is essential that we accelerate the transition to a more sustainable and low-carbon energy sources to mitigate climate change [18].

1.4.3 Energy Efficiency

Energy efficiency is an important concept in the field of energy management and conservation, as it allows us to reduce energy consumption while still meeting our needs for lighting, heating, cooling, transportation, and other activities that require energy.

Energy efficiency refers to the amount of energy needed to carry out a particular task or service compared to the amount of energy used in the process. By enhancing energy efficiency, we can fulfill the needs of society while utilizing fewer resources. Thus, improving energy efficiency across all sectors of the economy is a crucial goal. Energy conservation is the most cost-effective and efficient means to achieve this objective, rather than increasing energy production. Additionally, energy conservation is the most effective way to safeguard the environment and mitigate the impacts of global warming [19].

As per the International Renewable Energy Agency (IRENA) report [20], renewable sources of energy are now considerably cheaper than fossil fuels. In 2020, almost 62% of newly installed renewable energy sources like wind, solar, and others were cheaper than the most inexpensive new fossil fuel sources. This trend is driven by the significant reduction in the cost of renewable technologies, such as wind and solar. Over the past ten years, the cost of large-scale solar projects has plummeted by 85%, paving the way for the rise of renewable energy as the most cost-effective source of energy worldwide.

Nuclear energy has by far the highest capacity factor of any other energy source. This basically means nuclear power plants are producing maximum power more than 92% of the time during the year. That’s about nearly 2 times more as natural gas and coal units, and almost 3 times or more reliable than wind and solar plants [21].

1.5. Advanced control of Microgrids (Smart-Grids)

A smart grid refers to an advanced electrical power distribution system that incorporates modern communication, control, and monitoring technologies to enhance the efficiency, reliability, and sustainability of electricity delivery. It is building on digital infrastructure and real-time data to optimize energy generation, transmission, and consumption, while enabling bidirectional communication between the utility provider and consumers [22].

Intelligent networks are capable of dynamically manage the flow of electricity. It integrates various components, including power generation sources (both renewable and conventional), energy storage systems, transmission lines, distribution networks, and smart meters installed at consumer premises [23].

1.5.1 Integration and management of multiple energy Sources

A multi-source smart grid goes beyond conventional power generation by seamlessly integrating various energy sources. It brings together renewables such as solar, wind, hydro, and traditional power plants into a cohesive infrastructure. This integration ensures a balanced and reliable power supply by capitalizing on the strengths of each energy source and compensating for their intermittent nature.

Multi-source smart grids also incorporate energy storage technologies, such as batteries and pumped hydro storage. These systems address the intermittent nature of renewable energy sources by storing excess energy during periods of low demand and releasing it when demand exceeds supply. Effective energy management systems optimize storage and distribution based on real-time demand patterns, ensuring efficient utilization of resources.

1.6. Conclusion

Based on the energy systems description and analysis presented above, it is clear that the world's energy situation is in a critical state and that action must be taken to address the challenges associated with climate change. The use of nuclear and renewable energy sources presents a promising solution that can help achieving a cleaner and a more sustainable sources of energy.

In light of the current situation, it is strongly recommended to explore and invest in these sources of energy to minimize our dependence on fossil fuels and reduce greenhouse gas emissions. While there are challenges associated with the adoption of these sources, it is important that we recognize the long-term benefits that can be achieved by embracing them.

In conclusion, it is clear that nuclear and renewable energy sources offer a viable solution to the challenges associated with, availability and sustainability, as well as improving the efficiency, scalability, and cost-effectiveness of the Grid. We must continue to drive towards the adoption of these sources and minimize our reliance on fossil fuels if we are to achieve a cleaner and more sustainable future for generations to come.

Chapter 2

Description and mathematical modeling of multi-source energy systems.

2.1 Introduction

The electric utility industry has witnessed notable advancements that are promoting the integration of power generation and energy storage at the distribution level.

Microgrids generally aim to coordinate various energy systems of different nature. Furthermore, they are characterized by their small capacity and dispersed energy sources. These latter, have different operation principles, features and behaviors which lead their coordination and control complex tasks. For doing so, the mastery of the operation principles of these sources aiming to develop their appropriate models is a required step.

This chapter, deals with microgrid concept considering the following points: advantages, disadvantages, operation and control principles, and mathematical modeling.

2.2 Microgrid definitions and principles

A microgrid is a discrete energy system that operates alongside or independently from the main power grid. It consists of distributed energy sources and loads, providing local, reliable, and affordable energy security for communities. Microgrids are smaller versions of traditional power grids but offer distinct advantages. They bring power generation closer to the point of use, increasing efficiency and reducing transmission losses. They also integrate renewable energy sources, such as solar and wind power, minimizing carbon emissions. Microgrids enable autonomous operations, allowing them to function independently during grid failures and even feed power back to the main grid [24].

The advantages of microgrids include improved reliability and resilience (the ability to bounce back from a problem quickly), as they can continue supplying electricity during grid outages. They promote energy efficiency by reducing transmission losses and optimizing the utilization of renewable energy sources [25]. Microgrids also facilitate the integration of distributed energy resources, enabling communities to reduce their carbon footprint and embrace sustainable practices [24].

However, microgrids face certain challenges. The initial investment required to establish a microgrid can be high [22], encompassing generation sources, storage systems, control infrastructure, and distribution networks. Managing a microgrid with multiple energy sources and balancing supply and demand can be complex [25]. Proper coordination system is crucial to overcome these challenges and maximize the potential of microgrids.

2.2.1 Hybrid Energy Systems

Hybrid energy systems (HES) are combinations of different types of energy generation, storage, and conversion technologies that are integrated to achieve improved performance, efficiency, or environmental benefits compared to single-source systems. HESs may use Renewable Energy Sources (RES) such as solar, wind, hydro, biomass, or geothermal, as well as conventional sources such as diesel, natural gas, or nuclear. Hybrid energy systems may operate in grid-connected mode, isolated from grid, or for special purposes [26].

2.2.2 Energy Storage Systems

Energy storage systems (ESS) are an important part of power systems with integrated renewable energy resources. Due to the intermittency and variability of (RES), energy storage technologies have been utilized to compensate power generated for continuous and reliable operation, especially in Off-grid power systems. Demand for new energy storage systems is increasing for applications such as remote area power supply systems, emergency backup, and mobile applications. ESS can help maintain the balance between demand and supply in an energy system, assisting in system reliability by providing backup power during electricity shortages or consuming power during electricity surpluses [27].

ESS find applications in various cases. In [28], an energy storage device is employed to assist a double-fed induction generator in providing the required reactive power to the grid during grid faults, providing voltage support. Another energy storage application in microgrids include fluctuation suppression as well as in long term applications like load levelling [29], peak shaving [30].

2.3 Energy sources description and modeling

2.3.1 Concentrated solar energy

Concentrated solar power (CSP) plants collect solar radiation using reflective or emissive optical elements that concentrate the radiation to a central region where it is directly converted into thermal or electrical energy. Figure 2.1 shows different types of capturing solar radiation.

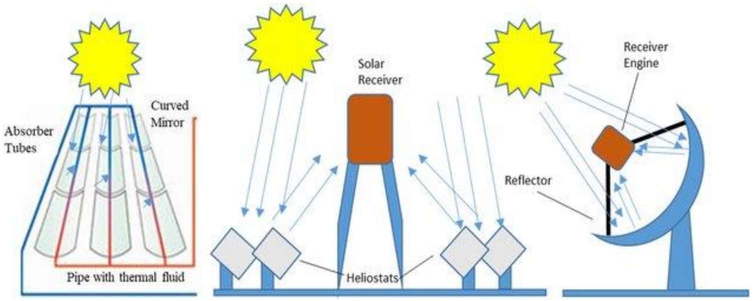


Figure 2.1 Three different CSP systems.

2.3.2 Photovoltaic panels

Unlike (CSP) Photovoltaic (PV) panels directly convert light into electricity through the photovoltaic effect. Solar panels made of semiconductor materials, such as silicon, absorb photons from sunlight, releasing electrons and generating an electric current.

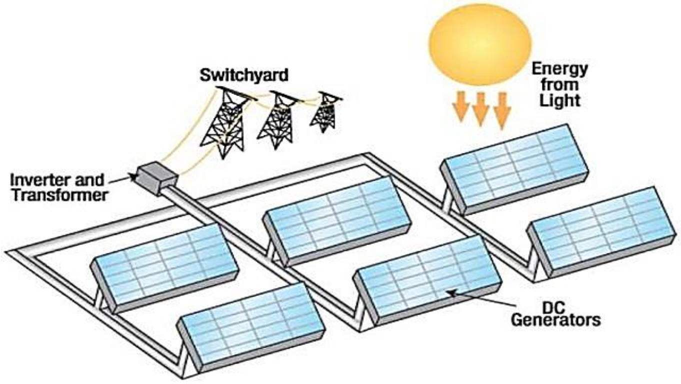


Figure 2.2 PV power plant illustration.

2.3.3 Photovoltaic system

In the modeled system we used 24000 parallel Amerisolar AS-6P30 250 solar panel which will produce a nominal power of 6 MW [31]. The Amerisolar AS-6P30 250 is a solar panel model with a power output of P_{mp}=250 watts that is designed for use in residential, commercial, and industrial systems. It features polycrystalline silicon solar cells that are highly efficient and can convert a large amount of sunlight into electrical energy, and an anodized Aluminum frame that is sturdy and corrosion-resistant, making it suitable for use in various weather conditions. The panel specifications are shown in Table 2.1.

Table 2.1 AS-6P30 solar panel specifications.

Nominal Power (P_{max})	Open-Circuit Voltage (V_{OC})	Short Circuit current (I_{sc})	Nominal Power Voltage (V_{mp})	Nominal Power Current (I_{mp})	Operating Temperature (C°)
250 W	38 V	8.75 I	30.3 V	8.26 I	-40° to +85°

The panel has a high maximum system voltage of DC 1000V, a power tolerance of +/- 3%, and can produce a high amount of power even in low-light conditions. Overall, the Amerisolar is a reliable and high-quality solar panel that can help reduce electricity bills and carbon footprint.

The power generation of the PV panels depends on pre-defined characteristics based on data from Laghouat's Solar Plant in Algeria Figure 2.3. The actual power output of the PV panels will vary based on sunlight availability and other factors.

Figure 2.3: El Kheneg Solar Plant (Laghouat).

2.3.4 Wind energy source

In the modeled system we used 12 parallel Nordex N50/800 with a capacity of 830 kW each. The power generation of the wind turbines depends on the wind speed, following the defined characteristics based on data from Adrar's Wind Plant in Algeria. The actual power output of the wind turbines will vary based on its power curve.

The power curve shows that the Nordex N50/800 starts producing power at a wind speed of around 4 m/s and reaches its maximum rated power output of 830 kW at a wind speed of 15 m/s. The turbine is designed to operate optimally in moderate wind speed conditions, with its peak power output achieved at wind speeds between 13 and 14 m/s [32] [50].

Figure 2.4 Ararat Wind farm (Adrar, Algeria).

2.3.5 Nuclear Power

Nuclear power plants (NPP) are very much like a conventional steam power plant. The only difference is that the heat, used to heat the steam that runs the steam turbines and the electric generator, is not obtained by burning coal, gas, or oil, but is derived from controlled nuclear fission see Figure 2.5. Nuclear fission is a process where atoms of a heavy element, such as uranium, are split into smaller atoms, releasing energy and particles [48].

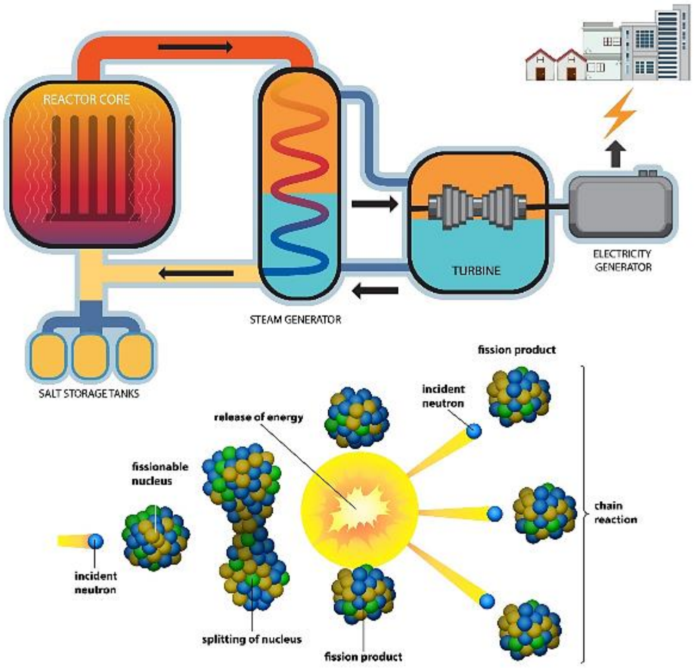


Figure 2.5 NPP working principle.

2.3.5.1 Small Modular Reactors

Small Modular Reactors (SMRs) are a type of nuclear reactor with a power capacity of up to 300 MW [35]. They differ from traditional nuclear power reactors in that they are smaller, simpler, and can be assembled in a factory before being transported for installation [35]. SMRs offer several advantages, including flexibility, affordability, scalability, and suitability for remote areas or industrial applications [36]. They are equipped with enhanced safety features that rely more on passive systems [37] and inherent reactor characteristics [35]. As a result, SMRs are considered an innovative and promising option for the future of nuclear energy [38].

2.3.5.2 Ramping Control Capability

Ramping control capability for nuclear power plants is the ability of nuclear reactors to change their power output over time in response to changes in net load or system operator dispatch. Nuclear power plants are traditionally operated in a baseload mode, producing their maximum rated capacity whenever online, but they are technically capable of more flexible operation, including providing frequency regulation and operating reserves. Flexible operation of nuclear power plants can help integrate higher shares of variable renewable energy sources, such as wind and solar power, by reducing curtailment and lowering system operating costs [39].

Most of the modern Generation (III/III+ reactors) designs implement a relatively higher manoeuvrability capabilities, with the possibility of planned and unplanned load-following in a wide power range and with ramps of 5% Pr/minute. Some designs are capable of extremely fast power modulations in primary or secondary frequency regulation modes with ramps of several percentage points of the rated power per second, but within a narrow band around the rated power level [40].

According to the current version of the European Utility Requirements (EUR), the NPP must be capable of a minimum daily load cycling operation between 50% and 100% Pr, with a rate of change of electric output of 3-5% Pr/minute [40].

2.3.6 Energy storage systems

The main purpose of energy storage systems is to balance the supply and demand of electricity, especially from intermittent sources such as renewable energy. It can also provide various system services such as frequency regulation and voltage control [41] [42].

Some examples of energy storage technologies are pumped hydroelectric storage, compressed air energy storage and battery energy storage.

2.3.6.1 Battery Energy Storage

Battery energy storage system (BESS) is an advanced technological solution that enables electricity to be stored until it is needed. Rechargeable batteries, particularly Lithium-ion (Li-ion) battery storage systems are the most popular type for energy storage (86.5% of deployed energy ESS in 2015) due to their high energy density and efficiency [43]. They have also some several advantages, including economic savings, and sustainability, owing to reduced consumption. BESS typically have a lifetime of five to 15 years [44].

BESS are commonly used for renewable energy integration, backup power, grid stability, and electric vehicle charging. BESS provide benefits such as time-shifting energy, grid flexibility, and renewable integration.

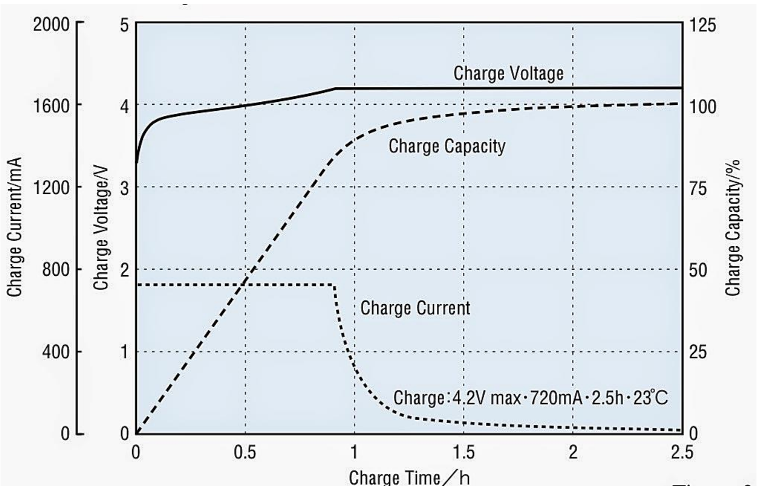


Figure 2.6 Battery Charging characteristics.

2.3.6.2 Pumped Storage Hydropower

Pumped storage hydropower (PSH) is a method of energy storage that utilizes water to balance electricity grids and meet peak energy demands. It involves pumping water from a lower reservoir to an upper reservoir during low-demand periods, storing the energy. When demand increases, the stored water is released downhill through turbines, generating electricity and supplying it to the grid Figure 2.7. This technology offers efficient and flexible energy storage, allowing excess electricity to be utilized during off-peak hours and providing quick-response power during peak demand. It helps integrate renewable energy sources by storing surplus energy from sources like wind and solar power, ensuring a stable and reliable electricity supply.

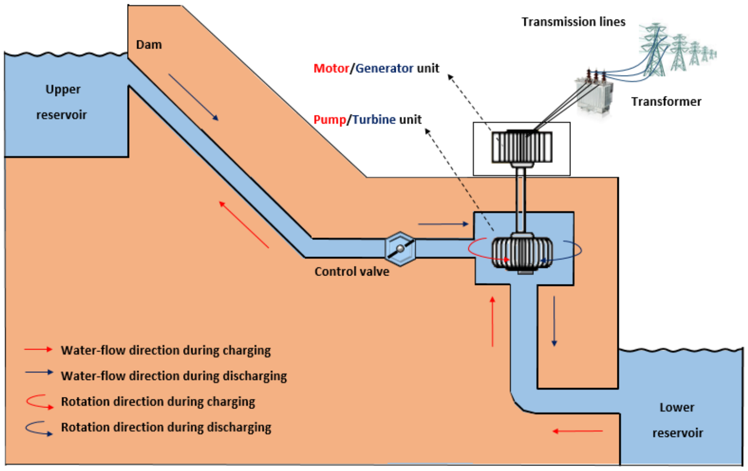


Figure 2.7 PSH working principle.

Until recently PSH units have always used fresh water as the storage medium. However, in 1999 a PSH facility using seawater as the storage medium was constructed [45], see Figure 2.8; corrosion was prevented by using cathodic protection. A typical PSH facility has 300m of hydraulic head (The vertical distance between the upper and the lower reservoir).

Figure 2.8 Yanbaru Okinawa PSH plant (Japan).

2.3.7 Load profile

The load characteristics utilized in this analysis were obtained from Sonelgaz electricity distribution company (June 2022). The load variation curve revealed that there is two peak one at midday and the other in the evening, while the off-peak was marked around 5am to 6am.

The base load represents the minimum level of electricity demand that remains constant over time. It signifies the essential continuous load that persists regardless of the time of day. In our model base load power generation is provided by plants that operate consistently and efficiently, in our model it is provided by the SMR.

On the other hand, the peak load denotes the highest level of electricity demand during a specific period, necessitating additional power generation capacity to meet the surge in consumption, managing the peak load is crucial for maintaining grid stability.

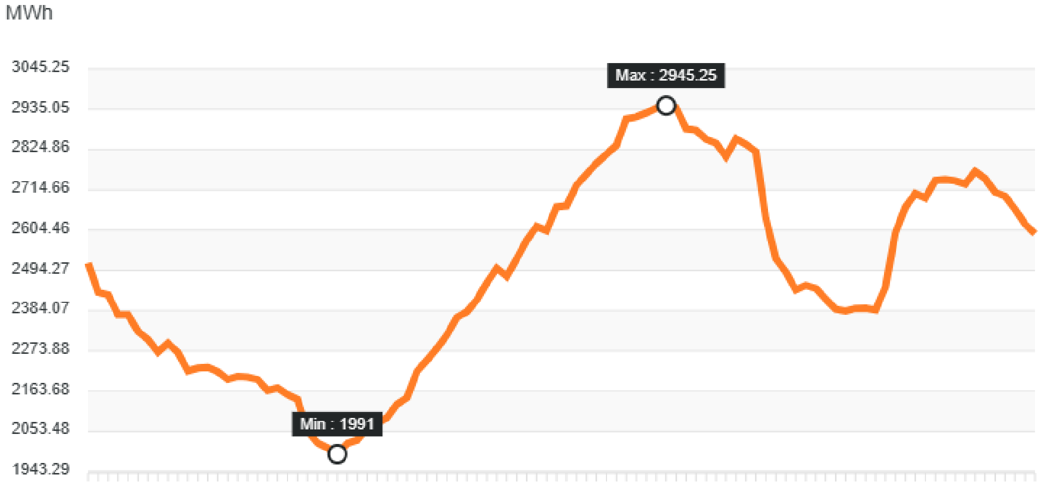


Figure 2.9 Electricity consumption curve (Algeria, summer day).

2.4 Mathematical models of energy sources

2.4.1 PV mathematical model

The power equation for PV energy is given by [46]:

$$P_{PV} = A_{PV} * G * \eta \tag{1}$$

Where:

- **P_{PV}** is the power output from the solar panel (Watts). It is directly proportional to the surface area of the solar panel, a larger surface areas can capture more sunlight and generate more power.
- **A_{PV}** is the surface area of the solar panel (m^2).
- **G** is the solar irradiance (W/m^2), which represents the intensity of sunlight incident on the solar panel. It depends on factors such as the angle of incidence, atmospheric conditions, and shading. Solar irradiance can vary throughout the day, seasonally, and based on geographic location.
- **η** is the efficiency (%). It represents the overall efficiency of the PV system, including the efficiency of the solar cells, electrical losses, temperature effects, and other system losses. It accounts for factors such as optical losses, reflection losses, electrical losses in the wiring and connections, and temperature losses.

PV power generation variation during one day Figure 2.10 depends on the solar irradiance G. the peak genetion is reached during midday, while at night PV generation is nil.

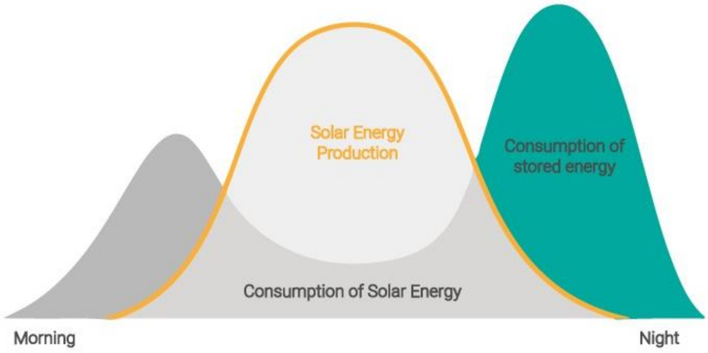


Figure 2.10 PV panel power generation curve.

2.4.2 Wind turbine mathematical model

The power equation for wind energy is given in (2) [47]. From (2), the cubic relationship between P_w and V^3 implies that small changes in wind speed can have a significant impact on the power output.

-

$$P_w = \frac{1}{2} * \rho_{air} * A_T * Cp * {V_W}^3 \tag{2}$$

Where:

- **P_w** is the power output from the wind turbine (watts).
- **ρ_{air}** is the air density (m^3).
- **A_T** is the swept area of the wind turbine blades (m^2)
- **Cp** is the power coefficient of efficiency of the wind turbine (%).
- **V_w** is the wind speed (m/s).

Cp, is a factor related to design and characteristics of the wind turbine. It represents the proportion of the wind's kinetic energy that can be converted into electrical power. Higher value of Cp indicates a higher efficiency of the wind turbine. ρ is related to specifications such as altitude, temperature, and humidity.

$$C_P = \frac{(1+\lambda)(1-\lambda^2)}{2} \tag{3}$$

And

$$\lambda = \frac{v_d}{V_w} \tag{4}$$

Or

$$\lambda = \frac{blade\ tip\ speed}{wind\ speed} \tag{5}$$

A, is the total area covered by the rotating blades of the wind turbine. It is calculated by multiplying the square of the radius of the rotor by π (pi).

V_d The blade tip speed refers to the linear speed at which the outermost point of a wind turbine blade moves through the air during rotation. It can be obtained using the rotational speed of the rotor (rpm) and the length of the wind turbine blade.

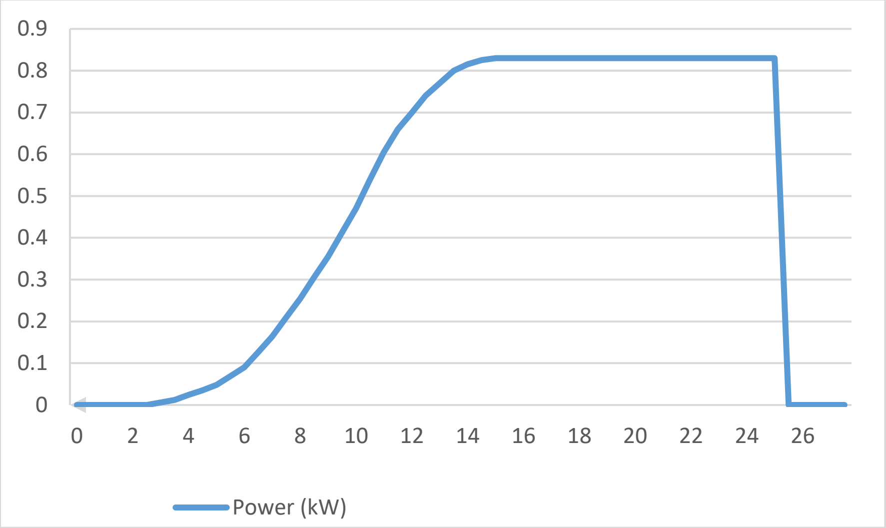


Figure 2.11 Nordex N50/800 power curve.

2.4.3 SMR mathematical model

The power output of a small modular reactor (SMR) can be represented by a mathematical equation that takes into account various factors, including reactor design, fuel characteristics, and operational parameters. The equation for SMR power output can be expressed as [48]:

$$P_{smr} = RR \cdot V \cdot E_f \tag{6}$$

Where:

- P_{smr} is the power output of the SMR (Mw)
- RR is the fission reaction rate per unit volume (reactions/m^3.s)
- V is the total volume of the core (m^3)
- E_f the energy released per fission in (joules)

The fission reaction rate can be calculated from the neutron flux and the macroscopic cross-section of the fissionable material as:

$$RR = \Phi \cdot \Sigma_f \tag{7}$$

Where:

- Φ is the neutron flux (neutrons/m^2.s)
- Σ_f is the macroscopic fission cross-section (m^2)

The neutron flux depends on the geometry, material properties and operating conditions of the reactor.

The energy released per fission depends on the type of fuel and the number of fission products N. N, depends on the reactor power level, which is determined by the reactivity and the control of the reactor. The reactivity is controlled by adjusting the position of control rods and other mechanisms to maintain stability and desired power output. To relate the reactor thermal power to the power output, one needs to account for the efficiency of conversion from thermal energy to electrical energy, which depends on the type of heat engine used.

2.4.4 Pumped Storage hydropower mathematical model

To calculate the power output of a PSH facility, the following relationship can be used [49]:

$$P_{psh} = \rho_w * g * Q * H * \eta_{psh} \tag{9}$$

Where:

- $\mathbf{P_{psh}}$ is the power output (MW).
- $\boldsymbol{\rho_w}$ is the density of water (kg/m^3).
- **g** is Acceleration due gravity (m/s^2).
- **Q** is flow rate of water (m^3/s).
- **H** is the height of the head (m).
- $\boldsymbol{\eta_{psh}}$ is the efficiency (%).

The explanation of the parameters of the model presented in (9) is presented as follows:

- ρ_w, the density is a measure of how much mass is contained within a given volume. In this case, it refers to the density of water, which is around 1000 kg/m^3.
- g, the acceleration due to gravity is used to account for the potential energy of the water. The standard value for acceleration due to gravity is approximately 9.8 m/s^2.
- Q, the flow rate of water refers to the volume of water passing through the PSH turbine per unit of time.
- H, the height difference or head between the upper and lower reservoirs in the PSH facility is the measure of the vertical distance through which the water falls.
- η_{psh}, the efficiency of the PSH facility refers to the efficiency of converting the potential energy of the water into electrical energy.

2.5 Conclusion

In conclusion, this chapter has provided a comprehensive overview of microgrids, their advantages, and disadvantages, as well as an examination of various energy sources, energy storage systems, and the load profile considerations within microgrid systems.

We started by defining microgrids as a decentralized power system that can operate independently or associated with the main power grid, providing numerous benefits such as increased reliability, increased energy efficiency and better integration of renewable energy sources. However, we also discussed some of the challenges associated with microgrids, including high initial costs, regulatory barriers, and the need for advanced control and management systems.

Furthermore, we explored several energy sources that can be utilized within microgrid systems. Solar energy, both through photovoltaic (PV) and concentrated solar power (CSP) technologies, offers a sustainable and abundant source of power, while wind power provides a reliable and scalable option for electricity generation. Additionally, nuclear energy was discussed as a viable baseload option due to its high-power density and low carbon emissions.

In terms of energy storage, we examined two prominent technologies: battery energy storage systems (BESS) and pumped storage hydropower (PSH). BESS can store excess energy during periods of low demand and release it during peak demand, thus improving grid stability and enhancing renewable energy integration. On the other hand, PSH utilizes the potential energy of water by pumping it to an elevated reservoir during times of excess generation and releasing it to generate electricity during peak demand.

Moreover, the discussion also encompassed the load profile considerations within microgrid systems. Understanding the load profile, including the energy consumption patterns, peak demand periods, and load variability, is crucial for effective microgrid design and operation. By analyzing the load profile, one can optimize the sizing and operation of energy sources and storage systems to meet the specific energy demands of the microgrid while ensuring stability and reliability.

In addition, this chapter delved into the mathematical models employed for the different system components. By developing the mathematical models, it becomes possible to simulate the behavior and performance of these technologies within microgrids, enabling optimization, control, and better decision-making.

Chapter 3

Overview on DigSilent PowerFactory software

3.1. Introduction

The implementation and analysis of complex energy systems, such as multisource microgrids, require advanced simulation tools to assess their performance and behaviour.

This chapter provides an overview of DigSilent PowerFactory, emphasizing its primary features and capabilities, as well as its significance in analysing and implementing complex energy systems like multisource microgrids. The utilization of advanced simulation tools becomes crucial for assessing the performance and behaviour of such intricate energy systems.

3.2. DigSilent PowerFactory 2023 software

Figure 3.1 showcases the initial window of the DigSilent PowerFactory software, used in this thesis. It represents the 2023 version with service pack SP3. For the purpose of this thesis, a complimentary thesis license of the software was granted by DIGSILENT. The following subsections provide a comprehensive overview of the software and its primary simulation functions.

Figure 3.1: Starting window of DigSilent PowerFactory software.

3.2.1 Software overview

The software PowerFactory from DigSilent is a computer-aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.

“DigSilent” is an acronym for “**Dig**ital **Si**mu**L**ation of **E**lectrical **Net**works”. DigSilent Version 7 was the world’s first power system analysis software with an integrated graphical single-line interface. That interactive single-line diagram included drawing functions, editing capabilities, and all relevant static and dynamic calculation features.

PowerFactory was designed and developed by qualified engineers and programmers with many years of experience in both electrical power system analysis and computer programming. The accuracy and validity of results obtained with PowerFactory have been confirmed in a large number of implementations by organizations involved in the planning and operation of power systems throughout the world [51].

3.2.2 Importance of using simulation software in research

Simulation software is essential in power systems research due to its ability to model, analyze, and optimize complex systems. It provides a visual representation of the power system, allowing researchers to better understand its components and their interactions. By simulating different scenarios, evaluating the system's performance under various conditions, and making informed decisions regarding system planning and design. Simulation software is an invaluable tool for assessing stability, voltage profiles, power flow, and other important parameters, ensuring the efficient and reliable operation of power systems.

3.2.3 Explanation of why PowerFactory was chosen for study

PowerFactory is a new and advanced software for power system modeling and analysis that is becoming more popular in the field. In this thesis, PowerFactory is chosen as the main simulation tool because it is relevant and useful for the theses’ objectives. Also, PowerFactory is not common in Algeria, which gives the study a unique edge as it uses software that few others have used in their theses. This makes the study more valuable and original. Furthermore, learning and using a complex and novel software like PowerFactory shows the researcher's commitment and skill in handling difficult tools, which increases the importance and reliability of the study.

3.2.4 Software main features

DigSilent PowerFactory offers a range of key features and benefits that make it an indispensable tool for power system analysis and simulation. Firstly, it provides comprehensive modeling capabilities, allowing users to create and configure complex network components, incorporate renewable energy sources, and define equipment parameters with ease. Secondly, the software offers a wide array of analysis functions, including load flow analysis, short circuit analysis, quasi-dynamic simulation, dynamic simulation, stability analysis, and harmonic analysis [51]. These capabilities enable users to evaluate system performance, assess fault conditions, analyze transient phenomena, and investigate harmonic distortion, empowering them to make informed decisions and optimize power system operation.

Additionally, DigSilent PowerFactory offers advanced analysis techniques such as optimal power flow and sensitivity analysis, allowing users to optimize economic dispatch and assess system vulnerabilities. The software's intuitive user interface and extensive library of pre-defined components further enhance usability and productivity. With DigSilent PowerFactory, engineers and researchers can gain valuable insights into power system behavior, improve system reliability, and efficiently plan for future challenges, ensuring the effective and sustainable operation of electrical networks.

3.2.5 Digsilent Programming Language

Digsilent Programming Language (DPL) is a C-like syntax language that supports unlimited access to PowerFactory objects, parameters, and their functionality. It can be used to automate tasks, extend the function scope of PowerFactory, and access external data and applications. DPL scripts can be encrypted for security purposes [52].

DPL and Python are both scripting languages that can be used to automate and extend PowerFactory tasks, but they have different advantages and disadvantages. DPL is more integrated with PowerFactory, as it can directly access its objects, parameters, and functions. It also has the ability to encrypt its scripts and connect with external data and applications through C-Interface. Python, on the other hand, is more widely used and supported, as it has a large community and a rich set of modules and libraries. It also has more features and syntax options than DPL, making it more flexible and expressive. Both languages can be used in combination, as PowerFactory allows calling DPL scripts from Python and vice versa.

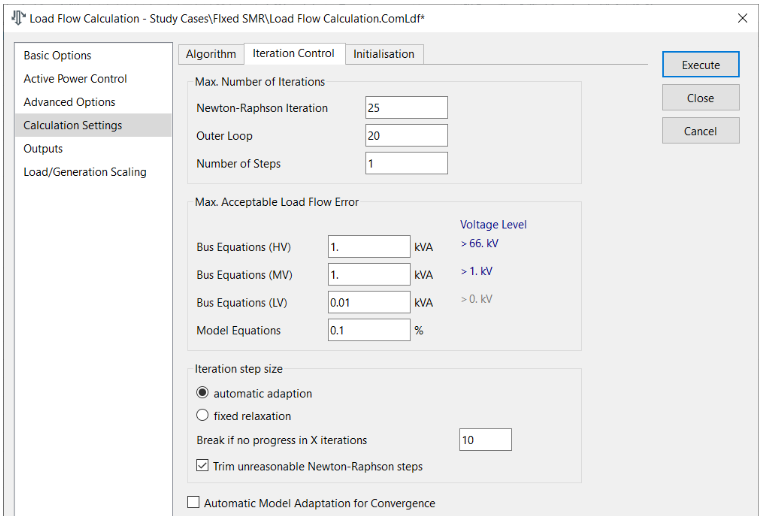
3.3. PowerFactory simulations’ setup and parameters

3.3.1 Load flow analysis

Load flow analysis in PowerFactory is a computational method used to understand how electricity flows through a power system. It calculates the voltages, currents, and power flows in the network to ensure everything works properly. By solving equations (Using Newton-Raphson Method) based on the system's characteristics and constraints, it tells us the voltages profiles, power losses, and how much load the system can handle. This helps engineers make informed decisions about planning and improving the power system.

Load flow analysis can be executed by pressing Load flow icon in PF interface; different parameters need to be set up before the execution of load flow analysis:

- Load Flow Method: This parameter allows you to choose the load flow method to be used for the analysis. PowerFactory offers different methods such as Gauss-Seidel, Newton-Raphson, Fast Decoupled, and others. It can be configured in the calculation settings Figure 3.2.
- Iteration control: Shown in Figure 3.1, iteration control in load flow analysis, it sets convergence criteria and determines when the load flow solution has reached a stable state. It involves defining maximum allowable differences in voltage, power, and angle between iteration.
- Active power control: It adjusts the output of power generation sources or regulates load demand to maintain the desired level of active power in a power system by controlling the active power dispatch priority Figure 3.3.



Max. Number of Iterations

Newton-Raphson Iteration: 25
Outer Loop: 20
Number of Steps: 1

Max. Acceptable Load Flow Error

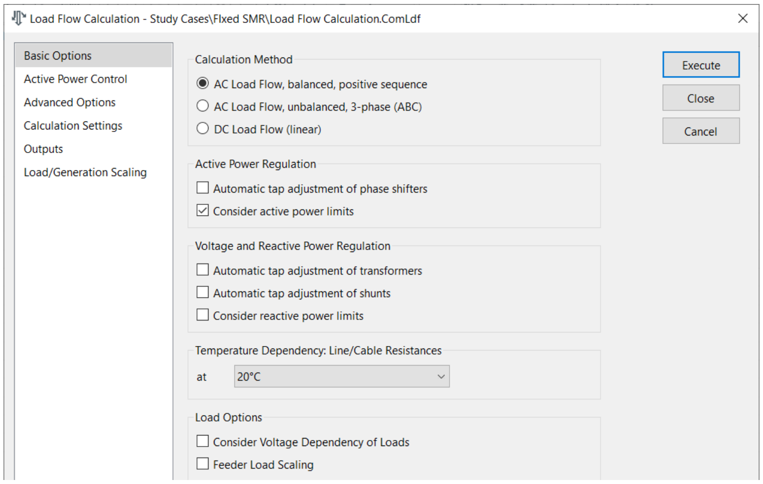
			Voltage Level
Bus Equations (HV)	1.	kVA	> 66. kV
Bus Equations (MV)	1.	kVA	> 1. kV
Bus Equations (LV)	0.01	kVA	> 0. kV
Model Equations	0.1	%	

Iteration step size

● automatic adaption
○ fixed relaxation
Break if no progress in X iterations: 10
☑ Trim unreasonable Newton-Raphson steps

☐ Automatic Model Adaptation for Convergence

Figure 3.2: Load flow calculation settings tab.



Calculation Method

● AC Load Flow, balanced, positive sequence
○ AC Load Flow, unbalanced, 3-phase (ABC)
○ DC Load Flow (linear)

Active Power Regulation

☐ Automatic tap adjustment of phase shifters
☑ Consider active power limits

Voltage and Reactive Power Regulation

☐ Automatic tap adjustment of transformers
☐ Automatic tap adjustment of shunts
☐ Consider reactive power limits

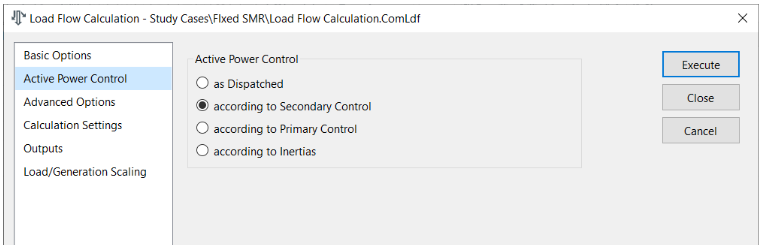
Temperature Dependency: Line/Cable Resistances

at 20°C

Load Options

☐ Consider Voltage Dependency of Loads
☐ Feeder Load Scaling

Figure 3.3: Load flow basic options tab.



Active Power Control

○ as Dispatched
● according to Secondary Control
○ according to Primary Control
○ according to Inertias

Figure 3.4: Load flow active power control tab.

3.3.2 Newton-Raphson Method

Newton-Raphson method is a way to quickly find a good approximation for the root of a real-valued function$f(x) = 0$. It uses the idea that a continuous and differentiable function can be approximated by a straight-line tangent to it [53].

The Newton-Raphson method can generally be used directly in solving the power flow power equation of a power system.

Block diagram of Newton-Raphson method power flow calculation [54]:

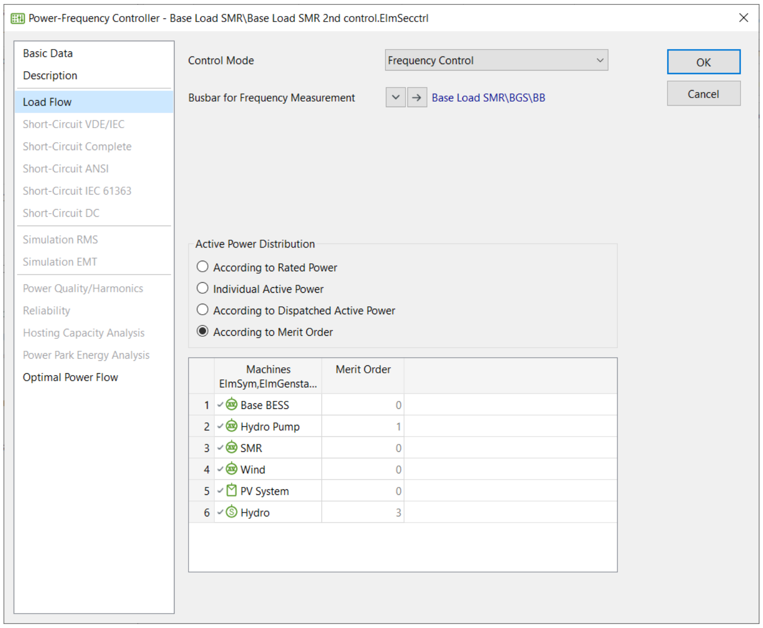
1. Forming a node admittance matrix based on network parameters.
2. Given the initial values of each node voltage.
3. The initial value of each node voltage is used to calculate the offset of the node power and node voltage in the modified equation $\Delta P_i^{(0)}$, $(\Delta U_i^{(0)})^2$.
4. Find the elements in the Jacobian matrix.
5. Solve the correction equation and find the correction amount of each node voltage.
6. Find a new initial value of voltage.
7. Find $\Delta P_i^{(1)}$, $(\Delta U_i^{(1)})^2$.
8. Check for convergence. When the voltage tends to be true, its power offset will tend to zero.

$$\left|f(x_i^{(k)})\right|_{max} = \left|\Delta P_{max}^{(k)}\right| < \varepsilon$$

9. If it does not converge, return to step 4 and re-iterate; if it converges, do the next calculation.
10. Calculate the power distribution and balance node power in each line and output the result.

3.3.3 Secondary control

In PowerFactory, active power control allows us to prioritize and to coordinate the energy units. This control method provides various options, including secondary control as shown in Figure 3.3. Secondary control adjusts power frequency in a specified busbar, several parameters need to be considered, these parameters include the distribution mode and the priority parameters Figure 3.4.



Power-Frequency Controller - Base Load SMR\Base Load SMR 2nd control.ElmSecctrl

Control Mode: Frequency Control

Busbar for Frequency Measurement: Base Load SMR\BGS\BB

Active Power Distribution

○ According to Rated Power
○ Individual Active Power
○ According to Dispatched Active Power
● According to Merit Order

	Machines ElmSym,ElmGensta...	Merit Order
1	✓ Base BESS	0
2	✓ Hydro Pump	1
3	✓ SMR	0
4	✓ Wind	0
5	✓ PV System	0
6	✓ Hydro	3

Figure 3.5: Frequency control tab.

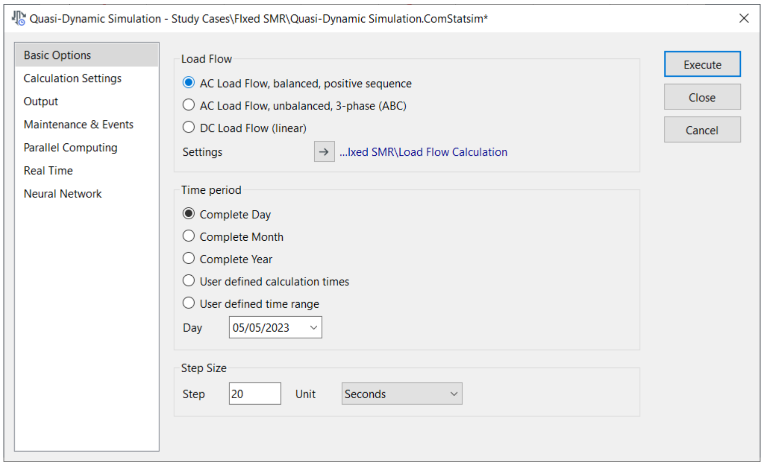
3.3.4 Quasi-Dynamic analysis

Quasi-dynamic analysis is the main function used in this thesis to coordinate between multiple energy sources. It is an advanced simulation technique that combines the benefits of steady-state and dynamic analysis to investigate the behavior of power systems over a predefined time span, ranging from a few minutes to as long as years. This methodology offers a valuable tool for studying power system dynamics and transient phenomena while considering the time-varying nature of loads, renewable energy generation, and other time-dependent factors. Unlike traditional dynamic simulations that necessitate detailed modeling of all system components and their control systems, quasi-dynamic analysis simplifies the model by assuming a constant network topology and control settings throughout the simulation interval.

By employing quasi-dynamic analysis, the power system will be divided into discrete time intervals, and within each interval, the system behavior is considered quasi-steady. This approach captures the impact of varying load demands, renewable energy integration, and other temporal factors on key power system parameters such as voltage profiles, power flows, and stability margins. Quasi-dynamic analysis strikes a balance between computational efficiency and accuracy, making it a highly suitable technique for various applications, including short-term load forecasting, renewable energy integration studies, and the evaluation of control strategies [51].

Quasi-Dynamic simulation is executed by clicking this icon and setting up the following parameters Figure 3.5:

- Initial Conditions: Initial conditions need to be specified accurately to start the simulation from a realistic operating state.
- Time Step Size: This parameter determines the resolution of the simulation and represents the interval at which the system's dynamic response is calculated. It should be chosen carefully to capture both fast and slow dynamics properly.
- Simulation Time-period: It defines the duration for which the simulation will be executed. Sufficient time should be assigned to capture the desired system behaviour, including transients and long-term dynamics.
- Fault and Disturbance events: Occurrence of faults and disturbances at specific locations and times should be considered to assess the system's transient response.



Quasi-Dynamic Simulation - Study Cases\FIxed SMR\Quasi-Dynamic Simulation.ComStatsim*

Load Flow
● AC Load Flow, balanced, positive sequence
○ AC Load Flow, unbalanced, 3-phase (ABC)
○ DC Load Flow (linear)
Settings ...lxed SMR\Load Flow Calculation

Time period
● Complete Day
○ Complete Month
○ Complete Year
○ User defined calculation times
○ User defined time range
Day 05/05/2023

Step Size
Step 20 Unit Seconds

Figure 3.6: Quasi-dynamic simulation tab

3.3.5 Quasi-Dynamic simulation language model

Quasi-dynamic simulation language (QDSL) model is a user-definable model that can be used for quasi-dynamic simulation in PowerFactory. A QDSL model can represent the behaviour of different network elements or controllers by defining equations for load flow and quasi-dynamic variables.

Both Python and DigSilent Programming Language (DPL) can be used to configure the parameters for Quasi-dynamic simulation model (QDSL) and Dynamic simulation model (DSL) [51]. Figure 3.6 shows how a QDSL model function during simulation.

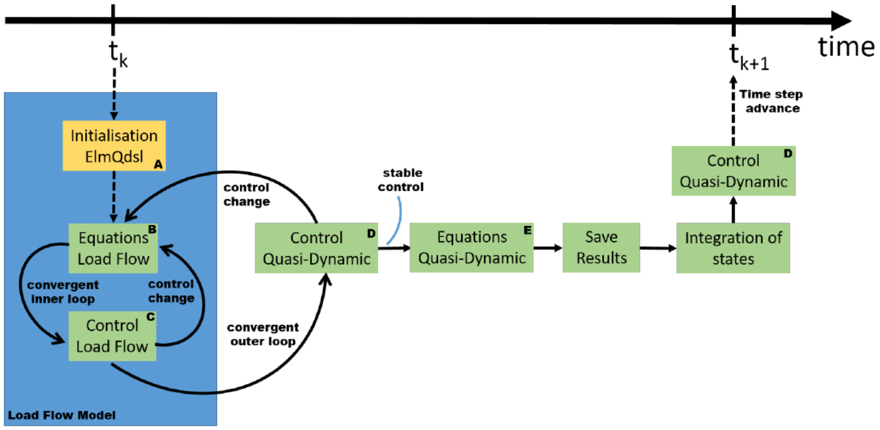


Figure 3.7: QDSL models Simulation Procedure.

3.4. Conclusion

This chapter presented a brief overview of Digsilent PowerFactory and its functions for power system simulation. At first, the choice of PowerFactory as the software tool for our study was justified. After that, the main functionalities and the Digsilent Programming Language were presented. Furthermore, the key functions within PowerFactory that are relevant for our analysis, such as load flow analysis, secondary control, quasi-dynamic analysis, and quasi-dynamic simulation model were highlighted and focused.

This chapter aims to leverage the capabilities of quasi-dynamic analysis in DigSilent PowerFactory to explore and analyze the dynamic performance of power systems under realistic time-varying conditions, thus contributing to the control and optimization of multi-energy sources in microgrid.

Chapter 4

Modeling and coordination of multi-source micro-grid using DigSilent PowerFactory

4.1. Introduction

This chapter presents multi-source microgrid modeling and management using Digsilent PowerFactory software. The analyzed micro-grid is composed of renewable energy sources (RES), including wind and photovoltaic (PV) systems, a small modular reactor (SMR), and energy storage systems (ESS) such as batteries and pumped storage hydro (). These sources supply a load for 24 hours.

This chapter is composed of two parts: the first one deals with modeling of each energy source in the PowerFactory environment. In addition, three operation modes of SMR are proposed. Whereas, the seconds part presents a proposed energy management and coordination methodology.

The obtained results demonstrate the effectiveness of the proposed energy management and coordination methodology in maintaining a balance between generation and demand. Additionally, ESS and PSH plays a crucial role in compensating and mitigating the power ramp ratio constraint of the SMR, and thus enhancing the flexibility of the microgrid.

4.2. Energy source modeling using Digsilent PowerFactory

Figure 4.1 presents the multi-source microgrid scheme. As illustrated in this figure, the microgrid consists of a wind farm, a PV system, an SMR, pumped storage hydropower and batteries energy storage system that must be coordinated efficiently to supply a load for 24 hours. The detailed models of each energy source in the Digsilent PowerFactory environment are presented in the flowing subsections.

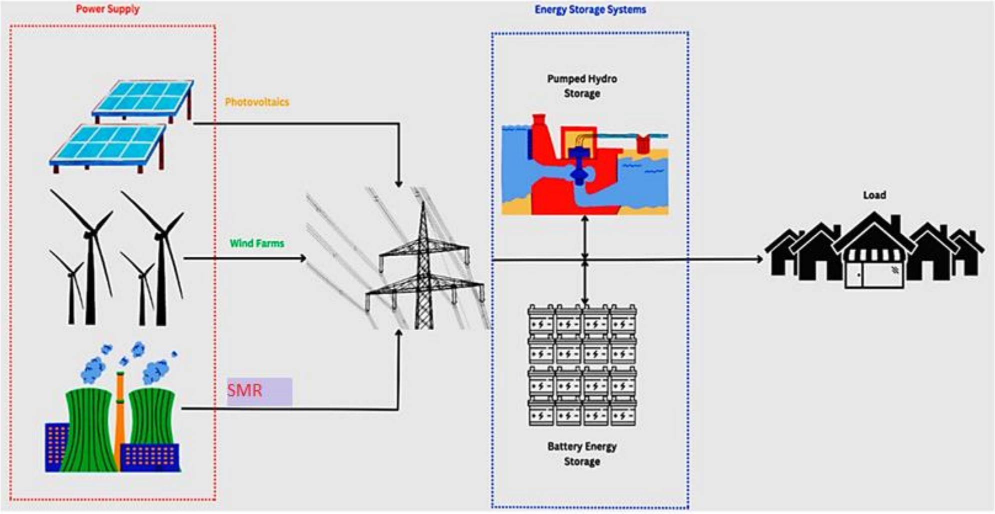


Figure 4.1: Multi-source microgrid scheme.

4.2.1 PV system model

PV system model is created by adding PV components and configuring its different parameters such as the PV model, number of panels and inverters, operational limits and operating point. The operating point is configured by adding defined Time Characteristics obtained from an Algerian PV plant. The generation curve of PV is presented in Figure 4.2.

As shown in Figure 4.2, the PV generation starts around 6:30am increasing to reach its peak 5.189 MW at 1pm. Subsequently, the generation begins to decline and eventually reaches zero around 7 pm.

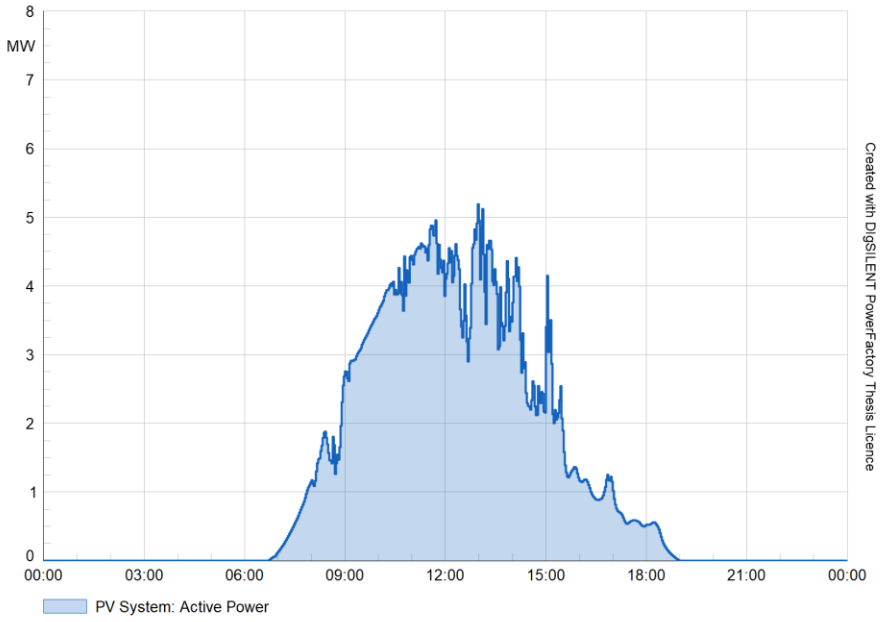


Figure 4.2: PV generation curve.

4.2.2 Wind turbine model

Similarly to the PV system, the wind turbine model is created by adding windmill icon and configuring its different parameters, such as the wind system model, number of units, operational limits, and dispatch parameters. The dispatch parameters should be configured by adding a specific wind power curve (refer to Chapter 2, Figure 2.11) and defining the wind speed Time Characteristics (detailed in 4.4 a). Figure 4.3 shows the wind generation curve taken from an Algerian wind farm.

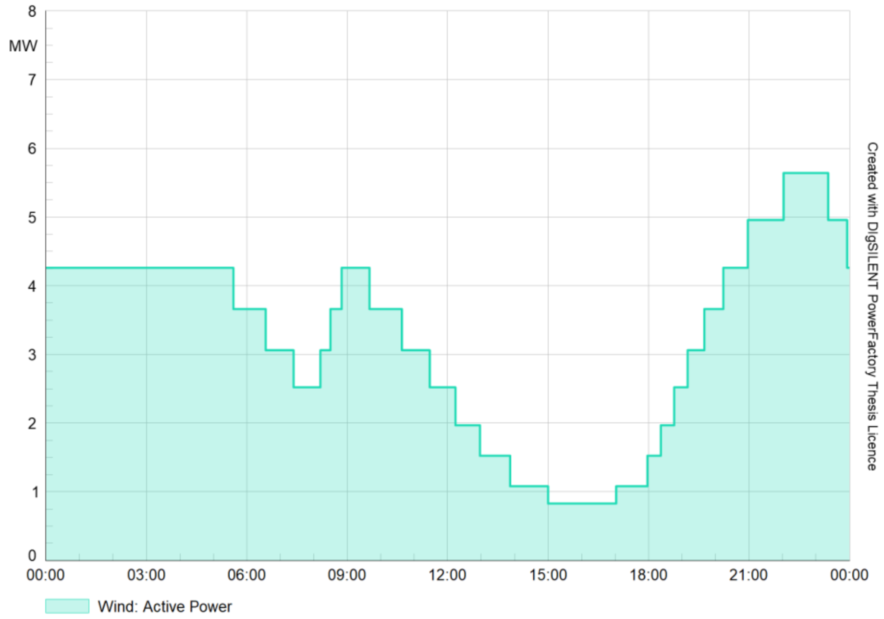


Figure 4.3: Wind generation curve.

4.2.3 Battery storage model

PowerFactory offers a variety of methods to model the battery storage system. In this thesis, the battery with the following symbol has an integrated bidirectional converter. The battery storage system has a set of parameters to be configured, including the number of units, nominal and maximum power, and operational limits.

More parameters of battery such as battery state of charge (SOC), capacity, power to start feed/store, and conditions of charge/discharge are presented in Table 4.1. These are added, latter, by integrating a QDSL model to the battery (detailed in section 3.5).

In order to enhance the life cycles of BESS, it is necessary to establish limits on their discharge and charge capacities, which is commonly referred to as Depth of Discharge (DOD). This parameter ensures that batteries are not charged to their maximum capacity or discharged completely to 0%.

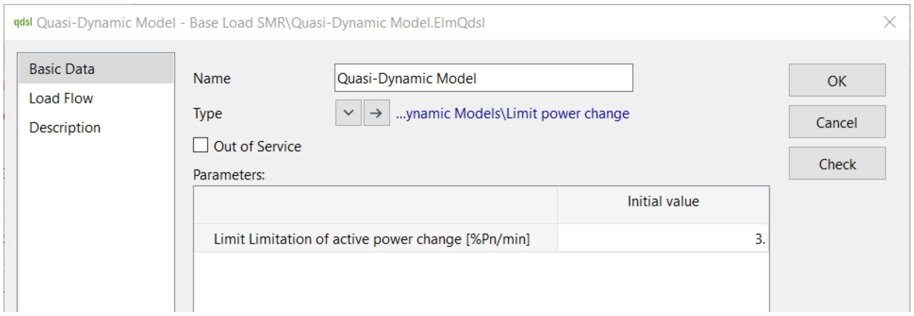
Table 4. 1 Summary of Battery QDSL parameters.

Parameter	Description
Eini	Battery full capacity [MWh]
SOCini	Initial state of charge [%]
SOCmin	Minimal state of charge [%]
SOCmax	Maximal state of charge [%]
$P_{start\ store}$ / $P_{start\ feed}$	ΔP to start Store/Feed [MW]
$P_{full\ store}$ / $P_{full\ feed}$	ΔP to Store/Feed at full power [MW]
P_{store} / P_{feed}	ΔP Battery full Store/Feed power [MW]
Orientation	Line (1) orientation to the Busbar [1 or -1]

4.2.4 SMR model

Unlike the previous models, there is no SMR defined model in Power Factory, the developed SMR is modeled by adding a static generator and configuring its parameters to follow the SMR operation principle. A static generator in PF is a generator that feeds the available generated power without considering the demand and it can be used as a generator or/and a motor [51] [55]. The static generator's parameters include operational limits, dispatch parameters, these parameters changes according to 3 studied scenarios (section 3.2).

The most critical parameters of the SMR is the power ramp factor %P nominal per minute Figure 4.4, this last is configured using the QDSL model and set to 3% (Detailed in section 3.3).



Quasi-Dynamic Model - Base Load SMR\Quasi-Dynamic Model.ElmQdsl

Name: Quasi-Dynamic Model

Type: ...ynamic Models\Limit power change

☐ Out of Service

Parameters:

	Initial value
Limit Limitation of active power change [%Pn/min]	3.

Figure 4.4: SMR power ramp parameter.

4.2.5 Pumped storage hydropower model

The PSH system modeling was done by combining two machines in parallel. One machine is presented by a Static Generator and functions as a pump, which used during the off-peak load period, while the other machine is presented by a synchronous machine and operates as a turbine, generating electricity when there is a shortage in generation.

4.2.6 Load profile model

The load model is modeled by connecting the load icon ↑ to the system and setting up its parameters including load type and operating point.

The load variation depends on the Time Characteristics and presented in Figure 4.5. It is observed that the load is at its lowest during the off-peak period at 6 am. Afterward, it gradually rises until it reaches its peak at 2 pm. Following 2 pm, the load decreases to the base load level, fluctuating between 11 MW and 13 MW.

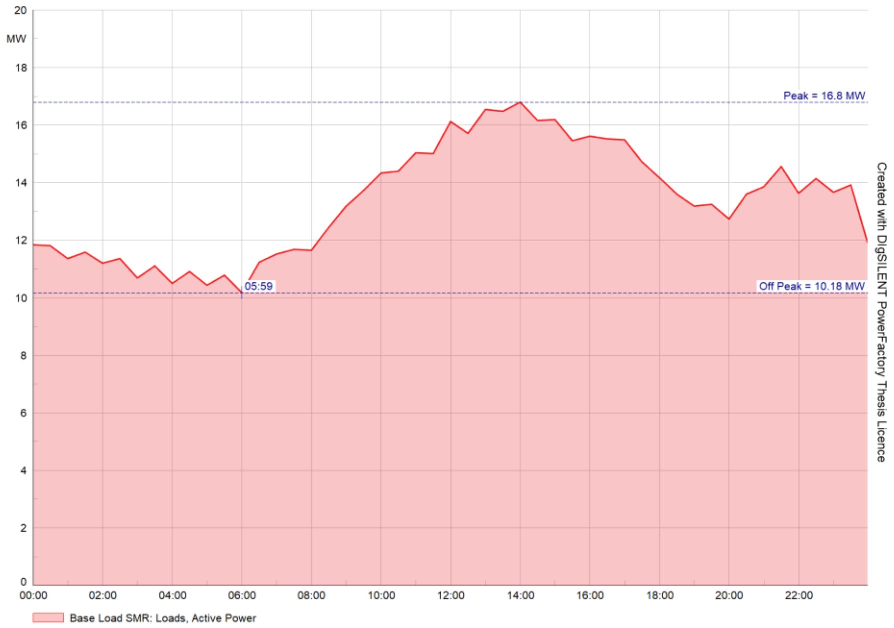


Figure 4.5: Load variation curve.

4.3. Proposed multi-source management and coordination methodology

Figure 4.6 presents the proposed multi-source coordination methodology implemented in DIgSILENT PowerFactory software and tested using quasi-dynamic simulation function. This methodology favors wind and PV sources as renewable and intermittent energy sources, along with the SMR according to its operation mode. In case of an imbalance between demand and generation, this issue will be solved by both pumped hydropower and battery storage systems.

This microgrid configuration and its coordination strategy will ensure flexible, green energy production without GHG emissions. More technical explanations of the proposed coordination strategy are provided in the following points:

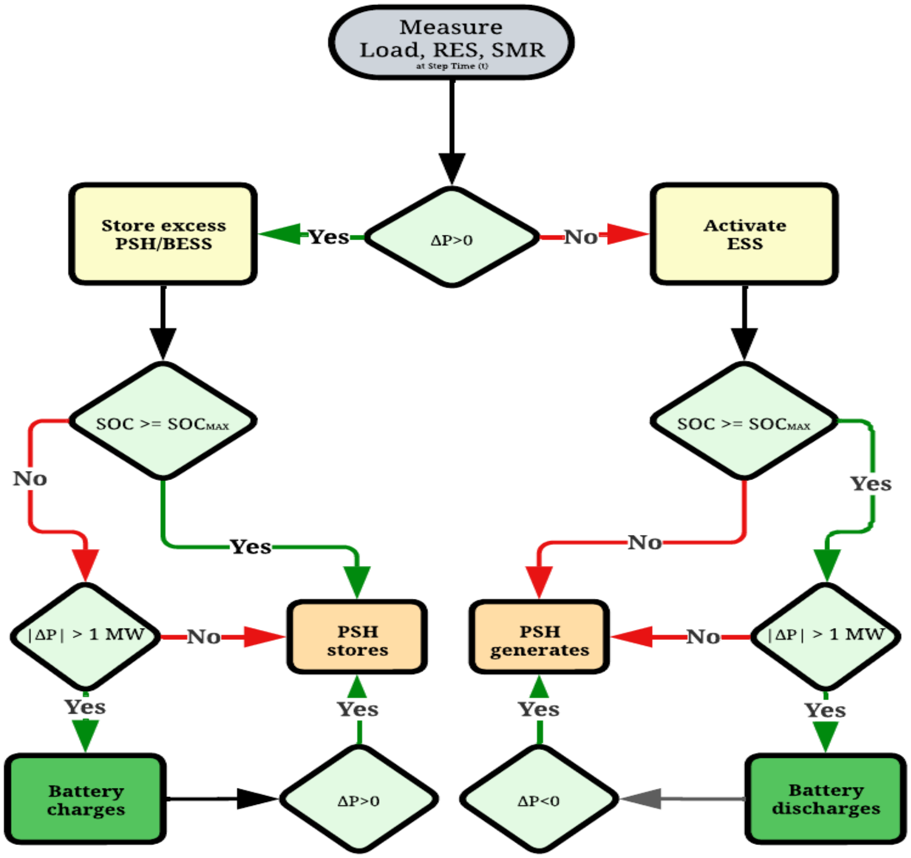


Figure 4.6: Generation dispatch flowchart.

- Renewable Sources Priority: The prioritization of renewable sources is driven by several factors:
    - Environmental Impact: Renewable sources, such as wind and solar, have minimal environmental impact compared to fossil fuel-based sources. They produce clean energy without contributing to greenhouse gas emissions.
    - Resource Availability: Algeria, as the reference for data, have favorable conditions for wind and solar energy due to its geographical location.
    - Cost Efficiency: With advancements in technology, the cost of renewable energy generation has significantly decreased, making it a more cost-effective option in the long run.
- Small Modular Reactor (SMR) Integration: The SMR is included in the power system for several reasons:
    - Baseload Power Generation: The SMR can provide consistent baseload power, complementing the intermittent nature of RES. This helps maintain a stable power supply throughout the day, ensuring reliable electricity for critical operations.
    - Diversification of Energy Sources: The inclusion of an SMR diversifies the energy mix, reducing dependence solely on RES which is technically very difficult. This adds a level of energy security and stability to the system.
- Energy storage system: Storage are integrated into the system for the following reasons:
    - Load Balancing: ESS, allows excess power generated during periods of high RES production to be stored for later use.
    - System Stability and Reliability: Storage and backup options enhance the system's stability and reliability by mitigating the effects of intermittent RES.

By combining RES, SMR and ESS, the power system aims to achieve a sustainable, reliable, and resilient energy supply while minimizing environmental impact and maximizing cost efficiency.

4.4. Simulation and results

4.4.1 Microgrid single-line diagram

The DigSilent PowerFactory model of the proposed Microgrid is presented in Figure 4.7. As mentioned earlier, the system consists of an SMR, a PV system, a Wind system, a pumped hydro power plant, a battery storage system, and a load. The system underwent testing using the quasi-dynamic simulation function over a duration of 24 hours.

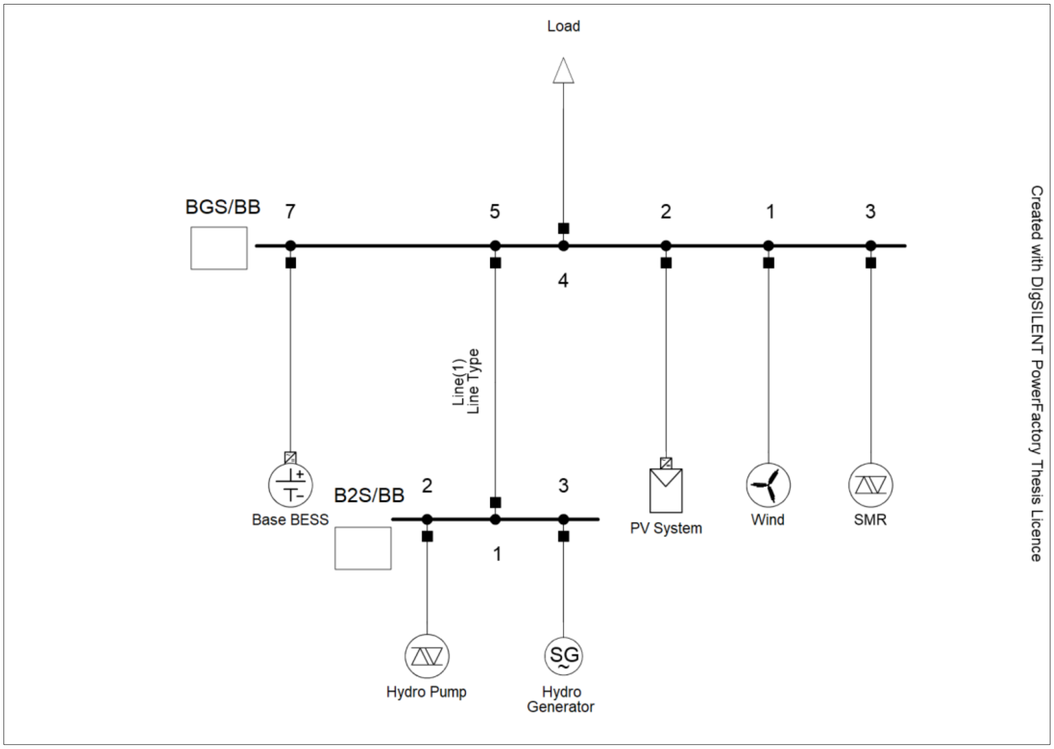


Figure 4.7: Digsilent power factory single-line diagram of the Microgrid.

4.4.2 SMR operation modes

Three simulation scenarios are considered in this thesis, according to SMR [57]:

1) **Scenario (A): Baseload operation of SMR**

In this case, Small Modular Reactor consistently generates 10MW during 24 hours. The SMR fulfills the base load requirement, ensuring a continuous power supply. Meanwhile, ESSs function as backup solutions, compensating any excess or shortage of energy that may occur.

2) **Scenario (B): Load following operation mode of SMR**

Second case, SMR generation will changes according to a predefined operation profile as illustrated in Figure 4.8. From this figure, it is clear that the SMR operates at its full capacity (10MW) during the day time (from 6am to 9pm) to satisfy the peak demand. Otherwise, it operates at 50% of its full capacity for the rest of the day. It should be noted here that the power ramp ratio limit of SMR is considered 3%Pn/min. The QDSL model of SMR is presented in the annex.

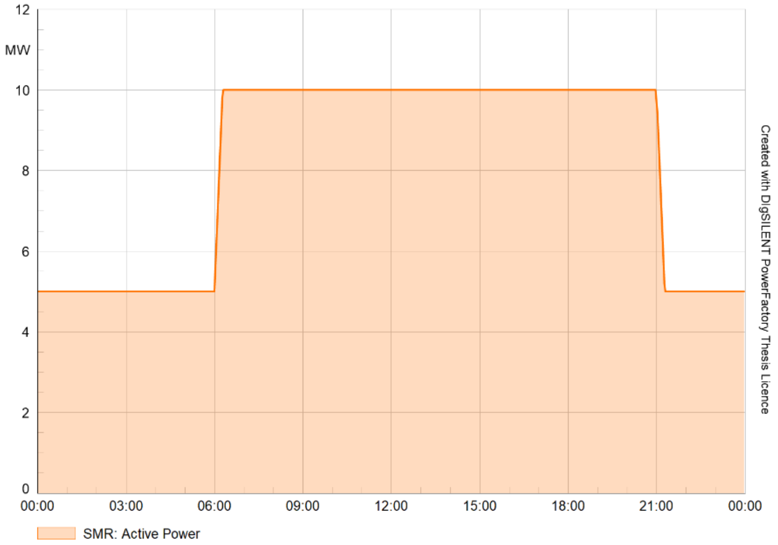


Figure 4.8:Load following operation mode of SMR.

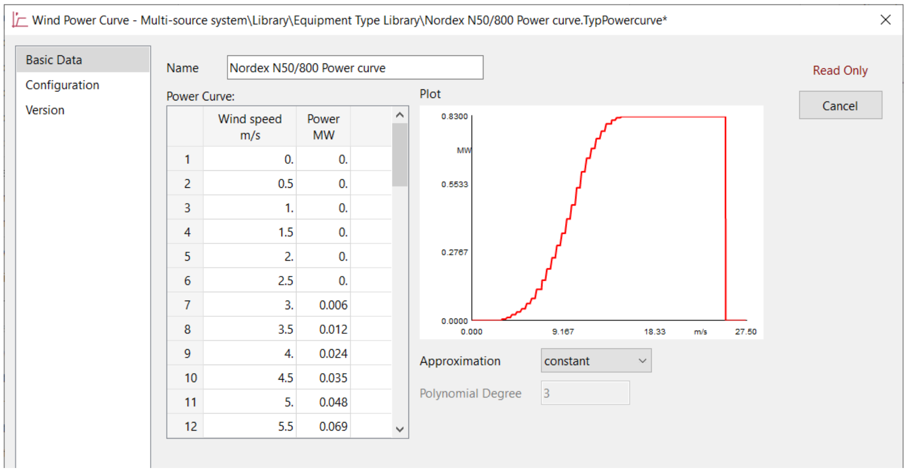
3) **Scenario (C): Frequency control operation mode of SMR**

In this case, the SMR power output has a limited variation between 90% and 100% of its total capacity without considering the power ramp ratio limit. Therefore, the SMR power is limited between 9 MW and 10 MW.

4.4.3 Renewable energy sources configuration

1) Wind turbine

To configure wind power sources, a set of parameters and data must be added. Wind power curve illustarted in Figure 4.10 sets the generator power output that corresponds to the speed of wind. This allows the power output to vary according to the wind-speed time characteristics presneted in Figure 4.11.



Name: Nordex N50/800 Power curve

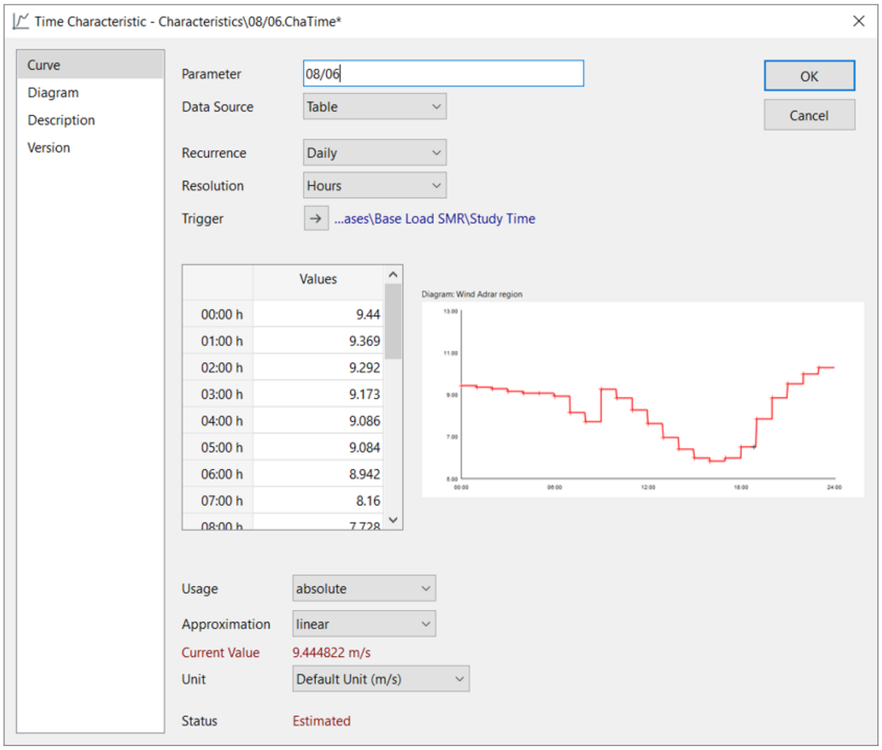
Power Curve:

	Wind speed m/s	Power MW
1	0.	0.
2	0.5	0.
3	1.	0.
4	1.5	0.
5	2.	0.
6	2.5	0.
7	3.	0.006
8	3.5	0.012
9	4.	0.024
10	4.5	0.035
11	5.	0.048
12	5.5	0.069

Approximation: constant

Polynomial Degree: 3

Figure 4.9: Wind power curve tab in PowerFactory.



Parameter: 08/06

Data Source: Table

Recurrence: Daily

Resolution: Hours

Trigger: ...ases\Base Load SMR\Study Time

	Values
00:00 h	9.44
01:00 h	9.369
02:00 h	9.292
03:00 h	9.173
04:00 h	9.086
05:00 h	9.084
06:00 h	8.942
07:00 h	8.16
08:00 h	7.728

Usage: absolute

Approximation: linear

Current Value: 9.444822 m/s

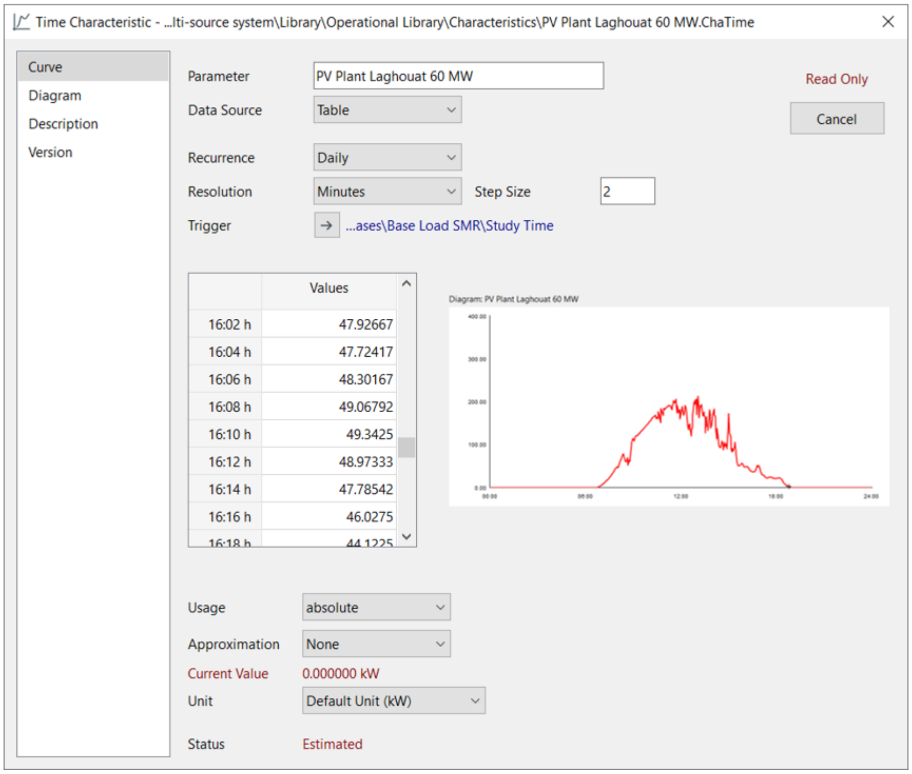
Unit: Default Unit (m/s)

Status: Estimated

Figure 4.10: Wind speed time characteristics tab in PowerFactory.

2) Photovoltaic

PV panels in PowerFactory can be configured in two ways either by inputting the panel's technical characteristics and specifying the geographical position, or by directly adding predefined time characteristics for the panel's output. In our case, PV power data were inserted directly into the time characteristics as illustared in Figure 4.12.



Time Characteristic - ...lti-source system\Library\Operational Library\Characteristics\PV Plant Laghouat 60 MW.ChaTime

Parameter: PV Plant Laghouat 60 MW
Data Source: Table
Recurrence: Daily
Resolution: Minutes
Step Size: 2
Trigger: ...ases\Base Load SMR\Study Time

	Values
16:02 h	47.92667
16:04 h	47.72417
16:06 h	48.30167
16:08 h	49.06792
16:10 h	49.3425
16:12 h	48.97333
16:14 h	47.78542
16:16 h	46.0275
16:18 h	44.1225

Usage: absolute
Approximation: None
Current Value: 0.000000 kW
Unit: Default Unit (kW)
Status: Estimated

Figure 4.11: PV power time characteristics tab in PowerFactory.

4.4.4 Battery QDSL model

Battery QDSL in our model is set to control the battery charge and discharge conditions with respect to power and demand, and the SOC of the battery. The detailed battery QDSL model in presented in the annex.

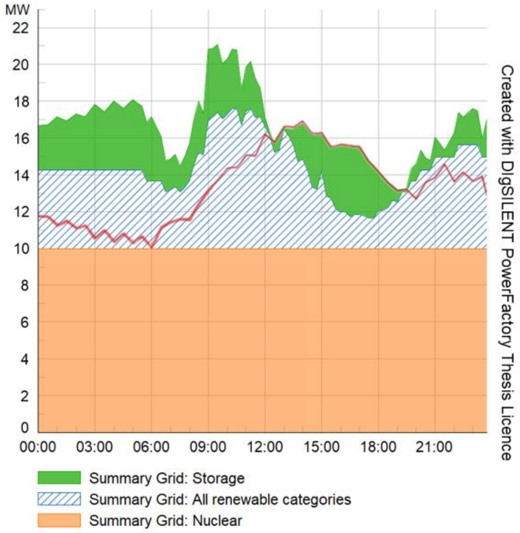
4.5. Results and discussion

4.5.1 Results

4.5.1.1 Scenario (a): SMR baseload operation mode

Figure 4.13.1 shows the absolute value of RES, SMR, and ESS generation for SMR baseload operation mode scenario. Notably, the graph reveals that the ESS remained engaged throughout the entire 24-hour period but the storing has gone on longer than the generating period.

It is important to note that term “absolute value (Figure 4.13.1)” signifies that both power generation and consumption of ESS are represented by positive values.



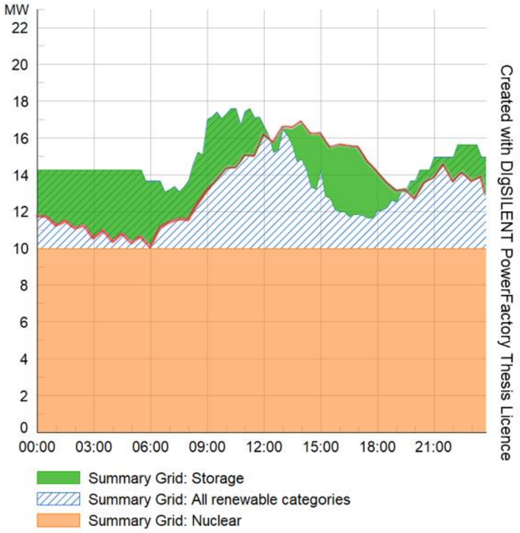


Figure 4.13.1: Absolute power generation for scenario(a). *Figure 4.13.2: Normal power generation for scenario (a).*

Figure 4.13.2 illustrates the normal values of the 3 systems. From this figure, red curve represents Load which outlines the difference between generation and consumption. Furthermore, all above the red curve is consumed by ESS while the green part below corresponds to stored energy.

Table 4.2 shows the contribution of each sources in MWh. It is noticed that ESS total generation was (-24.325 MWh) means ESS’s stored a high amount of energy from RES, which was storage was divided between batteries and PSH. However, by the end of the day, batteries stored only (0.317 MWh) in total, while PSH stored the rest.

Table 4. 2 Scenario (a) Total generation.

	SMR	PV	WIND	ESS			TOTAL ESS	LOAD
				BESS	PUMP	TURBINE		
TOTAL GENERATION (MWH)	240	77.52	28.267	-0.317	-31.73	7.812	-24.235	321.552

As it is demonstrated in Figure 4.14, BESS SOC rose from 20% (initial SOC) to its maximum SOC 90% due to the low electrical demand at night and in the morning. PSH was instantly activated when BESS reached SOC_{max}. During Base-load time batteries were inactive while PSH was storing energy until midday.

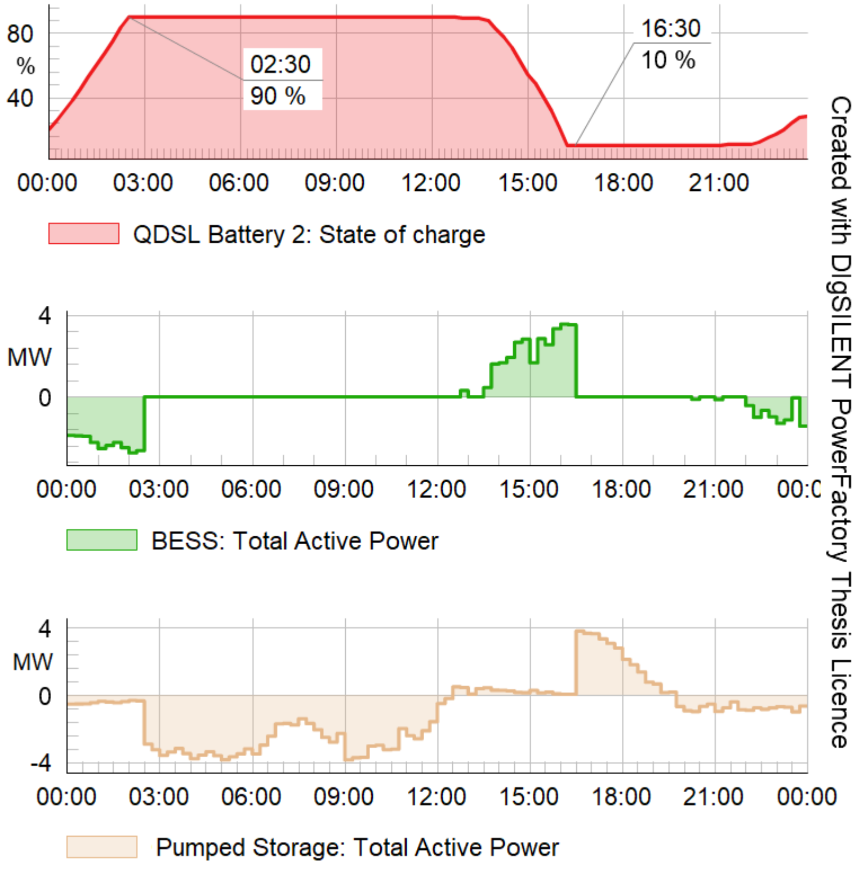


Figure 4.13: Battery SOC scenario (a).

At midday the (Peak-load period), PSH started compensating ($\Delta P < P_{START\ FEED}$). After a while, BESS started discharging to reach their minimum SOC 10%. Instantly PSH started feeding to meet the load demand, as illustrated in Figure 4.15.

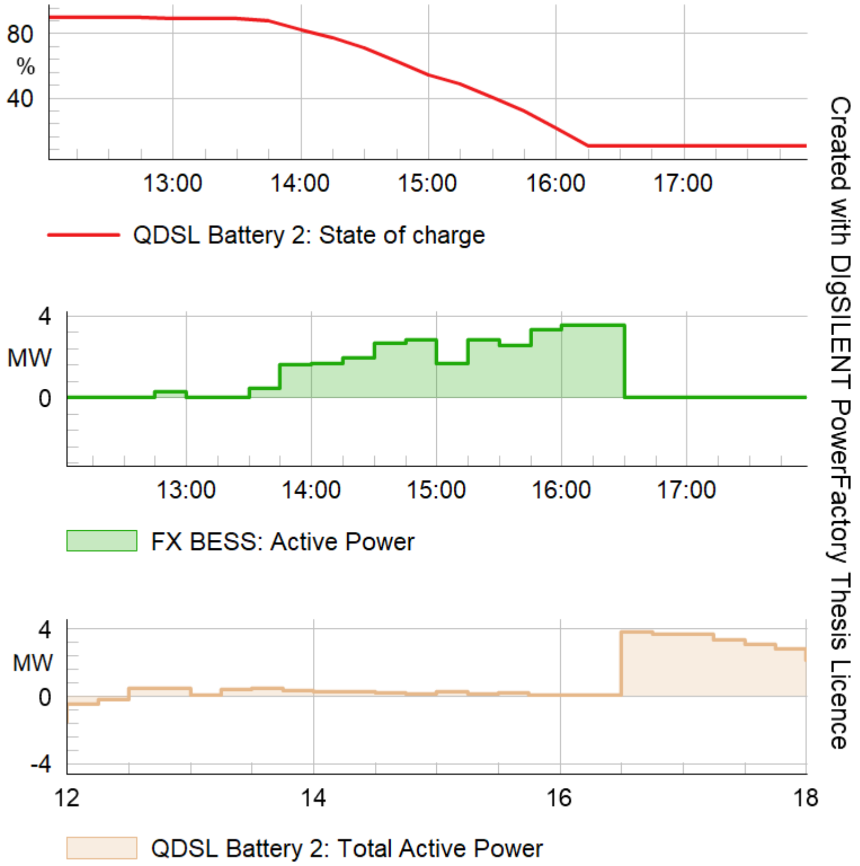


Figure 4.14: Zoomed part from Figure 4.14 graphs.

4.5.1.2 Scenario (b): SMR load following operation mode

Figure 4.16.1 displays the absolute power generation of RES, SMR, and ESS for scenario (b). From this figure, it can be remarked that the ESS has generated more power than it stored.

For the first 5 hours of the simulation, SMR and RES generation were lower than the load, which required the activation of the ESS to compensate for the shortage. After 6:15a.m., SMR generation rose to 10 MW as defined in its time characteristics; this allowed the ESS to store energy before peak shaving.

At 12am the load was at its peak-time while RES generation was declining, this required the ESS to fill the generation deficiency.

At 7:30pm, demand was low, RES generation increased. This led to excess energy which in turn was stored by ESS until 9pm, where SMR generation started decreasing to reach 50% of its capacity following its defined characteristics. This latter caused generation shortage that must be compensated by ESS.

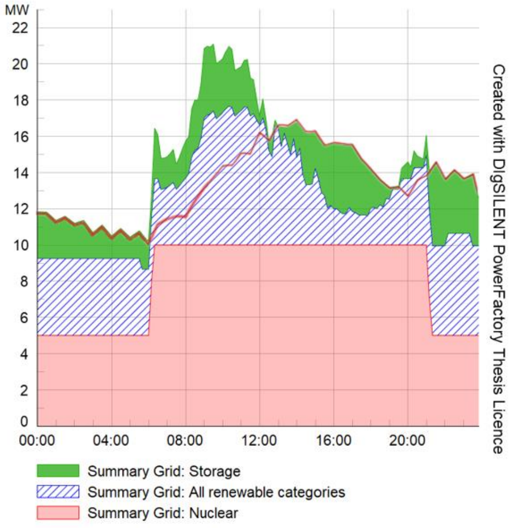


Figure 4.16.1: Absolute power generation for scenario (b).

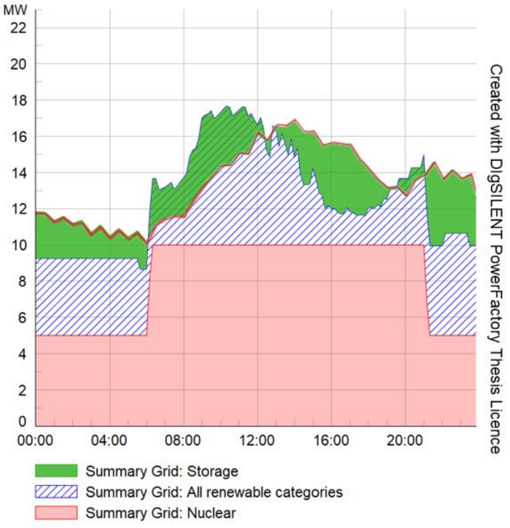


Figure 4.16.2: Normal power generation for scenario (b).

Generation by source in MWh displayed in Table 4.3 shows that ESS total generation was (20.765 MWh), signifies that ESS injected a high amount of energy to the microgrid. This generation was divided between BESS and PSH. PSH generated (19.462 MWh) in total, while BESS generated (1.303 MWh) which represents (16.28 %) of its total capacity.

Table 4. 3 Scenario (b) Total generation.

	SMR	PV	WIND	ESS			TOTAL ESS	LOAD
				BESS	PUMP	TURBINE		
TOTAL GENERATION (MWH).	195	77.52	28.267	1.303	-7.864	27.326	20.765	321.552

Figure 4.17 shows that battery started by discharging from its initial capacity (20 %) at 12am to reach SOC$_{min}$ (10 %) at 12:20am. Immediately, PSH generation increased from 0.2 MW to above 2 MW. PSH kept feeding power until 6am, this corresponds to the rise in SMR generation (Full capacity 6am to 9pm).

The period after 6 am shows BESS charging from 10% reaching its SOC$_{max}$ at 9:30am. Period after 9:30, PSH stored the additional power until load reached peak-time where this latter generated power for a short time (<1h) before BESS started discharging ($P_{start\ feed} \leq \Delta P$). BESS discharging to its minimum capacity took around 4hours, and immediately PSH replaced BESS to keep generating balance.

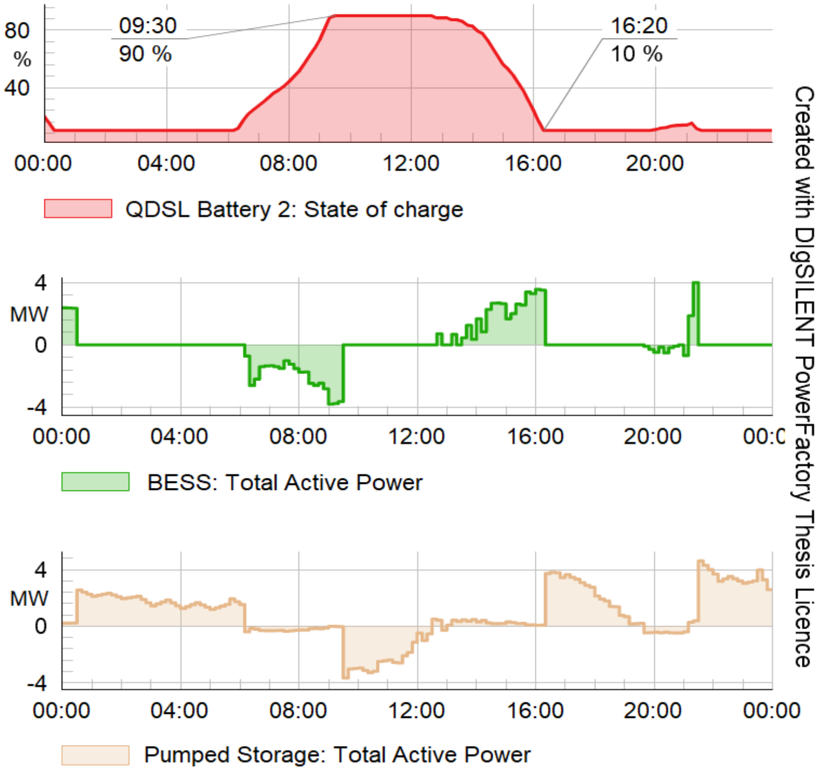


Figure 4.16: Battery SOC scenario (b).

4.5.1.3 Scenario (c): Frequency control operation mode of SMR

Absolute power generation of RES, SMR, and ESS of SMR of scenario (c) presented in Figure 4.18.1, it is notable that the simulation period was divided into 2 main intervals:

- The first interval from 0 to 12 hours: the SMR power output was at the minimum and did not changes (90% of Pn) while ESS was in storing mode.
- The second interval from 12 to 20 hours: the SMR operates at its maximum power and the ESS discharges for balancing the demand.

For the last 4 hours of the simulation, the SMR fluctuating between 90% and 100% of its full power to balance the demand with the generation.

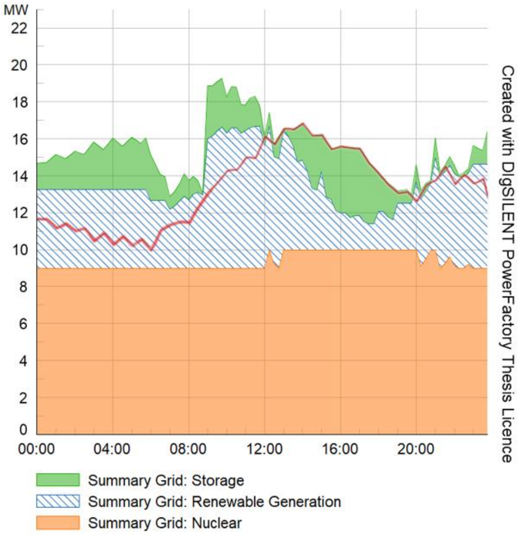


Figure 4.18.1: Absolute power generation for scenario (c).

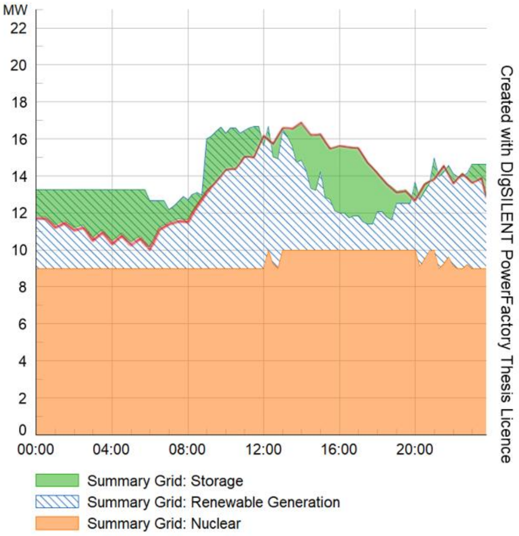


Figure 4.18.2: Normal power generation for scenario (c).

Table 4.4 shows that ESS total generation value of -8.725 MWh that represents the storage energy by the ESS. This last is shared between BESS and PSH as follows: BESS stores 0.47 MWh while PSH stores 8.255 MWh. This results show that the PSH is favorited over the BESS. This is due that BESS QDSL aims to perverse its life by reducing the number of charge/discharge cycles.

SMR generated 224.49 MWh contributing by 69.81 % in the total load supply.

Table 4. 4 Scenario (c) Total generation.

	SMR	PV	WIND	ESS			TOTAL ESS	LOAD
				BESS	PUMP	TURBINE		
TOTAL GENERATION (MWH).	224.49	77.52	28.267	-0.47	-18.437	10.182	-8.725	321.552

In Figure 4.19, BESS SOC rose from (20 %) initial SOC at 12am to reach SOC_{max} (90 %) at 3:45am. BESS remained inactive during Base-load period (4am to 12:30pm), during this period PSH stored 14.88 MWh which represents 78.7% of the total excess generation.

At 12:30pm BESS started discharging to compensate the peak demand. At the end of the simulation, BESS SOC was 17.34% which means that the BESS total consumption (0.407 MWh) represents 7.37% of the BESS full capacity.

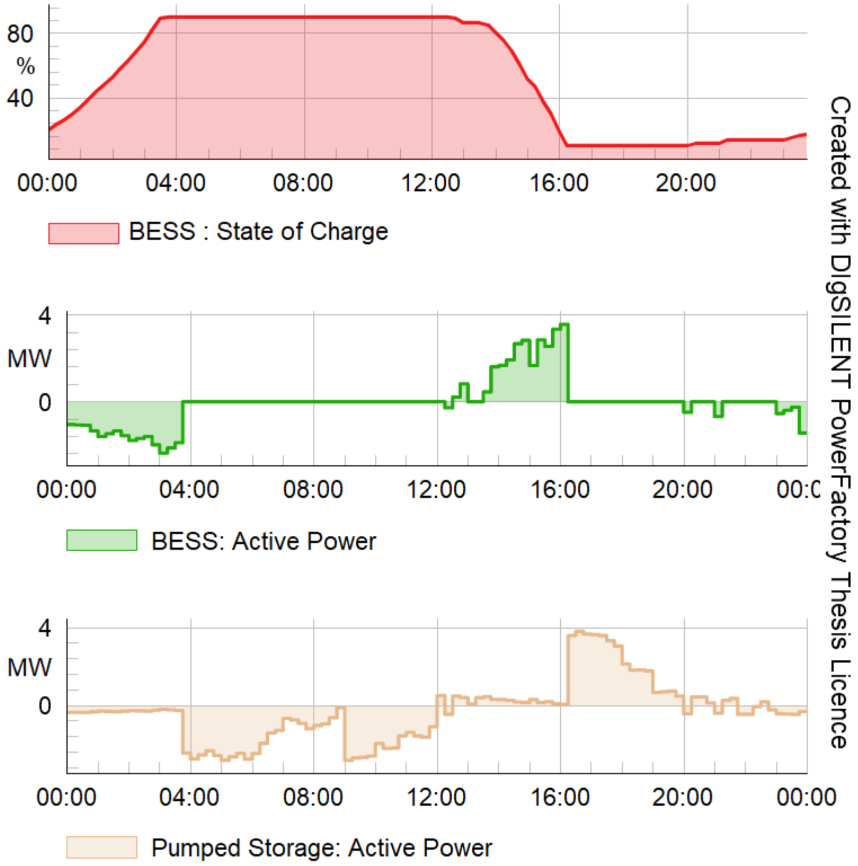


Figure 4.18: Battery SOC scenario (c).

4.5.2 Discussion

When observing the results of the three scenarios, we come across a variety of differences; thus, it is essential that we opt for the most desirable finding by comparing the results based on the previously discussed constraints and points of leverage.

4.5.2.1 Comparative Analysis of Three Scenarios

Table 4.5 presents energy generated by sources in three scenarios. In case (b), the energy produced by BESS and PSH was positive, which means that this SMR operation mode requires additional energy to satisfy the load thanks to the ESS.

Scenarios (a) and (c) show relatively small differences between them in terms of SMR and BESS generation. In both cases, the ESS operated in storage mode, which means there was an excess of energy. However, in scenario (a), PSH has consumed a higher amount of energy (23.918 MWh) compared to scenario (c) (8.255 MWh). This last, gained more advantage from the SMR frequency control mode (scenario c), which has the ability to regulate the SMR output.

Table 4.5: Energy sources for the three scenarios.

	CASE (a)	CASE (b)	CASE (c)
SMR (MWH)	240	195	224.49
BESS (MWH)	-0.317	1.303	-0.47
PSH (MWH)	-23.918	19.462	-8.255

Table 4.6 presents the time BESS took to charge from its initial SOC to maximal SOC and to discharge from its maximal SOC to minimal SOC. Slow charge/discharge can extend the battery's life cycle by avoiding stress and damage to its materials, while fast charge/discharge can increase the risk of overheating and fire [58] [59] [60]. Comparing table results, case (c) took a relatively longer period to charge/discharge, this gives it an advantage as it contributes to batteries health and better life cycle.

Table 4.6: Battery time to charge/discharge

	CASE (a)	CASE (b)	CASE(c)
SOC_{INI} TO SOC_{MAX}	2h24m	2h54m	3h29m
SOC_{MAX} TO SOC_{MIN}	3h14m	3h12m	3h44m

4.5.2.2 Finding

Result’s discussion indicates that case (c) exhibits the most favorable behavior for SMR. By adopting the strategies and characteristics associated with case (c), it is expected that the microgrid can optimize its performance and achieve desirable outcomes in resource allocations.

4.6. Conclusion

In this chapter, the quasi-dynamic analysis was performed in DigSilent PowerFactory to explore and analyze the dynamic performance of the proposed multi-source microgrid under realistic time-varying conditions, considering three different scenarios.

Results, interpretation, and discussion led us to identify case (c) as the most convenient scenario to have optimum source management. The findings in this chapter contribute to a better understanding of effective SMR behavior and provide insights for decision-making in similar scenarios.

Further research and validation are recommended to consolidate these findings and explore potential enhancements in SMR and ESS performance.

General conclusion

General Conclusion

This thesis highlights the need for a transition towards cleaner and more sustainable energy sources. The global energy system is facing critical challenges, particularly in relation to climate change and greenhouse gas emissions. The adoption of low-generation nuclear reactors and renewable energy sources is a promising solution to address these challenges. By reducing our dependence on fossil fuels and moving towards less polluting sources, we can achieve a cleaner and more sustainable future.

Furthermore, the thesis emphasizes the importance of advanced simulation tools, such as DigSilent PowerFactory, in analyzing and optimizing complex energy systems. These tools enable a deeper understanding of the dynamic performance and behavior of power systems, contributing to the effective management and coordination of energy sources.

A set of study cases for small modular reactor behaviors (a, b, and c) were proposed in order to achieve optimal resource allocation.

The findings presented in this thesis point out the importance of using an energy management methodology that can optimize the utilization of energy generated from SMR and the intermittent renewable energy sources (RES).

Overall, this thesis reinforces the importance of embracing nuclear and renewable energy sources, along with efficient energy management strategies, to mitigate climate change impacts and ensure a more sustainable energy system. Continued research, development, and implementation of these technologies are essential to accelerate the global energy transition and pave the way for a cleaner and more resilient future for generations to come.

Future prospects for this thesis include addressing some inadequacies and further advancing the research on microgrid simulations. Firstly, determining the initial capacity of PSH will improve the accuracy of the simulation results. Secondly, developing a program to effectively control BESS life cycle constraints in long-term simulations (1 year, for example) will ensure realistic modeling.

Additionally, conducting seasonal comparisons and collecting extensive data for analysis using artificial neural networks (ANN) will provide more precise and comprehensive results. Exploring additional study cases and considering criteria such as GHG emissions, cost, and efficiency will enhance resource allocation and system evaluation. These future efforts will contribute to the continued progress and development of microgrid simulation techniques and their application in practical scenarios.

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[62]

1. SMR QDSL model of load following operation mode

To match the SMR power variation ramp constraint a QDSL model was integrated in BESS. The control algorithm regulates the generator power output and limits the change of Pset by controlling the difference between the allowed power variation by unit of time and the targeted power (presented by $diff$ in the equations) between every two consecutive time steps in quasi-dynamic simulation.

The calculation of Pset is done following the next steps:

- Read SMR pgini_a which represents the value of SMR power at step i.
- Calculate the P_target which represents the value of P_{SMR} for step i+1 without considering the variation limit.
- Calculate Diff value, which represents the difference between pgini and P_target.

$$diff = P_{target} - pgini\_a$$

- Check if the difference respect the limit by the next equation.

$$-\left(\frac{\frac{3}{60}}{100} \cdot Pn \cdot T\right) \leq diff \leq \left(\frac{\frac{3}{60}}{100} \cdot Pn \cdot T\right) \tag{1}$$

With

T, is the step size in seconds.

Pn, is the nominal power of SMR in MW.

- If condition (1) was valid, Limit is respected:

$$Pset = pgini\_a + Diff$$

Quasi-dynamic simulation continue. If (1) was invalid, Limit is not respected.

- Condition (1) invalidity requires following equation (2):

$$Pset = Pgini\_a \pm \left(\frac{\frac{3}{60}}{100} \cdot Pn \cdot T\right) \tag{2}$$

(+) In case $diff$ was positive, and (–) in case $diff$ was negative.

Taking Figure 4.9 as example, the graph slope (T=20 seconds) is respecting the 3% ramping rate. We observe that SMR generation took 16min to reach 10MW, in normal case (without applying QDSL model to SMR) the generation will rise instantly to 10MW at 6am.

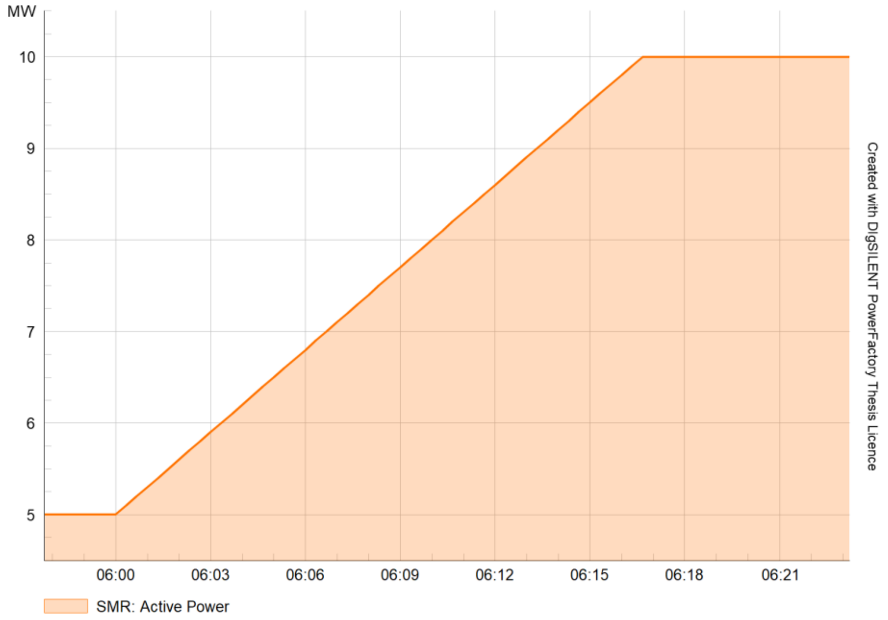

Figure 4.19: SMR ramping rate (Zoomed from Figure 4.8).

As shown in Figure 4.7 *(single-line diagram)* PSH is connected to a secondary busbar (B2S) which is connected to the general busbar (BGS) with Line (1). This was done to treat the PSH as a separate area so we can get shortage and excess calculations from loading on Line (1) and use these calculations to decide the ESS behaviors.

Line (1) loading is equal to the difference between generation and demand and it is represented by ΔP. Positive value of ΔP means there is excess in generation, while a negative value means shortage in generation.

2. Battery QDSL model

Batteries control algorithm is summarized in the following steps [56]:

- Read values of SOC and ΔP.
- The battery behaviors in step i will be based on the states
  - Condition (1)

$$P_{start\ store} \leq \Delta P < P_{store}\ AND\ SOC > SOC_{min} \quad (1)$$

If (1) is valid. Battery will charge.

  - Condition (2)

$$\Delta P = P_{store}\ AND\ SOC > SOC_{min} \quad (2)$$

If (1) is valid. Battery will charge at full power.

  - Condition (3)

$$P_{start\ feed} \leq \Delta P < P_{feed}\ AND\ SOC \leq SOC_{max} \quad (3)$$

If (3) is valid. Battery will discharge.

  - Condition (4)

$$\Delta P = P_{feed}\ AND\ SOC \leq SOC_{max} \quad (2)$$

If (4) is valid. Battery will discharge at nominal power.

Else. Battery will remain inactive.