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Parametric study on a polygeneration grid optimization

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TESI DI LAUREA MAGISTRALE
IN
INGEGNERIA ENERGETICA

Studio parametrico sull'ottimizzazione di una rete poligenerativa

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Abstract

Effective energy management is essential for organizations in all sectors to optimize energy consumption, reduce costs and minimize environmental impact. The thesis presents the EMS developed for the ROBINSON project (Horizon 2020) by the university of Genova. The EMS includes a decision-making system and a model predictive control (MPC) tool for real-time optimization of energy strategies. The decision system considers fuel costs and electricity market prices and uses an optimizer to minimize costs while meeting electricity and heat demand

The EMS integrates various technologies to satisfy the user demands: CHP, boiler, electrolyzer, AD-BES, a gas mixer, and renewable sources. In this thesis various input parameters such as fuel cost, electricity cost, demands (thermal and electrical) were changed to check tool the robustness. According to these parameters the EMS (decision maker and MPC) computed results related to the system operations to satisfy the demands with optimized operation while maintaining integrity of the system.

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1. Introduction

The population of the globe was 1.65 billion people at the beginning of the 20th century; by its conclusion, it had more than quadrupled to 6.1 billion people. The main causes of this rapid expansion were the improvement in medical facilities and technology, which decreased death rates. As of 15 November 2022, the world's population reached 8 billion. While it took 12 years to grow from 6.1 billion to 8 billion and is expected to increase by nearly 2 billion persons in the next 30 years [1] that is from 8 billion to approximately 9.7 billion in 2050 and is expected to touch a mark of almost 10.4 billion persons in the mid-2080s (an indication that the population's total growth rate is pacing down [1]). Furthermore, there is a different distribution of population growth depending on the continent considered.
This increase in population leads to many problems, such as:

- **Increased demand for resources:** As the population grows, so does the need for energy, food, and water. This may cause overuse as well as depletion of resources.
- **Increased Energy demand and Climate Change:** Growth in population also leads to increased demand which results in more use of fossil fuels, thus playing a significant role in climate change.
- **Energy Infrastructure:** Growing population may require significant investment in energy infrastructure such as power plants, transmission lines, grids, etc. As the population is increasing daily to satisfy the demands of current energy infrastructure will require a significant investment in the energy infrastructure sector that includes powerplants, grids, transmission lines, etc.
- **Uneven Distribution:** Population density is not even throughout the planet. Some regions experience rapid growth, and some do not. This may create a challenge as the area where high demand may be least developed.

To cope with this increase, humans need to optimise the use of resources (including energy) so that it has the most negligible impact on the planet's resources and can make sustainable consumption. Though there are, many indicators to assess environmental damage, one of the prominent indicators is ecological footprint. It gives us insight into the impacts of population on the environment and resources. It was introduced in 1990 to study the environmental effects of human activity or human demands on the biosphere [2]. If the trend is not altered in the coming 3.5 decades, we will need almost three earth to support humanity [3].

IEA reported that energy consumption increased by 158% from 1973 to 2018[60]. The problem of future exhaustion of energy sources based on fossil fuels such as coil, gas, and oil and their deleterious effect on climate change can be addressed in many ways, such as greater use of renewable sources (solar, wind, etc.) and better management and service of existing resources and increasing the energy efficiency.

1.1. Energy efficiency

Lowering the quantity of energy needed to provide goods and services is known as efficient energy use or just energy efficiency. For instance, insulating a building enables it to achieve and keep thermal comfort with less heating and cooling energy. It measures how effectively we use energy to produce a given level of service, such as heating or cooling a building, powering a machine, or delivering goods.

Energy efficiency is the quantitative and measurable relationship between a result (in energy terms) achieved with a machine or process. Energy efficiency is also known as the "first fuel" in clean energy transitions as it provides some of the quickest and most-effective ways for CO_2 mitigation options. At the same time, it lowers energy bills and strengthens energy security. Energy efficiency is the most prominent measure to avoid energy demand in net zero emissions by 2050. These measures also shape the global energy intensity - the amount of energy required to produce a unit of GDP which is a crucial measure of the economy energy efficiency [4].

In legal terms, it is described as the proportion of energy used during the process to that which is actually required to produce a given level of work, output, good, or service. Minimising energy waste and lowering energy usage while maintaining the same level of performance or output are both examples of energy efficiency. Energy-saving technology, such those found in LED lighting, well-insulated buildings, and efficient transportation systems, can be used to achieve this. Energy efficiency is important because it lowers energy use, lowers energy costs, and lowers greenhouse gas emissions. It also promotes sustainable energy use and helps to reduce our dependence on non-renewable energy sources [13] (coal, oil, and gas), which can be depleted over time. Overall, energy efficiency is a critical component of efforts to reduce energy waste and address climate change.

1.2. Pollution and its effect on the environment

Pollution refers to the term introduction of harmful materials into the environment. These pollutants can be naturally occurring, such as volcanic ash or introduced into the atmosphere by human activity. These human activities include trash or runoff produced by the factories and many more. Pollutants damage the quality of air, land as well as water [10].

In the 21st century, our lives have become easy because of the advancement of technology. Still, on the other hand, this has taken a toll on our biosphere, such as automobiles, which spew pollutants into the air, and fossil fuels used for electricity and heat generation, which are significant sources of air pollution. Land and water pollution results from producing sewage and refuses materials by residential and commercial properties that harm the ecosystem. According to the latest research done in the Ross region of the Antarctic snow, researchers have found traces of microplastics due to increasing pollution [11].

Pollution (land, water, and air) can have a wide range of severe effects on our biosphere, including all living organisms and their interaction among themselves and the environment. According to data from the World Bank, pollution causes more than 9 million premature deaths, mainly because of air pollution. Air pollution also costs around $8.1 trillion in 2019, almost equal to 6.1% of the Global GDP [12].

1.2.1. Air Pollution

Focusing on human health and how it gets deteriorated by pollution, especially air pollution, has an important role. Various pollutants are present in our atmosphere such as :

- **Particulate Matter**: In the air, there exists a variety of solid and liquid droplets that make up particulate matter. They are characterised according to their size, 2.5 micrometres in diameter being more harmful than 10 micrometres in diameter as they penetrate deep into our lungs and cause many health issues, including cardiovascular and respiratory disease. The leading causes of PM are coal-fired power plants, vehicle exhaust, especially diesel engines etc.
- **Nitrogen oxides:** Nitrogen oxides are gases that are created when fossil fuels are used, mostly in the transportation and industrial sectors. In addition to contributing to smog and acid rain, they can result in respiratory issues.
- **Sulphur Dioxide:** Burning sulphur-containing fossil fuels, such as coal and oil, releases the gas known as sulphur dioxide. Both respiratory problems and acid rain may result from it.
- **Carbon Monoxide:** An odourless gas called carbon monoxide is created when fossil fuels burn partially. High quantities can be dangerous and cause headaches, wooziness, and nausea.
- **Ozone:** When nitrogen oxides and volatile organic molecules combine in sunlight, ozone, a gas, is created. In addition to contributing to smog formation, it can result in respiratory issues.
- **Volatile Organic Compounds:** VOCs are gases generated by various consumer and industrial goods, including paint and cleaning agents. They can irritate the respiratory system and contribute to smog generation as well as unburnt hydrocarbons.

Numerous nations have developed restrictions regulating the emissions mentioned above, air quality standards, and other pollutants to combat the negative impacts of air pollution on human health and the environment. Improved engine efficiency, the promotion of cleaner fuels, and increased reliance on renewable energy sources are all strategies.

1.2.2. Water Pollution

Water pollution contaminates aquatic bodies such as rivers, lakes, seas, and underground water with various substances, chemicals, and microorganisms. Our health is in danger due to this pervasive issue of water pollution; consequently, it kills more people globally than any other violence. According to a study by the Lancet in 2019, water pollution was responsible for almost 1.4 million premature deaths [14].

Some causes of water pollution are:

- **Agricultural:** Agriculture is one of the most prominent reasons for water pollution, especially in places with no or significantly fewer regulations. As for the protection of crops, farmers use pesticides and fertilisers, and they are high in potassium and nitrogen, cause oxygen depletion and lead to vegetation overgrowth. These pesticides and fertilisers get washed away with runoff water and rain mixed with rivers, polluting the water, and killing the fish.

- **Sewage and Wastewater:** Another primary source of water pollution is untreated sewage from households and wastewater from industries that are allowed to flow into the rivers, causing enormous damage to aquatic life and human life.
- **Oil Pollution:** Oil pollution is also a big challenge as, while transportation if oil spills from containers, it makes a layer on the surface of the water due to a difference in viscosity which hinders the sunlight from penetrating the water surface and thus causes issues. Even farms, vehicles, and factories also add to this as, in the end, oil ends up in the seas and rivers.

1.2.3. Land Pollution

Land pollution is the degradation of the quality and safety of soil, water, and air due to the existence or introduction of dangerous substances, chemicals, or other contaminants. Human activities like industrialisation, urbanisation, mining, unsustainable agricultural methods, and improper refuse disposal are to blame.

The ecosystem and human health can be negatively impacted by land pollution in various ways. It can impair air quality, contaminate groundwater, harm plant and animal life, and decrease soil fertility. Humans can develop severe health issues due to land pollution, including neurological disorders, cancer, congenital disabilities, and respiratory diseases. Industrial and manufacturing processes, mining, agricultural practices, and improper waste disposal are typical causes of land pollution. Production and industrial processes can release pollutants.

1.3. Problems related to the increase of CO_2 in the atmosphere

Carbon dioxide (CO_2) is an odourless, colourless gas in our atmosphere. It comprises one carbon atom and two oxygen atoms; the chemical formula is CO_2. Various natural and human activities produce carbon dioxide, including respiration, volcanic eruptions, and burning fossil fuels.

Carbon dioxide is one of the essential heat-trapping gas or GREENHOUSE GAS that comes from burning fossil fuels such as coal, oil, and natural gas from wildfires and biological processes such as volcanic eruptions. Since the beginning of industrial times (18th Century century), human activities have raised atmosphere CO_2 by 50%-meaning the amount of CO_2 is now 150% of its value in 1750. This is greater than what naturally happened at the end of the last ice age 20,000 years ago [5].

The atmospheric concentration of CO_2 (and other greenhouse gases) acts as a blanket or a cap, thus trapping some of the heat that the earth might have radiated into outer space. When sunlight reaches the earth's surface, it absorbs some light energy and then releases it as infrared waves, which we feel as heat. As the concentration of CO_2 in the atmosphere acts as a blanket, it does not allow these waves to escape to outer space, thus trapping them in the earth's atmosphere. CO_2 absorbs energy at various wavelengths ranging between 2000 to 15,000 nanometres. As CO_2 soaks up this infrared energy, it vibrates and then re-emits it half to the atmosphere and half to the earth as heat, thus contributing to the 'greenhouse effect.'

Produced by human activities, it is considered one of the primary greenhouse gasses in the earth's atmosphere (runaway production causes the greenhouse effect, contributing almost 70% to global warming). However, potentially more dangerous greenhouse gases (such as methane, nitrogen trifluoride, and perfluorotributylamine) exist in the atmosphere in much lower concentrations than carbon dioxide. In general, the amount of CO_2 in the atmosphere should be balanced; if not, the overall earth, the temperature will rise, leading to global warming. On the other hand, if the level of CO_2 is limited, then plants cannot do photosynthesis for oxygen production, which again causes problems, and the temperature of the earth then would not be suitable for life on earth.

NOAA laboratories in Mauna Loa, Hawaii, detected 418.22 ppm of CO_2 in December 2022 compared to 416.22 ppm in December 2021 [6]. An increase of 2 ppm compared to 2021. One of the most critical indicators of climate change is the concentration of CO_2 in the atmosphere. According to the data from Maua Loa observatory in Hawaii, the concentration of CO_2 was 280 ppm before the industrial revolution; as of February 2023, the attention has reached 420 ppm, which is significantly higher than at any other time in the past 800,000 years. The increase in atmospheric CO_2 concentration has also been accelerating over the past few decades, from 1.5 ppm in the 1980s to 2.5 ppm per year in recent years.

The adverse effects of increased CO_2 concentration in the atmosphere are:

- **Global Warming:** CO_2 being a greenhouse gas, traps heat that was meant to be released in outer space, thus increasing the atmospheric temperature, which leads to changes in the weather pattern, melting of the polar ice cap and glaciers, rising sea levels, and more frequent and severe weather events such as drought, heatwaves, hurricanes, acid rains, etc.
- **Ocean acidification:** CO_2 dissolves in seawater, thus forming carbonic acid. This decreases the pH level of the ocean, making it acidic acidification can hurt flora and fauna underwater.
- **Changes in plant growth and distribution:** Higher CO_2 levels can enhance plant growth and productivity in some cases, but prolonged exposure may or will have an adverse effect, such as reduced nutrient content, altered species distribution, and increased susceptibility to pests and diseases.
- **Impact on human health:** The impact of global warming, such as heat waves and extreme weather events, can also indirectly and directly affect human health. If nothing is done to control the concentration of CO_2 in the atmosphere, it will have many more adverse effects than what we are experiencing now.
- **Elevated Temperatures:** According to Intergovernmental Panel on climate change (IPCC), if the greenhouse gases continue to rise at the current rate, global temperature could increase by 1.5°C between 2030 to 2052 [7]. This can lead to more frequent, longer, severe heat waves, leading to drought.
- **Sea Level Rise:** As global temperature rises the glaciers and ice caps are expected to melt at an accelerated rate leading to an increase in the sea level and coastal flooding. According to a report by the National Ocean Service, by 2050, the expected sea level rise along the US coastline will be around 0.25-0.30 meters [8].
- **Changes in Precipitation patterns:** Changes in global temperature patterns are expected to lead to altered precipitation patterns, with some regions experiencing more frequent draughts, whereas some are experiencing more rainfall.

- **Changes in the ecosystem:** Changes in climates are expected to result in changing ecosystems as species shift their ranges in response to changing temperatures and other environmental factors, which can lead to reduced gain production at lower altitudes.

Having hypothesised the future consequences, new directives have been imposed by the different governments of the world that foresee the movement of industry towards a low carbon economy; nonetheless, the effect of greenhouse gases will have recursions for the rest of the century.

1.4. The sustainable development

According to the definition of "sustainable development," this means meeting the current generation requirements while preserving future generations' capacity to do the same. It is a holistic approach that recognises the interdependence of social, economic, and environmental factors and aims to achieve a balance between them.

The four pillars of sustainable development are:

- **Social Development:** This pillar emphasises creating an inclusive, equitable, and just society. It is a proactive approach to managing and recognising how business impacts affect employees, workers in the value chain and local consumers/communities. By addressing this issue, it is possible to understand the situation as well as the needs of their workers and work accordingly to provide a better environment for work which in the end will be beneficial for both workers as well as enterprise.
- **Environmental Protection:** This pillar focuses on protecting the natural environment and preserving biodiversity. This includes reducing pollution and greenhouse gas emissions, promoting sustainable land use and resource management practices, and protecting natural habitats.
- **Economic Development:** This pillar emphasises creating a sustainable and thriving economy by ensuring resources are used efficiently and equitably. This includes promoting fair trade practices, investing in small businesses, investing in renewable energy, and providing basic amenities. A possible approach to achieve this is using the circular economy model rather than the linear one. Today most governments are switching towards a circular economy where the emphasis is being made on the traditional way of doing business by pursuing zero waste policy and mindful use of natural resources.
- **Institutional Development:** This pillar emphasises good governance and effective institutions promoting sustainable development. It is necessary to ensure that the resources are managed efficiently and effectively. Institutional development can occur at various levels that are from the local to national and international levels. Overall, it is possible to conclude that institutional development plays a crucial role in sustainable development. Diverse public and private enterprises maintain social balance sheets or sustainability reports and then compare and manage the impacts generated by their economic activities by the United Nations Sustainable Development Goals. The United Nations Department of Economic and Social Affairs has set 17 goals with 169 targets to take care of [9]. A sustainable economy does not just work for profit but also works towards a better quality of life.

The sustainable economy is not oriented only to profit but to well-being and improving the quality of life. Therefore, some international organisations have adopted the so-called 'integrated balance sheet', which combines financial activity reporting with non-financial actions (social balance sheets). In this approach, the concept of sustainability must be a central and fundamental part of all nations' social, economic, and environmental development.

Economist HERMAN EDWARD DALY proposed three rules for sustainable development:

- The use rate of renewable resources must not exceed their regeneration rate [15].
- Introduction of pollutants and waste must not exceed the absorption capacity of the environment [15].
- The withdrawal of non-renewable resources must be offset by producing an equal amount of renewable resources capable of replacing them [15].

To ensure that current requirements are met without jeopardising future needs, this process links the protection and enhancement of natural resources to the economic, social, and institutional dimensions in a relationship of interdependence.

Harnessing renewable energy assets, such as solar, wind, and hydropower, to reduce our reliance on fossil fuels and minimise the impacts of climate change is one example of sustainable development. Countries can reduce greenhouse gas emissions, boost energy security, and generate new employment using renewable energy. Another illustration is sustainable agricultural practices, which involve increasing food yields and helping local communities while using methods to preserve the health of the soil, conserve water, and use fewer harmful chemicals.

In both scenarios, sustainable development encourages long-term advantages for the economy, society, and ecosystem instead of immediate gains that might adversely affect future generations. Governments, corporations, and individuals must support sustainable growth and collaborate to create a more just and resilient future for all.

In conclusion, sustainable development is vital for balancing economic growth, environmental protection, and social equality. Moreover, it also helps create a prosperous and equitable future for all. By prioritising ecological safety, social equity, and economic development, it will be possible to create a more sustainable world that meets the needs of both present and future generations.

1.4.1. Sustainable Development Goals

More than 150 world leaders gathered in September 2015 at the UN to advance environmental protection, human welfare, and global development.

The international community of states has endorsed the 2030 Agenda for Sustainable Development. The fundamental components are the 17 Sustainable Development Goals (SDGs) and 169 sub-goals, which aim to end poverty, combat inequality, and promote social and economic development. Additionally, they address issues vital to sustainable development, like addressing climate change and establishing peaceful societies by 2030.

The SDGs have universal validity, meaning that all countries must contribute to achieve the objectives according to their capabilities.

Figure 1.1 SDGs[63]

Figure 1.1 displays 17 goals that are essential for sustainable development.
A summary of the 17 Sustainable Development Goals is as follows:

- End all forms of poverty in the world.
- End hunger, achieve food security, improve nutrition, and promote sustainable agriculture.
- Ensuring health and well-being for all and all ages.
- Provide quality, equitable and inclusive education and learning opportunities for all.
- Achieve gender equality and empower all women and girls.
- Ensure the availability and sustainable management of water and sanitation facilities for all.
- Ensure access to affordable, reliable, sustainable, and modern energy for all.
- Promote sustained, inclusive, sustainable economic growth, full and productive employment, and decent work.
- Resistant infrastructures, sustainable industrialisation, and innovation.
- Reduce inequalities.
- Make cities and human settlements inclusive, safe, long-lasting, and sustainable.
- Guarantee sustainable models of production and consumption.
- Promote actions at all levels to combat climate change.
- Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
- Protect, restore, and promote sustainable use of the terrestrial ecosystem.
- Peace, justice, and strong institutions.
- Strengthen the means of implementing the objectives and renew the global partnership for sustainable development.

1.5. Programs at the world level

Governments are developing various policies and procedures all over the world to address the situation of rising CO_2 and climate change. For instance, by 2050, the European Union wants to achieve carbon neutrality. The United States has a goal date of 2050, while other nations have set theirs to 2060. This will be accomplished through numerous programs and policies put in place by the governments of other countries, as presented as follows.

1.5.1. Kyoto Protocol

The Kyoto Protocol is an international agreement ratified on February 16, 2006, following its adoption on December 11, 1997, at the Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in Kyoto, Japan. There are 192 parties connected as of right now [16]. The Kyoto Protocol final goal is to reduce greenhouse gas emissions and CO_2 emissions to a point without environmental or climate risk.
Kyoto Protocol was implemented in two phases:

- **The First Commitment period:** This phase ran from 2008 to 2012 and recommended that developed countries reduce their emissions by an average of 5% compared with levels of 1990 [17]. During this period, countries were required to meet their emissions reduction targets through domestic actions or by participating in emission trading.
- **The Second Commitment period:** This phase began in 2013 and is set to end in 2020. It builds upon the first commitment period and includes new emission reduction targets for developed countries. The target for this period is to reduce emissions by at least 18% below 1990 levels. Additionally, some countries have agreed to take on legally binding emission reduction targets for the first time in this phase.

It is important to note that the Kyoto Protocol only applies to developed countries, and developing countries are not legally bound to reduce their emissions under the agreement. However, developing countries are encouraged to take voluntary actions to reduce their emissions, and many have done so through programs such as the Clean Development Mechanism.

1.5.1.1. Doha Amendment to Kyoto Protocol

Doha Amendment is an extension of the Kyoto Protocol adopted at the 18th Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in Doha, Qatar, in 2012 and came into force in 2020. It sets new targets for GHG emission for developed nations to reduce their GHG emissions by up to 18% compared with the level of 1990 for 2013-2020 [19].

The Doha Amendment also established a second commitment period for the Kyoto Protocol from 2013 to 2020. During this time, developed countries that are Parties to the Protocol must meet their emissions reduction targets and report on their progress in reducing greenhouse gas emissions.

1.5.2. Paris Agreement

The Paris Agreement, drafted in Le Bourget, France, replaces the Kyoto Protocol, which was approved in 2015 and entered into force in 2016. This protocol emphasises climate change and is a legally binding accord between 196 nations.

The agreement sets long-term goals to guide all nations[18]:

- Holding the rise in the world's average temperature to well below 2°C over pre-industrial levels is the Paris Agreement's first objective. This is crucial because rising temperatures can have negative effects on ecosystems, infrastructure, and human health by causing more frequent and severe extreme weather events like heatwaves, droughts, and storms.
- The second goal is to increase the ability of countries to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production. This is important because climate change is already causing significant impacts worldwide, such as changes in precipitation patterns, more frequent and severe natural disasters, and changes in the timing and length of seasons, which can have serious implications for agriculture and food security.
- The third goal is to make finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development [39]. This is important because financial resources are needed to support climate action implementation and ensure that countries can transition to a low-carbon economy.
- The fourth objective is to reinforce and improve the transparency of climate action through a strong, expanded transparency framework for action and support, with built-in flexibility to consider the various capacities of the Parties and build upon common experiences. This is significant because ensuring nations implement climate change policies depends on transparency and accountability.

According to the Paris Agreement, nations must take increasingly ambitious climate actions over five years. Each country must file an updated national climate action plan, or Nationally Determined Contribution, or NDC, every five years. Countries outline how to use their NDCs to decrease greenhouse gas emissions to meet the protocol objectives.

The first "global stocktake" will evaluate the Paris Agreement objectives in 2023. This procedure will motivate nations to adopt ambitious climate change measures that keep global temperatures below 1.5 degrees Celsius.

The Paris Agreement encourages nations to develop and submit long-term strategies to frame their efforts toward the long-term objective better. They are not required, in contrast to NDCs.

The UN Climate Change Conference (COP24) in Katowice, Poland, in December 2018 led to adoption the Paris Rulebook, also known as the operational guidelines for implementing the Paris Agreement. The rulebook was finalised at COP26 in Glasgow, Scotland, in November 2021 [18].

1.5.3. Copenhagen Accord

The UNFCCC's 15th Conference of the Parties (COP15), which took place in Copenhagen, Denmark, in December 2009, resulted in the political accord known as the Copenhagen Accord. Although the agreement was not legally binding, it was a significant step in worldwide climate negotiations.

The Copenhagen Accord acknowledged the need to keep world temperatures from rising by more than 2 degrees Celsius and to work toward keeping the rise to 1.5° Celsius [20]. The agreement also acknowledged the significance of developing nations receiving financial and technological assistance to handle climate change and reduce emissions.

Under the Copenhagen Accord, developed countries committed to providing $30 billion in funding from 2010 to 2012 to help developing countries address climate change and reduce their greenhouse gas emissions. The accord also established a goal of mobilising $100 billion annually by 2020 to support developing countries in addressing climate change.

While the Copenhagen Accord was a significant development in global climate negotiations, it did not result in a legally binding agreement. Instead, it paved the way for further talks and discussions on addressing climate change and reducing greenhouse gas emissions globally.

1.5.4. International Solar Alliance

International solar alliance is a treaty-based intergovernmental organisation headquartered in Gurugram, INDIA. It was launched in 2015 at the UNCCC in Paris by the government of India and France. This alliance promotes sustainable energy solutions to reduce GHG emissions and mitigate climate change. As of 2022, the ISA has 89 member countries, including India, Brazil, UK, France, and UAE.

The primary objective of ISA is to promote solar energy use and help its member countries to achieve universal access to solar energy. By 2030 ISA seeks to mobilise investment worth $1 trillion and facilitate the development of solar projects in member countries through partnerships, knowledge sharing, and technical assistance. The organisation has undertaken several initiatives to promote the use of solar energy, such as launching a program to provide solar-powered pumps to farmers in several African countries and establishing a solar atlas to map solar energy potential in member countries [21].

The ISA is a significant global initiative to promote sustainable energy solutions and reduce greenhouse gas emissions, particularly in developing countries.

1.5.5. Horizon 2020

The European Commission established the funding initiative Horizon 2020 to encourage and support studies in the Eurasian Study Area (ERA). It is the eighth Framework Program for Research and Technological Development explained in paragraph 1.6, focusing on innovation, accelerating economic development, and offering end-user solutions, frequently government agencies.

The program aims to complement the ERA by coordinating national research policies and pooling research funding in certain areas to avoid duplication. The Innovation Union and other high-level EU policy projects, like Europe 2020, are being implemented through Horizon 2020.

The European Union's environmental research and innovation seeks to define and make a transformation plan for the green economy and society into reality to achieve sustainable development, which is also being implemented through Horizon 2020. The initiative supports open access to research results to create greater efficiency, improve transparency and accelerate innovation. The European Open Science Cloud project was launched in 2015.

The program ran from 2014 to 2020 and provided funding of around 80 billion euros, an increase of 23% compared to the previous phase. On 25 March 2020, the European Commission announced the allocation of additional funds for 47.5 million euros for the coronavirus emergency.

The program funds research and innovation programs through open and competitive calls for proposals. These requests are available to project ideas from legal entities worldwide. The European Union is strongly urged to participate, and participants from EU member states and affiliated nations are automatically supported for Horizon 2020. The association nations have signed an association agreement for this framework program objectives.

The ROBINSON project, which, regarding this thesis activities, is a component of the European initiative Horizon 2020.

1.5.5.1. Horizon Europe

Horizon Europe is a European Union scientific research initiative lasting 7 years, the successor to the recent Horizon 2020 program and the previous framework programs for research and technological development explained in paragraph 1.6. The European Commission has developed and approved a plan for Horizon Europe to increase EU spending on science by 50% over 2021-2027 [40]. The initiative supports open access to research results to create greater efficiency, improve transparency and accelerate innovation. The European Open Science Cloud project was launched in 2015. As of May 2021, the € 95.5 billion budget for Horizon Europe - whose launch was made in 2021 - is higher than the € 77 billion for the old Horizon 2020 [40].

The final approved funding appears to be much lower after the completion of lengthy negotiations with the European Parliament and EU Member States. In recent years, EU Commissioner Carlos Moedas and many advocacy groups have been pushing for a more expansive EU science budget. In order to build political support for the budget increase, it intends to use the American-born ideas of "moon shots" to focus research efforts and raise public interest [40].

1.6. Technology Readiness Level

Originally devised by NASA in 1974 and later refined, the term Technology Readiness Level which can be translated as Technological Maturity Level, denotes a methodology for determining a technology maturity level. Several American and European organisations presently use it, including the US Department of Defence, NASA, the European Space Agency, the European Commission, and others. It is based on a scale from 1 to 9, with 1

being the lowest value (specification of the fundamental principles) and 9 representing the highest value (the system already used in the operating environment).
In 2013, the International Organization for Standardization (ISO) published its own standard to define the levels of technological maturity and the related evaluation criteria (Table 1.1) [37].

Table 1.1 Technological Maturity Levels according to the European Commission[37]

TRL Level	Description
TRL1	Observe the basics
TRL2	Formulated the concept of technology
TRL3	Experimental proof of concept
TRL4	Laboratory validated technology
TRL5	Technology validated in (industrially) relevant environment
TRL6	Technology demonstrated in (industrially) relevant environment
TRL7	Demonstration of a system prototype in an operating environment
TRL8	Complete and qualified system
TRL9	Real system tested in operational environment (competitive production, commercialization)

1.7. The ROBINSON Project

The ROBINSON project intends to produce integrated energy to assist in decarbonizing (industrialized) islands, better integrating renewable energy sources, enhancing biomass and wastewater, industrial symbiosis, and optimising novel technologies. A gas microturbine based on the combined heat and power unit (CHP), an anaerobic digester assisted by Bio-Electrochemical Systems (AD + BES) to allow the conversion of liquid waste into biomethane, an innovative mobile wind turbine, a gasifier to use organic waste, and other newly developed energy and storage technologies will all be incorporated into ROBINSON Energy Management System (EMS) to support the decarbonization of the islands shown in (Figure1.2)[23].
By lowering CO_2 emissions, this integrated system will guarantee a dependable, affordable, and robust energy source, aiding in the decarbonisation of the European islands [22].

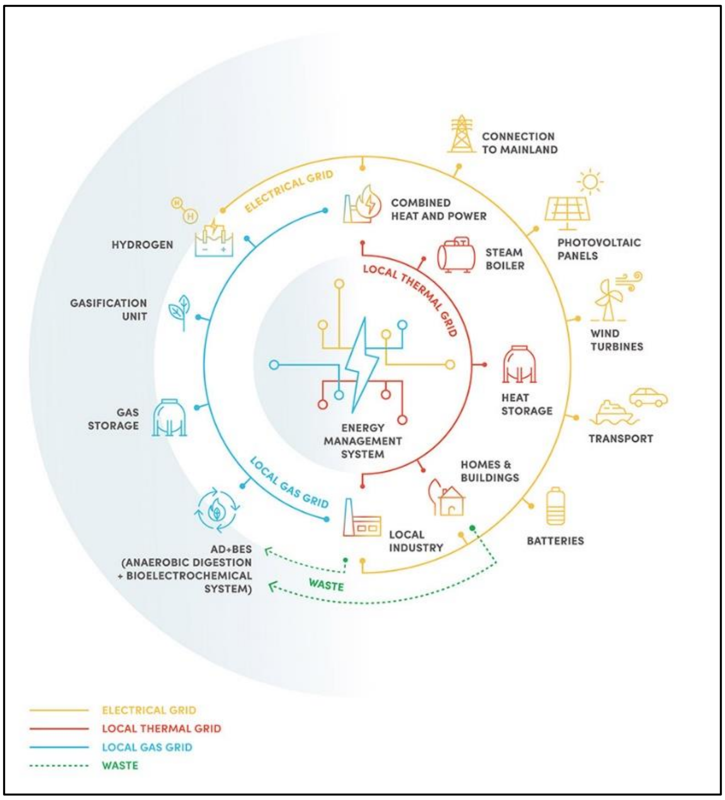


Figure 1.2 EMS System [23]

Due to the geographic island up to ten times higher energy production costs than the mainland, the widespread adoption of local energy sources, renewable energy, and energy storage systems not only benefits the economy but also helps to decarbonize the island energy system, reduce greenhouse gas emissions, and improve, or at least maintain, air quality [22].

1.7.1. Objectives of the ROBINSON Project

Specific technological, socioeconomic, and environmental goals are part of the ROBINSON initiative. Every component of ROBINSON is designed to assist islands in achieving their decarbonisation objectives. While this is happening, ROBINSON helps the islands and Europe by advancing technology, raising living standards, preserving the environment, and being cost and market-competitive.
Various Objectives are [23] reported in the following sections.

1.7.1.1. Technological Objectives

- **Develop and validate a modular and flexible EMS:** ROBINSON will develop an Energy Management System (EMS) considering electrical and thermal needs, weather forecast, electricity cost, demand-side response, and market functions to minimise the system operation. Digital and cybersecurity technologies will be integrated for anomaly detection, interoperability, integrity, and traceability of the collected data.
- **Develop, integrate, and demonstrate a renewable fuel-based CHP unit:** In addition to biological methane and hydrogen, syngas, created when waste wood is gasified, will serve as the primary fuel for Eigerøy combined heat and power (CHP) system. It will

provide dispatchable energy to the local electrical grid and generate process steam using waste heat from a boiler or HRSG (Heat Recovery Steam Generator). A sophisticated gas turbine modified to burn syngas and hydrogen will be at the centre of the cogeneration system. The 400 kWel CHP gas turbine was chosen for its dependability, low running costs, and low maintenance requirements. In order to further reduce NOx emissions to 25 ppm, ROBINSON will also build and modify a specialised combustion system that can burn accessible carbon-free hydrogen and carbon-neutral syngas. Figure 1.3 displays a layout of the CHP pant.

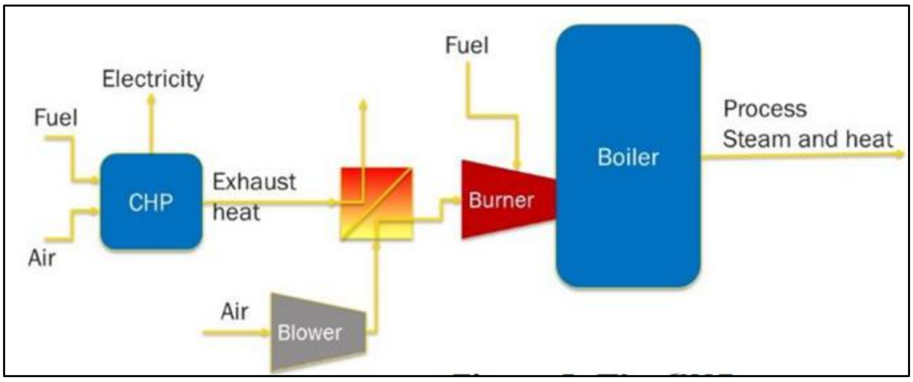


Figure 1.3 Diagram of CHP unit

- **Develop, integrate, and demonstrate an AD+BES:** The Eigerøy fishing industry process wastewater will be effectively treated using anaerobic digestion assisted by a bio-electrochemical system (AD + BES), which will also produce biomethane from the organic matter in the wastewater. With the help of a bio-electrochemical system, this technique comprises of an anaerobic digester that treats wastewater more effectively while also producing more biomethane by enhancing microbial activity thanks to the electrode electrical supply. Due to the high process efficiency, great flexibility, and availability of biomethane, AD + BES provides a dependable seasonal chemical energy storage alternative for excess renewable energy. Figure 1.4 [35] displays the representation of AD-BES system.

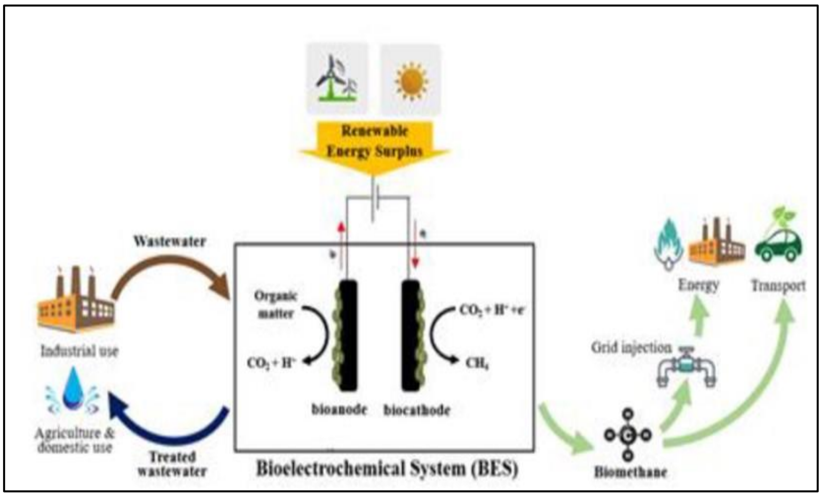


Figure 1.4 Diagram of an AD+BES system

1.7.1.2. Demonstration Objective

- **Demonstrate the large-scale applicability of the ROBINSON system:** The integrated ROBINSON system, including the novel technologies and the validated EMS software, will be demonstrated on the island of Eigerøy (Norway). Eigerøy existing infrastructure and pre-installed technologies will be combined with new technologies to allow energy balancing and storage for different time scales.

1.7.1.3. Environmental Objectives

- **Reduction of fossil fuel consumption:** The objective of ROBINSON will be to prove that, once fully operational, it will enable a 100% coverage of the current and future energy demand of the demonstrating island with non-fossil resources and associated technologies.
- **Demonstrate a significant positive impact on human health and the environment:** ROBINSON aims to substantially affect human health and the environment by increasing the share of RES sources in power and heat generation and enabling sectorial integration and industrial integration symbiosis.

1.7.1.4. Socio-Economic Objectives

- **Reduction of energy costs:** The deployment of the ROBINSON system will allow islands to reduce their levelized cost of electricity by maximising the use of RES and avoiding expensive infrastructure costs of the transmission grid.

- **Demonstrate the replicability of the system:** In close collaboration with local communities and other European actors, ROBINSON will demonstrate the replicability of the design on the two follower islands while ensuring wider dissemination of the project.

1.7.2. Impacts of the ROBINSON project

ROBINSON will contribute to a healthy, fossil-fuels independent society with increased employment opportunities. By reducing CO_2 and NOx emissions, ROBINSON will directly improve the quality of the air that Europeans breathe, having a positive impact on reducing the number of respiratory diseases and other negative impacts on human health. Secondly, ROBINSON will contribute to mitigating the EU islands' dependency on imported fossil fuels, thus increasing the independency of islands communities, and supporting decarbonisation. Moreover, this will help create new sustainable job opportunities transforming local communities from consumer into prosumers. Finally, thanks to its multi-sectoral and multi-actor outreach, ROBINSON will contribute to the low-carbon targets as set by the EU's Energy Union, and by the Paris Agreement [35].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 957752[22]. This project has a budget of €8.37 million. The period of this project is from October 2020 – September 2024, and there is a total of 18 partners and 10 European countries involved.

2.Power grids, energy Storage and hydrogen

A power grid is a complex system that distributes electric power from generation facilities to consumers. It consists of a network of interconnected power transmission lines, transformers, substations, and other electrical equipment (Figure 2.1 [24]) that work together to ensure a reliable and efficient delivery of electricity to homes, businesses, and other facilities.

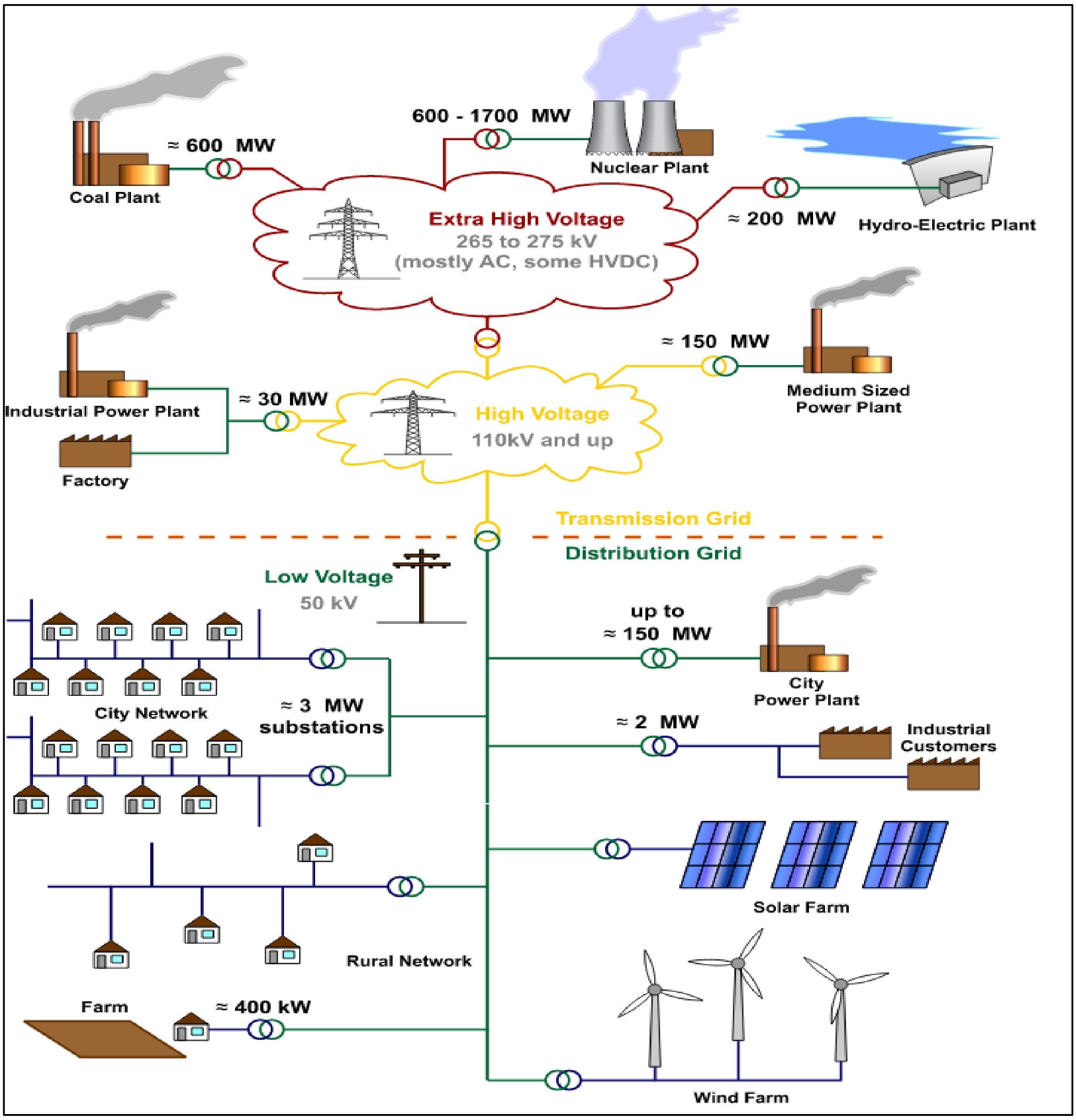


Figure 2.1Power Grid[24]

Power grids can be divided into three main components.

- **Power generation**: The term "power generation" refers to the process of producing electrical energy through the burning of fossil fuels (coal, natural gas), nuclear fuel, and renewable energy sources (solar, wind, and hydro). High-voltage transmission lines transmit the electricity generated during power generation over significant areas.

- **Power transmission:** Getting electrical energy from power generation facilities to local substations over great distances is known as power transmission. The transmission system usually runs at high voltages between 110 kV and 765 kV to reduce energy losses during the long-distance transfer of electricity.
- **Power Distribution:** Power distribution is the final stage of delivering electric power to end users such as homes, businesses etc. This is achieved with the help of local distribution networks that include transformers, distribution lines and other equipment that help lower the voltage level suitable for end-users.

2.1. Conventional Grids

A traditional power grid, also known as a conventional power grid, is a centralised electricity generation and distribution system that has been in use for many decades. The traditional power grid typically consists of large-scale power plants, such as coal-fired, natural gas, or nuclear power plants, that generate and transmit electricity over long distances using high-voltage transmission lines. The electricity is distributed to homes, businesses, and consumers through low-voltage distribution lines and transformers.

Though traditional grids have successfully provided a reliable and affordable electricity supply to millions of people around the globe for decades. However, there are some limitations as well as challenges, such as:

- **Limited flexibility:** Traditional power grids are designed to operate on a one-way flow of electricity, with power flowing from large, centralised power plants to consumers, thus making it difficult to integrate renewable energy sources (solar or wind power), which are more distributed and intermittent.
- **Vulnerability to disruptions:** Traditional power grids are vulnerable to disturbances, such as extreme weather events, cyber-attacks, or equipment failures, which can cause widespread power outages and economic losses.
- **Environmental impacts:** Traditional power plants can have a significant effect on the environment, such as air and water pollution, greenhouse gas emissions, and land use changes.
- **Cost:** Building and maintaining traditional power grids can be expensive, particularly in remote or hard-to-reach areas, making electricity more expensive for consumers.

There is a growing interest in developing more flexible, resilient, and sustainable power grids, such as smart grids, microgrids, and decentralised renewable energy systems, to address these challenges.

2.2. Smart Grids

The need for more efficient and reliable transmission and distribution networks to integrate the growing proportion of power plants using renewable sources paves the way for the new concept of Smart Grids. Smart Grids are modern “active” grids designed to gather and exchange information and energy [31]. Smart Grid is an electrical grid with automation, communication, and IT systems that can monitor power flows from points of generation to points of consumption (even down to the appliances level) and control the power flow or curtail the load to match generation in real-time mode. Smart Grids can be achieved by implementing efficient transmission & distribution systems, system operations, consumer integration and renewable integration.

Smart grid solutions can contribute to reducing T&D losses, peak load management, improved quality of service, increased reliability, better asset management, renewable integration, better accessibility to electricity etc. and lead to self-healing grids[25].

Some features of smart grids are:

- **Real-time observation:** Real-time observation of a smart grid is an essential feature that enables the grid operators to monitor and control it in real-time, ensuring that it operates efficiently and effectively. This can be achieved by advanced metering infrastructure (AMI) and sensors placed throughout the grid, thus providing real-time information about energy consumption, voltage levels and other important parameters allowing grid operators to monitor and manage energy flow.
- **Enhanced market optimization[41]:** Enhanced market optimization of the smart grid can have benefits for both energy providers as well as consumers. It can lead energy providers to a more efficient and effective energy market operation. It can help energy consumers reduce energy costs and wastage and incentivize energy efficiency. Smart grids use this market concept to optimize energy use and production throughout a 24-hour cycle because the price is a key factor in determining the demand for any resource or good. Demand Response and Dynamic Demand are the two main technologies powering this. By programming devices to alter their energy use in response to grid needs, these technologies use sensors to balance or "even out" supply and demand within a smart grid.
- **Broader energy generation [41]:** Although switching to low-carbon, renewable energy sources have long been advocated to reduce dependency on fossil fuels. Efficiency problems have severely impeded this transition. For instance, the average global efficiency of wind power is 38% [42], while that of solar photovoltaic (PV) is less than 20% [42], significantly lower than coal or fossil fuels. This gap can be filled thanks to smart grids improved demand flattening. During periods of high generation, an additional load can be taken on through demand response and dynamic demand. The greatest boost for renewables will come from battery and hydrogen conversion technology advances, which will enable substantially higher energy capture. Adopting large-capacity energy storage technologies, such as pumped storage, considerably improves grid power resiliency.

2.2.1. Description of smart grids

The completely automated high and extremely high-voltage electricity transmission network can handle power plant failures or service outages while dispatching is ongoing. The medium and low voltage distribution network must be intelligent to handle voltage peaks and dips brought on by a distributed generation of electricity.

To maintain consistent dispatching alongside production power plants, this must be done in self-producing facilities that utilise renewable energy sources with erratic characteristics, such as wind and photovoltaic energy.

Traditional power networks are designed to produce reliable and consistent electricity to meet demand; nevertheless, this can lead to inefficiencies and waste, particularly during periods of low demand. Smart grids, on the other hand, are able to dynamically modify energy production and distribution to meet the fluctuating energy needs of consumers in real time. The tools for integrating renewable energy into these grids and smart monitoring tools that keep tabs on the system overall electrical flow are all used to manage these grids. Appropriate management software also controls the information flow in these systems.

An infrastructure or ICT (Information Communication Technology) layer must be built over or alongside the electrical grid to respond properly to energy demands. This layer will connect the self-generation plants on the distribution network with the centralised high-power plants, exchanging data about the energy produced and, as a result, regulating the dispatching of energy. This architecture can use the power network itself to transmit information or an ad hoc TLC network infrastructure. (e.g., powerline technology).

The smart grid, often referred to as the "intelligent grid" or "widespread generation," is essentially a development of the electrical grids that, during the 20th century, have typically "distributed" energy from a few generators or power plants to a sizable number of customers. The development of intelligent electricity distribution and management systems is being pushed by several governments worldwide to achieve energy independence and combat global warming.

To fulfil the different requirements of the Smart Grid, the following enabling technologies must be implemented.

2.3. Microgrids

A microgrid is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to operate in grid-connected or island mode. Microgrids can improve customer reliability and resilience to grid disturbances[27].

Microgrids are localized grids that can disconnect from the traditional grid to operate autonomously. Because they are able to operate while the main grid is down, microgrids can strengthen grid resilience and help mitigate grid disturbances as well as function as a grid resource for faster system response and recovery. Microgrids support a flexible and efficient electric grid by enabling the integration of growing deployments of distributed energy resources such as renewables like solar. In addition, the use of local sources of energy to serve local loads helps reduce energy losses in transmission and distribution, further increasing efficiency of the electric delivery system[28].

The Consortium for Electric Reliability Technology Solutions (CERTS) initiative in the United States and the MICROGRIDS project in Europe were the first systematic research and development initiatives. CERTS was established in 1999, and it has been acknowledged as the pioneer of the contemporary grid-connected microgrid concept. To overcome perceived barriers to DER integration, it envisaged a microgrid that could integrate several DERs while appearing to the existing grid as a regular consumer or small generator. Passive control techniques like reactive power vs voltage, active power versus frequency, and flow versus frequency were highlighted together with seamless and automatic islanding and reconnection to the grid.

The goals of these strategies were:

- To remove reliance on high-speed communications and master controllers, yielding a “peer-to-peer” architecture.

- To lower the initial costs of the system and ensure the freedom to position CHP plants adjacent to the thermal loads, create a flexible "plug-and-play" system that does not require major redesign with the addition or removal of DERs.

Figure 2.2 shows the structure of a microgrid.

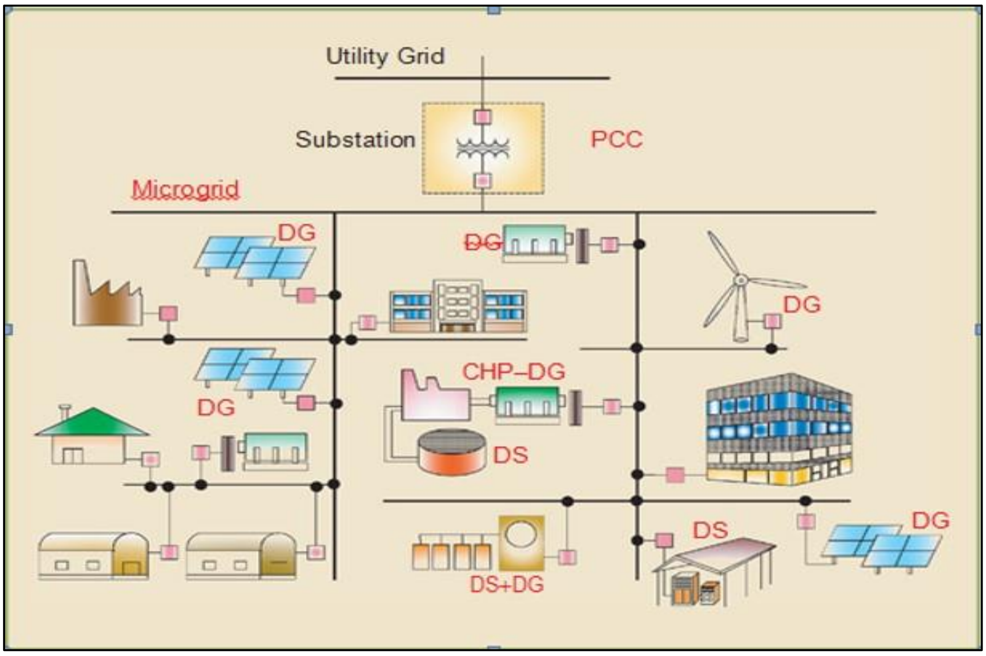


Figure 2.2 Microgrid Structure

2.3.1. Characteristics of microgrids

- **Microgrids are local:** This is a form of local energy, meaning it creates energy for nearby users. This is the key difference between microgrids and centralized grids. A microgrid overcomes this inefficiency by generating power near the users as transmission losses can be up to 15%[43].
- **Reliance on renewable energy sources:** This is because renewables have a less environmental impact and cause less pollution than the energy produced by burning fossil fuels. They can help reach energy to geographically constrained areas as microgrids can also be designed to work independently. Though setting up a renewable energy system can be expensive once they are running, it can generate electricity at a price cheaper than fossil fuels.
- **Integrated energy storage:** This can lessen the effects of power disruptions and guarantee the availability of vital services. One of the advantages of energy storage also that it can reduce costs by allowing microgrids to sell surplus energy back to the main power grid during times of high demand. This can compensate for the cost of the energy storage system and make microgrids more economically sustainable.
- **Advanced control systems:** These control systems use advanced technologies to monitor and optimize energy production, storage, and distribution in real time. Intelligent software forecasting energy demand and production is a key component of advanced microgrid control systems. The advanced control systems can also help detect disruptions in real-time and respond accordingly.

2.3.3. Implementation

Despite writing much about the concept and promise of microgrids, many can also learn from examples of real, working microgrids, according to Navigant Research, which has been monitoring microgrid deployment since 2011. The United States was the historic leader in deployed capacity; today, the United States and Asia are approximately one the same operating capacity. In the future, the microgrids proposed and under development will lead to satisfying 42% of the market[32]. In the other cases, the forecasts affair smaller percentages. For example, Europe has 11%, Latin America 4%[32], and the Middle East and Africa currently have only 1%[32]. Total capacity was around 1.4 GW in 2015 and is expected to grow to around 5.7 GW (considered a conservative estimate) or 8.7 GW (in an "aggressive" scenario) by 2024[30,45]. Navigant splits the market microgrid into the following segments (with% of total distributed electricity capacity starting from the first quarter of 2016): Remote (54%), Commercial / Industrial (5%), Community (13%), Utility Distribution (13%), Institutional / Campus (9%) and Military (6%)[30,46]. It should be noted that Navigant Research does not track remote microgrid systems based on diesel generators; to be considered, they must include at least one renewable generation source. Although describing different microgrid applications here is impossible, some examples are given in the following sections.

2.3.4. Classification of microgrid

Microgrids can be classified based on several factors, such as their size, source of energy, mode of operation, control strategies, and application. Here are some common classifications of microgrids.

2.3.4.1. Size based/operation mode classification

- **Residential microgrids:** These microgrids are made to provide electricity to a single residence or a small cluster of homes.
- **Community microgrids:** These microgrids are made to support residential areas or small villages, and they generally demand more power than residential microgrids and need more complex control systems.
- **Institutional microgrids:** These microgrids are designed to supply power to a single institution like a hospital or a university campus.
- **Commercial microgrids:** These microgrids are made to provide energy to industrial or commercial buildings, and they often need much power and must be extremely reliable and resilient.

In reality, many microgrids can alternate between operating islanded and connected to the grid, depending on the circumstance. The decision between grid-connected and islanded microgrids ultimately comes down to many variables, including the amount of energy needed, the location, the cost, the reliability, and the environmental impact. Every type of microgrid has advantages and disadvantages of its own, and the particular decision depends on the objectives and specifications of the microgrid project.

2.3.5. Smart Polygeneration Microgrid in Savona Campus

The smart polygeneration (SPM) has been developed by the University of Genova at Savona Campus and awarded the European Electricity Grid Initiative EEGI Label, an important sustainability acknowledgement at the international level [31]. The SPM project began in 2010 between the University of Genova and the Italian Education Ministry, University and Research being the public body funding the project [32,47].

The SPM at the Savona campus is a 3-phase low voltage (400V line to line) ‘intelligent’ distribution system and permits optimizing thermal and electrical consumption, CO_2 emissions, annual operating cost, and primary energy usage. The overall system is monitored from a control room where the signals coming in real-time from field sensors are stored and analysed to regulate all the equipment and devices and determine optimal management strategies [32,47].

2.3.5.1. SPM technologies

The SPM consists of (see figures 2.3 and 2.4)

- 3 CHP fed by natural gas
- 1 PV field
- 1 refrigerating and absorbing plant
- 2 boilers fed by natural gas
- 2 electrochemical/thermal storages
- 2 electrical vehicle recharge stations
- Electrical battery storage

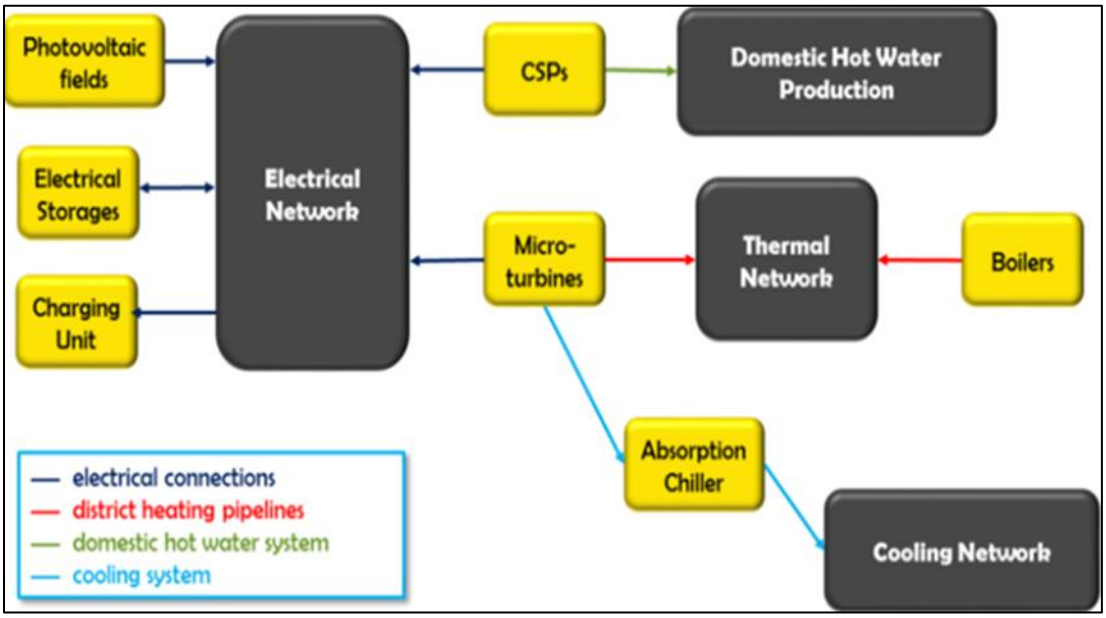


Figure 2.3 SPM Components[31]

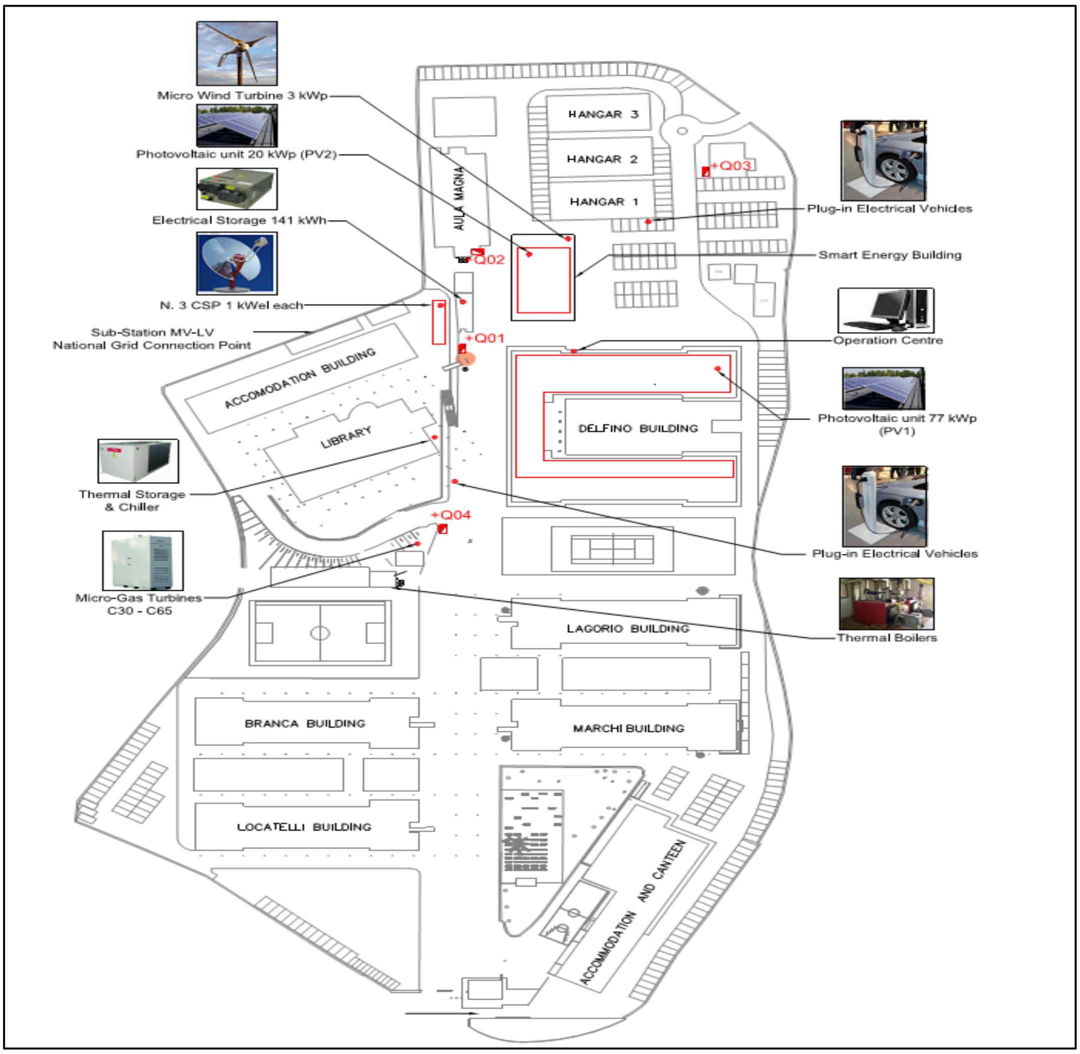


Figure 2.4 SPM Layout[48]

2.3.5.1.1. The micro-CHP gas turbine

The significant amount of demand (electrical thermal) is satisfied by the installed micro-CHP gas turbines. The characteristics of turbines are provided in the table 2.1 below[32].

Table 2.1 The micro-CHP gas turbine data

Rated electrical power	65	kW_{el}
Rated thermal power	112	kW_{th}
Fuel consumption	23	m^3/h
Exhaust gas mass flow rate	0.49	kg/s
Overall efficiency	85	%
Electrical efficiency	29	%
Exhaust gas exit temperature	309	°C

2.3.5.1.2. The photovoltaic unit

The photovoltaic unit is installed on the roof of a building inside the campus that covers a total area of 400 m^2 depicted in figure 2.3 and the technical data is presented in table 2.2 [32].

Table 2.2 The PV installation data

Rated power	49.9	V
Estimated annual energy production	58.0	MWh_{el}
Tilt angle	30	deg
Azimuth angle	-30	deg
Module efficiency	14.5	%
Open circuit voltage	37.92	V
Short circuit voltage	8.63	A
Cell voltage at maximum power	27.73	V
Cell current at maximum power	8.08	A

2.3.5.1.3. Absorption chillers

Two absorption chillers are also deployed to cool the library during the summer. As a result, it can use the cogeneration gas turbine during the summer without releasing high-temperature gas into the atmosphere. The exhaust gas will give the heat input to the systems at the exit of the gas turbine. A cooling tower will be connected to the two absorption chillers to transport the waste heat to the ambient temperature. Each absorption chiller is characterized by the main technical data reported in table 2.3 [32].

Table 2.3 Absorption chiller data

Cooling capacity	32.5	kW_{th}
COP	0.75	-
Thermal power output	43.3	kW
Hot water inlet temperature	70/95	°C
Cooling water inlet temperature	25/40	°C
Chilled water minimum temperature	6	°C

2.3.5.1.4. Boilers

There are two boilers installed at the Savona Campus with a total capacity of 400 kW_{th} each which will help to satisfy thermal demand along with heat pumps and CH. All the buildings at the campus have centralized air conditioning system whereas the hangers are neither equipped with air conditioners nor heating system.

2.3.5.1.5. Electrical Storage

The installed electrical storage system is based on high-voltage sodium-nickel batteries that will make the SPM flexible. The storage capacity is about 100 kWh. These batteries are known as 'SoNick' batteries. The anode is composed of molten sodium, and the cathode is composed of nickel chloride ($NiCl_2$). The electrolyte used is beta-aluminum and is of tubular type. The battery system will be monitored in real time, and the main purpose of the storage system is to balance power and demand with the generation, reduce problems related to variability and intermittency of renewable sources and provide the initial energy required for the transition between grid-connected and island operation mode [32].

In conclusion SPM offers a promising solution to satisfy energy demands (electrical and thermal) in a sustainable, efficient, and cost-effective manner. By combining multiple energy technologies, promoting sustainability, and enhancing energy security, these microgrids can transform the energy industry and offer a cleaner, more efficient, and more secure way of generating and distributing energy.

2.4. Energy storage and its importance

On a bright sunny day, solar cells will produce significant electricity that can be fed to the grid. However, if there is a change in weather and clouds appear, power output will drop suddenly. More fluctuating energy sources, such as solar and wind, are connected to the smart grids, making it more difficult to manage the grid and ensure stability. To prevent any disturbance, supply and demand should always be balanced. From this context, energy storage will be crucial in maintaining the balance between demand and supply [49]. So, if electricity is not needed at a given time, the energy storage can feed it back to the grid. Different types of energy storage options are available but the most widely used is 'Battery'.

The load levelling, represented by peak cut or peak shift, power system stabilisation as an adjustment force, and response to emergencies are all components of the battery-storage system in the smart grid. As shown in figure 2.5 [33], storage batteries for smart grid operation can be stationed next to generators, inside power system facilities, or inside user facilities.

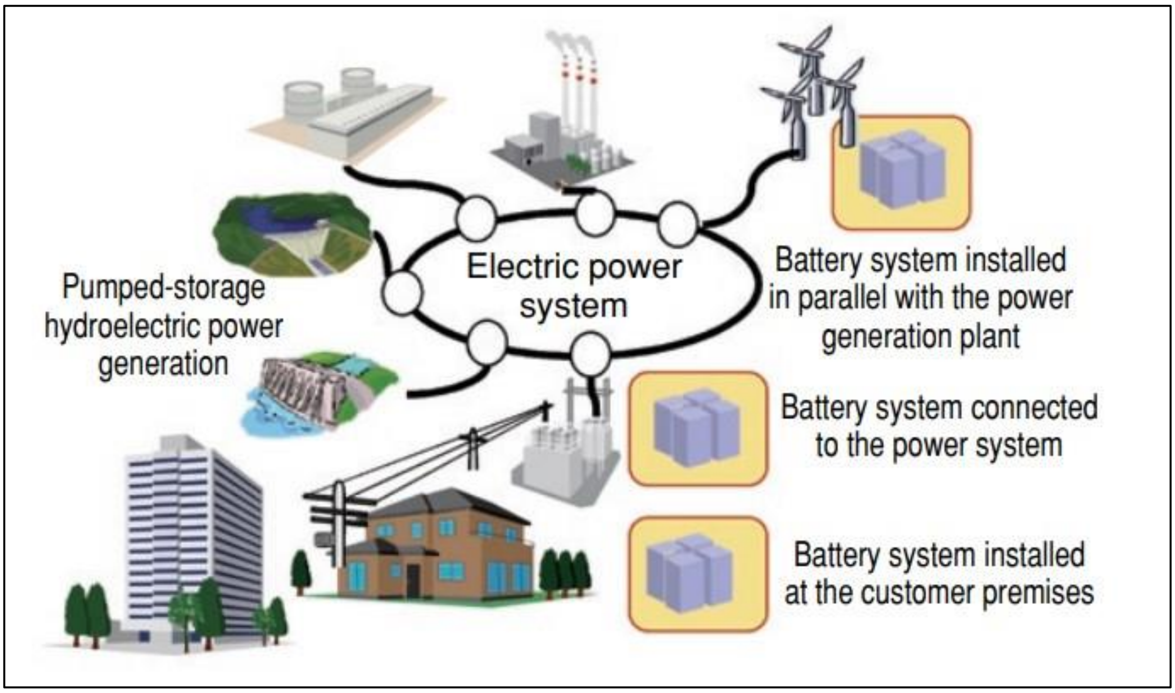
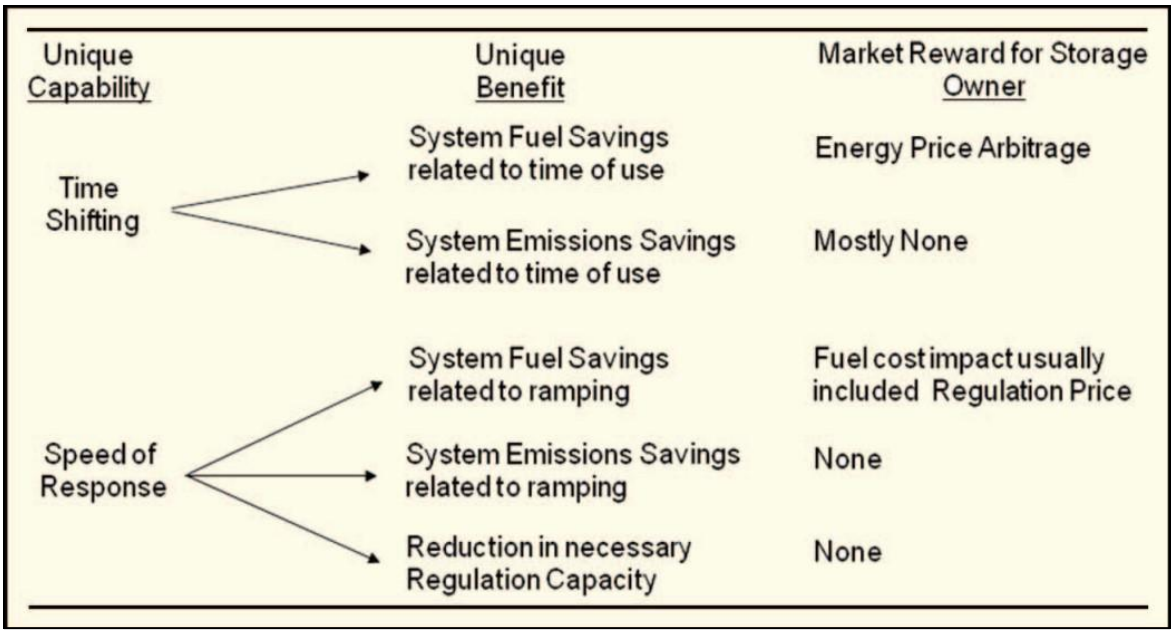


Figure 2.5 Smart-grid battery system[33]

Batteries use an electrochemical process to store power, transforming it into chemical energy when necessary and back again. These days, lithium-ion batteries are extensively utilised and are the energy storage technology with the fastest growth. This is because they have a high energy density, a long lifespan, and are ecologically friendly.
The two main benefits of electricity storage are shown in figure 2.6 [50].



Unique Capability	Unique Benefit	Market Reward for Storage Owner
Time Shifting	System Fuel Savings related to time of use	Energy Price Arbitrage
	System Emissions Savings related to time of use	Mostly None
Speed of Response	System Fuel Savings related to ramping	Fuel cost impact usually included Regulation Price
	System Emissions Savings related to ramping	None
	Reduction in necessary Regulation Capacity	None

Figure 2.6 Benefits categories of energy storage[50]

Electricity can be divided into three parts: generation, transmission, and distribution and storage application can help us in all three parts. Applications for energy storage can be found across the entire grid and can be useful for enhancing the system as a whole shown is figure 2.7 [34].

Storage in generation can help us in addressing the issue of stability as it can help in providing electricity when the demand is high than the current supply or at a time when renewables are not generating electricity, or at a time when there is any disruption in traditional network whereas on the transmission side energy storage can help in stabilising the grid, postponing the grid upgrade as well as provide steady electricity supply. Energy storage applications can also be applied in the distribution sector, such as backup power during power outages, microgrids, and reducing customer demand charges by providing additional power during peak periods.

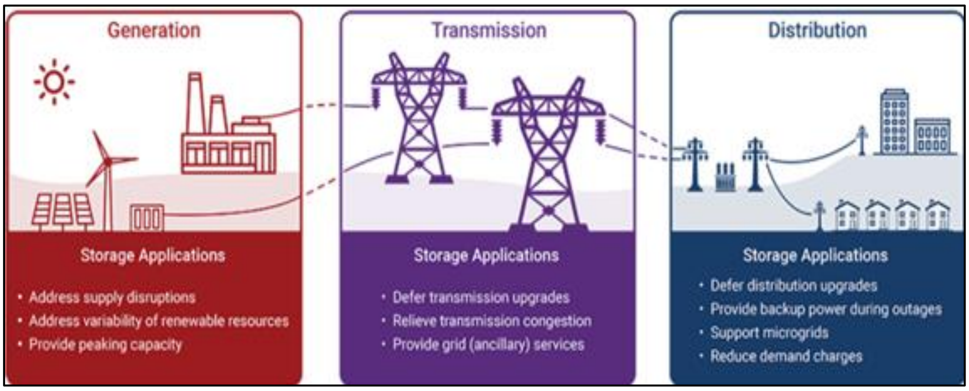


Figure 2.7 Storage application in different parts of the grid[34]

2.4.1. Hydrogen as an energy vector and its importance

Energy vectors are energy carriers that transport, store and can convert energy from one form to another. In general, energy vectors can be classified into three categories based on their physical state: solid, liquid, and gas. Energy vectors are essential to the energy system because they allow energy to be stored and transported from one place to another. This is important in case of renewable energy sources, which can be intermittent. For example, wind and solar power are only sometimes available when needed. However, if the energy generated from these sources can be stored using an energy vector, it can be used later.

Hydrogen is an energy vector not an energy source and can deliver or store huge amount of energy. It can be used in fuel cells to generate electricity or power or heat. Nowadays the main application of hydrogen is in refining petroleum and manufacturing fertilizers whereas in transport sector it is still emerging.

Though hydrogen is the most abundant element on earth [51] and can store and deliver energy that is usable, but it needs to be produced from other compounds as typically it doesn’t exist in nature by itself. Hydrogen can be produced from various sources such as fossil fuels (typically natural gas), renewable energy such as hydropower, solar and wind. Most prominent process to produce hydrogen is stem reforming a high temperature process. Another process is electrolysis of water in which water molecule splits in hydrogen and

oxygen. Biological process is being also used to produce hydrogen with the help of bacteria and microalgae. Many other processes exist such as thermochemical splitting of water, high temperature decomposition etc.
Figure 2.8 this various methods to store hydrogen [55].

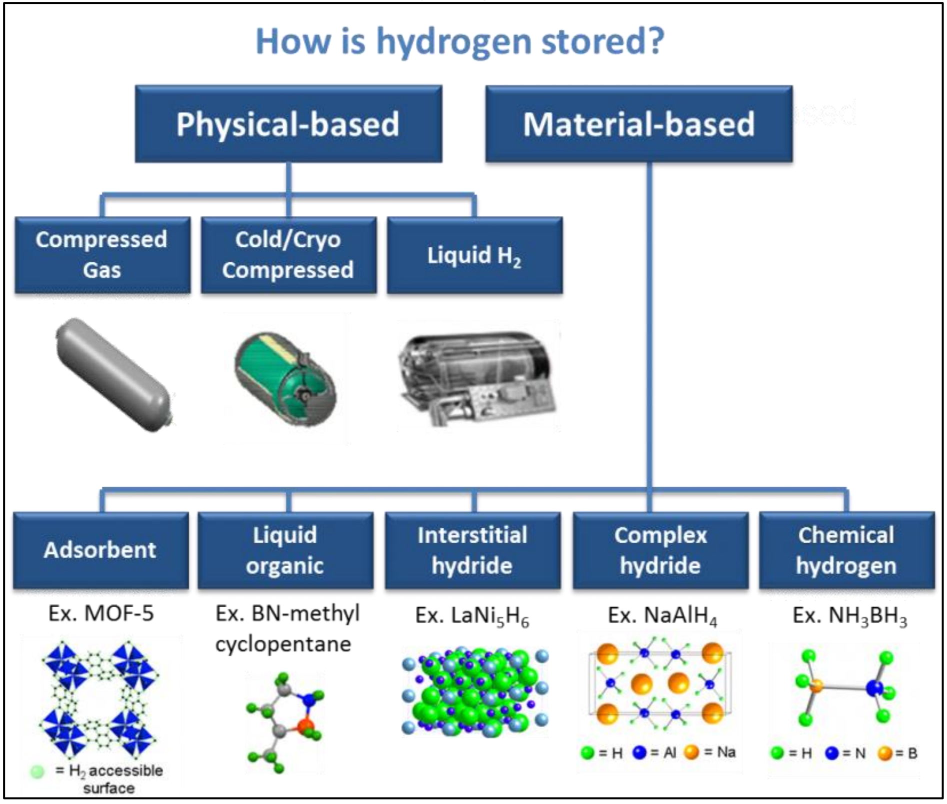


Figure 2.8 Hydrogen storage methods[55]

Hydrogen can be stored either in gaseous or liquid form or it can be stored with some materials.
Gaseous form of hydrogen can be stored in composite tanks under a pressure of 350-700 bar whereas liquid form of hydrogen can be stored at cryogenic temperatures to prevent it from boiling back to gaseous form that occurs at a temperature of -252.8°C and a pressure of 2-3 bar [52]. Chemical storage is another way of storing hydrogen in which hydrogen is generated through chemical reaction. Various materials are used such as Ammonia, metal hydrides, formic acid, carbohydrates, and liquid organic hydrogen carriers (LOHC).

Ammonia (NH_3) is the second most commonly produced chemical [53], and it can be reformed to produce hydrogen with no harmful waste or mixed with existing fuels and burnt efficiently. Ammonia has the significant benefit of producing no CO_2 emission at the end compared to hydrocarbons. The Haber-Bosch process is used to synthesize ammonia, where atmospheric nitrogen (N_2) is converted to Ammonia (NH_3) by reacting it with hydrogen (H_2) using a catalyst and under high temperature. Whenever there is a requirement for hydrogen, ammonia can be cracked, a process in which ammonia is heated in the presence of a catalyst, and by-product, nitrogen is released back into the atmosphere.
Methanol can also be used as an energy vector for hydrogen. The process involved is known as reforming, in which methanol (CH_3OH) is reacted with steam at a temperature ranging from 240-350°C, thus producing hydrogen with a purity of around 97% [54]. Methanol can be produced from various resources such as natural gas, CO_2, biomass etc.

Besides ammonia, metal hydrides can also store hydrogen by binding hydrogen to a metal to create a solid-state storage material. Thus, it becomes one of the safest and most efficient ways to store large amounts of hydrogen in a compact space, and whenever these metal hydrides are heated, they release hydrogen. One of the limitations of this method is that it requires high temperatures, and the process can be slow.

Hydrogen as an energy vector has its problems. Cost of production is one of the key obstacles. The cost of producing hydrogen currently exceeds that of conventional fossil fuels. However, as more effective production techniques are created, and economies of scale are attained, this cost is anticipated to decrease. The transportation and storage of hydrogen provide another difficulty. Due to its great flammability, hydrogen must be properly kept and transported. This need for specialised infrastructure and tools can be costly to construct and maintain.

In general, hydrogen is a promising energy source that has the potential to be very important in the shift to a more sustainable and clean energy system. While certain obstacles remain to be addressed, continuous research and development activities are attempting to find solutions and make hydrogen a more useful and affordable energy source.

3. Energy Management System and its components

Nowadays, effective energy management is a key priority for organizations in all industries. Rising energy costs, growing environmental concerns and the need for sustainable practices underscore the importance of optimizing energy consumption. An energy management system (EMS) is a comprehensive framework for monitoring, controlling, and optimizing energy-related activities, including policies, processes, and technology that systematically monitor, analyse, and improve energy efficiency. Implementing an energy management system can bring several benefits to an organization. Reducing energy consumption and improving operational efficiency can result in significant cost savings. Organizations can improve resource efficiency and minimize environmental impact by identifying and eliminating inefficiencies. EMS can also help organizations to meet regulatory requirements, achieve sustainability goals, and remain competitive. Key elements of an energy management system include collecting and monitoring energy consumption data, energy audits, goal setting, energy conservation measures, employee participation, and tracking results. By integrating these elements, organizations can develop a holistic approach to energy management and achieve long-term success. In addition, established frameworks, and standards, such as ISO 50001, guide effective energy management practices, ensure best practices, and demonstrate a commitment to sustainable energy management.

This chapter presents an EMS system with different components developed using MATLAB® and SIMULINK® for the ROBINSON project and an intelligent grid with highly integrated renewable energy sources. Using a state-space modelling approach [56], various components such as CHP, boilers, and electrolyzers were developed and the various elements were controlled to optimize energy generation [56]. In the ROBINSON project, each component was analysed as a black box and no internal performance was considered, only overall functionality.

3.1. The Energy Management System

An energy management system (EMS) is a system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation or transmission system. Also, it can be used in small scale systems like microgrids [58,59]. The EMS developed for the ROBINSON project aims at controlling the smart grid system in such a way that it integrates all the energy sources around it while minimizing the cost as well as managing the hydrogen vessel. It also aims to satisfy the user demands as well as carry out robust control in real-time mode [56,57].

The EMS must control generators and storage batteries and select the optimal energy strategy in real-time mode. Selecting the optimal energy strategy that minimizes OPEX while meeting user needs is the approach used in this analysis. Figure 3.1 [57] shows the layout of the EMS and it is constituted by a block named decision maker-market function and an MPC controller. The inputs necessary are demands (electrical and thermal), the fuel cost as well as cost of electricity market.

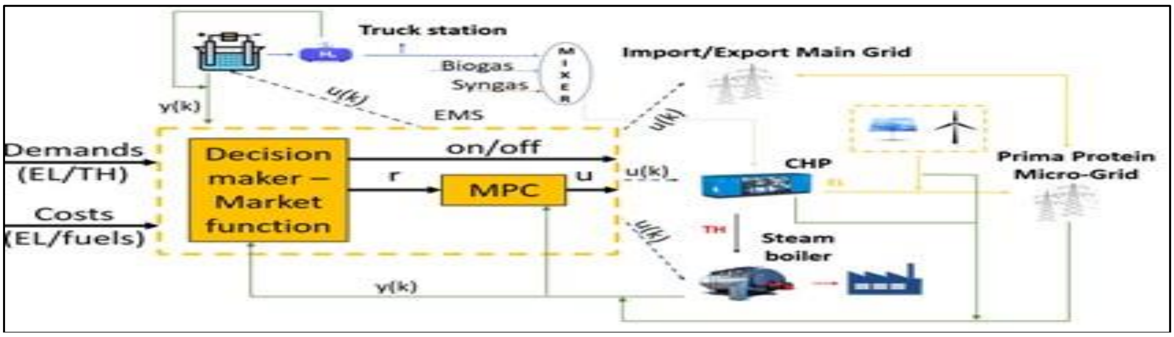


Figure 3.1 The Global Layout of the EMS with interaction with stimulated components [57]

Based on the demand curves, the decision maker will optimize the best energy strategy with a time step of 15 minutes, which will define the set points r shown in Figure 3.1 above to minimize the operational cost. This is achieved using an optimizer described later in this chapter. The set points signals (r in Figure 3.1) computed by the Decision-maker will be sent to the MPC controller and passed to the system as actuators (u in Figure 3.1). Then, the system will send an output that is the generation for the users (y in Figure 3.1) and is the feedback for the EMS. The three vectors (r, u, and y) included in this work are the setpoints or measurements for the CHP, the boiler thermal power and the electrical power of the electrolyzers [57].

To set up a controller, it must be learned in a simulation environment, which requires very accurate simulation. This is achieved with data-driven models of the individual system components. The models developed are used to configure and test the EMS in a simulation environment with subsequent implementation in cyber-physical mode.

The MPC controller is split into an actual discrete-time MPC and an observer that provides information on the system [57]. Predictive control must have a model of the system itself to accurately predict the response of the real system and adjust the optimal setpoint signal. Therefore, it is necessary to know the actual state of the system. However, it is usually not possible to know all system parameters. Therefore, observers are used to estimate the state of the real system. Thus, the observer is used to estimate the state of the real system from the measured output (y in Figure.3.1). Thus, the information about the 15-minute set points is obtained from the optimizers and based on the measured output information of the system, the MPC actuator signals are produced in 1 s time steps (this is the global simulation sampling time) [57].

3.1.1. Model Predictive Control (MPC)

Model Predictive Control (MPC) is an advanced control strategy that uses predictive models of dynamic systems to optimize control behaviour over a finite time horizon. MPC is a feedback control method that considers system dynamics, constraints, and goals to determine the optimal control.

Figure 3.2 shows a plant model that is used in order to predict the future controlled variables y for a determined prediction horizon Np at each instant k. The predicted controlled variables depend on states x of the model at the current time and on the future manipulated variables (or control signal) u (changing inside the control Horizon Nc and remaining constant afterwards). The set of manipulated variables is calculated by optimizing an objective function to keep the system as close as possible to the reference trajectory (set-point).

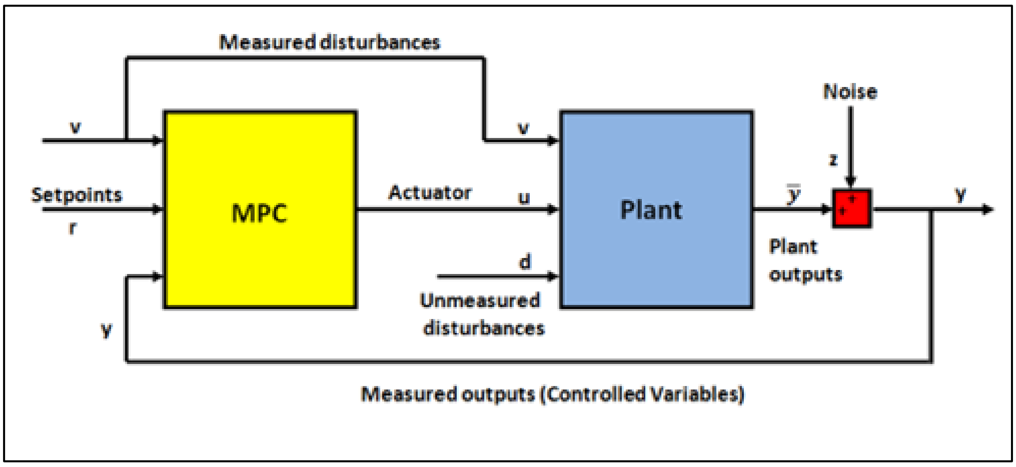


Figure 3.2 MPC operating model

MPC systems are controllers that are very stable and reliable, and at the same time produce excellent results from an economic point of view. Moreover, unlike other controllers, they are based on a predictive model. The current state of the plant is chosen at time t, and a cost-minimizing control strategy is calculated (using a numerical minimization algorithm using the Euler-Lagrange equation) for a relatively short time horizon in the future: [t, t + T]. When moment t + T is reached, the state of the system is calculated again, and the calculation is repeated starting from the current state of the system in question. In details, the forecast horizon continues to move forward at this time. A simplified scheme is shown in Figure 3.3

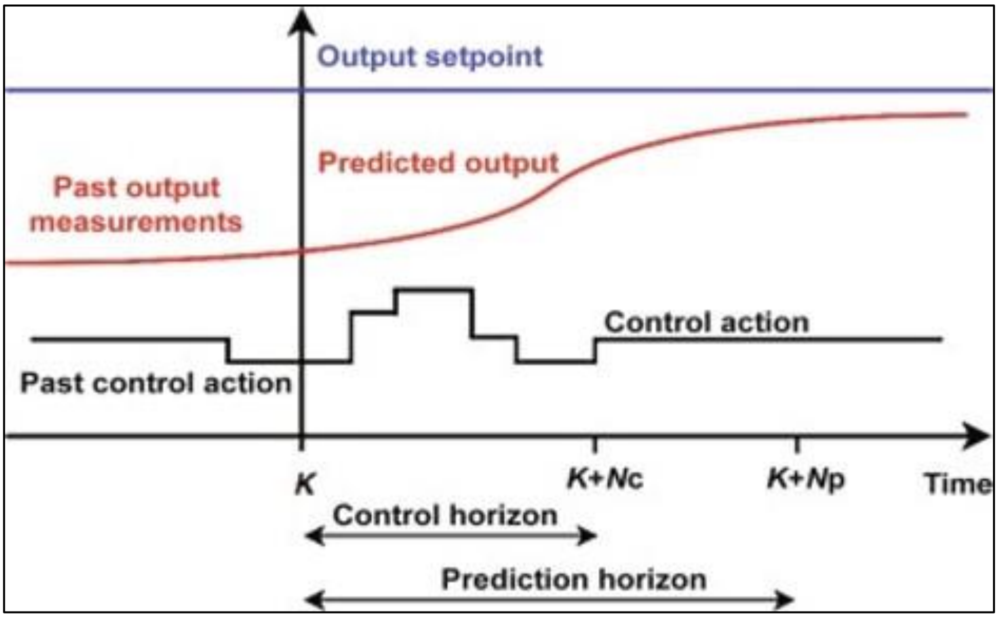


Figure 3.3 Example graph of the MPC operation

Various advantage of using MPC controllers are:

- MIMO system
- Adaptive to system changes

- Prediction horizon continuous recalculation
- It can handle constraints
- Performance and dynamic optimization

Some disadvantages of MPC are:
- It needs an accurate model of the process
- Sensitive to errors

3.1.2. The Decision Maker – Optimizer

The decision maker is an online scheduler that implements an optimizer so that the best-set point values can be found given the state of the system and demands and costs. The decision maker aims to minimize the operational and maintenance cost (*Jcost*) that is equal to 0.015€/kWh[64] including startup cost ,so that the electrical and thermal demand is always satisfied, leading to the set points every 15 minutes. To achieve this, the optimizer receives the electrical and thermal demand, the renewable energy production, the electricity, and fuel costs with the characteristics of the boiler and CHP. The variables for optimization are the electrical power that will be exchanged with the grid ($P_{el_{grid}}$) and the CHP electrical power($P_{el_{chp}}$). Equations 3.1 , 3.2 and 3.3 display the full objective function. Nstart is the number of startups we have in a day[57].

$$J\_cost = J_{cost} = (c_{el} + c_{O\&M}) \cdot P_{el_{grid}} + c_{fuel_{CHP}} \cdot m_{fuel_{CHP}} + c_{st} \cdot N \quad (3.1)$$

$$m_{fuelCHP} = f(P_{elCHP}, LHV_{CHP}, \eta_{CHP}, T_{amb}) \quad (3.2)$$

$$C_{el} = \begin{cases} C_{el} & if\ P_{elgrid} > 0 \\ C_{el} * Sell & if\ P_{elgrid} < 0 \end{cases} \quad (3.3)$$

The mass flow rate required to reach a certain CHP capacity is calculated from the consumption curve for a specific device, starting from the nominal value. If electricity is purchased from the grid, the cost is calculated based on the purchase price. Otherwise, if the electricity is sold to the grid, the capacity is multiplied by the value of the sale price (purchase price according to the ratio of sale price to purchase price). In other words, using this method, it is possible to use a sale price that is lower than the purchase price (as it is in some power contracts). The optimization is based on the constraints of Table 3.1. In addition, the tool also receives constraints on the power balance. The power bought (or sold) from the grid is the difference between the power demand and the power generated by the CHP (all values as power). If the sign is positive, the system buys power from the grid; if the sign is negative, the system sells power to the grid (generating the economic income in question).

Table 3.1 Constraints used by the decision maker

Parameter	Min Value	Max Value	Unit
CHP EL Power	70	400	kW
Grid EL Power	-1000	10000	kW
Boiler TH Power	2200	22000	kW

The optimization resulted in a 15-minute scheduling interval and a Boolean indicator of whether generating electricity in CHP is feasible and selling it to the grid. Assuming that the optimal CHP capacity is larger than the minimum, a Boolean indication is given whether generating electricity in CHP is feasible and selling it to the grid. If the optimal CHP capacity is greater than the minimum value or buying electricity from the grid is appropriate. If the optimal CHP capacity is below the minimum value, buying electricity from the grid is appropriate. This applies to the following logic, which aims to track the heat demand of the system, as shown in Figure 3.4 [57]. If the heat demand is below the minimum value that the CHP can provide, or if the heat demand is between the minimum and maximum value that the CHP can provide, integration with the boiler is not required.

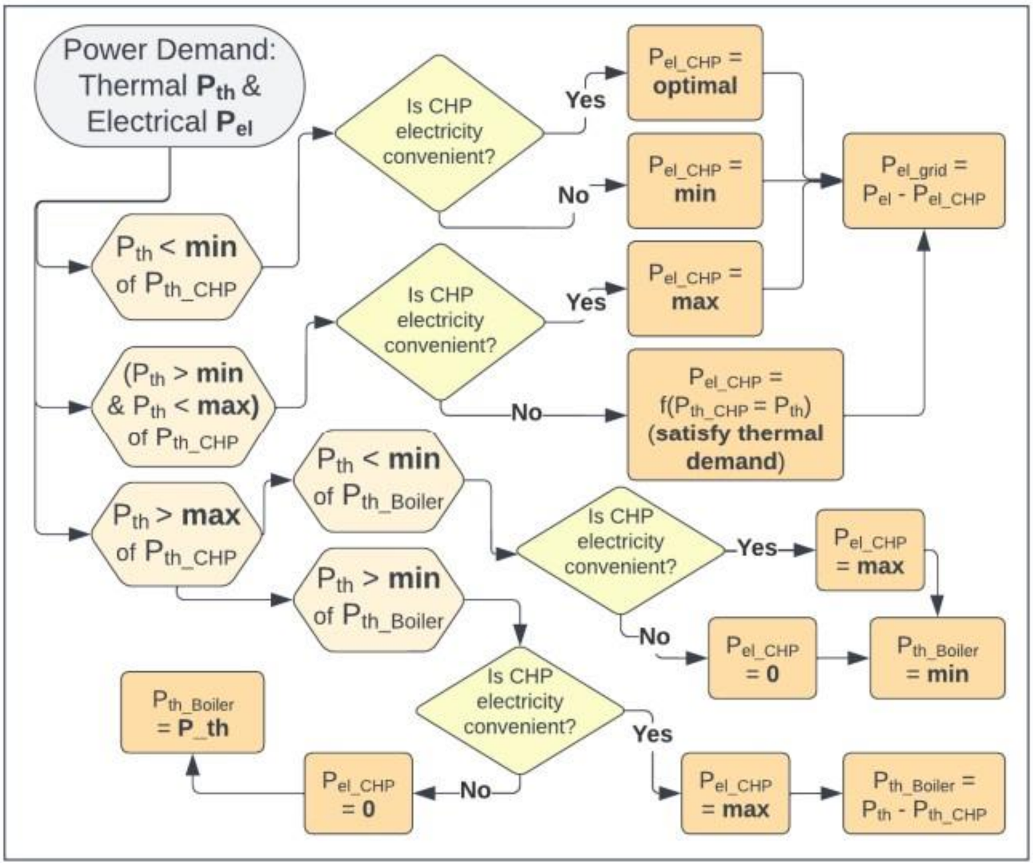


Figure 3.4 Flowchart logic of the decision maker

3.1.3. Hydrogen management

Hydrogen production mainly depends on electricity prices. Therefore, the main hydrogen production schedules are made off-line, resulting in a daily schedule in hourly increments. The electrolyzers are controlled by a flag system displayed in figure 3.5 below [56].

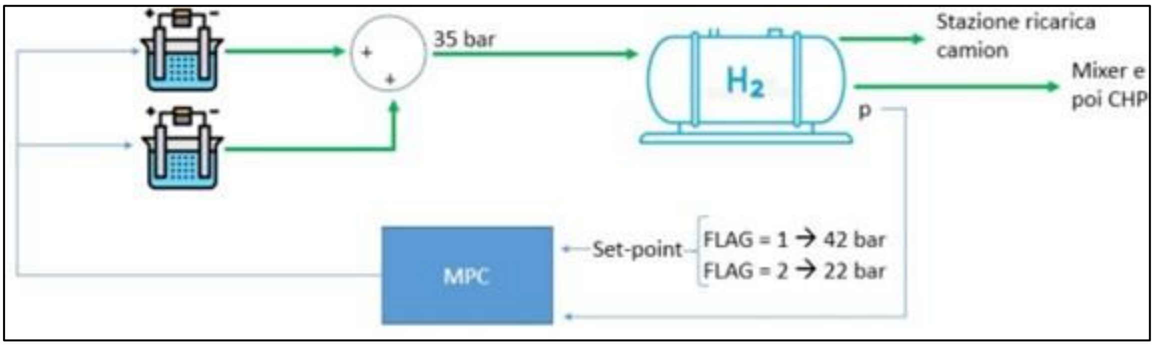


Figure 3.5 Scheduling scheme for the hydrogen production system

If the electricity price is lower than the average, the electrolyzers will run at the design point (flag 1). Otherwise, the electrolyzers will run at part load (flag 2). With price-based scheduling, the actual hydrogen control follows the storage pressure. Control follows storage pressure using online scheduling and dedicated MPCs. Online scheduling and dedicated MPCs are used. Specifically, the target pressure for hydrogen can be 40 bar (at low electricity prices) or 22 bar (at high electricity prices). The maximum value is 42 bar, and the minimum is 10 bar[57].

The electrolyzers are controlled by an online scheduler that takes the target H_2 storage pressure and daily offline scheduling and calculates the set-point for absorbed electrical energy. For flag 1 (low electric power cost),the target pressure is 40 bar. The electrolyser runs at the calculated point if the storage pressure is below 90% of the maximum value. A special MPC regulates the capacity of the electrolyser if the pressure is between 90% and 96% of the maximum value. The electrolyser is switched off if the pressure is above 96%. The target pressure for Flag 2 (high power cost) is 22 bar and the electrolyser shuts down if the storage pressure goes above this, otherwise the MPC controls the power to the electrolyser[57].

The electrolyser model, two identical electrolyzers running in parallel, obtains a given power value and calculates efficiency and production regarding H_2 and O_2 mass flow rate with a first-order dynamic delay. The hydrogen storage model then uses the mass flow rate to calculate the pressure in the storage itself (40 m^3 volume). The mass flow rate coming out of the storage depends on its use for transportation and the need to match the gas mixer to the hydrogen fraction of the fuel composition of the CHP. On the transport side, hydrogen-powered trucks are charged at exactly the right time, and truck tanks have capacity to hold 32 kg of hydrogen[57].

Another limitation is that the charging process must not cause the pressure in the storage chamber to drop below the minimum allowable value. Therefore, the hydrogen mass flow rate at the outlet is calculated, and the MPC takes this into account to adjust the absorption capacity of the electrolyzers to achieve the specified pressure in the storage chamber.

3.2. Components description

In this paragraph, the components that have been used in this study are described. These components include CHP, boiler, electrolyser, renewable energy sources (solar panels and wind turbines), hydrogen storage system, etc.

3.2.1. CHP

CHP stands from Combined Heat and Power. This also refers to as a cogeneration which means production of heat as well as electrical power at same time from a single fuel source.

Traditionally, electricity and heat are produced separately. Thermoelectric power plants, which release low-temperature heat energy into the environment, are used to generate electricity. Thermal energy is generated by boilers, which convert the primary energy of the fuel into thermal energy of high thermodynamic value. For example, if a consumer needs both electrical and thermal energy at the same time, instead of installing a thermoelectric plant and a boiler at the same time, he can switch to a CHP plant. This will result in less fuel consumption and greater energy savings compared to conventional power plants and boilers.

CHP (Combined Heat and Power Plant) efficiently generates electricity and useful heat from a single energy source. It is a decentralized method of power generation that uses various technologies such as gas turbines, steam turbines, engines, and fuel cells to generate electricity close to consumption. In CHP systems, the heat generated in electricity generation is recovered and used for heating, cooling, and other industrial processes, thereby maximizing overall energy efficiency. This process reduces the amount of wasted heat released into the environment in conventional power plants, where only part of the energy consumed is converted into usable electricity. Cogeneration systems are used in various industries, including industrial plants, hospitals, universities, district heating systems and residential construction. Various fuels, including natural gas, biomass, coal, and waste heat from industrial processes, can be used. In addition, CHP systems can be adapted to meet specific energy needs and integrated with renewable energy sources to increase environmental benefits. An example of CHP (produced by Aurelia Turbines, partner of the ROBINSON project) can be seen in Figure 3.6 [62].

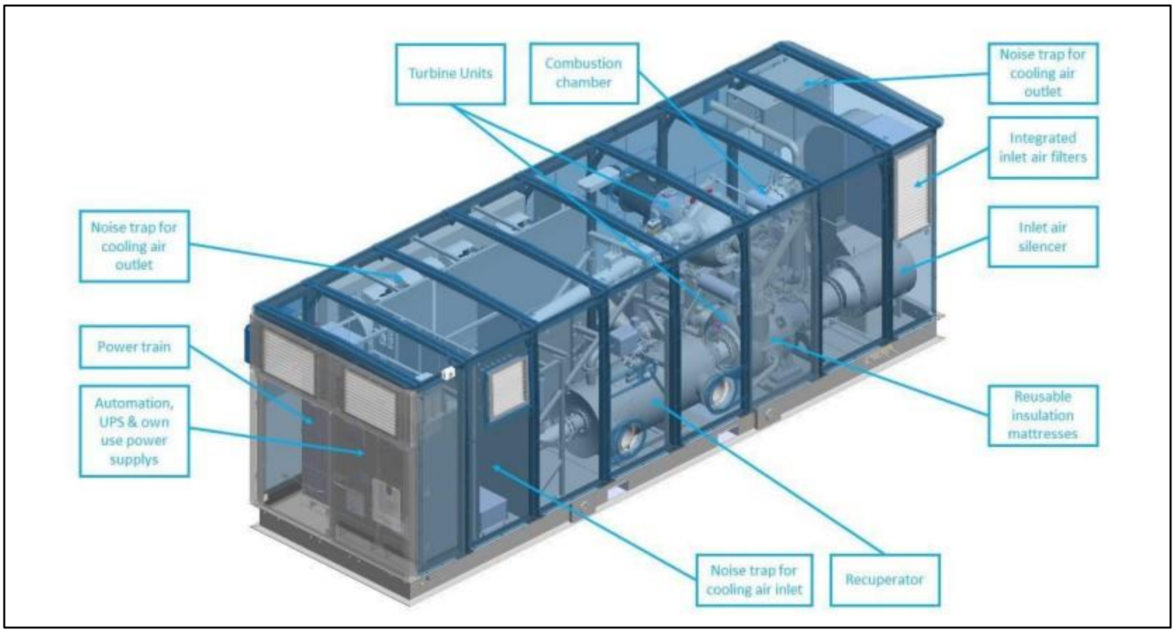


Figure 3.6 CHP - Aurelia Turbines A400 gas microturbine[62]

Figure 3.7 shows the implementation of the CHP in Simulink® [56].

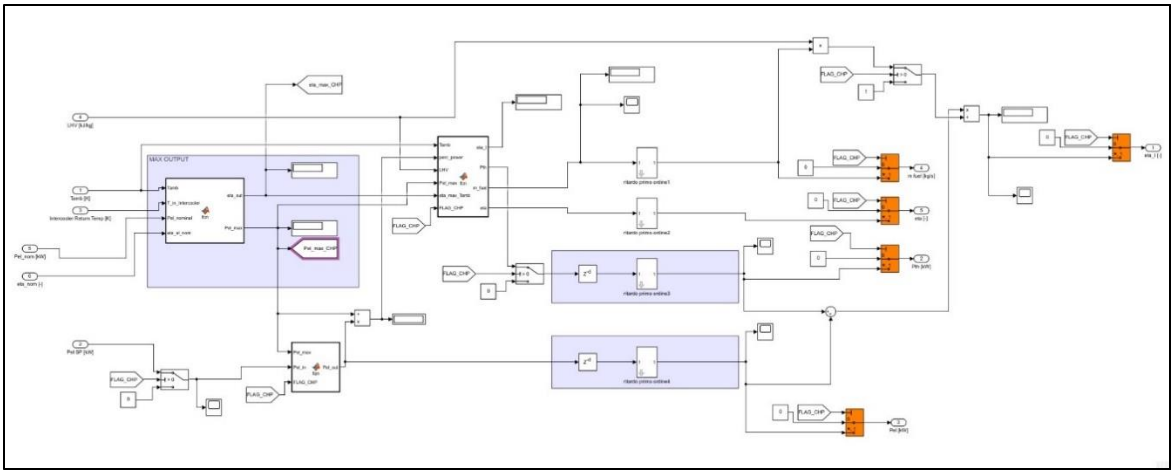


Figure 3.7 Representation of CHP in Simulink®

3.2.2. Boiler

A boiler is a device used to heat water or generate steam. They are widely used in residential, commercial, and industrial settings for various purposes, including providing hot water for heating, generating steam for power generation and industrial processes, and heating water for domestic use. Boilers work by transferring heat to the water in them. Various fuels, including natural gas, oil, coal, biomass, or electric heaters, can generate this heat. The heat source raises the temperature of the water, turning it into steam or hot water, which is then piped to the desired location. There are different types of boilers, including firetube and water tube boilers. In a firetube boiler, there is a large amount of water in the boiler, and the hot gases from fuel combustion pass through pipes soaked in water, transferring heat to the water. In water tube boilers, on the other hand, the hot gases pass through water-filled pipes, heating the water inside. Boilers are an integral part of many industries and homes, providing a reliable source of heat and hot water for various applications.
Figure 3.8 shows the representation of the boiler in Simulink® [56].

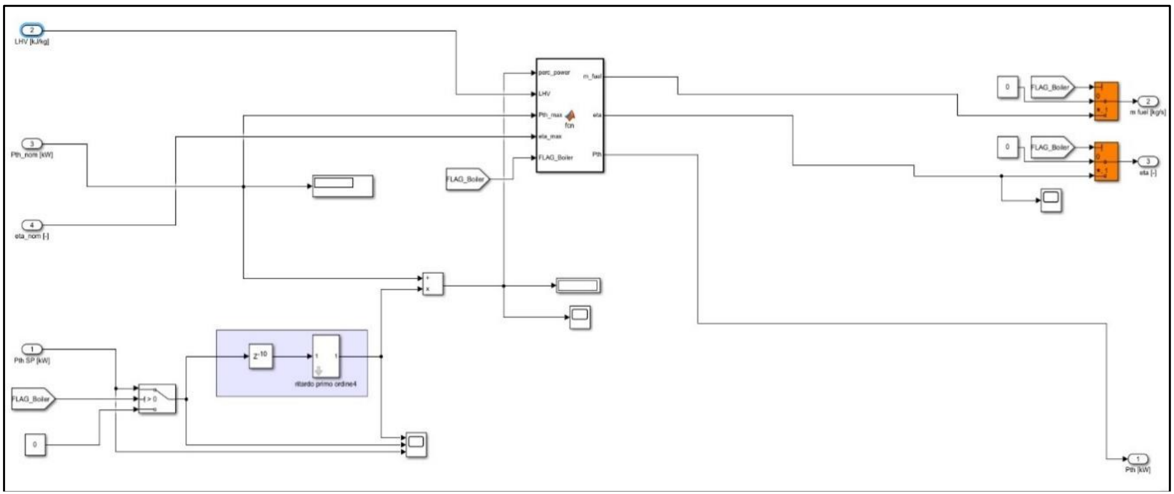


Figure 3.8 Representation of the boiler in Simulink®

3.3.3. Renewable energy sources

The renewable source generators such as solar photovoltaic panels and a wind turbine of 100 kW are used for the simulation and study of the EMS system. Figure 3.9 [56] shows the Simulink® model of the renewable energy sources.

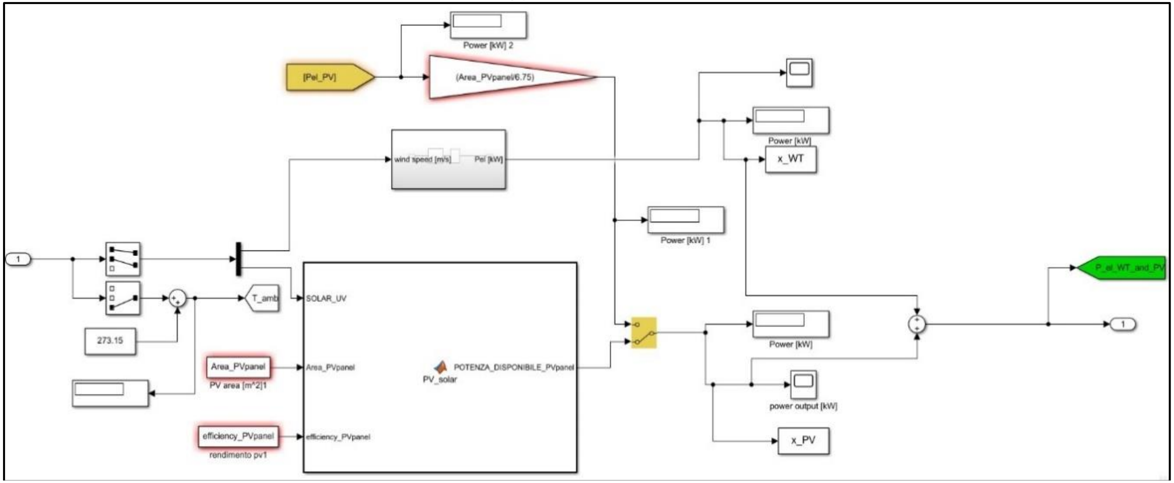


Figure 3.9 Simulink® representation of the renewable energy sources[56]

3.2.4. Electrolyzers

The electrolyzers utilize electricity to convert water into hydrogen and oxygen. Oxygen recently received more attention due to the COVID-19 pandemic; therefore, oxygen could generate an additional economic value. Hydrogen production is preferred during times with excess generation of renewable electricity or with (very) low or even negative grid electricity prices to minimize hydrogen production costs (Bauer et al., 2021). The electrolyzers with the production capacity of 200 kg or 500 kg will be used.[62].

For the study two A90 electrolyzers (500 kW power each) are used. Figure 3.10 [56] shows the implementation of electrolyzer in Simulink®.

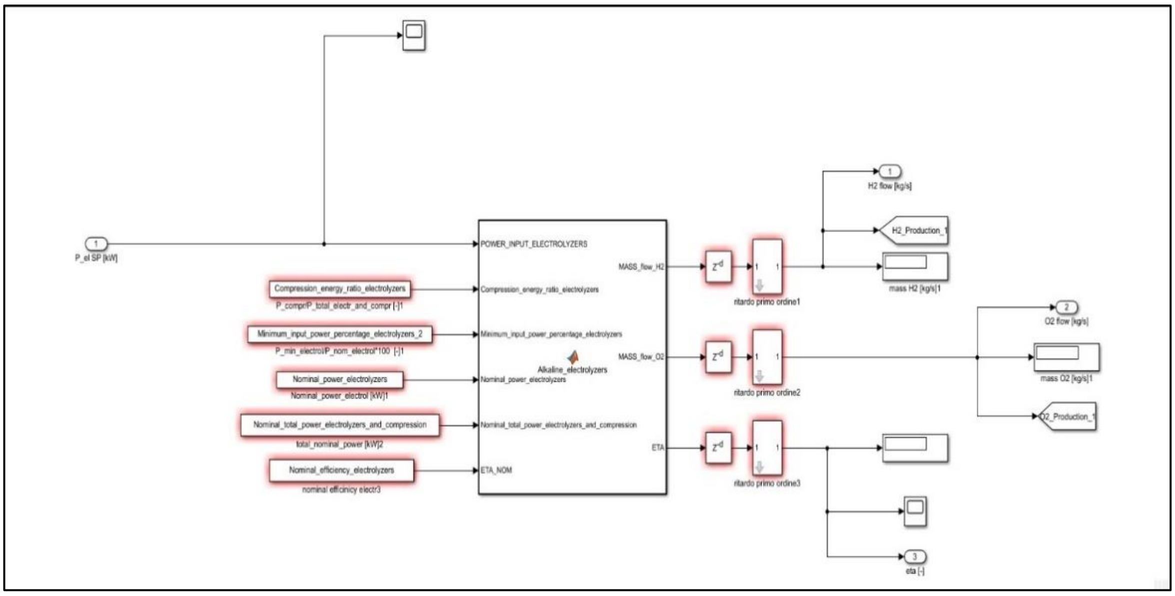


Figure 3.10 Simulink® diagram of A90 electrolyser[56]

3.2.5. Hydrogen storage

The hydrogen generation capacity is significantly higher than the needs, and the excess of hydrogen produced can be used/sold for transportation systems. Some hypothetical storage volume size and some hypothetical pressures have been assumed to implement this storage system within the project.
Figure 3.11 shows the Simulink$^{®}$ diagram of the hydrogen storage system [56].

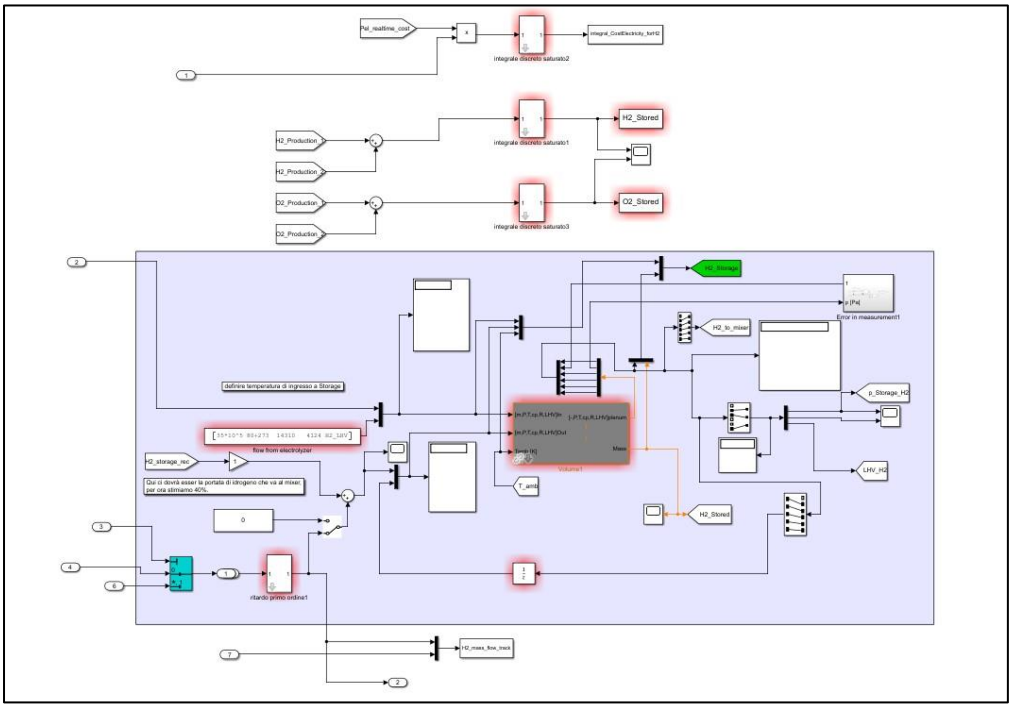


Figure 3.11 Simulink$^{®}$ diagram of the hydrogen storage[56]

3.2.6. Gas mixer

The gas mixer utilizes and mixes the fuels generated with the electrolyzer (hydrogen), gasification (syngas) and AD-BES unit (biomethane). The generated gas mixes are prepared to be used in the CHP [61].
A tool for fuel blending composition was developed. Two different results were presented for two innovative fuels. Both fuels have 30% hydrogen, but the performance is very different as the percentages of methane and syngas inside differ [56].
The mixer has been implemented inside the system, as in Figure 3.12 [56]. On the left side, the various incoming gases are visible with their concentrations, particularly syngas, H_2 and methane. These flow into the mixer, which defines the input quantities to obtain the correct mixing; everything is also controlled by a PID regulator appropriately calibrated through the Ziegler-Nichols method [56].

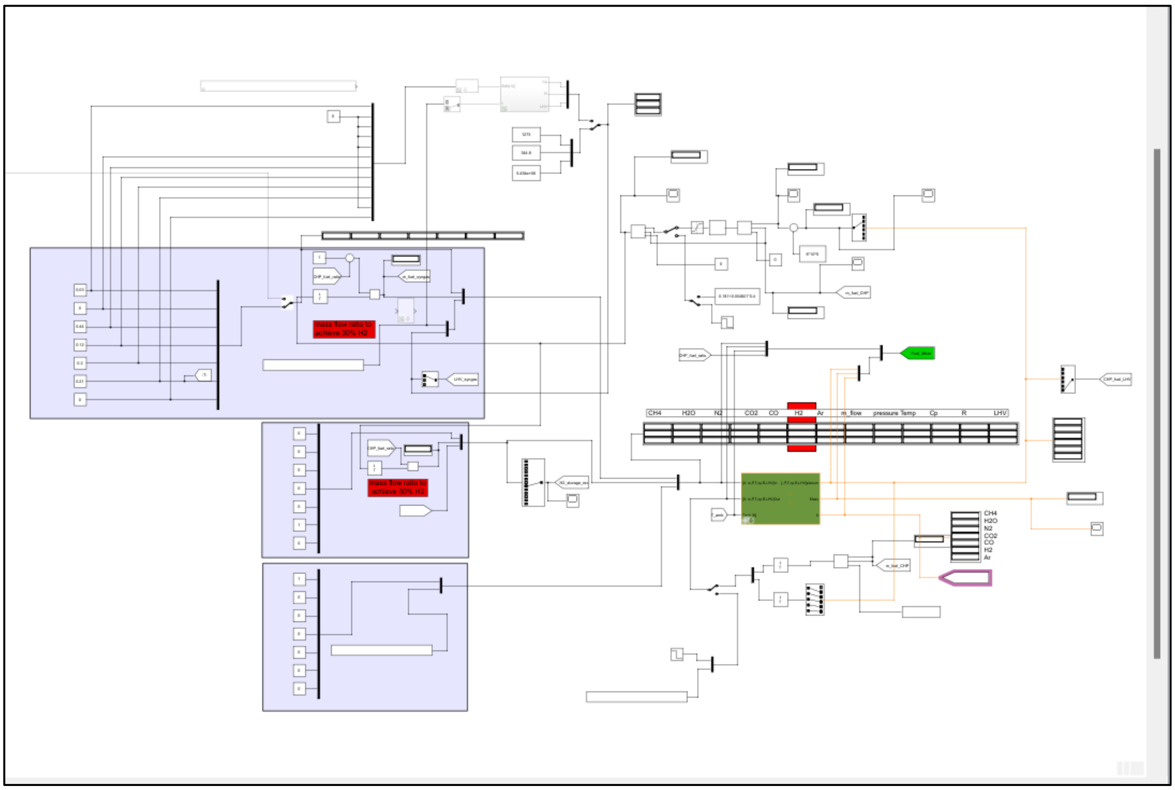


Figure 3.12 Simulink® representation of the gas mixer[56]

4. Results

In this chapter, the results/simulations gathered with the help of Matlab & Simulink® are discussed and compared by changing various parameters such as AEC, energy demands (electrical and thermal), syngas cost etc.

4.1. Parametric analysis changing different parameters

This section shows the results gathered by changing the different parameters and what effect they have on the different component management to satisfy the demands.

4.1.1. Performance comparison by changing the syngas cost

Figure 4.1 shows the electricity price (€/MWh) throughout a day and the AEC that is 150 €/MWh and the FLAG for the electrolyser management (see section 3.1.3) on the left-hand side whereas on the right-hand side the electrical demand in kW (blue line) and the thermal demand in kW (red line) is presented.

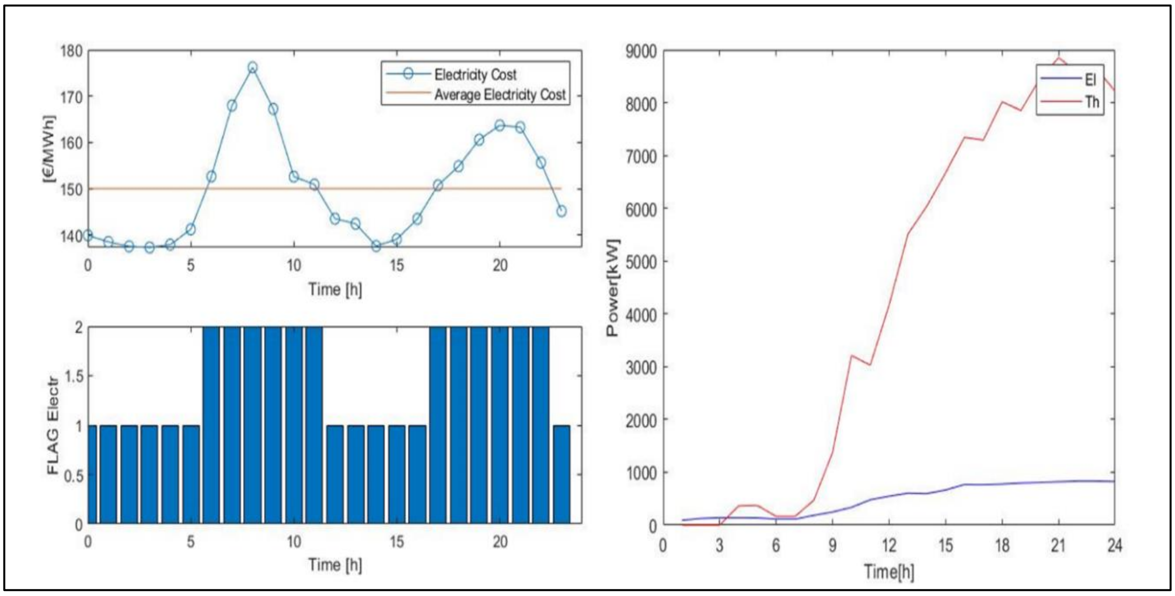


Figure 4.1 Trend in the cost of electricity and representation of the FLAG for the electrolyser management and energy demands

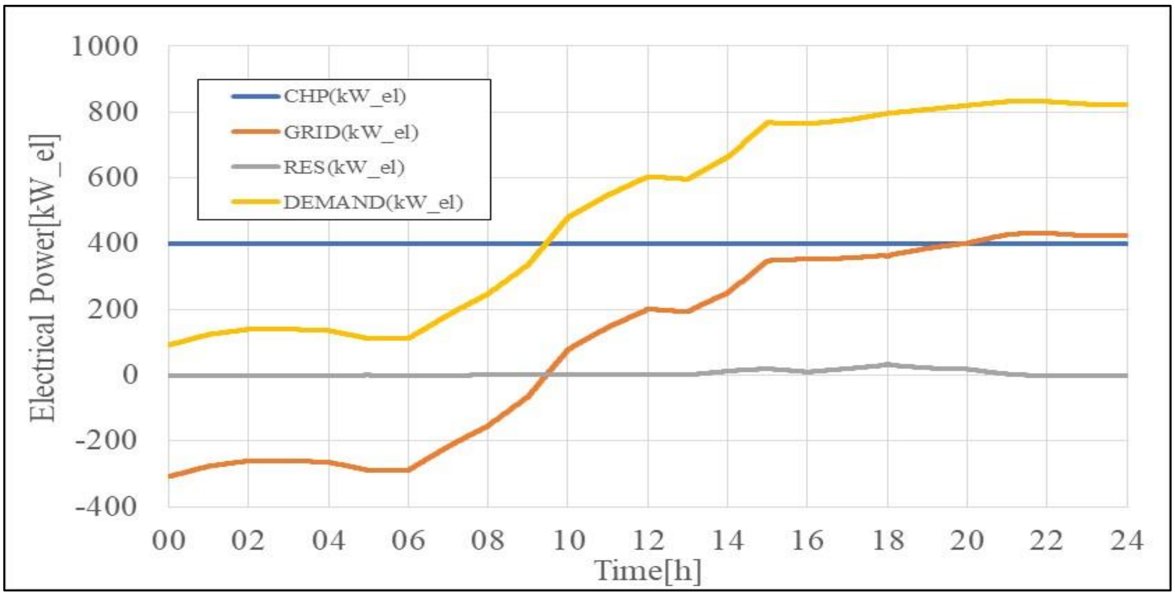


Figure 4.2 Electrical power trend (syngas cost: 5 €/MWh)

Figure 4.2 displays the trend of how electric power demand is being satisfied. The curve in yellow indicates the electrical demand, blue indicates the CHP generation, orange indicates the grid and grey indicates the renewable sources. The cost of syngas considered is 5 €/MWh. We can observe that being the cost of syngas low the CHP is working at full load. Early morning that is from 00:00 to around 9:30 hrs the electric demand is low; so, the excess energy being produced is sold to the grid and when the demand increases the energy is bought from the grid to satisfy the demand. From 14:00 to 16:00 hrs the RES generation contributes to satisfy the demand thus decreasing the grid dependence.

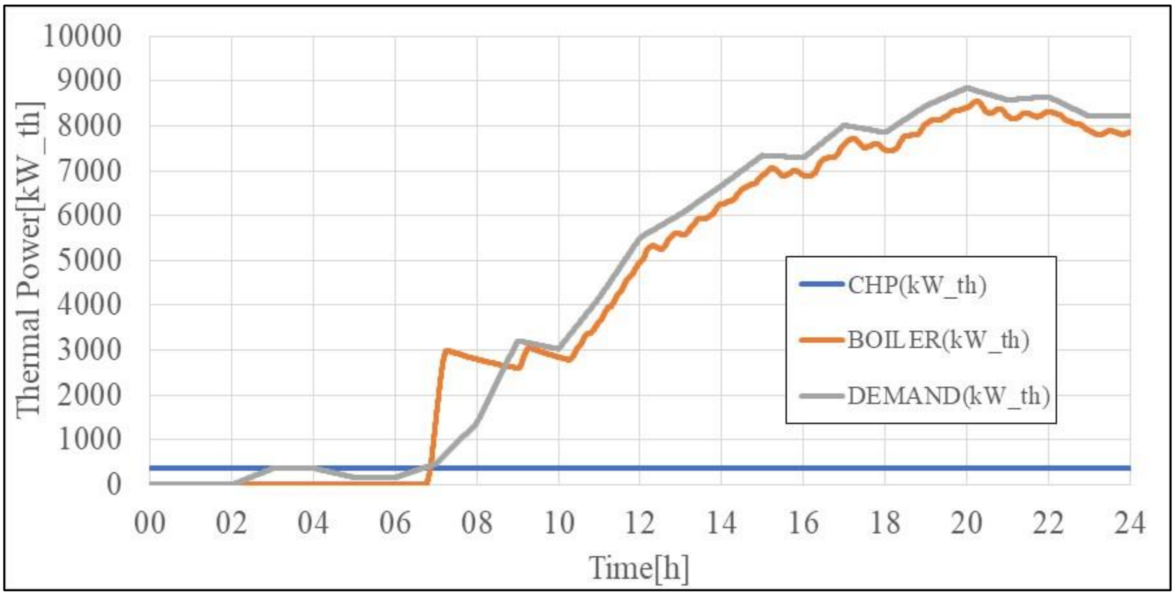


Figure 4.3 Thermal power trend (syngas cost: 5€/MWh)

Figure 4.3 shows the trend of thermal demand being satisfied. The curve in blue represents the CHP, the orange one shows the boiler, and the grey line shows the demand. Here the boiler can satisfy the maximum demand and the difference between the demand curve and the boiler curve is fulfilled by the CHP which is running at full capacity. From 00:00 to around 6:30 hrs. the boiler is not active because the power demand is being satisfied by the CHP itself.

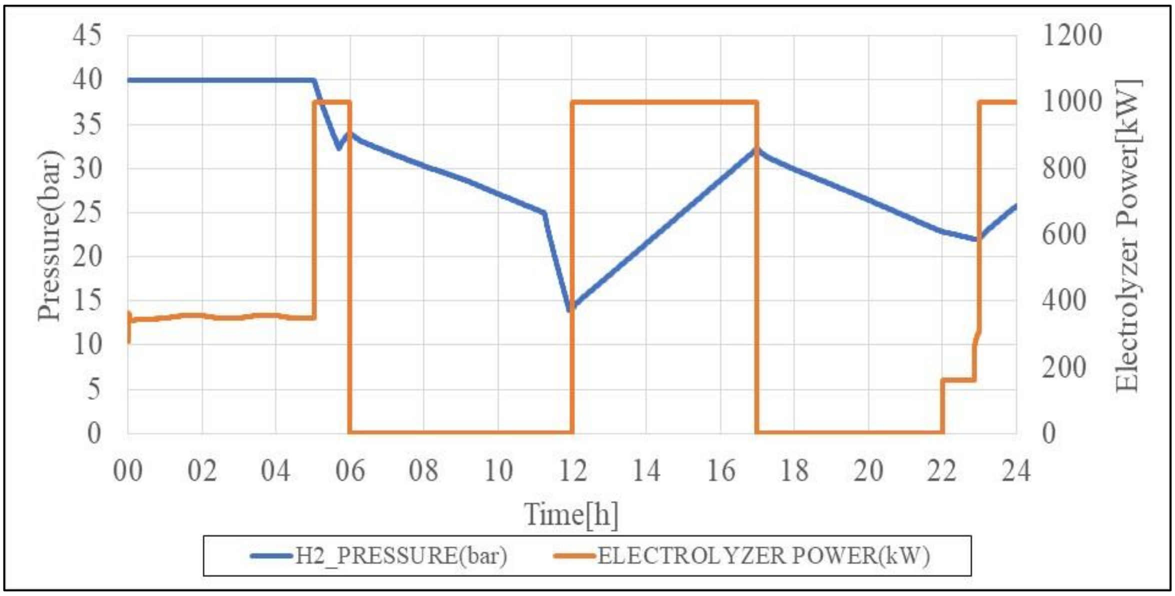


Figure 4.4 Pressure trend of hydrogen storage system & electrolyzer power (syngas cost: 5 €/MWh)

Figure 4.4 shows the pressure trend of hydrogen storage system in blue and the electrolyzer power in orange. Electrolyzers produce hydrogen and ensure that the chemical storage system is kept within operating limits. They also maintain a constant supply of hydrogen to meet hydrogen demand, for example, by feeding hydrogen to the gas mixer feeding the cogeneration system, filling two truck tanks. From figure 4.1 it is possible to observe that the price of electricity is lower than the AEC till 5:00 hrs. and during that period flag value is 1(set point of 40 bar) (see section 3.1.3). At 5:00 hrs. the first tapping takes place. The charging time is set from 45 minutes to 1 hour. It is possible to observe that during this period the electrolyzers work at maximum capacity. From 6:00 hrs. to 11:00 hrs. FLAG changes to 2 as the price of energy is high. At 11:00 hrs. the second tapping takes place and at 12:00 hrs. The electrolyzers again works at maximum capacity to fulfill the constraints of the storage. At 12:00 hrs. the pressure of storage drops to 15 bar thus turning on the electrolyzers to maximum capacity. At 17:00 hrs. the price of electricity increases above the AEC thus switching to FLAG 2(set point of 22 bar) and pressure being the higher than the set point electrolyzers are switched off (see section 3.1.3). From 17:00 hrs. to 22:00 hrs. the FLAG 1 is set as the price is less than the AEC and electrolyzers are turned off as the pressure is higher than 96% of the maximum value.

Figures 4.5 & 4.6 show the electrical power trend and thermal power trend with 150 €/MWh for the syngas cost. In figure 4.5 it is possible to observe that initially the CHP is running at minimum load (70 kW) due to the high fuel cost. During this time CHP and grid can satisfy the electrical demand. Around 2:30 hrs. the CHP starts to follow the upward trend and goes to maximum capacity because thermal demand starts to increase as for initial hours it is zero, that can be observed in figure 4.6. Around 7:00 hrs. the thermal demand shoots up thus switching on the boiler and shutting down the CHP as during this time it is not useful to generate electricity being the price of syngas very high.

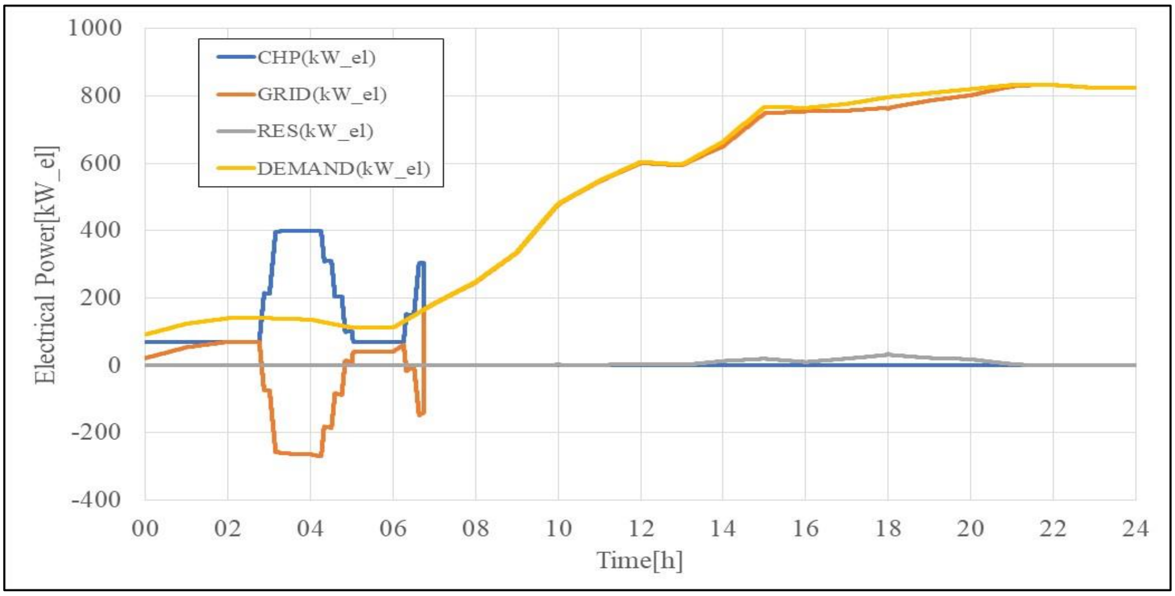


Figure 4.5 Electrical power trend (syngas cost: 150 €/MWh)

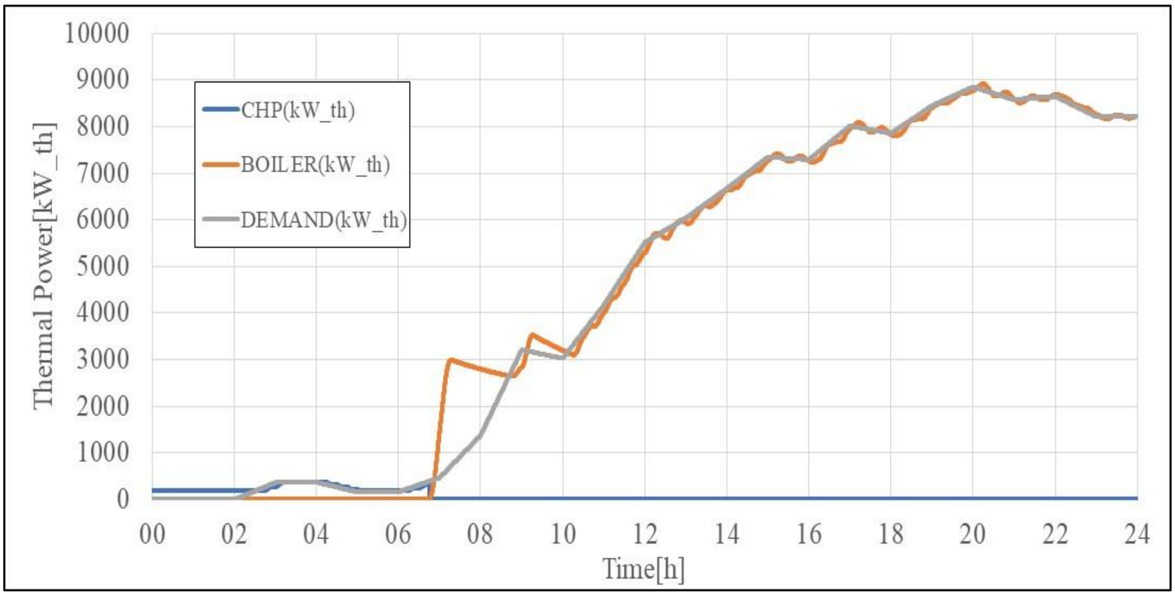


Figure 4.6 Thermal power trend (syngas cost: 150 €/MWh)

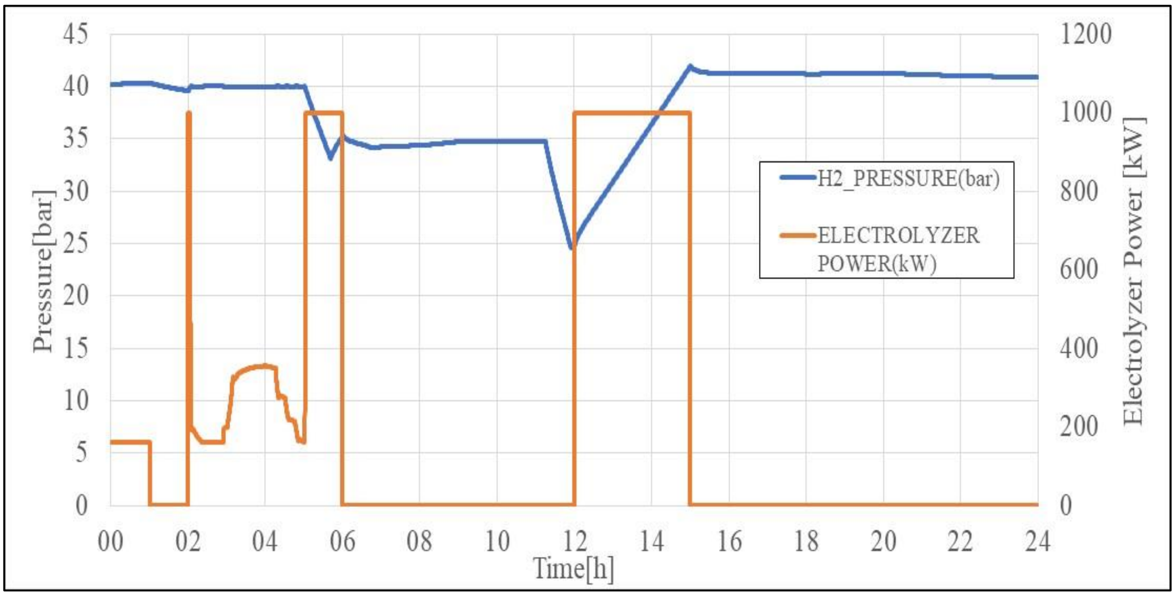


Figure 4.7 Pressure trend of hydrogen storage system & electrolyzer power (syngas cost: 150 €/MWh)

Figure 4.7 shows the pressure trend of hydrogen storage system(blue) and electrolyzer power trend(orange). Comparing figure 4.7 with figure 4.4 we can observe that there is significant variation in the working of electrolyzer as well as pressure of hydrogen storage. The electricity cost trend is same as presented in figure 4.1. From figure 4.1 it is possible to observe that from 00:00 hrs to 5:00 hrs price of electricity is lower than AES so pressure trend is flag 1 but due to the variation in working of CHP (see figure 4.5) the electrolyser switches on and the variation can be observed from 2:00 hrs. to 5:00 hrs. as the hydrogen is being supplied to gas mixer also for the working of CHP. From 5:00 hrs to 12:00 hrs the trend is similar and has been discussed above (see figure 4.4). From 12:00 hrs to 15:00 hrs to 17:00 hrs the price is lower than AEC but the electrolyzer is switched off at 15:00 hrs. because the target pressure is achieved, and the CHP is off for the following period(see figure 4.5).

4.1.2. Performance comparison by changing the syngas cost and AES

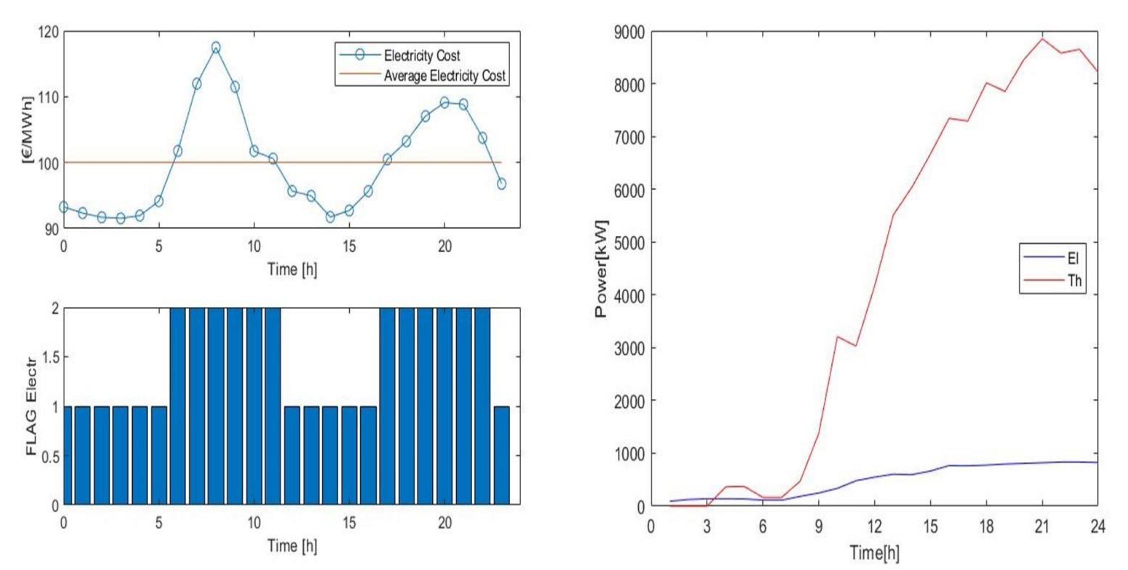


Figure 4.8 Trend in the cost of electricity and representation of the FLAG for the electrolyser management and energy demands

Figure 4.8 shows the electricity price (€/MWh) throughout a day and the AEC that is 100 €/MWh and the FLAG for the electrolyser management. Syngas cost considered is 30 €/MWh. On the left-hand side whereas on the right-hand side the electrical demand in kW (blue line) and the thermal demand in kW (red line) is presented. The demands are the as shown in figure 4.1.

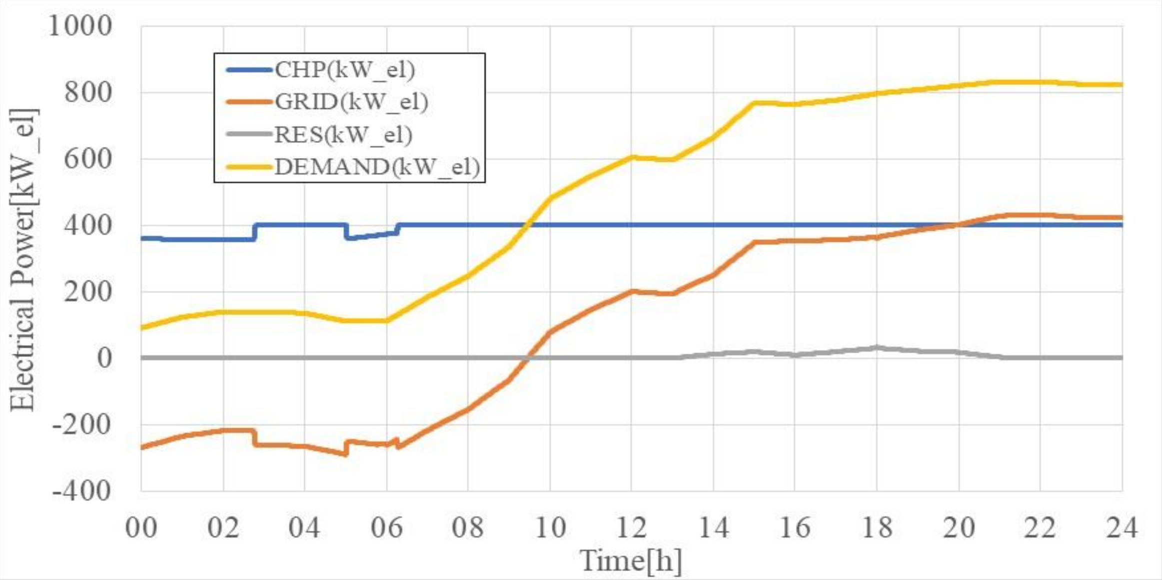


Figure 4.9 Electrical power trend (syngas cost: 30 €/MWh)

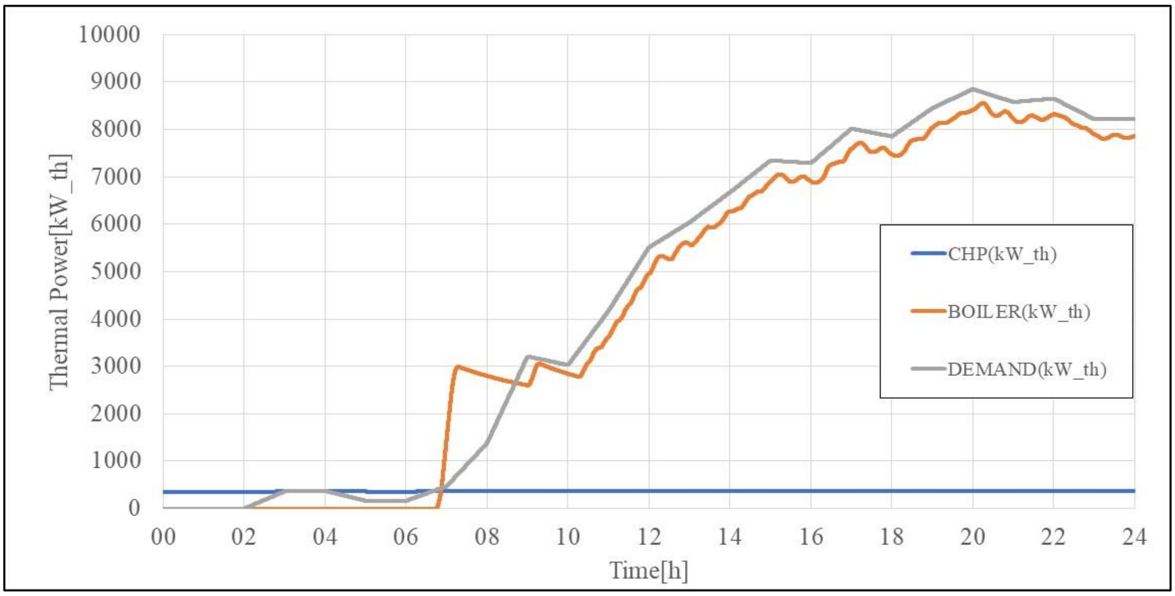


Figure 4.10 Thermal power trend (syngas cost: 30 €/MWh)

Figure 4.9 and 4.10 shows the electrical and thermal power trends. In figure 4.9 the blue line represents the CHP, orange grid, grey RES, and yellow demand whereas in figure 4.10 grey line represents the demand, orange boiler and blue CHP. Here we can observe changing the AES and syngas cost have an effect on the CHP working. Comparing with figure 4.2 it is possible to observe in figure 4.9 that the from 00:00 hrs. to 6:00 hrs the CHP fluctuates and then for the rest of the day becomes stable as the thermal demand is between the minimum and maximum value of thermal power provided by the CHP(see section 3.1.2 and figure 3.4) and for the thermal energy when the demand increase max capacity of CHP boiler is switched on to satisfy the demand.

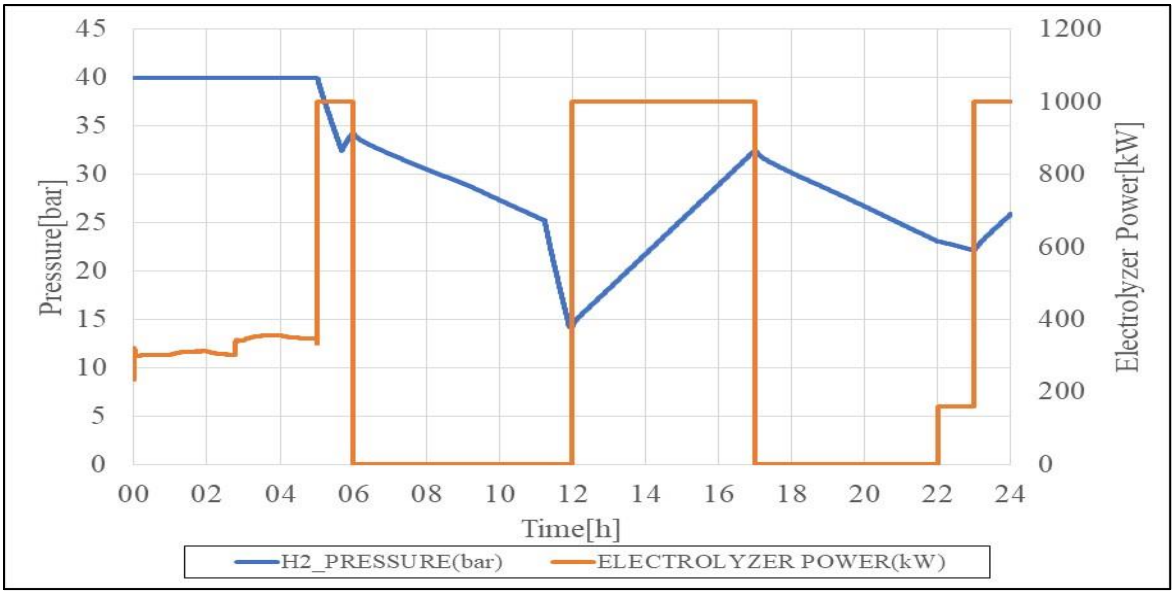


Figure 4.11 Pressure trend of hydrogen storage system & electrolyzer power (syngas cost: 30 €/MWh)

Figure 4.11 shows the pressure trend of hydrogen storage system in blue and electrolyzer power in orange. The trend is same as in figure 4.4. From00:00 hrs. to 5:00 hrs. it is possible to observe a little up and down in the trend line of electrolyzers as during that period CHP is changing its working point. From 5:00 hrs to 24:00 hrs the trend is similar to figure 4.4.

More simulations were performed for the above case with higher syngas cost which resulted in same graphs as shown in figure 4.5, 4.6 and 4.7 respectively.

4.1.3. Performance comparison by changing syngas cost, AES & demands

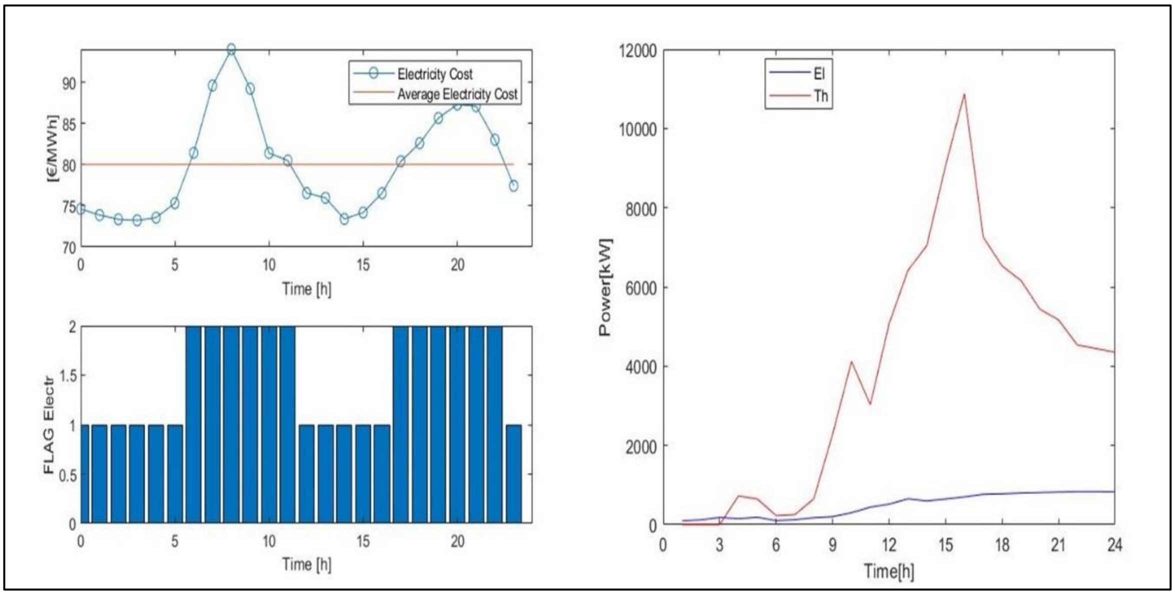


Figure 4.12 Graph with change in AEC (left) and energy demands (right)

Figure 4.12 shows the graphs with changes in the AEC (left) and demands (thermal and electrical) on the right. Here the AEC is considered as 80 €/MWh. The thermal demand and electrical demand are changed with more peaks in the thermal demand as compared to figure 4.1. More calculations were performed by considering different parameters before publishing the results.

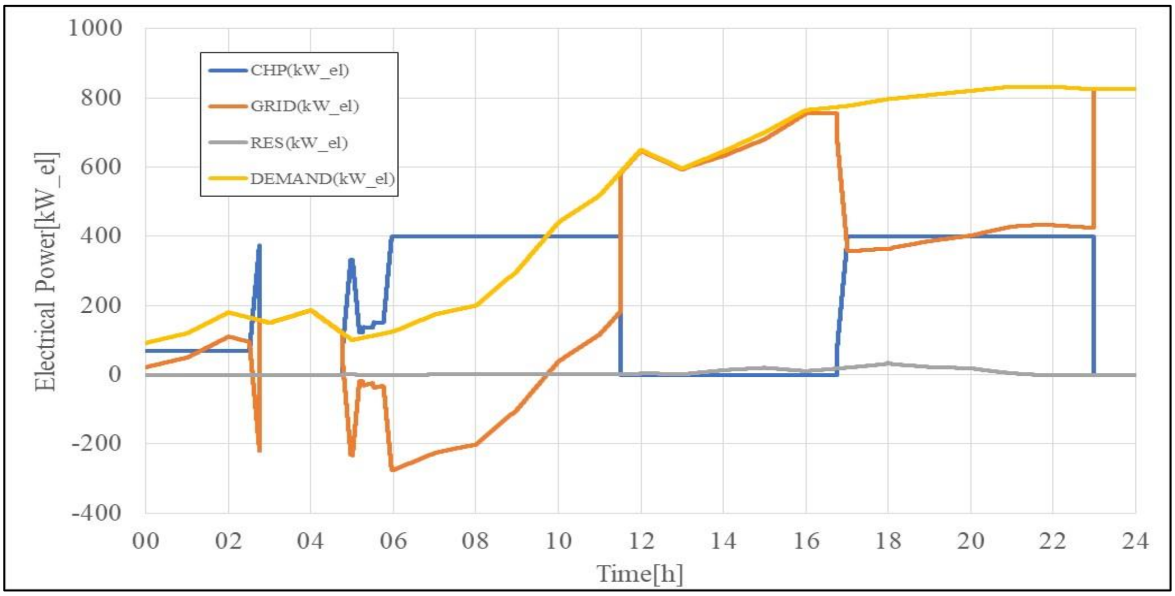


Figure 4.13 Electrical Power trend (syngas cost: 50 €/MWh)

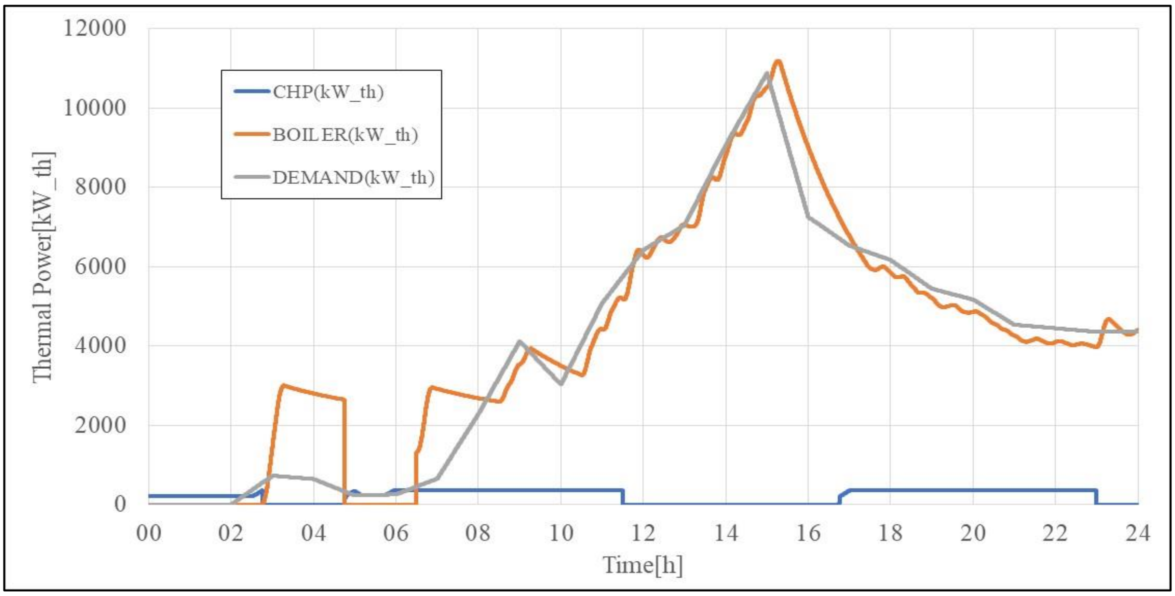


Figure 4.14 Thermal Power trend (syngas cost: 50 €/MWh)

Figures 4.13 and 4.14 show the trend of electrical and thermal power and the working of various components to satisfy the demand. The syngas cost considered here is 50 €/MWh. In figure 4.13 the blue line represents the CHP, the orange one represents the gid, the grey one the RES generation and yellow the electrical demand whereas in figure 4.14 blue represents the CHP, the orange line the boiler and the grey one the demand.

It is possible to observe that from 00:00hrs. to 2:30 hrs. the CHP is working at minimum values (see table 3.1) because the thermal demand is less than the minimum thermal power of CHP (see figure 3.4). Around 2:30 hrs. the thermal demand rises, which leads to switching on the boiler and switching off the CHP up to 4:30 hrs. and the electrical demand is satisfied by the grid which can be observed in figure 4.13. Again, a decrease in thermal demand can be observed from 4:30 hrs. to 6:15 hrs. shutting off the boiler and switching on the CHP as demand can be satisfied by CHP and during same period it is possible to observe that the CHP is exchanging electricity with the grid.

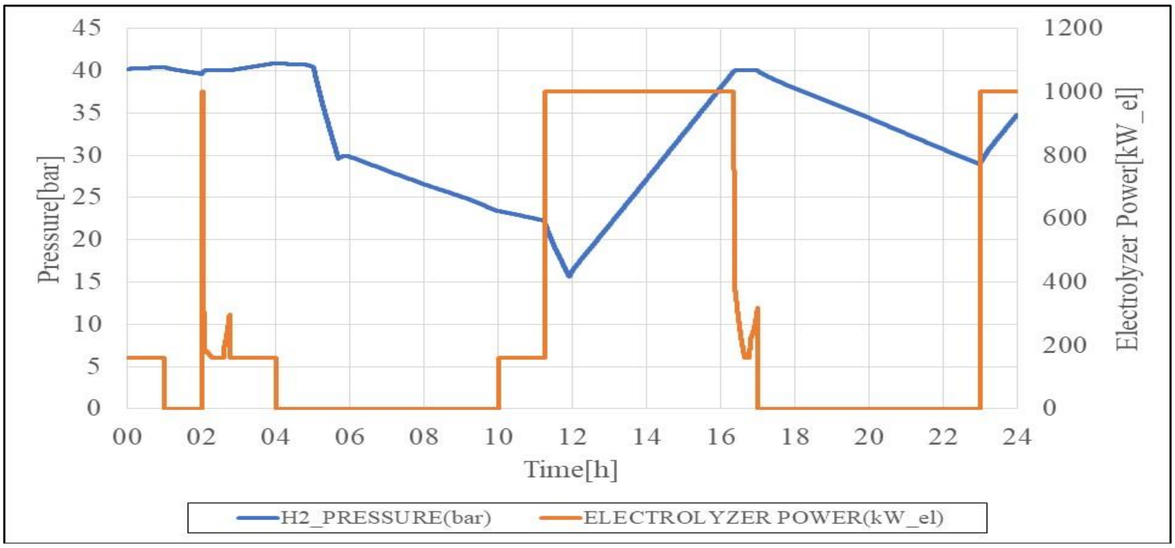


Figure 4.15 Pressure trend of hydrogen storage system & electrolyzer power (syngas cost: 50 €/MWh)

Figure 4.15 shows the pressure trend of the hydrogen storage system (blue) and electrolyzer power (orange). It is possible to observe from figure 4.12 that the cost of electricity is less than the AEC up to 5:00 hrs. so FLAG 1 is set (set point of 40 bar). At 5:00 hrs. decrease in pressure can be observed because of vehicle charging but the electrolyzer is shut down due to reason that the storage pressure value is within the limits(see section 3.1.3). At 11:00 hrs. second charging of vehicle takes place and during this period FLAG 2 is set (set point of 22 bar) and as the pressure drops below set point the electrolyzer are switched on. Small peaks can be observed in around 2:30 hrs. , 10:00 hrs and around 16:00 hrs due to fact that CHP is switching on .

For the same set of demands when the cost of syngas is very high (750 €/MWh), the following results have been obtained.

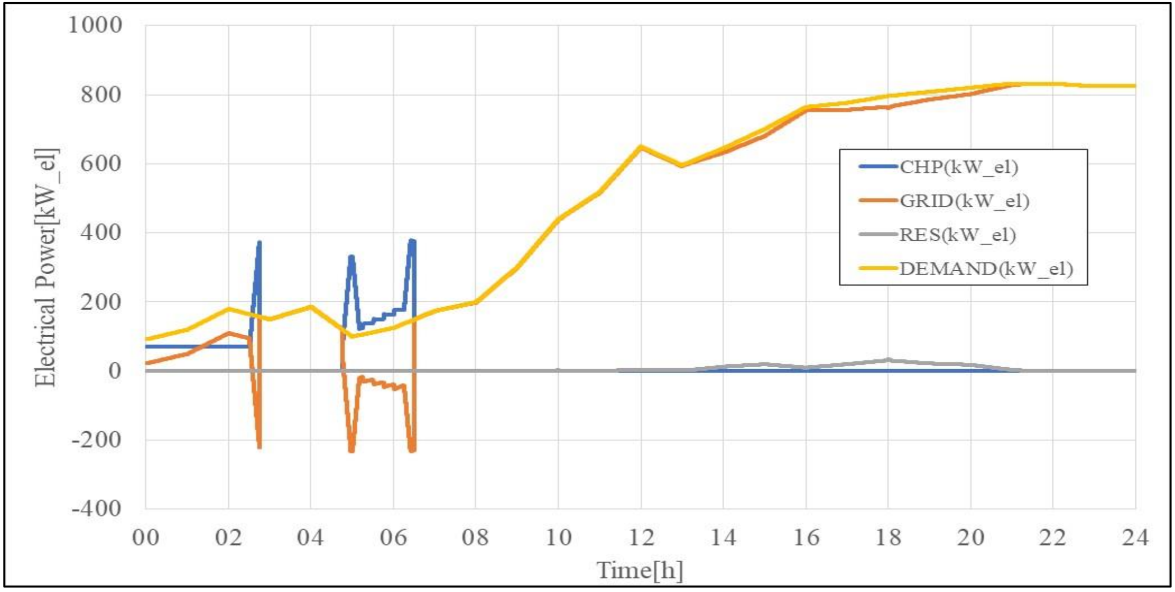


Figure 4.16 Electrical trend (syngas cost: 750 €/MWh)

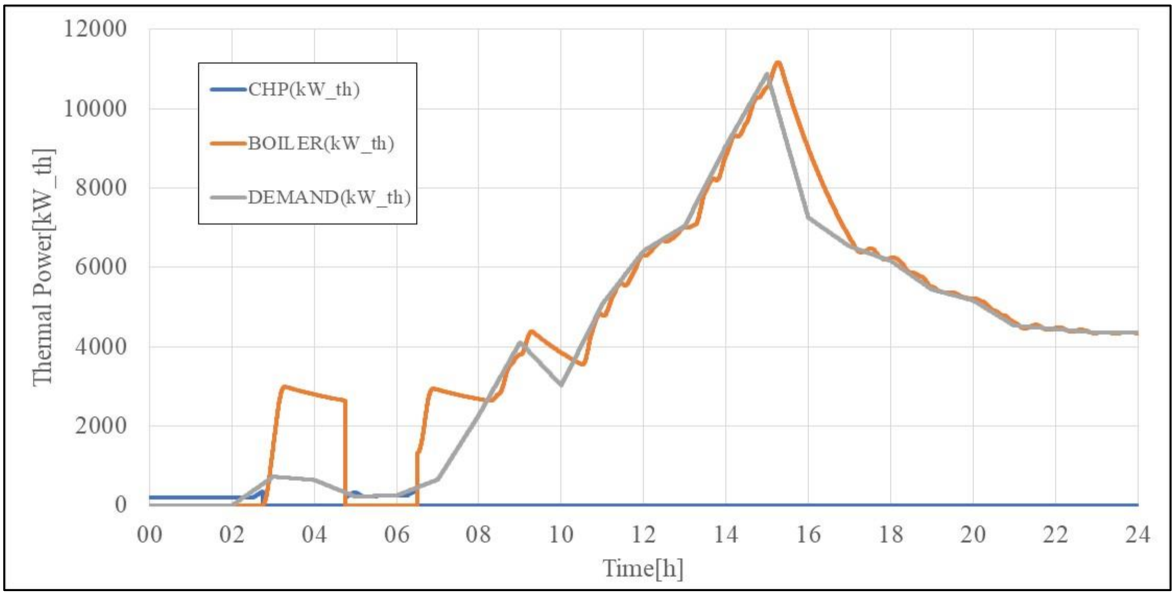


Figure 4.17 Thermal power trend (syngas cost: 750 €/MWh)

Figures 4.16 and 4.17 shows the electrical and thermal trend respectively with syngas cost of 750 €/MWh. It is possible to observe from the figures that up to 2:00 hrs. the thermal demand is zero and on the other hand demand of electricity is low. During these hours the CHP is running at minimum capacity (70 kW_el) (see table 3.1) as the thermal demand during this period is less than the minimum(see figure 3.4). Around 2:00 hrs. the thermal demand beings to rise up and the boiler turns on and CHP shuts down which can be observed in figure 4.16 also as during this time period electrical demand is being satisfied by the grid. Again from 4:30 hrs. to 6:15 hrs. the thermal demand is being satisfied by the CHP, so boiler shuts down. After 6:15 hrs. the CHP is totally shut off as the thermal demand is very high and boiler is on (see figure 3.4) and the electrical demand is being satisfied by the grid. In figure 4.16 from 12:00 hrs. to 20:00 hrs. the energy contributed by RES can be observed.

For the pressure storage system this configuration follows the same trend as shown in figure 4.18.

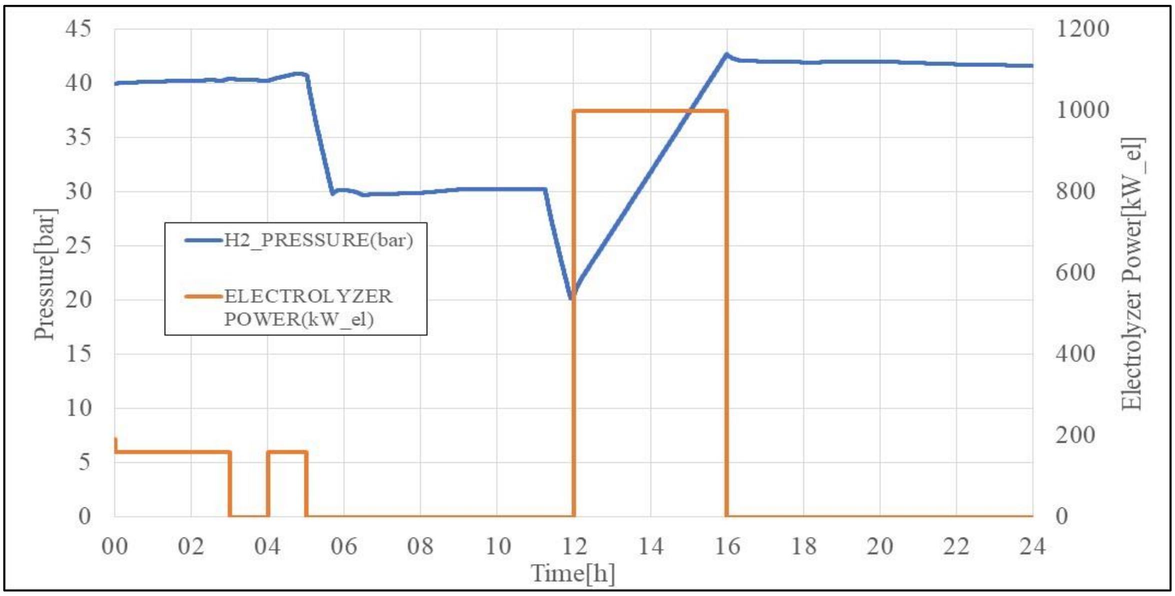


Figure 4.18 Pressure trend of hydrogen storage system & electrolyzer power (syngas cost: 750 €/MWh)

Figure 4.18 shows the pressure trend of hydrogen storage system with electrolyzer working. In this we can observe that there are less curves as compared with previous cases because in this scenario CHP is shut down around 6:15 hrs. and is not switched on throughout the day. Around 5:00 hrs. first charging of vehicle takes place and pressure drops. From 6:00 hrs the pressure stays constant as the CHP is shut down. At 11:00 hrs second charging of vehicle takes place and electrolyzers are switched on as soon as pressure goes below the threshold value the electrolyzers are switched on as at 12:00 hrs. we have set point of 40 bar (FLAG 1) as electricity price is lower than AEC. At 16:00 hrs. electrolyzers are shut down as the target pressure is achieved that is more than 96% of the maximum value (see section 3.1.3).

To check the robustness of the system the demands (thermal and electrical) were changed to include more fluctuations which can be seen in the figure 4.19 below.

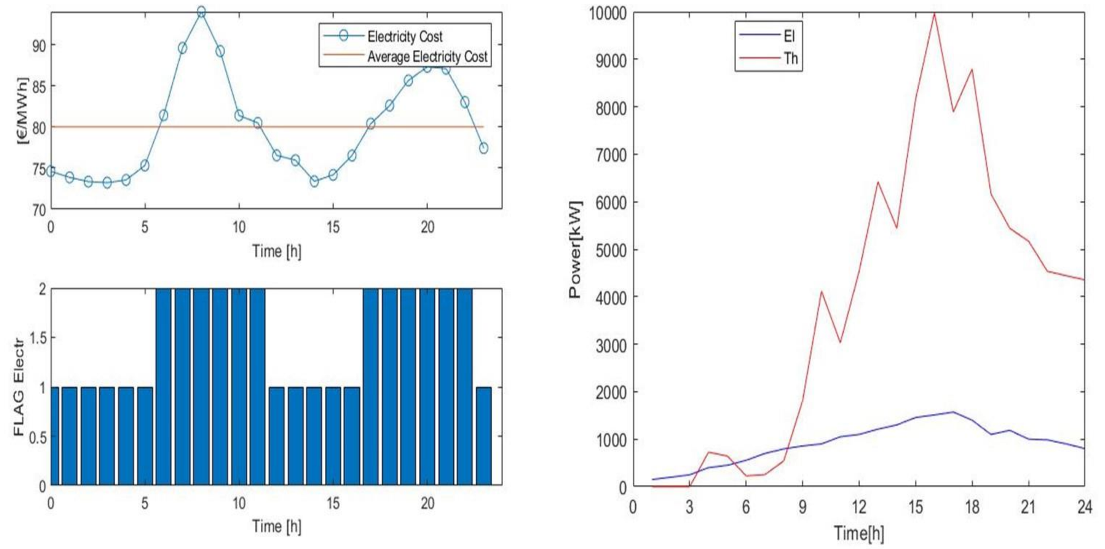


Figure 4.19 Changed demands (right) and electricity trend and flag (left)

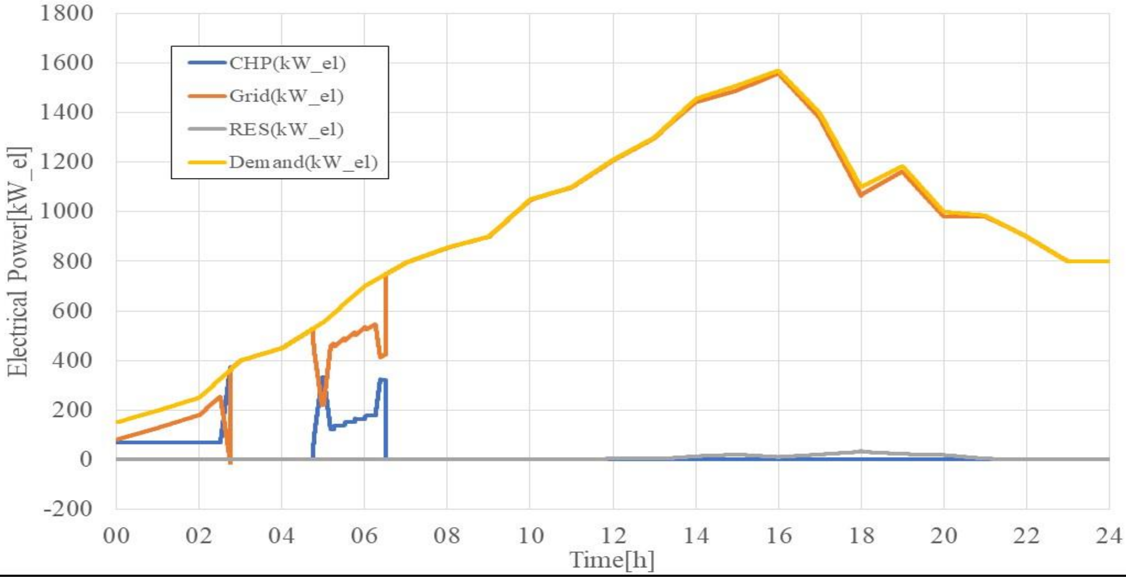


Figure 4.20 Electric power trend (syngas cost: 80 €/MWh)

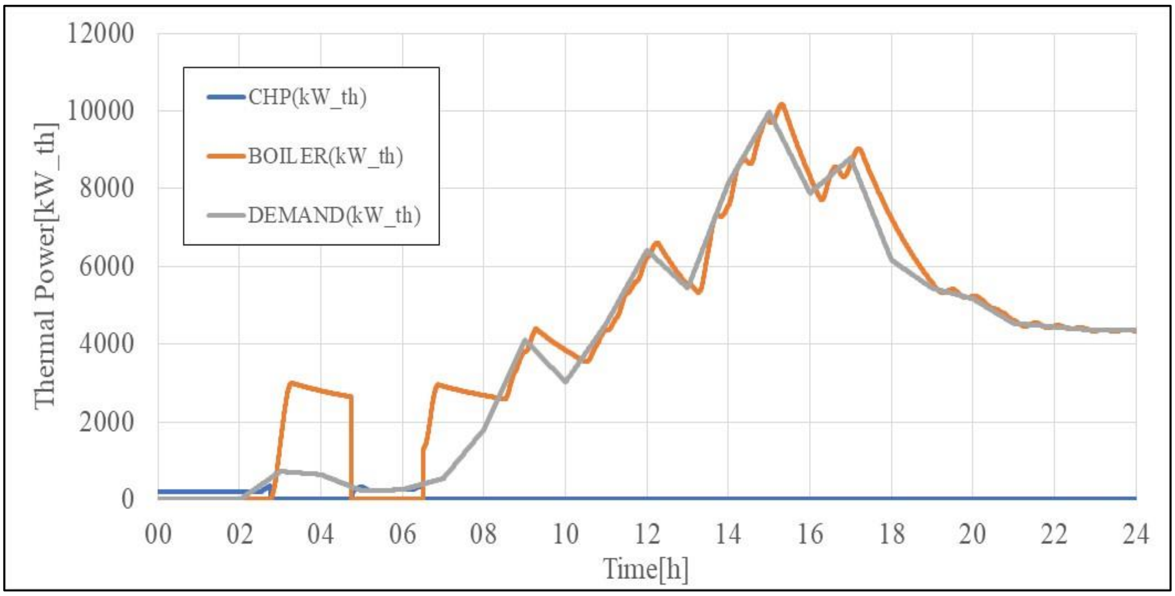


Figure 4.21 Thermal power trend (syngas cost: 80 €/MWh)

Figures 4.20 and 4.21 show the electric and thermal power trends. In this calculation the syngas cost was 80 €/MWh. In this case there is no electric energy exchange with the grid due to the fact that that the demand is very high as compared to previous results as well as the syngas cost is also considered very high. During initial phase the CHP turns on and then turns off as the boiler turns on which can be seen in figure 4.20 and 4.21. From 04:45 hrs. the CHP tuns on and a lot of variation is present because the CHP is satisfying the thermal demand also. Around 06:45 hrs., when the thermal demand begins to go up, the boiler turns on and the CHP is shut down as the EMS detects that it is not feasible to generate electricity being the cost of fuel very high. The simulations were also carried out with syngas cost of 1200 €/MWh and 2400 €/MWh which gives the same result as shown above.

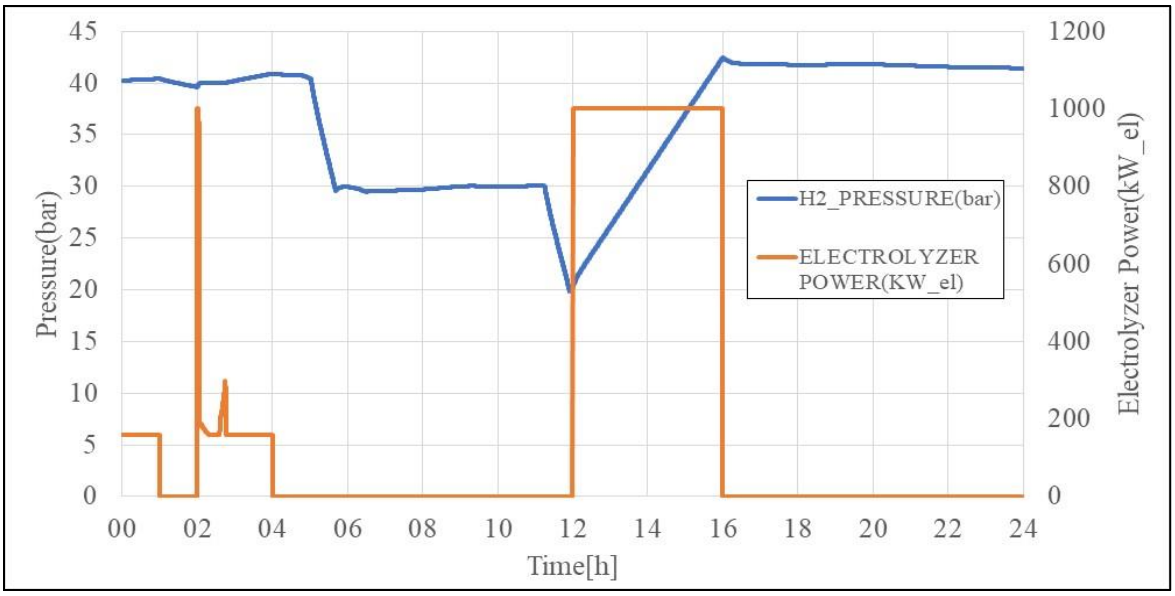


Figure 4.22 Pressure trend of hydrogen storage system & electrolyzer power (syngas cost: 80 €/MWh)

Figure 4.22 reports the pressure trend of the hydrogen storage system and electrolyzer working. We can observe that the pressure trend is quite like figure 18 but we can see variation in the electrolyzer power because we have fluctuations in the CHP working and to satisfy the optimal fuel supply the electrolyzers are increasing production of hydrogen for specific time. After 4:00 hrs. the trend of electrolyzer is similar to figure 18.

4.2. Performance comparison by adding O&M & startups

The number of start-up, maintenance and operational costs play a significant role in the performance of CHP. For this study these costs have been implemented (15 €/MWhel (0.015€/kWel)) [64].

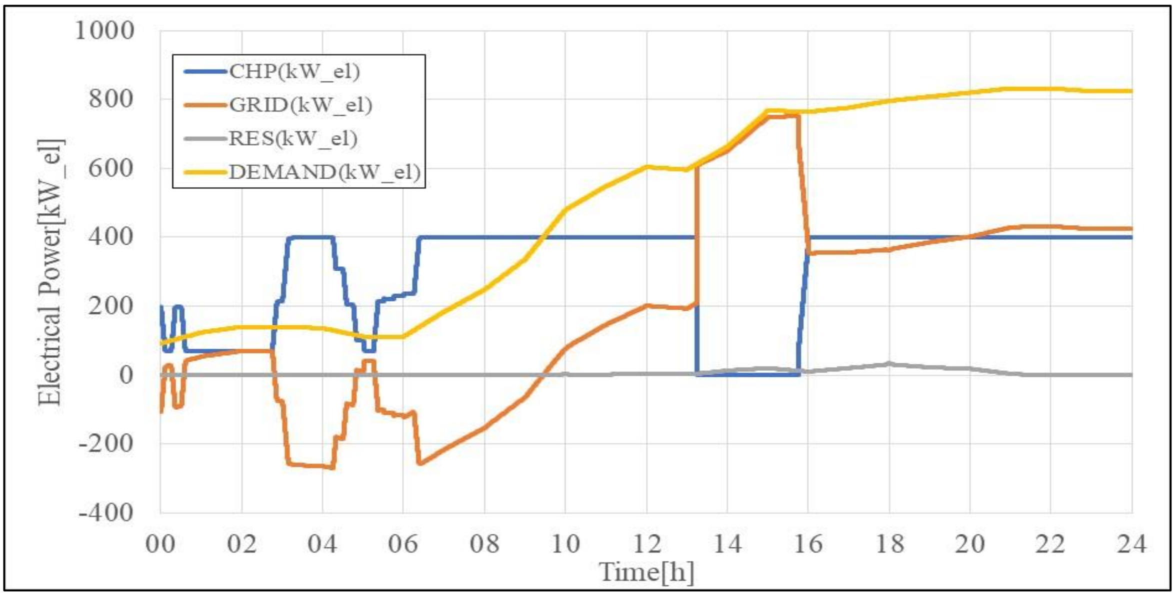


Figure 4.23 Electrical power trend with maintenance and start-up costs

Figure 4.23 shows the electrical power trend with maintenance cost and operational cost. The parameters used for this are same as shown in figure 1 and the cost of syngas considered is 80€/MWh. In this case it is possible to observe that adding O&M have a significant effect on the working of CHP. Comparing figure 4.23 with figure 4.5 it is possible to observe that in figure 4.5 from 00:00 hrs. to around 3.00 hrs. the CHP is working at minimum load (70 kW) but in figure 4.23 adding maintenance and startup cost and even the number of startups (2 in our case) initially for few minutes we see the variation. Around 13:00 hrs. we see the shutting down of CHP and around 16:00 hrs. again turns on thus increasing the cost of operation.

Adding the O&M costs as well as number of startups will also influence the working of the hydrogen storage pressure and electrolyzers. It is possible to observe from figure 4.24 that whenever there is fluctuation in the working of CHP its effect can be seen on the working of electrolyzer and hydrogen storage pressure. At 00:00 hrs. electrolyzers are working at maximum capacity then we can observe that they are working around 100 kW being the pressure 40 bar as they must produce hydrogen for the gas mixer.

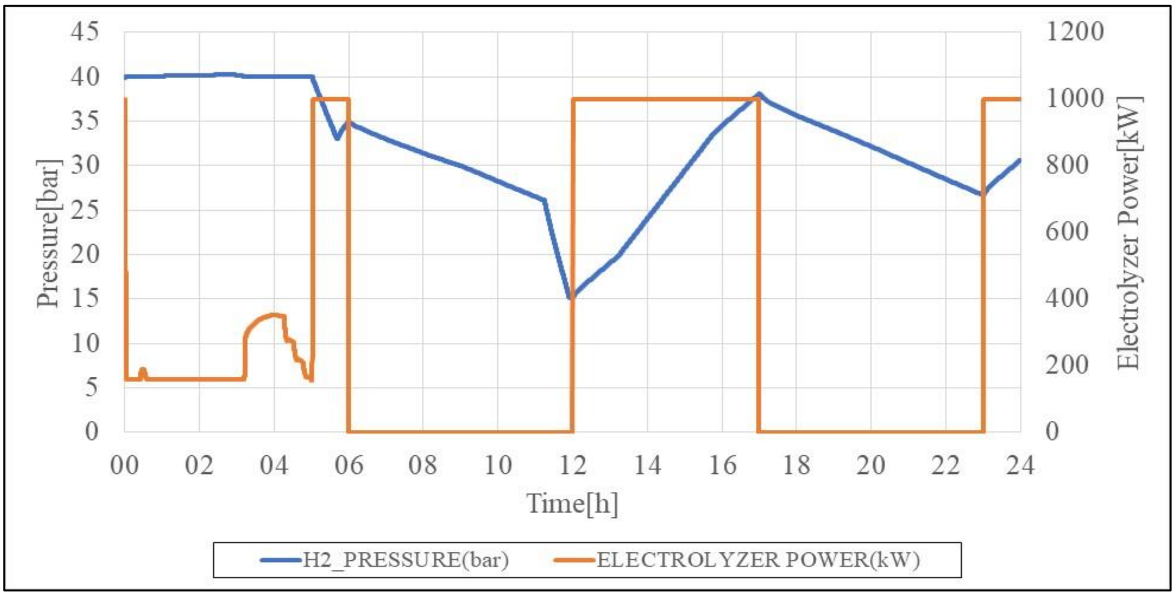


Figure 4.24 Pressure trend of hydrogen storage system and electrolyzer after adding the maintenance and start-up costs

4.3. Cost comparison with and without the O&M costs

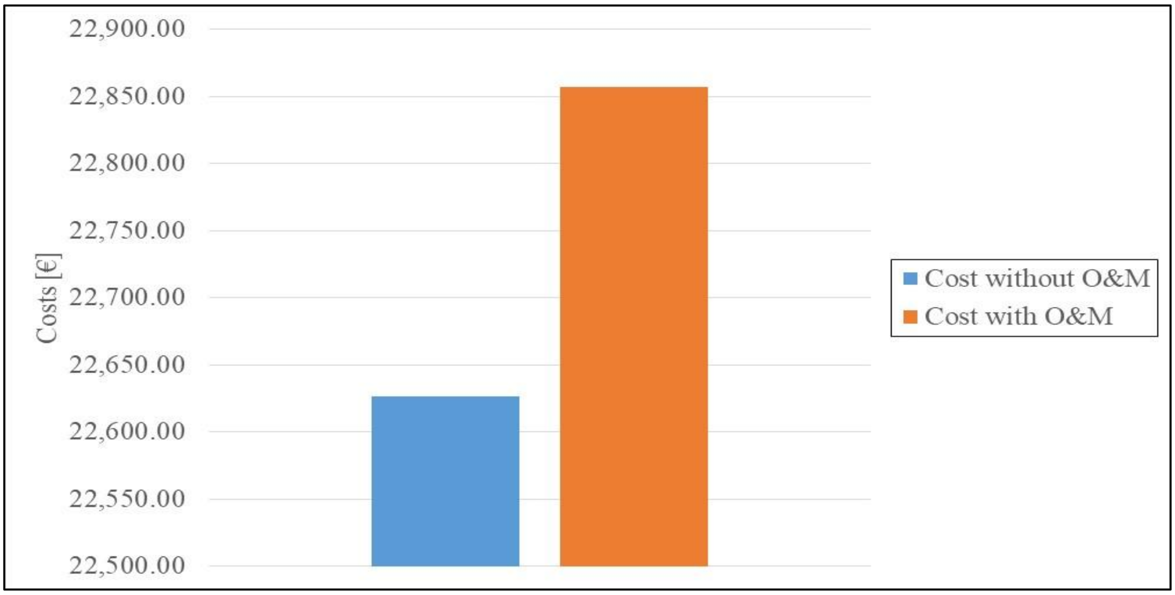


Figure 4.25 Total costs with and without O&M

Figure 4.25 shows the cost comparison with and without the O&M costs. The set of parameters used are same as shown in figure 4.1. By adding maintenance and operational cost and startup cost it is possible to see that the overall cost increases from € 22,626.40 to 22,857.40 € . Therefore, it is possible to conclude that by adding O&M cost and startup cost an increase of € 231.00 (about 1% cost increase) is obtained.

5. Conclusions

The core of this work regards the parametric analysis related to the performance on an EMS developed in the ROBINSON project for an industrial district in the Eigerøy island (Norway). The simulations were performed in Matlab/Simulink for the different components of the system. The tool includes a 400 kW CHP (A400 microturbine), a 22 MW boiler for steam generation, 2 electrolyzers of 500 kW (A 90 model) each, a connection with electricity grid, hydrogen pressure vessel, some RES (wind turbine and PV panels) and a gas mixer. A decision maker (optimizer) was used to calculate all the possible outcomes to obtain the most economical scenario whether to buy electricity or generate our own.
The main results obtained in this work are presented in the following points.

- A set of parameters were considered for the simulation such as syngas cost, average electricity cost and demands (thermal and electrical).
- A syngas cost of 5 €/MWh and average electricity cost of 150 €/MWh were considered as base case. Using these parameters, simulations were performed to check the EMS behavior to satisfy the demands minimizing the costs. To check the working and robustness of the EMS, parameters were changed and new simulations were performed with the cost of syngas of 150 €/MWh.
- For the next step, the syngas cost and average electricity cost were changed to 30 €/MWh and 100 €/MWh giving satisfactory results as the EMS was able to satisfy the demands. Changing the average electricity cost and syngas, the effect on the CHP and electrolyzers (to supply the hydrogen to the gas mixer for the CHP) is discussed.
- To check the robustness of the system a rigorous study was done with changes in demand (thermal and electrical) with more peaks in thermal demand and high electricity demand. Average electricity cost and syngas cost were considered equal to 80 €/MWh and 50 €/MWh respectively. Then the cost of syngas was changed to 750 €/MWh (no realistic value) and simulations were carried out showing a good behavior by the EMS with minimum operations for the CHP.
- After adding maintenance and operation cost and start-up costs, the system functioning was observed. A cost comparison with and without O&M and startups costs showed an increase in total system cost of € 230.68 (1%).

Considering this study and results gathered, it is possible to conclude that the EMS is robust and can satisfy the demands using the integrated technologies of the system. Moreover, it is ready for tests and demonstration activities, As planned in the ROBINSON project.

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Acronyms

AD-------------------------------Anaerobic digestor
AEC------------------------------Average Electricity Cost
BES------------------------------Bioelectrochemical System
COP------------------------------Coefficient of Performance
COP------------------------------Conference of Parties
DER------------------------------Distributed Energy Resources
EEGI-----------------------------European Electricity Grid Initiative
EL---------------------------------Electrical
EMS------------------------------Energy Management System
GDP------------------------------Gross Domestic Product
GHG------------------------------Green House Gases
HAWT---------------------------Horizontal axis wind turbine
ICT--------------------------------Information Communication Technology
ISA--------------------------------International Solar Alliance
ISO--------------------------------International Organization for Standardization
LOHC----------------------------Liquid hydrogen organic carriers
MIMO----------------------------Multiple input multiple output
MPC-------------------------------Model predictive control
NDCs-----------------------------Nationally Determined Contribution
O&M------------------------------operational and maintenance costs
OPEX----------------------------Operational Expenditure
PM--------------------------------Particulate Matter
PPM------------------------------Parts Per Million
RES-------------------------------Renewable Energy Sources
SGDs-----------------------------Sustainable Development Goals
SPM------------------------------Smart Polygeneration Microgrid
TH---------------------------------Thermal
TLC-------------------------------Telecommunications
TRL-------------------------------Technology Readiness Level
UNFCC-------------------------- United Nations Framework Convention on Climate Change
VAWT----------------------------Vertical axis wind turbine
VOCs------------------------------Volatile Organic Compounds
WP---------------------------------Work Package