NTNU

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Feasibility study of the implementation of a Small Modular Reactor with heat recovery for biogas production in the industrial plant of Nyhamna

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ABSTRACT

The Nyhamna natural gas processing plant (Norway) is one of the country's most important natural gas export facilities. Due to this activity, the plant has a high energy consumption that must be supplied by the Norwegian grid with significant energy losses as it is located in an area far from the main power generation points of the country.

For this reason, in order to achieve greater energy efficiency, a feasibility study has been carried out on the implementation of 3 small modular reactors (SMR) to supply the necessary energy to the facility. After analyzing different options, the X-Energy reactors were chosen. These reactors have a high degree of maturity compared to other modular reactors with high energy capacity, which is necessary for the Nyhamna plant.

On the other hand, in order to make the best use of the available resources in the area, the possibility of implementing a plant to produce biogas from salmon sludge has been studied. The objective of this study is to take advantage of the residual heat energy from the reactors, which would be used to heat the different processes involved in biogas production. This plant would use the salmon sludge generated at Salmon Evolution; a salmon farm located 3 km from the natural gas processing plant. This would achieve a valorization of the salmon sludge, which is currently discharged into the fjord, while supplying emission-free electricity to the natural gas processing plant.

This project therefore seeks to conduct a feasibility study of these SMRs with an innovative approach. Therefore, the ultimate goal of the project is to validate this type of installations in which nuclear energy is used more efficiently, and in line with renewable energies, and for this purpose the particular case of the Nyhamna plant has been studied.

The main results of this project indicate that these reactors could generate 240 MW of electricity, which is more than enough to process the natural gas. In addition, biogas production would reach 2,500 tons per year, enough to heat about 1,129 Norwegian homes per year.

PREFACE

This project has been developed with the aim of closely studying the energy scenario in Norway and assessing the capacity of the Small Modular Reactor (SMR) technology to meet the growing energy demand in the Nordic country. In addition, it has sought to incorporate an innovative approach by proposing possible benefits of these reactors, such as the use of residual energy to valorize waste and generate biogas.

During the development of this project, the established objectives have been achieved, confirming the adaptability of SMR reactors to the energy needs of industrial plants in Norway. The results obtained demonstrate the potential and effectiveness of this technology to provide a sustainable and efficient solution in terms of power generation.

This research has awakened in me a deep personal motivation and reflection about this technology. The ability of SMRs to address today's energy challenges should foster a new vision of nuclear energy as a viable and responsible option. At a time when we are facing pressing energy and environmental issues, it is crucial to explore innovative and sustainable alternatives that can ensure a reliable and environmentally friendly energy supply. I am confident that the findings presented in this project can contribute to informed energy debate and decision-making, and I hope that this research will motivate other researchers and practitioners to further explore the possibilities of SMR reactors and promote a broader and more progressive approach to nuclear energy.

I would like to take this space to express my sincere thanks to my mentor, Jan Emblemsvåg, for all his dedication and support throughout this project. His guidance and mentorship have been invaluable, and I am truly grateful for his availability and willingness to address all of my concerns. Without his expertise and encouragement, this project would not have reached its successful completion.

In addition to my tutor, I would like to extend my deepest thanks to the company Hyperthermics, and in particular to Elias Liavåg. Thanks to the data and information provided by this company, this project has been able to develop more accurately. Thanks to their support and availability in the face of the adversities experienced in developing this work, we have far exceeded the initial expectations set for this project.

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ACRONYMS

GHG – Greenhouse gas

SMR – Small Modular Reactor

SDG – Sustainable Development Goals

CFC – Chlorofluorocarbons

UNFCCC – United Nation Framework Convention on Climate Change

IEA – International Energy Agency

RE – Renewable Energies

IRENA – International Renewable Energy Agency

OECD – Organization for Economic Co-operation and Development

EPR – European Pressurized Reactor

IAEA – International Atomic Energy Agency

JEEP – Joint Establishment for Experimental Program

HBWR – Halden Boiling Water Reactor

EU – European Union

US - United States

HTGR – High Temperature Gas-cooled Reactor

PWR – Pressurized Water Reactor

LMR - Liquid Metal Reactor

CHP – Combined Heat and Power

WHCS – Water-Heat Combined System

JAEA – Japan Atomic Energy Agency

EOR – Enhanced Oil Recovery

SAGD – Steam-Assisted Gravity Drainage

EES – Engineering Equation Solver

UK – United Kingdom

MMR – Micro Modular Reactor

USNC – Ultra Safe Nuclear Corporation

LPS – License to Prepare Site

LCP – License to Construct Phase

NRC – Nuclear Regulatory Commission

PBR – Pebble Bed Reactor

TRISO – tristurctural- isotropic fuel

DCA – Design Certification Application

UAMPS – Utah Associated Municipal Power Systems

INL – Idaho National Laboratory

TS – Total Solid

MSR - Molten Salts Reactor

KEY WORDS

Small Modular Reactor (SMR), Biogas, Nuclear power, feasibility study Gas processing plant, Rest energy, Energy efficiency, Nyhamna, Salmon Evolution, Hyperthermics

1. INTRODUCTION

In a global scenario characterized by ongoing climate change and the continuous growth of population and technology, increasing energy demand has become a pressing need. However, it is essential to address this growing demand in a way that does not further compromise our environment and contribute to the climate crisis by moving away from energy produced by fossil fuels. It is in this context that the generation of energy from clean sources free of greenhouse gas (GHG) emissions becomes essential. While renewable energy presents itself as a promising option, its intermittency and the immaturity of some technologies pose significant challenges to fully meet this growing energy demand. This is where nuclear energy emerges as an alternative worthy of consideration, offering a continuous, high-performance energy source that can complement renewable sources and contribute to the transition to a more sustainable energy system.

In the field of nuclear energy, Small Modular Reactors (SMR) emerge as a promising and highly advantageous technology. These reactors stand out for their advanced design and inherent features that ensure a higher level of safety, mature technology and ability to adjust to energy demand (load following capability), resulting in more efficient power generation. Moreover, being smaller and modular, they allow for scalable and adaptable energy production, reducing costs and implementation times through industrial production in factories as opposed to the on-site construction of the large nuclear reactor today. In short, SMRs are presented as an improved option for increasing energy production capacity in an efficient and sustainable manner.

Given the growing interest and acceptance of nuclear energy as a reliable and sustainable energy source, the opportunity arises to develop a project that takes advantage of the benefits of fourth generation modular reactors. In this context, the present work aims to propose and evaluate the feasibility of implementing an energy generation system based on modular reactors to cover the electricity demand of an industrial plant, taking full advantage of the technological improvements and adaptability of this innovative nuclear technology.

The main objective of this project is to develop a feasibility study for the energy supply of a large industrial plan using the Nyhamna gas processing plant, located west of the city of Molde in Norway, as a case. This industrial plant is characterized by its high electricity consumption, which raises the need to find efficient and sustainable solutions for its energy supply. Therefore, it is proposed to evaluate the implementation of modular reactor technology as a viable option to cover this demand, taking advantage of the benefits of this innovative nuclear technology in terms of safety, efficiency and low GHG emissions. The ultimate goal is to design an energy system that guarantees a reliable and sustainable electricity supply for the Nyhamna plant, thus contributing to the optimization of its operation and reducing its environmental footprint.

In addition, this project will carry out an energy calculation of these reactors, and their possible operation to meet the electricity demand. In this analysis, the possibility of recovering the waste heat from the thermodynamic cycle, which is commonly discharged into the environment through a condenser, will be studied. This heat represents a large amount of energy provided by the reactor, and its waste is contrary to energy efficiency. Thus, the overall objective is to achieve a more sustainable energy system. In this work, the possibility of using this waste heat to heat the processes of a biogas generation plant has been evaluated.

This biogas plant will use salmon sludge as the organic material to be transformed. This material will be provided by the company Salmon Evolution, which is located 3 km north of Aukra Island, where the Nyhamna gas processing plant is located. Salmon Evolution is a Norwegian aquaculture company focused on becoming the world's leading producer of land-based farmed Atlantic salmon. To do this, they use a hybrid continuous flow system which ensures a sustainable production process with controlled and optimal growth conditions. In the course of its activity, Salmon Evolution generates large quantities of sludge, which, due to its apparent lack of usage, is dumped into the ocean. However, its energy potential has been evaluated for the production of biogas in a hybrid way together with the modular reactors. In order to make the best use of this resource, the option of pumping the sludge over a distance of 3 km under the ocean to the location of the biogas production plant has been considered.

In this way, the current project addresses a number of challenging problems facing the town of Møre og Romsdal:

- Firstly, there is the possibility of providing the Nyhamna gas processing plant, which has a very high consumption, with GHG emissions free electricity.
- Secondly, the salmon sludge problem is solved. In this way, this sludge can be valorized, giving it an outlet without having to be dumped into the ocean and polluting it. In this way, the present project will allow marine life in the area to remain unaffected.
- Finally, a value is obtained from salmon sludge in the form of fuel with a net zero emission value. This biogas, as a renewable resource, presents itself as a promising solution for sectors such as marine transport, where the implementation of electricity grids based on renewable energy systems can be more challenging.

Based on the case of study, this project aims to provide answers to the next four main research questions. First, the project seeks to prove the viability of SMRs to supply the electricity demand of industrial plants. In this way, the intrinsic flexibility of this technology, which has the capacity to adapt to demand, is proven. The second issue that has been tried to clarify is the possibility of using the rest energy of the reactors to heat the different processes of a biogas plant. In this way, the aim is to increase the energy efficiency of the SMRs by taking advantage of an energy that is not generally used. Implicit in these first two questions is the third question, which is to study and promote the collaboration of nuclear energy together with renewable energies in order to advance towards energy decarbonization. Finally, this project seeks to study the feasibility of generating biogas from salmon sludge. This will try to give a greater perspective on this technology, and will discuss its capacity in a project of this size.

This project is aligned with the Sustainable Development Goals (SDG) proposed by the United Nations in September 2015. These goals were established as a global agenda to address the world's most pressing socio-economic and environmental challenges, and set targets to be achieved by 2030. The ultimate goal of the United Nations is to promote prosperity while protecting the planet, and to this end, the United Nations conducts an annual update of these goals giving an overview of the status of each of them[1].

This feasibility study mainly contributes to the achievement of SDG 7: "Ensure Access to affordable, reliable, sustainable and modern energy for all". This goal emphasizes the need to increase GHG emission-free energy production. To this end, it is proposed that by 2030 international cooperation must be improved to facilitate access to clean energy research and technology[2]. Improving energy timeliness is the main motive of the study, and its implementation would be a contribution to this SDG.

In addition to contributing to SDG 7, this project also has a relevant contribution to other targets. In particular, it aligns with SDG 9, which talks about improving infrastructures and modernizing industries to make them sustainable as this project intends to do by developing on the one hand a nuclear power generation plant, and on the other hand a biogas production plant. It also contributes to SDG 12 which seeks to ensure sustainable production and consumption patterns by making efficient use of natural resources and SDG 14 which seeks to conserve and sustainably use the oceans, seas and marine resources by preventing pollution of all kinds. The latter two goals are contributed to through the valorization of salmon sludge, as this action makes better use of natural resources, preventing the ocean pollution that occurs when this sludge is dumped at the bottom of the fjord.

In order to carry out this project, it will first be analyzed the context in which it is situated, both globally and locally in Norway. Then, the state of art will be presented in which the topics of modular reactors, waste heat utilization and biogas production will be discussed. Afterwards, the methodology will be presented, where the project and the details surrounding it will be analyzed. After this, the results will be shown and an analysis of the project will be carried out. This will lead to the economic study, showing the financial viability of the project. Finally, a discussion of the results obtained will be made pointing out the main conclusions of the project.

2. BACKGROUND

The current global landscape presents a number of environmental challenges that are of vital importance for the protection of the planet as we know it. These problems have a direct impact on our health, well-being and the long-term viability of the planet. This global problem has to be solved by modern civilization, as it is the main cause of it.

In the late 18th century, a process of social, economic and technological transformation called the Industrial Revolution emerged in Great Britain (United Kingdom). Industrialization brought rapid economic growth and technological advances, but it also caused a number of environmental problems. The burning of coal and the emission of toxic gases contributed to air and water pollution, and deforestation intensified due to the demand for timber for industry.

2.1. Treaties in protection of the environment

In response to these problems, a number of important treaties and events in the history of the environment emerged. In 1972, the Stockholm Conference on the Human Environment, organized by the United Nations, was a crucial milestone. At this event, the interrelationship between unsustainable economic growth and environmental degradation was recognized, and principles were adopted to guide environmental management[3].

Another key milestone was the Montreal Protocol in 1987. This international treaty focused on the protection of the ozone layer and sought to phase out ozone-depleting chemicals, such as chlorofluorocarbons (CFCs) used in aerosols and refrigerants[4]. The Montreal Protocol has been highly successful in reducing the production and consumption of these harmful substances.

Later, in 1992, the Earth Summit was held in Rio de Janeiro, also known as the United Nations Conference on Environment and Development. At this summit, fundamental agreements were adopted, the most prominent being the United Nations Framework Convention on Climate Change (UNFCCC), which established a framework for global cooperation in the fight against climate change[5].

Subsequently, in 1997, the Kyoto Protocol was established as a complement to the UNFCCC. This international agreement established binding commitments to reduce GHG emissions, with specific targets for industrialized countries. It also introduced flexibility mechanisms such as emissions trading and clean development mechanisms[6].

Finally, in 2015, the Paris Climate Summit was held, resulting in the historic Paris Agreement. This global agreement aims to address climate change and sets out a commitment to keep global temperature rise below 2 degrees Celsius, as well as striving to limit it to 1.5 degrees Celsius. It also promotes international cooperation on climate change adaptation and provides financial support to developing countries[7].

This agreement has had a significant impact on the SDGs. These goals were adopted by the United Nations in 2015 as a universal call to end poverty, protect the planet and ensure that by 2030 all people enjoy peace and prosperity[2]. As far as climate change is concerned, in order to prevent global temperature rise, the Paris agreement directly addresses goal number 13: "Climate action". This goal establishes the need to take urgent action to combat climate change and its impacts. In addition, it also addresses goal 7: "Affordable and clean energy" which focuses on the need to generate clean, GHG-free energy. This energy generation is vital for global sustainable development.

2.2. Power generation

Power generation plays a key role in global energy supply. It is the process by which energy is produced to power various human activities, from the operation of homes and businesses to the operation of industries and transport systems.

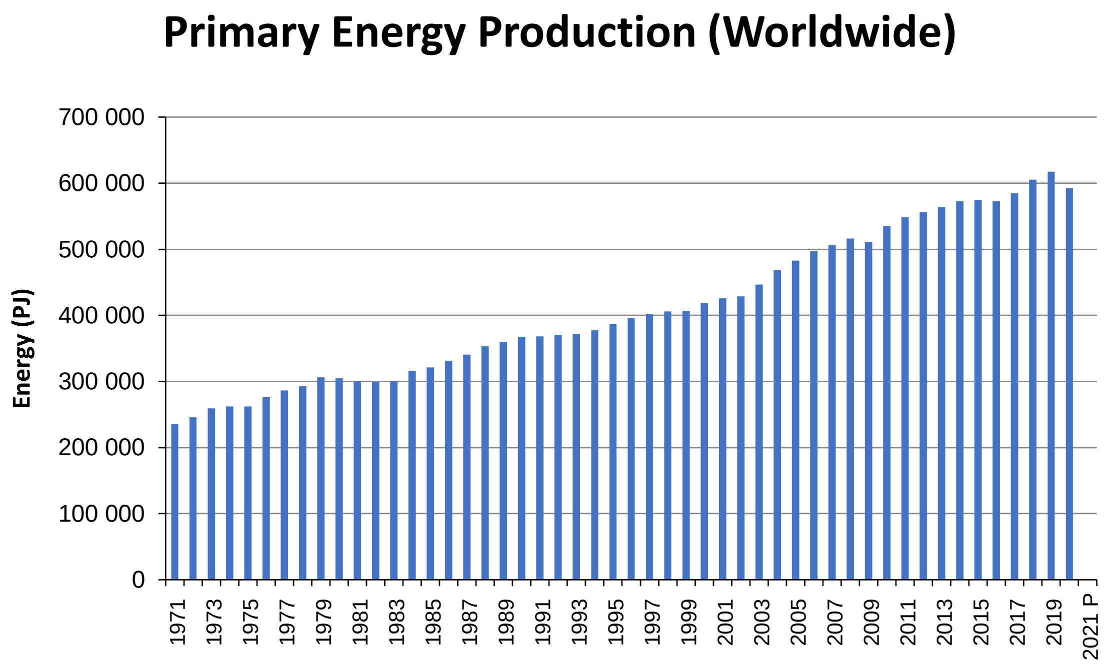

Figure 1 Primary energy production worldwide over the last 30 years[8].

As can be seen in Figure 1, global energy production has an upward trend, which is due to a clear increase in energy demand. This trend is due to world population growth and technological economic development, among other reasons. According to the International Energy Agency (IEA), the increase in energy production over the last 30 years has been 59.61%. However, this increase is not a good indication of sustainability because 79.96% of energy production is still based on fossil fuels[8].

Given the current climate crisis and the increase in global energy demand, it is essential to seek solutions to supply today's society with sufficient energy to carry out its activities. This must be done by limiting GHG emissions to reduce environmental impact and promote the transition to a more sustainable energy model. In this sense, renewable energy sources represent the main alternative to conventional energy production systems based on fossil fuels with a high level of emissions.

2.3. Renewable energies

Renewable energies (RE) are energy sources that are obtained from natural resources that are inexhaustible or continuously renewable. These sources include solar, wind, hydro, geothermal and biomass energy. Unlike conventional fossil fuel-based energies, renewable energies offer numerous benefits. Firstly, they are clean and environmentally friendly, as their generation does not produce significant GHG emissions or air pollutants. This contributes to mitigating climate change and improving air quality. In addition, renewable energies are local energy sources, which reduces dependence on energy imports and promotes the autonomy and energy security of countries.

Renewable energy is now playing an increasingly important role in the global energy mix. Thanks to technological advances and cost reductions, renewable generation capacity has experienced significant growth worldwide. Solar and wind energy, in particular, have become the most prominent renewable sources, with installations expanding in several countries[9]. These clean energies have the potential to provide a significant share of the world's energy demand, both residential and industrial.

In order to achieve greater deployment of these energy renewable resources, it is essential to drive greater electrification of energy systems. By promoting the adoption of electricity technologies in key sectors such as transport, industry and households, an enabling environment is created for the integration of renewable energy sources. Electricity is a versatile and efficient form of energy that can be generated from a variety of sources. Having a robust and well-developed electricity infrastructure in place facilitates the integration of these clean sources and reduces dependence on highly polluting fossil fuels.

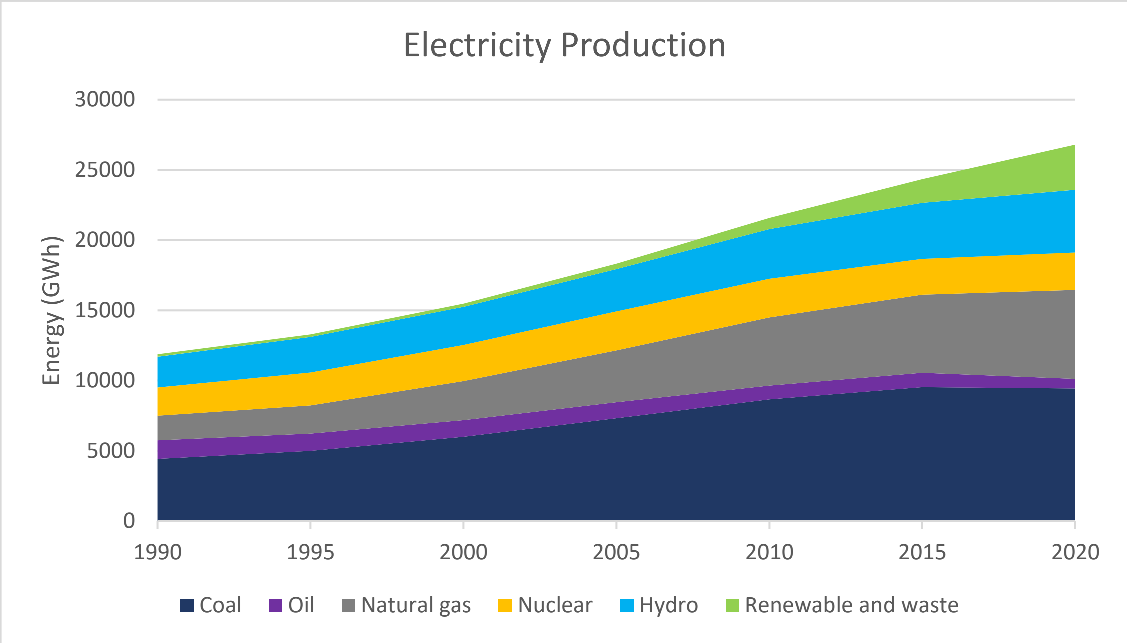

Figure 2 Electricity generation by source worldwide. Authors calculation using data from[8].

As can be seen in Figure 2, global electricity production has increased significantly in recent decades. It is worth noting that in the last five years, energy production from coal has decreased by 0.88% for the first time in history. Similarly, electricity from oil has fallen by 34.58%, a downward trend that has continued over the last three decades[8].

However, there has been a positive trend in the production of electrical energy from natural gas in recent years, resulting in a 2.16% increase in electricity generation from fossil fuels[8]. This is due to several reasons, such as the abundance and accessibility of natural gas reserves, its lower environmental impact compared to oil and coal, and advances in gas extraction and power generation technology. In addition, the increase in electricity demand is another factor explaining this growth in the use of natural gas for power generation.

It is also worth highlighting the evident increase in renewable electricity production in recent decades. This electricity production is mainly composed of wind and solar photovoltaic, although other energy sources also have a significant presence such as biofuels, waste, geothermal, solar thermal or marine. This increase has been even more evident since 2010 due to the growing recognition of the importance of addressing climate change. This has led to further progress in these technologies and the efficiency of renewable energy sources, making them more accessible and cost-effective. As a result, more investments have been made in renewable projects and their installed capacity has increased worldwide.

Although in the graph hydroelectric energy is represented apart from the rest of renewable energies, this energy source is included among renewable energies, and represents the most expanded source at present. This resource has experienced steady growth over the last few years, showing a significant increase in the last five years, with an increase of 11.85%. This positive trend demonstrates the key role that hydropower plays in the generation of clean and sustainable electricity, thus contributing to climate change mitigation and diversification of the global energy matrix.

Historically, Norway has been dominated by hydropower generation as its main source of energy. Thanks to its abundant water resources, Norway has taken advantage of its mountainous topography and numerous rivers and waterfalls to build a robust hydropower infrastructure. Currently, hydropower is Norway's main energy source, with 1681 hydropower plants with a total installed capacity of 33,055 MW at the beginning of 2021[10]. This form of power generation has been an integral part of the country's industrial and economic development, providing a reliable and sustainable source of electricity.

However, as energy demand grows and the country seeks to diversify the energy matrix to address challenges such as climate change, Norway is exploring other energy sources complementary to hydropower. This is mainly due to increasing electricity demand caused by population growth, industrial expansion and economic development. Hydropower, although a renewable and clean energy source, has certain limitations in terms of generation capacity and availability. Therefore, the search for other energy sources makes it possible to meet this growing demand in a more diversified and sustainable manner.

Furthermore, the diversification of energy sources in Norway is also driven by a long-term perspective and the need to ensure security and stability of energy supply. Relying solely on hydropower can expose the country to vulnerabilities in the event of prolonged droughts or changes in climatic conditions. By exploring other energy sources, Norway seeks to strengthen its energy resilience and reduce potential risks associated with exclusive reliance on a single source.

In order to achieve this goal, Norway is currently developing its renewable technologies in order to increase its electricity capacity. Currently, the most exploited renewable energy source apart from hydropower is wind energy. Norway's geographical location is ideal for the exploitation of this resource, with a long coastline and extensive mountainous areas, which provide excellent potential for wind power generation. The strong winds along the coast and in the mountainous areas provide an abundant and constant energy resource. For this reason, Norway has in recent years decided to invest in this energy source by installing 1405 MW of new capacity by 2020, giving it an installed wind power capacity of 3977 MW[10]. This has resulted in electricity production from wind power at 7.45%, which is a big jump from 0.71% in 2010[8].

In addition to these energy sources, the use of organic matter is also a widely expanded resource for energy supply. Through this resource, different types of derivatives can be obtained, which are called biofuels, and although they only represent 2.13% of the world's electricity generation[8], these fuels have great potential, and their development can imply a great advance towards a more sustainable energy system.

Within biofuels, 3 main families can be distinguished, which have different origins and applications: bioethanol, biodiesel and biogas. Bioethanol is an alcohol produced from the fermentation of sugars and starches present in crops such as sugar cane, corn and beet, and its main application is as an additive in vehicle fuels or as pure fuel in high-compression engines. Biodiesel is produced from vegetable oils or animal fats through a transesterification process, and can be used as an additive in conventional diesel fuels or as a pure fuel in diesel vehicles. Biogas, on the other hand, is produced by the anaerobic decomposition of organic matter such as agricultural residues, animal manure or food waste. In the present project, we will focus on biogas as an energy carrier of particular interest.

2.4. Biogas

For millions of years, organic matter has been used as a source of energy by mankind. Since ancient times, our ancestors discovered that burning wood, charcoal and other organic materials could provide heat for cooking, heating and various activities. This ancient practice laid the foundation for understanding the energy value of organic matter and has evolved over the centuries, leading us to explore new ways of harnessing and transforming these resources into renewable energy sources such as biogas.

Biogas is a form of renewable energy obtained from the decomposition of organic matter in the absence of oxygen, in a process known as anaerobic digestion. During this process, microorganisms break down organic matter, such as agricultural waste, animal manure, food waste and sewage sludge, releasing gases, a 70% of methane (CH_4) and a 30% of carbon dioxide (CO_2)[11].

The basic principle of biogas is based on capturing and using the methane produced during the decomposition of organic matter, and then using this methane as a fuel for various energy applications. This variety of biogas applications is one of the main advantages of this resource over other renewable energy sources. One of these applications is electricity and heat generation in biogas plants, where its exploitation is widely known, as it has the same basis as conventional gas plants.

In addition, it can also be used as a motor fuel, thus replacing conventional fossil fuels in those activities where the integration of the electricity system is more complicated, such as transport. This sector is the second largest energy consuming sector in the world, and by far the sector with the highest GHG emissions. Therefore, the implementation of renewable energies in this field is one of the main challenges facing our society. According to the International Renewable Energy Agency (IRENA), the use of this resource could reduce emissions by 60% to 80% depending on the organic material used for biogas[12], which would be a great step forward in terms of emissions reduction.

Biogas, when used as an energy source, undergoes a combustion process that produces carbon dioxide (CO_2) as a by-product. However, this is a renewable energy resource, as the balance of CO_2 emissions is neutral. This means that all the CO_2 emitted both in the production and consumption of biogas is equal to the CO_2 that the organic matter has absorbed during its lifetime. This makes biogas an ally in the fight against climate change.

On the other hand, biogas has proven to be an effective solution for waste recovery, resulting in a significant reduction of waste. By using this waste as a raw material for biogas production, in addition to obtaining a renewable fuel, it also reduces the amount of waste that would otherwise end up in landfills or undergo uncontrolled decomposition processes, which can generate harmful emissions for the environment. This is vitally important in today's society where, due to population growth and industrial development, waste generation continues to increase significantly.

However, there are several factors that limit the use of this resource. On the one hand, large quantities of organic matter are needed for its production, which is not available everywhere. In addition, this resource requires the construction of specialized infrastructures that can be very costly to build and maintain. It should also be noted that biogas has to be treated before combustion, as it may contain unwanted pollutant impurities such as hydrogen sulfide (H_2S), thus increasing the cost of its exploitation even more.

In terms of resource exploitation, this often leads to the creation of energy plantations, which have a negative impact on the environment. Due to these plantations, biodiversity and ecological balance is sometimes disturbed. In this regard, in order to stop the expansive damage to the world's forests and stop the acceleration of climate change, a letter signed by 800 scientists was drafted in 2018 for the European parliament about forest biomass[13]. In this letter, it is laid out that even if forests are allowed to regrow, the use of deliberately harvested wood for burning will increase carbon in the atmosphere and warming for decades or centuries. This is true even when wood substitutes for coal, oil or natural gas. Moreover, new tree growth and the displacement of fossil fuels may pay off this "carbon debt", but only in the long term. For these reasons, this letter argues for the need to look for alternatives and move away from deforestation for energy purposes. In addition, the intensive cultivation of these plantations may compete with the availability of land for food production, raising concerns about food security.

These facts mean that, in order to continue obtaining biofuels, other types of organic materials are used, such as food waste, such as fruit and vegetable peelings, agricultural waste, such as crop stalks, leaves and crop residues, or animal waste, such as excrement or sludge. In this way, these wastes acquire a higher value for the future.

However, the above-mentioned reasons have resulted in biogas having a very small presence in the international energy mix. Currently, according to the IEA, out of the global electricity production from biofuels that amounts to only 2.13% as we have already seen, biogas just accounts for 15.71% of these biofuels[8]. On the other hand, as far as thermal generation is concerned, only 5.45% of renewable consumption is by biogas, with the use of primary solid biofuels such as wood being more extensive[8]. This resource represents 64.77% of renewable thermal generation due to the simplicity and convenience of its use[8].

Despite the disadvantages and relatively low implementation of biogas as an energy resource, it is important to recognize its great potential and consider it as a viable option in the search for a more sustainable energy system due to its versatility and zero net emission balance. Furthermore, as mentioned above, this resource can be used in the same way as gas, which is a mature technology and does not present the usual problems of renewable energies such as intermittency. In the following, these problems are outlined in general terms trying to find a solution for them.

2.5. Renewable Energies issues

As shown above, renewable energy is the most promising way to address climate change. Their ability to generate energy in a clean and emission-free manner is critical to reducing our dependence on fossil fuels and mitigating negative impacts on the environment. With a focus on sources such as solar, wind, hydro and biomass, we can move towards a more sustainable and responsible future, where energy generation is in harmony with the protection of the planet and the preservation of its natural resources.

However, despite the great advantages of these renewable energies in terms of GHG emissions and diversification of energy production, there are certain disadvantages associated with the implementation of these sustainable energy sources. The generation of energy from these renewable resources is often dependent on natural factors and therefore results in undesirable intermittency in meeting energy demand. In addition, the availability of these resources is variable, and they are sometimes not available in certain geographical areas, limiting their deployment. These reasons, coupled with the low degree of maturity of certain technologies, highlight the need to explore other energy sources while solutions to the problems presented by renewable energies are being developed.

To achieve this purpose, the development and deployment of different technologies, together with policies that encourage the transition to low-carbon energy systems, are essential to achieve a sustainable energy future, both in Norway and globally. In this context, nuclear energy is presented as a viable, proven and guaranteed alternative to combat climate change, together with renewable energies, making it possible to reduce energy production from fossil fuels, while increasing energy generation.

2.6. Nuclear energy

Given these conditions, nuclear power has emerged globally as a major resource for combating climate change. As the world seeks to reduce GHG emissions and move towards a cleaner energy matrix, nuclear power stands out for its ability to generate large amounts of electricity without carbon emissions. Its strategic combination with renewable sources, such as solar and wind, presents a comprehensive and balanced solution to address growing energy demand, while reducing dependence on fossil fuels and limiting environmental impact.

Nuclear energy is based on the principle of nuclear fission, which involves the splitting of heavy atoms, such as uranium or plutonium, in a controlled process. These reactions occur when a neutron hits the nucleus of these heavy elements. At this instant, the neutron is absorbed by the nucleus producing its excitation, and subsequently its splitting, giving rise to lighter isotopes. This splitting also releases a large amount of energy and new neutrons. These neutrons can then collide with another nucleus, producing a new reaction, and giving rise to what is called a chain reaction[14]. Thanks to this chain reaction, the nuclear reactor is able to supply a large amount of energy, which in a nuclear power plant is used to produce high-pressure steam. This steam drives a turbine, which in turn is connected to an electrical generator. As the steam expands and passes through the turbine, its kinetic energy is converted into mechanical energy, which is finally transformed into electrical energy by the generator. This is how the steam acts as a means of converting heat into usable electrical energy.

Unlike renewable energies, nuclear energy has significant advantages in terms of stability and reliability. Nuclear power is not subject to weather or seasonal variations, as it is not dependent on the availability of sun or wind. This means that nuclear power can operate steadily and predictably, providing a baseload energy source that complements intermittent renewables. In addition, nuclear power does not emit GHG during electricity generation, making it a valuable option for combating climate change and reducing carbon emissions.

In addition to its stability and low GHG emissions, nuclear power also has a high energy density, meaning that a small amount of nuclear fuel can generate a large amount of energy. This makes it an efficient option in terms of resource use and space occupation. Moreover, nuclear plants tend to have a long lifetime and high generation capacity, which contributes to energy security and diversification of a country's energy mix.

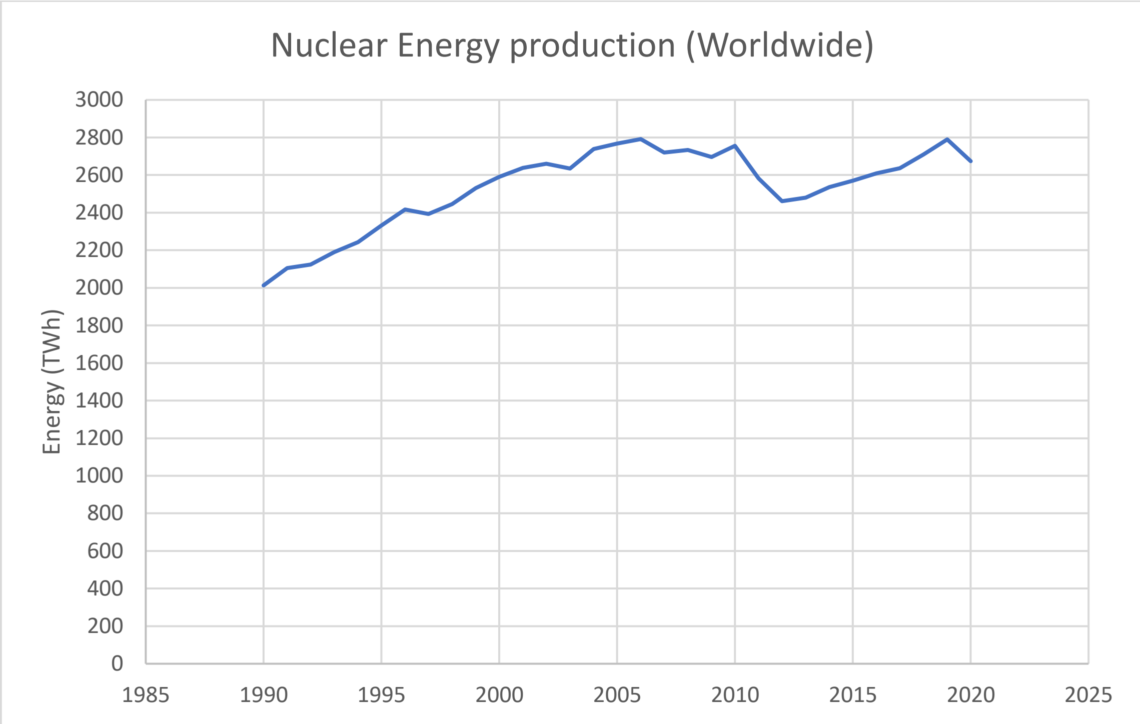

Figure 3 Nuclear energy production worldwide over the last 30 years. Authors calculation using data from[8].

This energy source has played an important role worldwide in terms of energy generation, accounting for 17.68% of the world's energy generation in 1996[10]. However, due to the nuclear accidents that occurred at the Three Mile Island nuclear power plants in 1979, Chernobyl in 1986, and Fukushima in 2011, public opinion regarding this energy source has been affected[15]. As a consequence of this low public acceptance particularly in OECD countries, nuclear energy production has declined, with nuclear energy now accounting for only 10% of global energy production[10]. An example of this is the drop in electricity generation that occurred in 2011 following the Fukushima accident, as shown in Figure 3.

However, given the world's energy crisis, coupled with the need to mitigate climate change, the nuclear energy debate has been reignited. In November 2022, President Emmanuel Macron announced the construction of 14 new nuclear reactors to supply the country's energy demand and cushion the volatility of energy prices caused by the war in Ukraine[16]. On the other hand, in Japan, despite the past Fukushima accident, due to high energy consumption, the decision has been taken to reopen nuclear power plants, with the objective of having from 20 to 22% of nuclear energy in its energy mix by 2030[17].

In Poland, a survey of the population on nuclear power was conducted in 2021 resulting in 74% of the inhabitants being in favor of a nuclear power plant being built in their country[18]. This is also reflected in the plans of the Slavic country, which is now in the process of building its first nuclear power plant based on AP1000 reactor technology, with the country's plans being to increase nuclear power capacity to 9 GW(e) by 2040 through 6 reactors[19].

Similarly, in Great Britain, the installation of a nuclear power plant (Sizewell C) consisting of two European Pressurized Reactors (EPR) with an installed capacity of 3.2 GW has been approved[20]. In Canada, $970 million have been invested in the development of fourth-generation reactor technology, the SMRs[21] (see chapter 2.8). In Germany, on the other hand, due to the fear of a possible accident, nuclear power generation was stopped on April 15 of the 2023[22]. In the US, in the state of West Virginia, laws preventing the construction of new reactors have been repealed in order to allow the expansion of this energy source[23]. This scenario is very changeable, and depends mainly on the policies of each country, as well as on the global context. Currently, 15 countries are now constructing nuclear power plants and another 30 countries plan to construct[24], [25].

In Norway, despite being part of the International Atomic Energy Agency (IAEA), nuclear energy has never played a significant role in power generation. Over the decades, Norway has explored the potential of nuclear energy, but has so far not built commercial nuclear power plants.

In 1951, research into nuclear energy began in Norway. For this purpose, the JEEP (Joint Establishment for Experimental Programme) Research Reactor was built in Kjeller, which was in operation from 1951 to 1995. Since then, three other research reactors have been built in Scandinavia: one at Halden, the Halden Boiling Water Reactor (HBWR) reactor, and two at Kjeller, N0RA and JEEP II. These reactors contributed to the development of nuclear technology and the training of experts in the field. However, in 1979, following the Three Mile Island nuclear accident in the United States, Norway decided to abandon plans to build commercial nuclear power plants in the 70s, and in 2018 and 2019 the decommissioning of the HBWR and JEEP II nuclear reactors began.

Despite this, Norway is part of the European Union (EU) taxonomy whose main objective is the establishment of a common classification system for environmentally sustainable economic activities. In this way, the aim is to provide clarity and transparency on what can be considered environmentally sustainable, in order to direct investment flows towards activities that contribute to the EU's environmental objectives. In this regard, nuclear energy has recently been accepted as environmentally sustainable economic activities, making it an asset for the continent's energy development[26]. Therefore, it could be expected that, since Norway is within this framework, the possibility of implementing this energy source will be explored in the future.

By contrast, currently, there is reduced deployment of this resource both in Norway and the rest of the world, and this is mainly due to doubts about its safety. However, there are also other uncertainties related to this energy source that have a direct impact on its use.

2.7. Nuclear Energy Issues

Nuclear energy currently represents one of the most important controversies on the world energy scene. This energy source has the capacity to mitigate the effects of climate change as it is a resource that, due to its nature, does not emit GHG. This, together with its energy capacity, makes it a viable solution to replace fossil fuels in energy generation, thus reducing the emission of gases that contribute to global warming.

However, despite these advantages, there are a number of problems associated with its use that led to society's misgivings about this resource and rejection of its deployment for electricity supply. These problems cover critical areas such as nuclear waste management, safety, nuclear proliferation and high construction and decommissioning costs in western countries.

One of the most significant challenges is the management of nuclear waste, which is highly radioactive and must be safely stored and managed for thousands of years. Despite advances in long-term storage technologies, such as deep geological disposal in Finland[27], the search for definitive solutions for the management of this waste remains a major concern.

Nuclear safety, as mentioned above, is another critical issue to consider, as it is one of the main causes of popular opinion against this energy source. However, nuclear power has the best safety record of all power plant technologies, which is due to the fact that these nuclear reactors are designed with multiple safety barriers. These barriers have been required by severe nuclear accidents, such as the Chernobyl and Fukushima catastrophes, which have demonstrated that there are significant risks associated with nuclear power. However, it should be noted that in both accidents the main culprits were human error: in Chernobyl, it was the lack of safety culture and management arrogance, while in Fukushima it was the failure to update a known tsunami risk (the initial risk assessment was basically wrong and the facility was ordered to improve the protection of key components such as cooling). The most technologically relevant nuclear accident is Three Mile Island, where the technology failed, but the backup systems worked as planned, eliminating the risk of releases (unlike Chernobyl and Fukushima).

These accidents have led to the development of great advances in nuclear safety, increasing preparedness to face possible accidents and guaranteeing the protection of the population and the environment. As mentioned above, this development has made nuclear energy one of the safest energy sources available (see Figure 4).

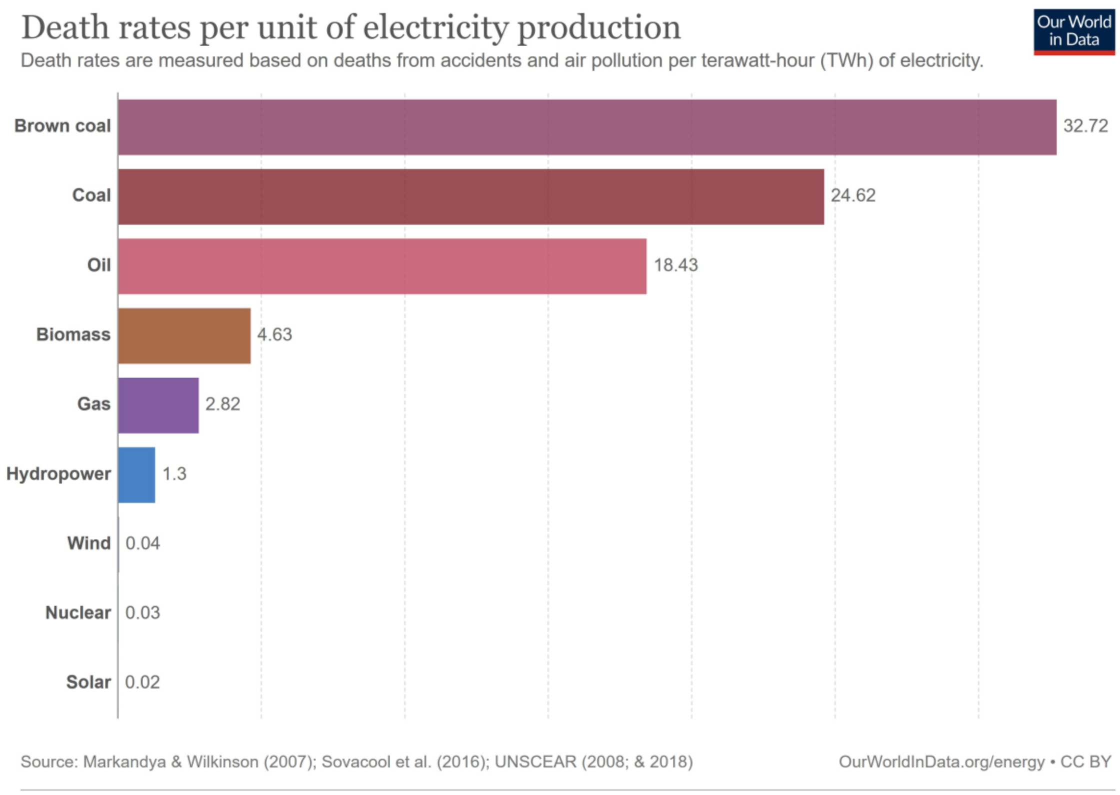

Figure 4 Death rates caused by air pollution or accidents per unit of electricity production. Chart made by Our World in Data[28]*. Sources: Markandya &Wilkinson*[29]*, Sovacool et al.*[30] *and UNSCEAR*[31]*.*

This Figure 4 compares the ratio of fatalities to electricity production at a global level. In order to make this comparison, Our World in Data[28] has compiled different data provided by different studies[29]–[31], which show that the death rate of nuclear energy with respect to electricity production is similar to that of wind and solar energy.

In addition, nuclear proliferation was an issue of international concern in the 20th century. Access to nuclear technology and materials posed risks in terms of global security and potential misuse for the production of nuclear weapons. This problem is of lesser importance today, since there is greater control, and there are solid regulations that prevent nuclear proliferation. Thus, the responsible use of this technology is guaranteed.

Finally, the high costs associated with the construction in the US (AP1000 Vogle) and EU (EPR 1600 – Hinkley Point C, Flamanville and OL3) and decommissioning (Holtec Oyster Creek and Pilgrim facilities) of nuclear plants are also a major challenge. The deployment of new nuclear plants requires significant financial investments, and the safe decommissioning of facilities at the end of their lifetime also entails considerable costs. While it is true that the operation of these plants is carried out at a very low cost, this initial and final investment in nuclear plants is very high and significant, since due to the management of radioactive materials, great efforts are required for nuclear safety and security.

It is essential to address these problems in an effective and universal manner, so that this resource can be exploited in a safer and more sustainable way. To this end, the IAEA states that SMR, have great potential to contribute to a safe and emission-free energy system[32].

2.8. Small Modular Reactors

Modular reactors are an innovative form of nuclear technology that differs from conventional nuclear power plants by their modular and scalable design. These reactors are smaller in size and power generation capacity. According to the IAEA, SMRs are defined as advanced nuclear power plants producing an electrical output of up to 300 MW(e)[32]. These facilities are divided into modules, with each module having a nuclear reactor that contributes to the total electrical generation. This design allows for the addition or removal of modules depending on the electricity demand of the area, giving this technology greater flexibility to adapt to fluctuating energy demands. These reactors have a fourth-generation design, where the main objective is to improve the efficiency, safety and waste management of previous-generation reactors.

In terms of safety, modular reactors are designed with advanced approaches built in from the outset. Their smaller size reduces the amount of nuclear fuel and thermal energy contained, which reduces the potential associated risks in the event of an accident. In addition, these reactors use concepts such as gravity, natural convection and passive cooling systems to maintain reactor integrity and dissipate residual heat in the event of a failure. Moreover, their modular design prevents accidents from spreading to other areas of the reactor, keeping any potential accidents inside the module, thus minimizing risks.

Similarly, thanks to the modular design, these reactors allow factory construction. This means that the reactors are manufactured in specialized facilities where more efficient and controlled construction can be carried out. Once manufactured, the modules are transported to the nuclear site and installed more easily and safely. As a result, costs and construction time are significantly reduced, making this technology more economically and practically viable.

Finally, with regard to nuclear waste management, SMRs have a special design to deal with this fundamental problem of nuclear energy. In these reactors, advanced nuclear fuels can be used which are better utilized, resulting in a higher energy density while reducing the amount of radioactive waste. Thus, the reactors are more energy efficient as they are able to extract a greater amount of energy while avoiding having to deal with large amounts of nuclear by-products, which present a major drawback.

These reasons place SMRs, and thus nuclear power, at the forefront of the energy sector, as one of the most innovatively developed technologies. Furthermore, these advances have resulted in greater public acceptance of this technology, which makes it a viable option for Member States interested in expanding their nuclear capacity as well as for those wishing to embark on new nuclear programmes, as indicated by the IAEA[33].

Therefore, in order to take advantage of this technology and analyze its implementation in the electricity grid, a feasibility study has been carried out on the installation of SMR to supply electricity to the Nyhamna gas processing plant, located west of the city of Molde in Norway. In order to adopt greater energy efficiency and make the best use of the resources of these reactors, this project has also studied the possibility of installing a biogas production plant to make use of the waste energy generated in these nuclear facilities. To produce biogas, this facility will use salmon sludge obtained from the Salmon Evolution company, which is located 3 km north of the gas processing plant.

3. STATE OF THE ART

The thermodynamic efficiency of the thermodynamic cycles of nuclear power plants is around 33%. This means that there is 66% of reactor energy that is not used. This energy corresponds mainly to the thermal energy that is poured into the condenser at the turbine outlet. The use of this energy could increase the efficiency of the plant by up to +70%[34], so, in this project, this energy potential has been studied to achieve this efficiency increase in the SMRs.

In order to be able to use this energy, the main parameter to take into account is the temperature required in the application in question. This temperature is an aspect of vital importance when using the waste heat from nuclear plants, since, in order to be able to use this energy, the temperature range of the application must be lower than the temperature at the outlet of the turbine of the thermodynamic cycle. To make an initial analysis of these temperatures, Figure 5 presents different thermal applications with their temperature ranges, and these are compared with the temperature obtained by the different reactor technologies according to IAEA[35].

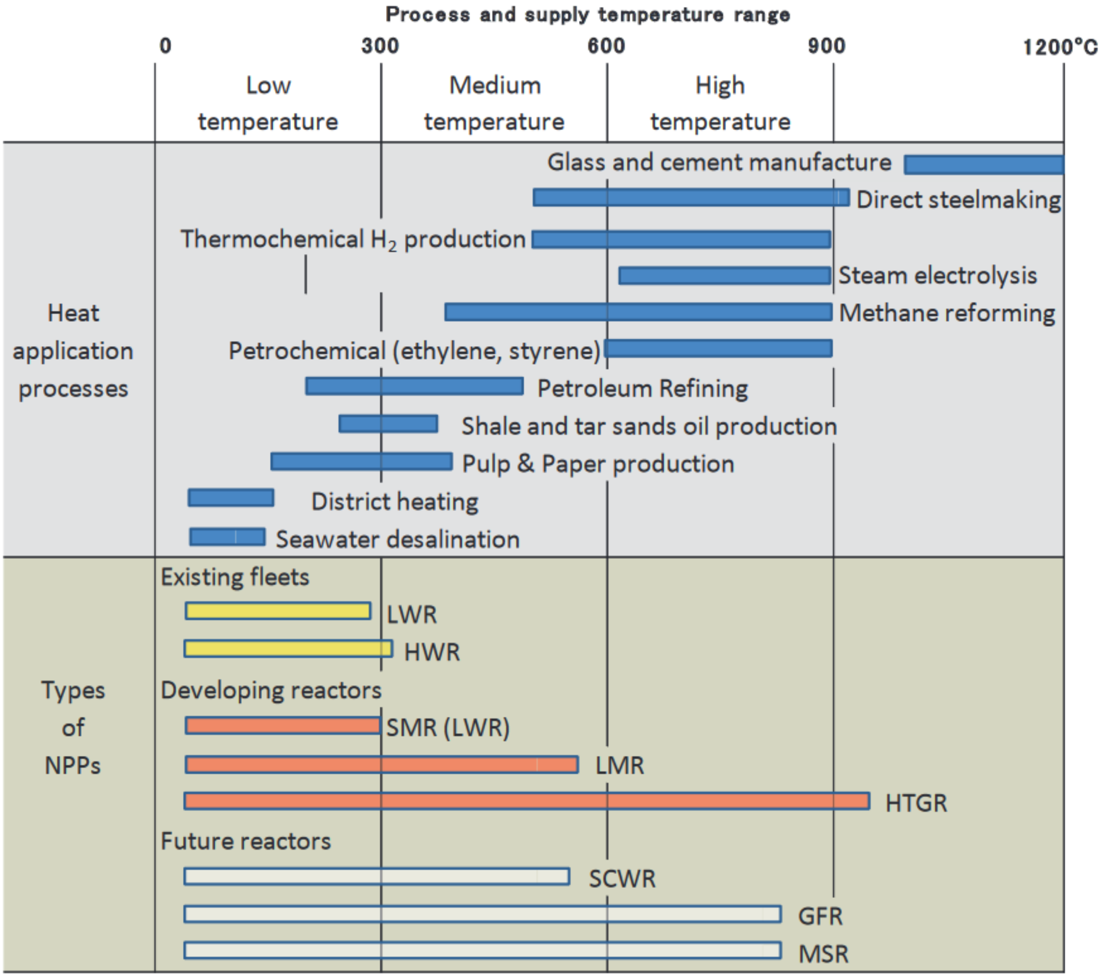

Figure 5 Temperature ranges of heat application processes and types of nuclear power plant[35].

The higher the operating temperature of the reactor, the greater its capacity to meet the thermal demand, since this energy can be used in a greater number of applications. Therefore, as shown in Figure 5, one of the best options for this purpose is the High Temperature Gas-cooled Reactors (HTGR).

For the development of the project, first of all, an exhaustive review of the literature related to waste thermal energy of nuclear reactors has been carried out. In this context, the aim is to analyze and understand how this rest energy can be used in an efficient and sustainable way. For this reason, in this study, the different possible applications of this waste energy have investigated, and an analysis has been done about the work done so far in each of these applications.

In 2019, there were 79 reactors harnessing reactor waste energy for desalination, district heating, or process heat[36]. However, this heat has the potential to be harnessed for many other applications such as low-temperature power cycles, process cooling, agriculture, or ammonia production. This chapter summarizes these applications and the current status of these applications, reviewing the studies carried out in this respect.

3.1. Water desalinization

Water desalination is a process that converts seawater or brackish water into fresh water suitable for human consumption and other applications. As the demand for freshwater increases and freshwater resources diminish, desalination has become a crucial solution in many parts of the world. Although there are several methods for desalinating water, the general process involves the removal of salt and other dissolved minerals present in salt water.

To achieve this goal, there are two main methods: reverse osmosis and distillation. In reverse osmosis, salt water is pressurized, forcing it to pass through a semi-permeable membrane. This membrane allows the water to circulate, but prevents the salt from passing through. Distillation, on the other hand, is based on heating and evaporation of the water. In this way, the water is converted into vapor, separating it from the non-volatile components. This water vapor is then condensed to obtain fresh water. In this process, some thermal energy is needed in the temperature range of 100 °C, which can be obtained from nuclear reactors.

In this area, Alonso et al.[37] evaluated the possibility of implementing a cogeneration plant using thermal energy for water production. In this study, two reactors were compared, a large reactor (AP1000) and a medium reactor (IRIS) combined with different desalination methods. This study concluded that the use of cogeneration in nuclear power plants for the production of fresh water and electricity is feasible and that the IRIS reactor, due to its cost and versatility, was a better option. Regarding SMR, Ahmed et al.[38] studied the potential of these reactors for desalination. The review compares different modular reactor technologies in terms of their technical characteristics.

The use of nuclear energy for water desalination is not new and has been explored since the early stages of nuclear technology. One of the first nuclear power plants to be installed for the specific purpose of desalination was the Aktau water desalination plant in Kazakhstan. This plant, built in the 1960s, used a nuclear reactor to generate heat, which was then used in a thermal distillation process to desalinate water. Although this plant did not rely on cogeneration to produce electricity and fresh water at the same time, through this pioneering project, the potential of nuclear power as a heat source for water desalination was demonstrated.

3.2. District heating

District heating systems are based on the generation of heat at a central location which is distributed through a network of pipes to multiple buildings and homes within an urban or communal area. This system provides heat for indoor space heating and, in some cases, can also be used for domestic hot water production.

District heating has great advantages over local heating systems. Among them is the reduction of investment costs for individual installations, and the possibility of using waste heat to increase energy efficiency. However, the main disadvantage lies in the high cost of these installations in terms of distribution pipes.

This energy application is in the range of low temperature applications, as can be seen in Figure 5. According to the study by Lipka et al.[39] in which the current situation of district heating supplied by nuclear reactors was analyzed, the typical supply temperature of these applications is 80-130 ºC, while the return temperature is in the range of 45-70ºC. This study highlighted that the temperatures used in district heating systems are adequate and affordable to harness the remaining energy from a nuclear reactor. What this means is that district heating can be a viable application for utilizing the energy that is not used in generating electricity in a nuclear reactor, providing heat to communities and buildings in an efficient and sustainable manner. However, the study by Lipka et al.[39] highlights that these applications have been reduced in recent years, and thus recommendations are made to expand their implementation in the future. There are currently 53 reactors using cogeneration for district heating purposes, being the most widespread application[35].

One of the main points addressed in the Lipka et al.[39] study is the need to perform the energy transfer at a higher temperature. Therefore, it is proposed to extract a portion of energy from the steam turbine before the steam cools down too much. This leads to some deterioration of the electrical power since this fraction of steam is not being used for electrical generation. Figure 6 shows the schematic of the technical solution presented to address this problem in nuclear plants.

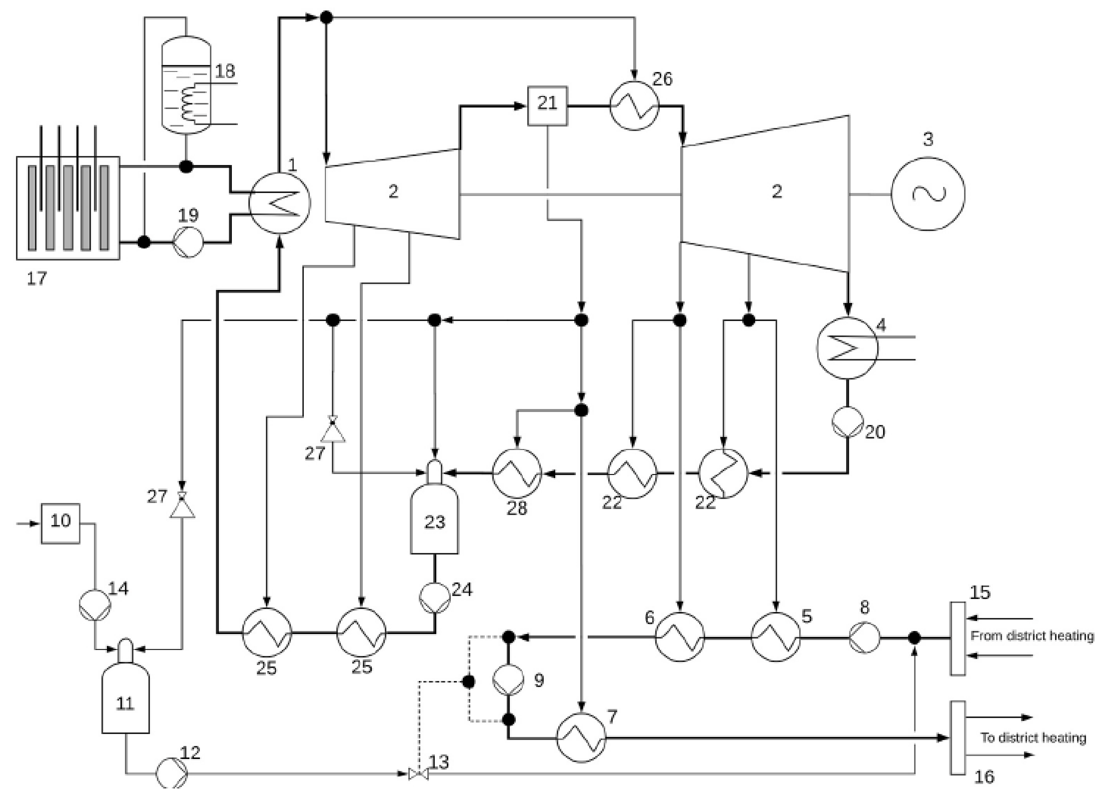

Figure 6 Schematic diagram of a nuclear power unit with a PWR reactor and extraction-condensing steam turbine.

Figure 6 shows how part of the steam is extracted from the turbine before it is expanded for use as preheating the district water in heat exchangers 5 and 6. Moreover, part of the steam is also extracted in separator 21 to ultimately heat the water that will later be consumed. These extractions cause the loss of electrical power in the reactor in order to obtain quality thermal energy for district heating supply.

It should be noted that this scheme corresponds to the needs of a Pressurized Water Reactor (PWR) nuclear plant, which, as shown in Figure 5, operates in a lower temperature range compared to other nuclear plants. Therefore, this problem would not occur with reactors using other technologies such as Liquid Metal Reactors (LMR) or High Temperature Gas-cooled Reactors (HTGR), and the remaining energy could be used more efficiently, without affecting electricity generation.

The use of nuclear energy for district heating has been explored since the beginning of nuclear power. An example of this is the Ågesta nuclear power plant in Sweden, which began operation from 1964 until it was decommissioned in 1974[40]. The plant built by ASEA was located underground and served mainly for district heating in the Stockholm suburb of Farsta, although it also had an output of 12 MW(e). Following this first experience, nuclear power has been used on numerous occasions for district heating and power generation, for example at the Beloyarsk nuclear power plant in Russia, which also began operation in 1964, until it was decommissioned in 1983.

Currently, the nuclear power station with the highest active heat recovery is the Zaporozhye station in Ukraine, with a thermal output of 1400 MW(th), which is used for both district heating and local industry[39]. As far as only district heating is concerned, the power plant generating the maximum power is the Leningrad 2 nuclear power plant in Russia with an output of 240 MW(th) followed by the Bohunice power plant in Slovakia with 240 MW(th)[39].

In order to increase the deployment of these applications, several research studies have been carried out in recent years. Terasvirta et al.[41] in 2020 published a study analyzing the economic impact of replacing peat and biomass-fired Combined Heat and Power (CHP) plants with heat-only reactors with a capacity of 24-200 MW and a maximum outlet temperature of 120 °C for a medium-sized Nordic city. In this study, it was concluded that the most promising solution consists of five 24 MW(th) SMR units combined with a 100 MW(th) CHP plant.

On the other hand, Tai et al.[42] studied the possibility of using waste heat from a coastal nuclear power plant. In this study, a Water-Heat Combined System (WHCS) based on waste heat from a coastal nuclear power plant was proposed and the thermodynamic characteristics, energy savings, environmental benefits and economic efficiency were analyzed. In this way, the feasibility of this heat source to provide district heating and water at the same time was studied. The main conclusions of this project were that this plant could save 8054.42 × 104 kWh of electricity and 20.4 tons of standard coal during the heating season, while reducing costs.

These studies and applications highlight the energy capacity of nuclear reactors to provide thermal energy for district heating. In this way, it is worth mentioning that this application is one of the most promising for the use of residual energy from nuclear reactors. Regarding the current project, this application has not been taken into account due to the lack of data on the energy needs of nearby communities. However, as discussed in chapter 8 "FUTURE WORK", the possibility of providing thermal energy for district heating to cities near the location of the gas treatment plant, such as the city of Molde, should be studied in the future.

3.3. Other uses

In addition to these applications, other options have also been proposed in the nuclear sector, which are either still under development or have not reached the same degree of maturity as the previous ones. These include the generation of hydrogen from nuclear reactors, or other higher temperature applications such as tertiary oil recovery or fuel synthesis in the petrochemical industry.

3.3.1. Hydrogen generation

Hydrogen is considered a fuel with great potential that could be capable of replacing conventional fuels. This fuel does not emit GHG in its combustion, and can be generated from the electrolysis of water. This technology is based on the decomposition of water into hydrogen and oxygen through the use of electricity. This process can be carried out at low temperatures, or at high temperatures, the latter method being the more promising of the two, since part of the energy is supplied in the form of heat without prior energy conversion and because the electrolysis reaction consumes less energy at higher temperatures[43]. Thus, nuclear power could help to reach these temperatures to maximize hydrogen production. However, this process still faces several challenges in the future, such as maintaining the high performance of electrolyzers[43].

Another way to realize hydrogen production is by thermochemical processes, which is based on a series of chemical reactions that separate water into hydrogen and oxygen as a by-product. Since the first studies on thermochemical water separation cycles in the 1960s, a large number of thermochemical reactions have been investigated. These reactions require heat sources higher than 1000 ºC, which could be a nuclear reactor. In this sense, it should be noted that in this case, nuclear energy would be used entirely to heat the hydrogen generation process, leaving aside the electrical generation. The most important project related to these thermochemical processes is known as IS process (iodine-sulfur process) and is currently being developed by the Japan Atomic Energy Agency (JAEA) where a pilot plant capable of generating 30,000 l/h of hydrogen is expected to be developed soon[43].

3.3.2. Tertiary oil recovery

Tertiary oil recovery, also known as Enhanced Oil Recovery (EOR), is a set of techniques used in the oil industry to extract additional oil from reservoirs beyond primary and secondary recovery methods. Primary recovery involves the initial extraction of oil by natural pressure within the reservoir, while secondary recovery uses techniques such as waterflooding or gas injection to displace the oil and enhance its extraction. The tertiary oil recovery techniques are implemented when primary and secondary recovery methods have reached their limits and there is still a significant amount of oil trapped in the reservoir. These techniques aim to alter reservoir properties, reduce oil viscosity or change flow behavior to improve oil recovery.

There are several methods of tertiary oil recovery, including thermal methods, chemical methods and miscible displacement methods. Thermal methods involve injecting heat into the reservoir to reduce the viscosity of the oil and improve its flow characteristics. Steam injection and in situ combustion are common thermal methods employed. This steam injection could be performed from a nuclear reactor rather than by natural gas.

This case was studied by Becerra et al. [44] in 2005, where the possibility of using energy from a reactor to a Canadian oil sands extraction facility using Steam-Assisted Gravity Drainage (SAGD) technology was studied. This project analyzed three scenarios for the use of the reactor: using the reactor for the sole production of steam to extract the oil, using the reactor to produce steam and electricity for the oil sands facility, and using the reactor to produce steam, electricity and hydrogen to upgrade the bitumen in the oil sands to syncrude, a material similar to conventional crude oil. This project shows how in all three scenarios the cost of energy is lower because natural gas has a higher cost than nuclear power. In addition, it was also calculated that a plant producing 100,000 barrels of bitumen per day would avoid the emission of up to 100 megatons of CO2 into the atmosphere per year.

The temperatures required to carry out this type of extraction must be between 212.4 ºC and 276 ºC[44]. Due to process inefficiencies, the inlet temperature to the SAGD system must have at least a temperature of 300ºC for the case of cogeneration of electricity and process heat. As discussed later in this paper, these temperatures are too high for the reactor in question, and in addition, in the area of interest there are no oil fields to exploit using this technique, so this possibility is not implementable in this project.

3.3.3. Fuel synthesis in the petrochemical industry

Regarding fuel synthesis in the petrochemical industry, Verfondern [45] reported that a refinery with a throughput of 6-7 million tons per year of crude oil needs a constant supply of about 400 MW(th). Due to the complexity of these processes, this energy is not used in a single application, but it is the cogeneration of electricity and overall process heat that would be of particular importance in these plants. This option has not been widely explored even though it has great advantages in terms of waste management and use of medium temperature thermal energy.

3.4. Selected use of the rest heat of the reactors

This study of the different applications of waste energy from nuclear reactors has served to get an idea of the different technologies and their effectiveness. It should be noted that all these paths are of vital importance to achieve greater energy efficiency in the nuclear sector, and to be able to take advantage of a higher percentage of the energy generated in the reactor core. However, depending on the needs of the area, some technologies will be of greater interest than others. The following is an analysis of the different proposals and the current situation of these technologies in Norway, particularly on the island of Gossa.

To begin with, in terms of water desalination, Norway does not require this type of technology due to the large amount of fresh water available in its rivers, lakes and glaciers. This technology is more necessary in those places that do not have these resources, such as islands and coastal regions that do not have drinking water, or in arid, semi-arid regions or those places that are affected by droughts.

Other options that have been discarded due to their inconsistency with the project have been hydrogen generation and oil extraction by tertiary methods. The technology of hydrogen generation by the above method is still under development, and requires particular research studies to prove its feasibility. Therefore, this option has been discarded when implementing a cogeneration system with modular reactors. Similarly, the extraction of oil by tertiary methods has been discarded, as this option is only applicable if there are oil deposits nearby.

As far as district heating is concerned, due to the large investment required, it is only feasible in large cities. In the area of the Nyhamna plant, there are 3 main cities that use this technology, and that could take advantage of the waste heat from the reactors. First, the closest, and therefore the most feasible, is the city of Molde, which is located 10 km from the Nyhamna natural gas processing plant, followed by the cities of Kristiansund and Ålesund, which are approximately 50 km away. As seen above, currently, these distances are assumable for transporting heat to district heating systems, and therefore, this could be a feasible application for waste heat utilization. However, in the current study, due to the lack of data on the thermal demand of these cities, this case has not been studied, although as it is mentioned in chapter 8 "FUTURE WORK" this possibility should be studied if modular reactors are implemented on the island of Gossa.

Finally, fuel synthesis in the petrochemical sector is an application with great adaptability to the project because it does not require high temperatures. The main disadvantage of this application is the availability of sufficient organic matter to carry out the fuel synthesis; however, for the development of this project, salmon sludge generated just 3 km north of the natural gas processing plant, at Salmon Evolution's facilities, is available.

For this reason, in the current project, it has been decided to explore the possibility of installing a biogas production plant from salmon sludge. In this way, a valorization of this waste could be achieved, generating another energy vector that is more than necessary for the future of the Nordic country.

The lack of studies investigating the feasibility and potential of using waste energy from nuclear reactors for fuel synthesis has been the impetus behind the development of the present work. The possibility of using this energy for fuel production opens new perspectives in terms of sustainability and energy security. Therefore, this study focuses on exploring the possibilities and challenges associated with harnessing waste energy from nuclear reactors for fuel synthesis, providing a solid foundation for future research and development in this promising field. For this purpose, the particular case of the modular reactors next to the Nyhamna plant has been developed, and the feasibility of implementing this biogas plant acting cooperatively with the reactors to obtain biogas has been studied.

4. METHOD

In order to develop this project as reliably and realistically as possible, a method based on an analytical and quantitative approach to data has been followed to better assess the capacity of SMRs in terms of energy supply, both electrical and thermal. This analytical and quantitative approach allows for an objective and data-driven evaluation, which is essential to assess the feasibility of implementing this project. Thus, the final dissertation will be supported by evidence, and pragmatic and objective results can be obtained.

With the aim of carrying out the project, a study of the situation in Nyhamna has been proceeded first. Within this study, efforts have been concentrated on analyzing the main activities of the companies Norske Shell, owner of the natural gas processing plant, and Salmon Evolution, a company dedicated to the aquaculture of salmon for human consumption. In this analysis, a comprehensive search has been carried out for project-relevant data such as the energy demand of the natural gas processing plant and the annual production of sludge from salmon in the aquaculture facility.

Once the situation surrounding the project was known, the different alternatives for meeting the energy demand of the Nyhamna natural gas processing plant were studied. For this purpose, different SMRs were studied, analyzing their advantages and disadvantages in terms of energy production, degree of maturity and technological advances. In this way, it is believed to have chosen the best option that will bring the most benefit to the facility by making maximum use of the available resources in the safest way.

After choosing the appropriate reactor for the progress of the analysis, the thermodynamic cycle of the reactor has been calculated. To perform this calculation, the software EES (Engineering Equation Solver) has been used, which has an extensive thermodynamic library. This program has been used to calculate the most relevant parameters of the project, such as the electrical generation of each reactor or the residual thermal energy resulting from the thermodynamic cycle. These values have established the energy available in the reactor, which will be used both in the gas processing plant and in the biogas plant.

Knowing these thermodynamic parameters, the approximate design of the biogas plant was carried out. When carrying out the design, the main parameter that has marked the dimension of the project has been the amount of sludge available. This data has made it possible to calculate the magnitude of the total amount of biogas that can be obtained from this organic matter. In order to determine this value, the company Hyperthermics collaborated with the project. Hyperthermics is a leading company in the sector and has extensive experience in the field of biogas production, so their collaboration in providing data and knowledge in the sector has been invaluable advice for the project. In addition to their knowledge of the sector, the company also provided information on their biogas extraction technology.

Moreover, using this data it has been possible to calculate the size of the biogas plant, and with it the size of the different processes of which this installation is composed. The magnitude of these processes has made it possible to calculate the thermal demand necessary to deal with the production of biogas. In order to make this calculation, it should be noted that two main sources of consumption have been taken into account. On the one hand, there is the need to raise the temperature of the salmon sludge to carry out the transformation processes required in a biogas plant. This energy demand is punctual, and occurs only at the beginning of the process, once the sludge is at the right temperature it will be ready to start the transformation process. To calculate the initial thermal demand related to the increase in sludge temperature, Eq 1 has been used.

$$Q_{initial} = m \cdot c_{p,sludge} \cdot \Delta T \tag{1}$$

Where " m " is the mass of sludge to be heated, "$c_{p,sludge}$" is the specific heat of the sludge, and "ΔT " is temperature increment to be achieved for the sludge.

On the other hand, the energy demand associated with the heat losses of the sludge in a cooler environment has been taken into account. This energy demand is constant while the transformation process of the sludge is taking place. To perform this calculation, the reactors have to be divided into 2 parts, the cylindrical part and the top cover of the cylinder. The study of both parts is similar. First, it has been assumed that the inside temperature of the cylinder is the same as that of the sludge “T_{in}”, and the outside temperature of the surface of the reactor “T_s” has been estimated with respect to the ambient temperature “T_∞”. It has to be noted, that as the heat transfer is different in the top cover, and the cylindrical part, the temperature of the surface will be different in both cases too. Once the temperatures are available, the values of the kinematic viscosity (υ), thermal conductivity (k) and Prandtl number (Pr) of the air under these conditions have been obtained from thermodynamic tables. From these variables, the Reynolds number (Re) was calculated using Eq 2.

$$Re = \frac{V \cdot D_{ext}}{\upsilon} \tag{2}$$

Where “V” is the wind speed, and “D_{ext}” is the outer diameter of the cylinder. Once the Reynolds number has been obtained, the Nusselt number (Nu) has been calculated. For this purpose, Eq 3 has been used to obtain the heat released by the reactor lid, and Eq 4 to find the heat released by the sides of the cylinder. These equations have also allowed to obtain the convective heat transfer coefficient (h).

$$Nu_{lid} = \frac{h \cdot D}{k} = 0.0308 \cdot Re^{0.8} Pr^{1/3} \tag{3}$$

$$Nu_{cylinder} = \frac{h \cdot D}{k} = 0.3 + \frac{0.62 \cdot Re^{1/2} Pr^{1/3}}{[1 + (\frac{0.4}{\mathrm{Pr}})^{2/3}]^{1/4}} \cdot [1 + (\frac{Re}{282{,}000})^{5/8}]^{4/5} \tag{4}$$

With this value, the convective heat "Q_{conv}" discharged to the environment from the reactor surface under these conditions has been calculated using Eq 5.

$$Q_{conv} = h \cdot A_s \cdot (T_s - T_\infty) \tag{5}$$

Where "A_s" is the outer area of the regarding surface, "T_s" is the surface temperature of the reactor, and "T_∞" is the ambient temperature. Finally, this value was verified by obtaining the conductive heat "Q_{cond}" transferred through the thickness of the cylinder under these conditions. For the case of the cylinder lid, this calculation was performed using Eq 6, and for the cylinder walls, Eq 7 was used.

$$Q_{cond,lid} = -k \cdot A_s \cdot \frac{(T_s - T_{in})}{t} \tag{6}$$

$$Q_{cond,cylinder} = \frac{2 \cdot \pi \cdot k \cdot L}{\ln\left(\frac{r_e}{r_i}\right)} (T_{in} - T_s) \tag{7}$$

Where "k" is the thermal conductivity of the material of which the reactor is made, "t" is the thickness of the reactor, "L" is the height of the reactor, "r_e" is the outer radius of the cylinder, and "r_i" is the inner radius of the cylinder.

The values of the convective heat and the conductive heat must be equal in each case, on the one hand, in the lid, and on the other hand, in the cylinder. If the calculations do not give the same result, this means that the assumption of the external temperature of the reactor is wrong and therefore it will be necessary to modify it, and iterate again the same process until obtaining the same result for both parameters.

After calculating this energy demand, to finalize the study, a comprehensive analysis was carried out to assess the feasibility of meeting this energy demand by using waste heat from the modular reactors. A detailed comparison was made between the thermal demand data of the biogas production plant and the amount of waste heat available in the reactors. This analysis has made it possible to determine the capacity of the modular reactors to efficiently cover the thermal demand required by the plant, taking into account the limitations and particularities of both systems.

This feasibility study, being focused on the feasibility of the project, has been developed in a more general way, without going into the specific details of the processes involved. This has implied the assumption and simplification of certain aspects, which may lead to a certain degree of uncertainty in the results. Furthermore, it is important to note that, while efforts have been made to use accurate data, in some cases the availability of this information has been limited. Therefore, approximations and estimates have been made, based on available data and expert knowledge in the field, which introduces a certain degree of error in the estimates, thus losing precision in the final result.

The composition and properties of the sludge has been one of the main factors of uncertainty into the study. Due to the variable nature of salmon sludge, its composition can be subject to fluctuations and variations at different times of the year, making it difficult to obtain precise and accurate data. In addition, no study has been carried out at Salmon Evolution on the composition of its sludge, which introduces further uncertainty. This uncertainty in sludge composition may have implications for the calculations and estimates made in relation to biogas production and energy potential. Aware of this situation and with the aim of minimizing the errors, the results obtained in the study by N. Teuber in 2006 [46] have been adopted. In this study, the characteristics of sea salmon sludge are presented, as shown in Table 1.

Table 1 Composition and properties of sea salmon sludge[46].

Characteristic	Value	Contribution ($kg\,t^{-1}$)
Dry matter (%)	15.8 ± 0.65	158
Total N (%)	0.13 ± 0.005	1.3
NH_4-N	0.008 ± 0.0003	0.08
P (%)	1.6 ± 0.04	2.5
K (%)	0.4 ± 0.02	0.6
Ca (%)	4.3 ± 0.09	6.8
Mg (%)	1.2 ± 0.03	1.9
Na (%)	5.0 ± 0.21	7.9
Mn ($mg\,kg^{-1}$)	172 ± 3.9	0.03
Zn ($mg\,kg^{-1}$)	280 ± 2.9	0.04
Fe ($mg\,kg^{-1}$)	16,662 ± 282.3	2.6
Cu ($mg\,kg^{-1}$)	106 ± 10.0	0.02
Al ($mg\,kg^{-1}$)	27,437 ± 865.3	4.3
Ash (%)	85 ± 0.2	
Organic matter (%)	14.7 ± 0.16	
Carbon (%)	8.2 ± 0.09	
Ratio C : N	9.8 ± 0.15	
pH (Water)	7.8 ± 0.02	
Density ($g\,cm^{-3}$)	1.06 ± 0.005	

Although it is acknowledged that the study carried out by N. Teuber in 2006 and the current study do not have the same conditions, these data are the most reliable and relevant source of information for the development of our project. These data provide a solid basis for understanding the properties and composition of the sludge, and allow us to make more accurate estimates and analyses regarding the biogas production and energy potential of the sludge.

Additionally, in relation to the composition of the sludge, it should be noted that it is a mistake to consider that the properties of the sludge are constant throughout the different processes. These sludges are subject to transformations in order to obtain biogas, and therefore their properties will change. Nevertheless, in order to simplify the calculations, these properties have been assumed constant throughout the different processes.

The composition of the sludge plays a fundamental role in the calculation of the biogas production. The determination of this production requires a complex process, and apart from the sludge composition it depends on other parameters on the operation of the biogas plant. For this reason, in the current project it has been decided to make an approximation of this production. This estimate is based on the experience of the company Hyperthermics, which as a company dedicated to the production of biogas from organic matter, has provided its knowledge for the development of the work. In this way, the estimation of biogas production has been made as accurately as possible, based on the experience provided by the Hyperthermics company's reactors. Eq 8 shows the amount of methane obtained from the available salmon sludge.

$$CH_4\, potential\ [Nm^3/year] = 33.3 \cdot m_{sludge\ (10\ \%TS)} \tag{8}$$

In addition, it should be noted that this plant can also extract a certain amount of hydrogen, which can be calculated using Eq 9.

$$H_2\, potential\ [Nm^3/year] = 0.7 \cdot m_{sludge\ (10\ \%TS)} \tag{9}$$

Once the quantities of these two gases have been obtained, Eq 10 allows to obtain the amount of carbon dioxide obtained by the plant.

$$CO_2\, potential\ [Nm^3/year] = \\ = \left(CH_4 \cdot \left(\frac{(1-0.6)}{0.6}\right)\right) + \left(H_2 \cdot \left(\frac{(1-0.55)}{0.55}\right)\right) \tag{10}$$

Using these parameters, the energy potential of biogas can be obtained using Eq 11.

$$Energy\, potential\ [MJ/year] \\ = CH_4\ \cdot 35.8\ MJ/m^3 + CO_2 \cdot 0.93\ MJ/m^3 \tag{11}$$

It should be noted that this analysis is an estimate, and that production varies with fluctuations in the operating conditions of the biogas reactors.

On the other hand, the ambient temperature of the island of Gossa also has a certain impact on the project, since the different reactors of the biogas plant will be exposed to heat losses to the environment that will have to be supplied with the waste heat from the SMRs. However, the ambient temperature of this island varies substantially depending on the season of the year, and therefore this implies higher heat losses in winter than in summer. These heat losses will also be affected depending on the insulating material placed on the outside of the cylinder. In contrast, for this study we wanted to analyze the maximum possible losses, and therefore it has been assumed that there is no insulation in the reactors.

To approach all these problems, the current study has adopted a conservative method, considering possible unfavorable scenarios to address errors and uncertainties during project development. This guarantees that the results obtained refer to the worst-case scenario, and therefore, the performance of the plant will always be more optimal and suitable. In this way, the associated risks are minimized, ensuring that the conclusions are based on solid and reliable evidence. In addition, it seeks to maximize the chances of project success and mitigate any negative impacts that may arise during implementation.

5. CASE

In this feasibility study, it is essential to understand the big picture of Gossa, an island located in the municipality of Aukra in Møre og Romsdal, Norway. With a strategic location close to the coast and abundant natural resources, this island is in a key industrial location, hosting the Nyhamna natural gas processing plant, which makes it one of the main pillars of the local economy. The Salmon Evolution aquaculture plant is located 3 km north of this gas processing plant. Figure 7 presents a map of the area where these two facilities are located.

Figure 7 Map of the Molde area highlighting the Nyhamna gas processing plant and the Salmon Evolution aquaculture plant.

Due to the industrial activities carried out in this locality, innovative and sustainable approaches that increase energy generation and efficiency will be explored, with the objective of maximizing the economic potential while minimizing the environmental impact. To this end, the case of the feasibility study on the implementation of modular reactors for clean energy and biogas production is developed below. First, the current situation of the area will be presented, talking about the Nyhamna gas processing plant and the possibilities it offers. Then the proposal of the study will be presented, and the work carried out will be developed showing the results obtained.

5.1. Gas processing plant of Nyhamna

The Nyhamna gas processing plant, located in the municipality of Aukra in the Møre og Romsdal region of Norway, is a leading industrial center in the natural gas industry. The plant was built in 2005 by the Norwegian company Norsk Hydro in cooperation with Royal Dutch Shell, ExxonMobil and Petoro. This construction project at the time was considered to be the largest construction project ever undertaken in Norway, costing approximately £5,500,000,000. Figure 8 shows this industrial plant, where its expansion and the different facilities that compose it can be appreciated.

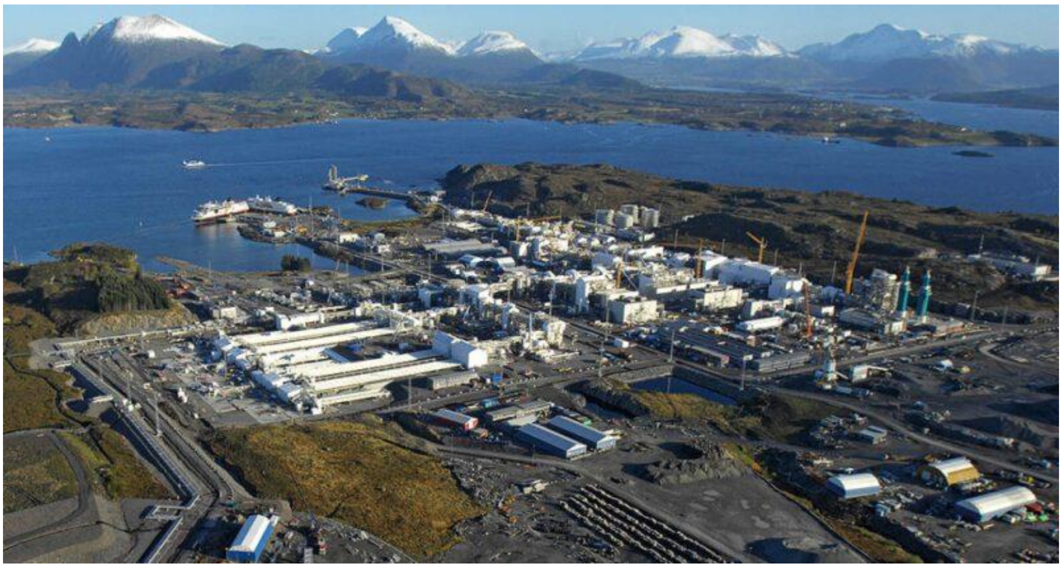

Figure 8 Panoramic View of Nyhamna Industrial Plant: A Glimpse into Industrial Operations. Image obtained from "Journal of Petroleum Technology"[47].

The industrial plant is currently operated by Shell, and plays a key role in the processing and treatment of natural gas in Norway. This natural gas is extracted from the deep-water Ormen Lange field, approximately 100 km off the Norwegian coast, and transported to the Nyhamna plant. At this plant, the gas is cleaned and treated to remove unwanted impurities, and once cleaned, it is compressed to a pressure of 200 bar for shipment to the UK via the Langeled pipeline. This pipeline, which connects the Nyhamna facility with the Easington gas plant, is the longest subsea pipeline in the world with a total length of 1,166 km. This pipeline transports 84 million m^3 per day, which accounts for 20% of the gas consumption of the whole of Great Britain.

In order to carry out this activity, the Nyhamna plant has a high energy consumption. With the purpose of obtaining the most accurate data possible on this consumption, the company Norske Shell was contacted and has cooperated by providing information on the electricity demand of their plant. It is important to note that, due to the confidentiality of the data, this quantity is an estimate used as a starting point for the feasibility analysis. This electricity demand, as indicated by Norske Shell, is mainly due to the consumption of the plant's compressors, which have an output of 55 MW each. Therefore, given that the facility has 4 compressors, the electricity demand of the plant has been estimated at 220MW, which has been verified in the Reuters article[48], where the status of the gas plant was reported in November 2018. On the other hand, as far as thermal demand is concerned, no precise information has been obtained. However, this is not considered to be very abundant and has been disregarded in the calculations, although this situation will be discussed later in the chapter 6 “DISCUSSION”.

This energy demand is very high and far away from the main energy generation points. Furthermore, as mentioned in chapter 2 “BACKGROUND”, there is a need in Norway to increase electricity generation by diversifying it, so as not to rely solely on hydroelectric power. Therefore, this project will study the possibility of implementing SMR, which offer the advantages of nuclear energy in terms of energy density, as well as providing greater safety thanks to the technology of the fourth generation of reactors.

5.2. Requirements of the Selected Reactor for the Project

Within the framework of this project, a comprehensive evaluation of different modular reactors has been carried out in order to make an informed decision. For this purpose, several key aspects that determine the suitability of each reactor have been considered. These requirements to be met by the selected reactor are presented below.

First of all, one of the main requirements of this project is the implementation of a proven reactor with advanced technological maturity. SMR technology is an innovative technology, and currently none of these reactors have been implemented for power generation, as the vast majority are in pre-application activities or in designing processes. However, there are several models that have already been contracted, and will be implemented in the near future to guarantee clean and safe energy. In this project, those SMRs with a higher degree of maturity have been analyzed, as these are currently the most reliable for possible implementation in the near future. Therefore, it has been decided to select a reactor that is licensed for implementation or will be licensed in the near future, which means that the reactor is at the forefront of SMR technology.

Secondly, the energy capacity, which implies the reactor power, has been evaluated. For this project, an installed capacity of 220 MW(e) is required, so the sum of the power of all the installed reactors has to exceed this amount. To achieve this power, it has been established that the best option would be to install between 3 and 8 reactors to ensure an optimal balance between power generation and system reliability. The implementation of 1 or 2 reactors would result in excessive dependence on them, and in the event that any reactor has to be shut down, either for maintenance or for any other reason, generation would be greatly affected. On the other hand, more than 8 reactors would imply a great cost in terms of space and infrastructure construction. For these reasons, it has been established that, for the development of the project, the power of the selected reactor must be between 100 and 30 MW(e).

Consequently, the subcategory of microreactors, which have a power of less than 10 MW(e)[32], has been disregarded in this project. The implementation of this subcategory of modular reactors would mean that at least 22 reactors would be needed to meet the plant's electrical demand. This has caused reactors with a high degree of maturity to be rejected, such as the Micro Modular Reactor (MMR) developed by the Ultra Safe Nuclear Corporation (USNC). This reactor is currently in the first phase of licensing authorization (License to Prepare Site, or LPS), which will be followed by the

License to Construct Phase (LCP) [49]. The demonstration units are scheduled to be installed in 2026, making it one of the most advanced technologies in terms of licensing in the industry. However, their electrical output is only 5 MW(e), so at least 44 modules would be needed to power Nyhamna's compressors. For this reason, these reactors have been discarded despite their advantages, and alternatives with higher power capacity have been sought.

In relation to reactors with more power than 100 MW(e), we can distinguish the AP300 of Westinghouse and the BWRX-300 of GE-Hitachi Nuclear Energy as two reactors above this power with advanced licenses. The AP300 is a design based on the AP1000, a proven large-scale reactor with more than 15 years of operating experience, which endorses its design. As for the second, a construction license application has already been submitted, and this reactor is expected to be operational by 2028[49]. However, these reactors would be implemented alone, creating a high dependency. In addition, these reactors considerably exceed the plant's needs, and although this surplus energy could be fed into the power grid, this would go against one of the project's main objectives: energy efficiency. This project aims to increase the energy efficiency of the Norwegian energy system by bringing power generation closer to the points of consumption, and thus the choice of these reactors would go against this principle.

The reactor technology used by these modules has also been evaluated from a functionality perspective for the project, taking into account the context in which the project is located. In relation to this, different aspects have been evaluated, such as the availability of the necessary elements for the operation of this reactor in Norway, or the capacity to obtain the residual energy from these reactors to make use of it. In addition, this reactor must be able to be installed in the vicinity of an industrial plant, so its safety systems must be very advanced. For this purpose, reactors with 4th generation technology will be positively valued. These designs have the most advanced features in terms of nuclear safety, such as greater resistance to extreme events, passive cooling systems, better management of nuclear waste and lower risk of core meltdown, among others.

Besides all these considerations, other important features of the reactor have been considered, such as efficiency, operational flexibility and the availability of resources necessary for its proper operation. The final selection of the reactor will be based on a comprehensive evaluation of all these factors, seeking to ensure the optimal choice that meets the requirements of the project and maximizes its benefits. The main reactors considered in this project are presented below, showing their operation and their advantages and disadvantages according to the above factors.

5.3. Small modular reactors assessed for energy supply

Taking into account the above considerations, two different reactors have been finally considered for the development of this project: the VOYGR reactor and the Xe-100. As will be seen subsequently, each of these reactors corresponds to a different reactor technology, the first being a PWR and the second an HTGR. Both models are presented below, explaining the characteristics of each of these technologies.

5.3.1. VOYGR

The VOYGR is a reactor developed by Portland, USA-based NuScale Power Corporation. This reactor is the first and only SMR to receive design approval from the U.S. Nuclear Regulatory Commission (NRC). The Figure 9 shows the dimensions of this reactor and its different components. The NuScale power module design is based on proven PWR reactor technology, and was developed to provide power for electric generation, district heating, desalination, commercial-scale hydrogen production and other process heat applications[50].

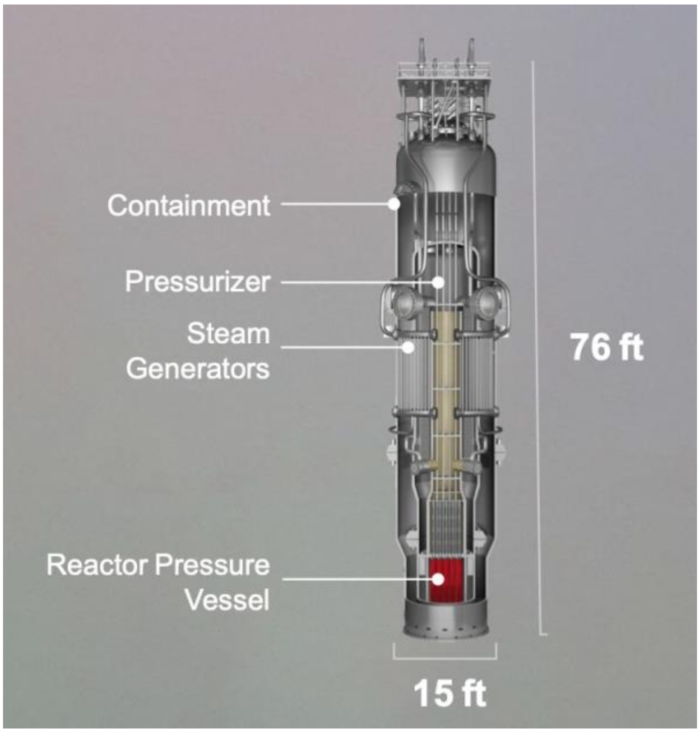

Figure 9 Detailed Insight into the VOYGR reactor: Components and Dimensions [50]

PWR reactors use water to cool and moderate the reactor core. In these reactors, there are two water circuits. In the first, the water is heated by being in contact with the sheath containing the nuclear fuel, although this water remains in a liquid state due to the high pressure at which it is found. Once this water from the primary circuit is hot, it is used in a steam generator to obtain steam in a secondary circuit, and this steam is used to turn a turbine by means of a Rankine cycle[14]. This is a proven technology as the vast majority of reactors use it.

Each module has an output of 77 MW(e) and 250 MW(th), and these modules can be composed of 3 configurations depending on the electrical demand:

- The **VOYGR-12** configuration is the one with most power and consist of 12 modules offering a total installed power of 924 MW(e).

- The **VOYGR-6** configuration is the intermediate configuration, and includes 6 modules, to give a power output of 462 MW(e). This configuration can be upgraded to VOYGR-12 in case of increased energy demand.
- Finally, the **VOYGR-4** configuration is the configuration with the lowest installed power, consisting of only 4 modules generating a total power of 308 MW(e).

These modules have a design life of 60 years, and use UO_2 pellets enriched to 4.95%. In addition, they have the advanced passive safety systems characteristic of 4th generation reactors, providing stable and long-lasting core cooling under all conditions, including the most severe accidents. In addition, one of the great advantages of these SMRs is their reduced construction period, which is only 36 months, and their installation is planned for the year 2030[51].

5.3.2. Xe-100

The Xe-100 reactor is a fourth-generation reactor developed by X-energy. This company, founded in 2009 by Kam Ghaffrian and based in Maryland, US, is dedicated to the design of reactors and nuclear fuels. Since its foundation, this company has taken giant steps in the nuclear sector, to become today one of the most relevant companies in the sector, having received several grants and government contracts. Since its beginnings, X-energy has focused its efforts on the design of this innovative SMR capable of revolutionizing the nuclear engineering market due to its great design advantages.

The Xe-100 is a graphite-moderated, helium-cooled, Pebble Bed Reactor (PBR), and within the 4th generation reactors it is classified as a HTGR (see Figure 10). With a capacity of 200 MW(th) and 80 MW(e), this reactor uses tri-structural isotropic particle fuel (TRISO), which are also marketed by the company X-energy[49]. These pebbles contain the fuel (UO_2 and UCO) enriched to 15.5% and are surrounded by three different carbon layers that provide structural integrity, and make this fuel extremely accident resistant[49]. Figure 11 shows different characteristics of these pebbles, and the layers in which these fuel spheres are divided.

This fuel also eliminates the need for massive containment facilities, as the TRISO cladding itself creates an airtight seal around the uranium core that helps retain fission products and gases produced during operations. This containment prevents 99.99% of fission products from escaping, according to X-energy[52]. This feature makes it possible to build these modular reactors within 500 meters of factories or urban areas.

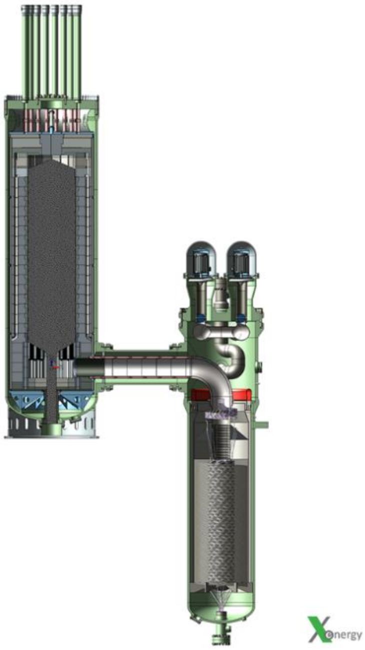

Figure 10 Detailed Insight into the Xe-100 reactor: Arrangement of the parts of the reactor[52]

The Xe-100 reactor contains 220,000 pebbles, which are gravity-fed and are in continuous rotation through the core. In this way, the reactor is continuously replenished by adding fresh pebbles daily from the top, as older pebbles are discharged from the bottom of the core. Each pebble remains in the core for just over three years and is circulated through the core up to six times to achieve complete combustion. This cycle allows the reactor to operate continuously without shutdowns to refuel the core for 60 years.

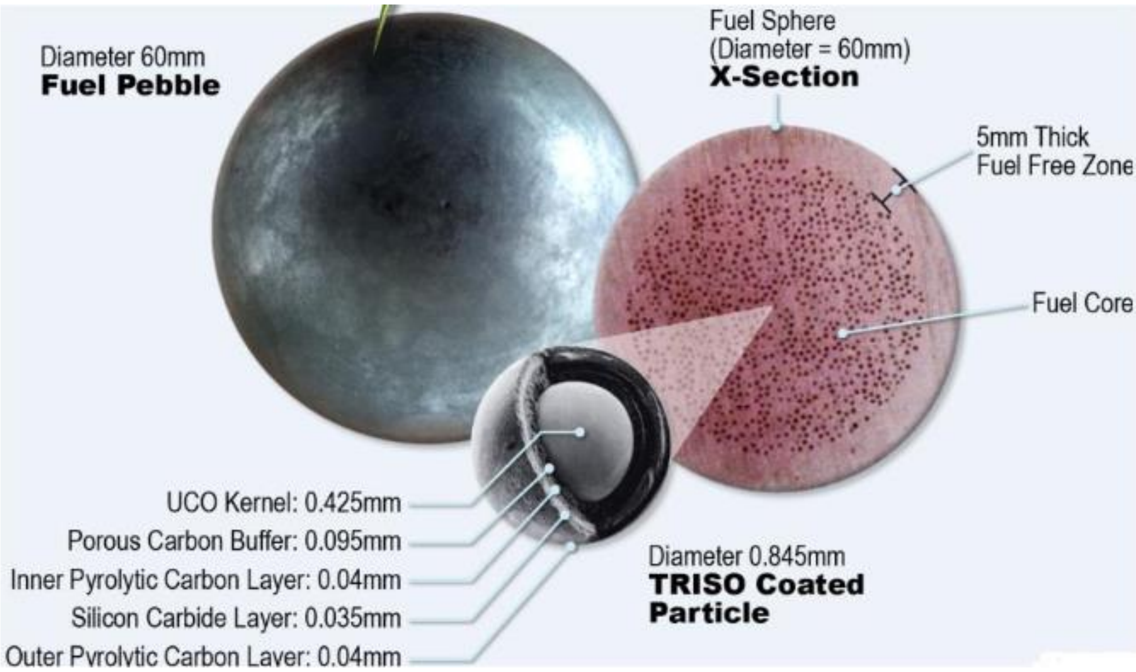

Figure 11 Characteristics and composition of the TRISO fuel pebbles manufactured by X-energy[52].

Helium circulates through the reactor acting as a coolant. Helium does not react chemically with the fuel elements, nor does it readily absorb neutrons or impurities, making it more efficient and less likely to become radioactive than water. Once it has passed through the reactor core formed by fuel pebbles, this helium is redirected to a steam generator, where the heat absorbed in the reactor is transferred to the steam to obtain energy by turning a turbine.

Since the reactor is designed to withstand high temperatures, it can be cooled by natural circulation and still survive in the event of an accident. In addition, as a 4th generation reactor, it has all the passive safety features. However, one of the main disadvantages of this technology is that enclosing the fuel in graphite can pose a hazard, since, if the graphite burns, the combustible materials could be carried away by the smoke. To overcome this obstacle, it is essential that the vessel be purged of oxygen, preventing the graphite from burning.

In conclusion, the Xe-100 reactor shows great potential in the nuclear power generation landscape. Although currently in pre-application stages, this promising reactor is expected to be commercially available by 2027. With its innovative design, generating capacity and focus on safety and efficiency, the Xe-100 presents itself as an attractive option to drive the transition to a more sustainable and emission-free energy matrix.

5.4. Selection of the reactor for the project

Once the two selected reactors and their main characteristics have been analyzed, the next step is to select the most suitable reactor for the energy supply of the Nyhamna plant. It is important to note that the choice between different types of nuclear reactors does not imply that one is inherently better than another. Each reactor has its own characteristics and advantages, and the selection of one over another has been based on the reactors' ability to meet the requirements and needs of the project. Each technology has its strengths and limitations, and the important thing is to find the reactor that best fits the established technical, economic and safety criteria.

In order to select the most suitable reactor, an exhaustive evaluation of the requirements established in section 5.2 “Requirements of the Selected Reactor for the Project” has been carried out. For this purpose, the technical aspects of each candidate reactor have been analyzed in detail. A complete comparison highlighting the main characteristics and performance of both reactors is presented in Table 2.

Table 2 Major Technical Parameters of the chosen reactors. Data acquired from IAEA [49].

	VOYGR	Xe-100
Technology developer	NuScale Power Corporation	X-Energy
Generation	4	4
Reactor Type	PWR	HTGR - PBR
Coolant/Moderator	Light water / Light water	Helium / Graphite
Thermal/Electrical capacity, MW(th)/MW(e)	250 / 77	200 / 80
Fuel type/Assembly array	UO2 pellet /17x17 square	UCO TRISO pebbles
Number of fuel assemblies in the core	37	220000 pebbles per reactor
Fuel enrichment (%)	<4,95	15,5
Refueling cycle (months)	24	Online fuel loading
Design life (years)	60	60
Design status	Equipment manufacturing in progress	Basic design
Expected deployment	2029	2030

To evaluate the technological maturity of each reactor, two main aspects have been taken into account in this project: the licensing status of each reactor, and its expected implementation date. It should be noted, that, in this regard, the VOYGR reactor has a certain advantage over the Xe-100. In 2016, NuScale Power Corporation submitted the Design Certification Application (DCA), and in 2020 the NRC issued the Standard Design Approval, making it the first SMR to receive this approval from the NRC[49]. In terms of deployment, NuScale Power has reached several agreements to deploy their design. Among these agreements, we can highlight the agreement with Utah Associated Municipal Power Systems (UAMPS) to install this reactor at the Idaho National Laboratory (INL) by 2029[49], [53], or the agreement with the copper and silver producer KGHM to implement this technology in Poland by 2029[54]. The Xe-100 on the other hand, has not yet received NRC approval, having submitted the DCA in 2021. However, this design is expected to be approved soon, as X-energy together with DOW are planning implementation as early as 2030 at the Gulf Coast facility[55]. It should also be noted that HTGR technology is the technology that is advancing the fastest in terms of licensing of all SMRs, so that this option is currently presented as one of the most important options in the market.

In terms of electrical capacity, as can be seen in Table 2, both reactors have a similar power output, which fits within the established range of 30 to 100 MW(e). In addition, both companies market these modules in "four-pack" to provide higher power, which amounts to 308 MW(e) in the case of VOYGR, and 320 MW(e) for Xe-100. However, this power is excessive, since to supply Nyhamna's energy demand it would be enough with 3 reactors in both cases, achieving a generation of 231 MW(e) with the NuScale modules, and 240 MW(e) with the X-energy modules. In these cases, the excess power would be much smaller. This could be fed into the grid to supply power to nearby towns such as Varhaugvika, Aukrasanden, Hollingen or Molde, among others (see Figure 7). However, this project is mainly targeting the Nyhamna plant as a case, and the energy needs of these villages have not been studied. This will have to be analyzed in the future as mentioned in section 8 "FUTURE WORK".

In terms of safety, as both reactors are fourth-generation reactors, they are designed with advanced nuclear safety systems that integrate multiple barriers and features to ensure maximum safety in their operation. These features include passive cooling systems, which help improve safety in the event of power supply failure, protection against extreme events such as earthquakes, floods or external attacks, and in general, an intrinsically safe design that guarantees the correct operation of the plant and eliminates the possibility of serious accidents. However, there are certain distinctive aspects between the two technologies, which have led to the choice of the Xe-100 module over the VOYGR.

First of all, it is important to remember that the current project aims to install these reactors in Norway, a country that does not have a sufficiently advanced nuclear structure to meet the needs of a large-scale plant. For this reason, the selected reactor is intended to operate as autonomously and efficiently as possible. In this regard, there is a significant difference between the two reactors in terms of fuel management. In this sense, the VOYGR requires refueling every 18 months, which, in addition to stopping electricity generation during this process, is also a logistical problem, since there is currently neither the nuclear industry nor the necessary resources to carry out this process in Norway. In contrast, the Xe-100 reactor does not require refueling outages, since the reactor itself is designed to be able to perform this process without interrupting electricity generation. This fact, apart from the fact that the modules can operate constantly for 60 years, also facilitates the refueling process, reducing the resources required and making it possible to implement it in any region.

Another great advantage of the X-energy reactor for implementation in this project is its high temperature operation. In the Xe-100 reactor, the coolant (helium) reaches up to 750 °C, a big difference with respect to the 316 °C reached in the coolant of the NuScale reactor. This difference makes it possible to extract energy from the reactor more efficiently, facilitating electricity production and favoring the recovery of the reactor's rest energy. The use of this rest energy is one of the main aspects of this project, since the main goal is to study the feasibility of using this energy to heat the processes of a biogas production plant.

At the same time, the design of the Xe-100 reactor has certain distinctive features that make it a suitable choice for implementation. This reactor uses pebbles inside the core which, in addition to containing the fuel, act as containment for the fission products. This reduces the need for containment barriers, allowing it to be installed only

400 meters from the Nyhamna industrial plant. Given that it is a small island, it is of great importance to have as much flexibility as possible to install the reactor, and although this project has not carried out a detailed study of where to deploy these facilities, greater flexibility would be a major advantage when deploying this reactor on the island of Gossa.

All these reasons have contributed to the choice of installing 3 SMRs from the X-energy company next to the Nyhamna gas processing plant. This fourth-generation reactor meets the key requirements of advanced technology and design, providing a high level of safety. Considering also the availability of data and the maturity of this technology, the Xe-100 reactor presents itself as the most suitable option to ensure the feasibility and success of the project.

5.5. Design of the thermodynamic cycle

Once the Xe100 reactor has been selected as the appropriate choice for the project, the next step will be to carry out the thermodynamic design of the plant. This process will involve the detailed analysis of the heat flows, the optimization of the thermal distribution networks and the optimal configuration of the heat exchangers. This study will seek to maximize energy efficiency and ensure optimal utilization of the energy generated by the reactor. The thermodynamic design will be a fundamental step to ensure an efficient and sustainable operation of the plant, making use of the waste heat generated in the plant, and meeting the objectives established in the feasibility study.

This thermodynamic cycle is represented in Figure 12, where the different thermal machines that compose the cycle are shown, as well as the different thermodynamic states in which the fluids are found when passing through these machines.

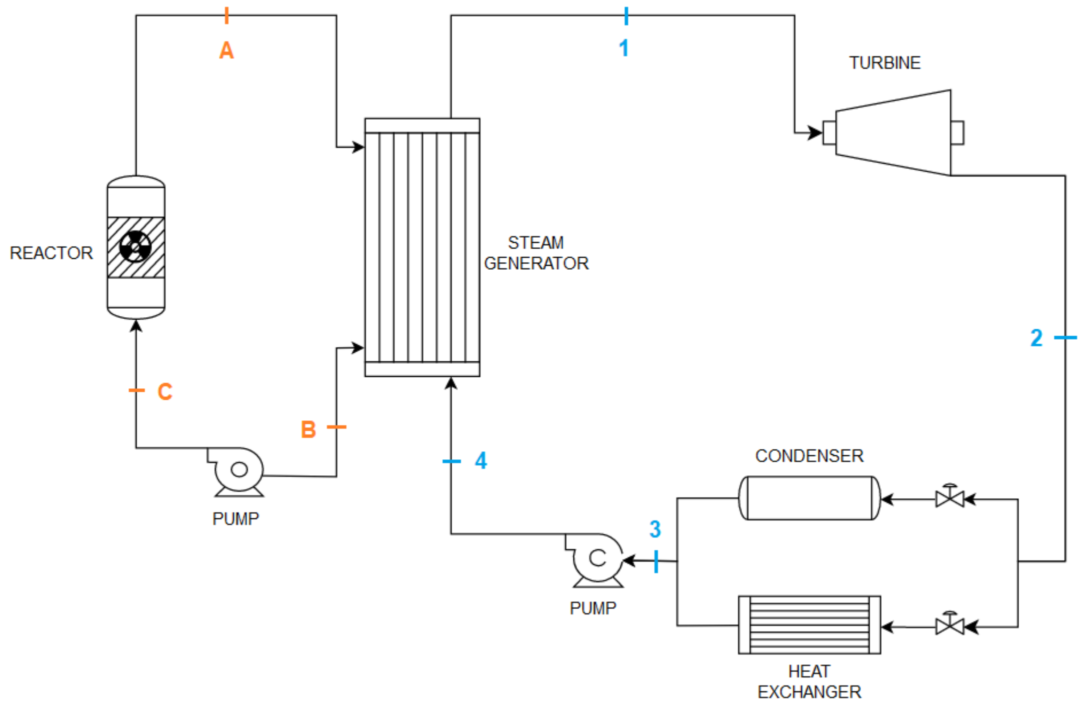

Figure 12 Xe-100 reactor's thermodynamic cycle diagram.

As previously mentioned, when explaining the operation of the PBR, in this diagram two circuits can be distinguished. In the first circuit, the circulating fluid is helium. This helium circulates through the reactor, cooling it and extracting heat, which is later used in the steam generator, where it exchanges heat with the secondary circuit. Once the helium leaves the steam generator, it passes through a pump, which injects the helium back into the reactor to start over the process. The secondary circuit, on the other hand, is a Rankine cycle. In these cycles, steam is generated from the heat exchanged with the primary circuit in the steam generator, and this steam is directed to a turbine. As the steam passes through the turbine, it gives up energy, producing a spin on the turbine shaft, which is harnessed by a generator to produce electrical energy. On leaving the turbine, the steam is at lower pressure and is transported to the condenser or the heat exchanger, where the vapor is converted into liquid, capable of being pumped back into the steam generator. When this phase change is made in the condenser, a large amount of thermal energy is released, which is called rest energy. This project will try to take advantage of this rest energy by means of an exchanger, to heat the processes of a biogas production plant.

Once the operation of the thermodynamic cycle is understood, we proceed to the calculation of the thermodynamic states. In this project, only the thermodynamic calculations of the secondary circuit have been carried out, since this are the most relevant. To perform this calculation, the data provided by X Energy has been used, which include the temperature and pressure of the water vapor at the outlet of the steam generator (state 1)[52]. From these data, the other thermodynamic states along the secondary circuit have been calculated, using the relevant thermodynamic equations and relationships. These calculations allow obtaining detailed information on the properties and behavior of the fluids at each point of the cycle, which is essential for the analysis and efficient design of the plant. It should be noted that in order to carry out this thermodynamic design, certain circuit parameters such as the isentropic performances of the thermal machines had to be assumed. As mentioned in chapter 4 "METHOD", these assumptions have been made conservatively in order to make the results as realistic as possible. The results of the thermodynamic states of the primary and secondary circuit are shown in Table 3.

Table 3 Thermodynamic states of the secondary circuit.

	$T\ (°C)$	$P(MPa)$	$h(kJ/kg)$	$s\ (kJ/(kg \cdot K))$
1	565	16.5	3475.3	6.51
2	99.8	0.1	2638.6	7.26
3	99.8	0.1	417.5	1.30
4	101.9	16.5	438.8	1.31

These values have been obtained from the thermodynamic study of the secondary circuit. In this cycle, the steam passes through the steam generator, the turbine, the condenser or heat exchanger and a pump, to be reintroduced into the steam generator and restart the cycle. Starting from the data of state 1, an isentropic efficiency of 75% in the turbine and 80% in the pump has been assumed. As for the pressure drop, it has been neglected to simplify the calculations. This simplification may introduce a small error to the final result, which is considered acceptable for the development of the feasibility study.

After having calculated all the thermodynamic states, the main parameters of the thermodynamic cycle have been calculated. To do this, first of all, the flow rate circulating through the secondary circuit was studied, taking into account a net electrical generation of 80 MW(e), and an efficiency of the turbogenerator set of 90%. These calculations have resulted in a mass flow of 109.3 kg/s. Once the mass flows in both circuits are known, the energy exchanged at each point of the cycle could be determined. Eq 12 shows the steam turbine power.

$$W_{turbine} = m_{steam} \cdot (h_1 - h_2) = 91.5\ MW \tag{12}$$

The performance coefficients previously mentioned (90%) have been applied to this power, and the power consumed by the pump has been subtracted, resulting in the net electrical power extracted, which is 80 MW(e) in each cycle. The following is the calculation of the heat exchanged in the steam generator (Eq 13)

$$Q_{steam\ generator} = m_{steam} \cdot (h_1 - h_4) = 332.0\ MW \tag{13}$$

After obtaining these values, the thermodynamic efficiency of the Rankine cycle can be quantified, which deals with the division of the work extracted and the heat introduced in the cycle, both terms previously calculated in (Eq 12) and (Eq 13) respectively. In (Eq 14) this calculation is represented.

$$\eta_{Rankine} = \frac{W_{turbine}}{Q_{steam\ generator}} = 27.55\% \quad (14)$$

However, the most relevant value for the development of this project is the thermal energy available between states 2 and 3. This energy, called rest energy, represents the heat that can be extracted in the heat exchanger, and in this proposal, it will be used to supply the energy needs of a biogas plant. This heat is represented in (Eq 15).

$$Q_{rest} = m_{steam} \cdot (h_2 - h_3) = 242.8\ MW \quad (15)$$

As mentioned above, it should be noted that these values refer to a single cycle, therefore, since 3 reactors have been installed, the energy available under these circumstances is 3 times higher than the values previously mentioned. The values of the electrical energy produced in the SMRs, and the residual energy generated, are shown below (Eq 16 & Eq 17).

$$W_{net} = 240\ MW \quad (16)$$

$$Q_{rest} = 728.4\ MW \quad (17)$$

These values define the electrical and thermal energy obtained from the installed reactors. The electrical energy generated in the turbogenerators will be used to power the compressors of the Nyhamna gas processing plant. These compressors require a power of 220 MW(e), so the 3 SMRs installed will be able to meet this energy demand, and there will still be 20 MW(e) left over, which will be fed into the power grid. The residual energy from the reactors, on the other hand, will be used to provide thermal energy to the different processes of a biogas plant.

The final objective of this study is to verify the feasibility of this biogas production plant together with the modular reactors. For this purpose, in this project the design of this installation has been carried out, analyzing its needs in order to determine the thermal demand of its different processes. However, before going into the processes to be carried out in this biogas plant, it is essential to talk about the organic material to be used in this complex: salmon sludge. This sludge will be obtained from the company Salmon Evolution, which is located 3 km north of the Nyhamna gas processing plant. The following is a discussion of the context of this company, and the relationship it will have to this project.

5.6. Salmon Evolution

Salmon Evolution founded in Norway in 2017, is a company dedicated to land-based salmon aquaculture. This company is one of the first companies to use the hybrid continuous flow system to grow salmon on land, which ensures a sustainable production process in which salmon growth conditions are optimal and controlled, while limiting operational and biological risks. This is the main reason that places the Norwegian company at the forefront of the food sector in relation to sustainability, becoming a reference in the area.

Salmon Evolution was born with the objective of deploying its facilities at Indre Harøy, an industrial facility located 3 km north of the Nyhamna gas processing plant (see Figure 7). After receiving permission from the county council of Møre og Romsdal in 2018 to carry out the construction of such facilities, in 2022 about 100,000 salmon smolts were released at the facility, inaugurating the start of salmon production in Indre Harøy. In this way, the Norwegian company has begun its journey in the food sector, where it expects to grow significantly in the coming years.

In relation to this growth, it should be noted that Salmon Evolution's facilities are still in the first phase, generating a total of 7,900 tons of salmon per year. However, they have ambitious plans to expand their capacity. In the second phase, they expect to increase production by another 7,900 tons, and finally, in the last phase, they plan to increase production by an additional 15,700 tons, reaching a total of 31,000 tons of salmon per year. It is estimated that this last phase will be fully constructed and operational by 2028[56].

During the development of its activity, Indre Harøy's facilities generate large quantities of salmon sludge due to the feces and other metabolic wastes of the fish. Currently, this sludge, far from having a positive value for the Norwegian company, is a setback, as it needs to be evacuated periodically to clean the tanks and ensure the correct growth of the salmon. Furthermore, once the sludge is evacuated from the tanks, it is dumped into the fjord, altering the aquatic ecosystems and affecting water quality, which has a detrimental impact on marine life.

The aim of this project is to valorize this waste by converting it into biogas, and to develop this activity, the company Salmon Evolution has collaborated with the company. This collaboration has consisted in the delivery of data about its sludge generation, which will be used in this project for the production of biogas. The data provided indicates that the plant currently produces 7,900 tons of salmon annually, and from this production, a total of 9,000 tons of sludge are generated per year. However, as mentioned above, the plant is still in the process of expansion, and is expected to increase its production to 31,500 tons of salmon per year when all three phases are completed. Under these final conditions, it has been calculated that the plant would generate a total of 36,000 tons of sludge per year.

In order to take advantage of these 36,000 tons of waste per year, a biogas plant has been designed in this study. It has been decided to install the biogas production plant next to the gas processing plant in order to use the residual energy from the reactors in a simpler way, and not to have to transport this energy, which would generate additional logistical problems.

In order to carry out this activity, the salmon sludge has to be transported from the Salmon Evolution facilities to the biogas production plant. These two sites are divided by 3 km of water. To address the logistical challenge of transporting the salmon sludge from the fish farm to the biogas plant, the installation of a subsea pipeline has been proposed. Through this infrastructure, sludge would be pumped through the pipeline from the fish farm site to the biogas plant. This solution would allow an efficient and safe transport of the sludge, avoiding the need to use other means of transport and minimizing possible environmental impacts.

To pump the salmon sludge from Salmon Evolution to Gossa Island, a pump is required that is capable of delivering enough power to the sludge to traverse 3 km of pipeline. To calculate the power required, a 10 cm diameter pipeline made of commercial steel (ε=0.046 mm) was assumed. The selected conditions can be considered conservative in terms of power. This means that a safety margin has been taken into account to compensate for possible additional losses and to ensure adequate fluid flow through the pipe. However, when comparing the power required by the pump (approximately 5 kW) with the power generation of the reactor, it is observed that this amount is relatively low. In this scenario, the power required for the pump can easily be supplied by the reactor without significantly affecting the power generation.

Once the Salmon Evolution company has been presented, and having dealt with the challenge of sludge transport, we will now study these sludges by looking at their properties in order to make a more precise analysis of the plant.

5.7. Salmon sludge

To carry out this project, it is essential to characterize the salmon sludge, since this will be the raw material that we will have to use in the project. Throughout the project, this sludge will be extracted from the Salmon Evolution facilities, transported to the biogas plant and subjected to transformations to obtain a value from it in the form of biogas. To design all these processes in such a way that the operation of the plant is as optimal as possible, it is necessary to detail the properties of the salmon.

However, detailing these properties is not a simple task, since no study has been carried out on these sludges in Salmon Evolution, which generates great uncertainty about their composition. Therefore, in order to provide a solution, as mentioned in section 4 "METHOD", it was decided to take the data collected by N. Teuber in his 2006 study[46]. The composition and properties of the salmon sludge are shown in Table 1. From this table, the most relevant parameters for this study are the density and the dry matter percentage of the sludge.

As can be seen in Table 1, the dry matter (%TS, from Total Solid) of these sludges is 15.8%, which can lead to possible failures such as blockages in the pipes, resulting in a more inefficient plant operation. For this reason, it has been decided to add water to these sludges, to reduce the dry matter percentage, and improve plant operation. In this way, adding water to the mixture would result in a greater amount of sludge to be treated, the calculation of this sludge is shown in Eq 18.

$$sludge\ capacity = 36{,}000\,\frac{tons}{year} \cdot \frac{\%TS}{10} = 56{,}880\,\frac{tons}{year} = 6.5\,\frac{tons}{h} \tag{18}$$

Once the amount of sludge has been obtained, and based on the properties of the sludge, the specific heat has been calculated. This calculation is shown in Eq 19.

$$cp_{sludge} = \left(1 - \frac{\%TS}{100}\right) \cdot 4.18 + \frac{\%TS}{100} \cdot 1{,}255 = 3.89\ kJ/(kg \cdot K) \tag{19}$$

The first term of the equation refers to the specific heat provided by the water, and the second term refers to the specific heat of the sludge solids. It is also important to notice that the %TS considered in Eq 15 has been 10% as said above.

These variables are of great importance for the development of the thermal calculation of the biogas plant. In the following section, the biogas plant is specified, describing the processes that compose it in a general way, to then study one by one these processes, and the structural and thermal needs of each one of them.

5.8. Biogas plant

The biogas plant is a fundamental infrastructure in the project being developed. Its main objective is to take advantage of the salmon sludge from the Salmon Evolution fish farm to carry out transformation processes to obtain biogas as a final result. This plant, located next to Nyhamna's gas processing plant, will efficiently process and use the raw material, thus contributing to the generation of renewable energy and the reduction of polluting waste. Through innovative and sustainable technologies, the biogas plant is positioned as a key part of the project's value chain, promoting the circular economy and sustainable development in the region.

Hyperthermics has assisted in the design of the plant in this project. Hyperthermics is a Norwegian biotechnology company dedicated to the development and construction of fast-running biogas plants. These plants use microorganisms and bacteria from extreme seabed environments to convert different types of biomasses into biogas, or into high quality protein which can be used for pet food among others. In this project we will focus only on the production of biogas, leaving aside the production of this protein. On the other hand, it should be noted that, thanks to their fast operation, these plants allow reducing the retention time, which implies a greater capacity of treated biomass, or the possibility of using smaller reactors, thus reducing the dimensions of the plant.

As this technology is one of the most innovative in the market regarding the treatment of biomass as sludge for biogas generation, it has been decided to use it for the development of the project. It should be noted that in this project the amount of biomass to be treated is fixed, and therefore, this technology will simply facilitate the implementation of a plant of these characteristics on the island of Gossa, since this plant requires less space than other plants in the sector. Therefore, in order to elaborate the project, the company Hyperthermics has been contacted and has made its technology available to the project, providing information about its design, and providing data on the generation of biogas in this type of plant. Figure 13 shows the distribution of the Hyperthermics plant where the different processes that compose it can be observed.

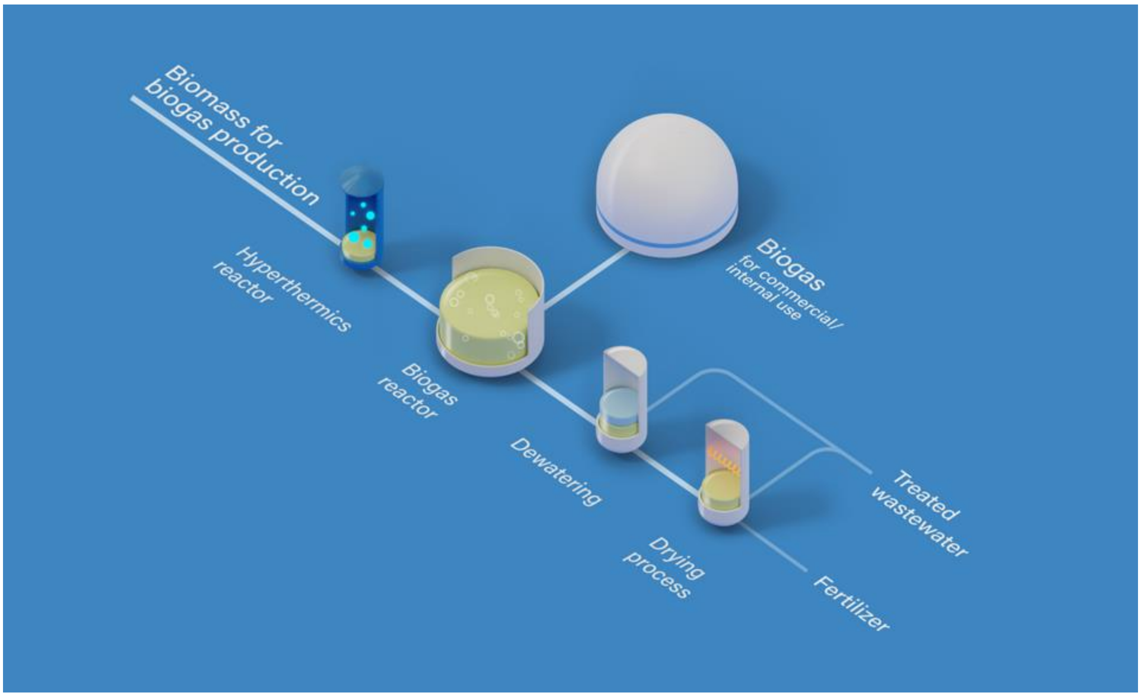

Figure 13 Hyperthermic's biogas and protein generation plant layout [57].

As can be seen in the Figure 13, in the biogas plant, the biomass, in this case salmon sludge, is first introduced into the Hyperthermics reactor, also called hygenisation reactor. In this reactor, the sludge is treated for 8 hours at a temperature of 80 °C, where thermophilic microorganisms and bacteria are used to accelerate the biogas transformation process. Once this process is completed, the sludge enters the biogas reactor, or anaerobic digestion reactor.

Within an anaerobic digestion reactor, a controlled biological process is carried out without the presence of oxygen. In this environment, the salmon sludge is decomposed by specific microorganisms under optimal conditions of 52 °C. During this process, which lasts 30 days, the organic materials present in the sludge are decomposed by anaerobic bacteria, generating methane and carbon dioxide, the main components of biogas. The reactor provides ideal conditions of temperature, pH and retention time to allow the gradual decomposition of the sludge and the continuous production of biogas. This anaerobic digestion process in the reactor is essential to efficiently and sustainably obtain biogas from salmon sludge, making responsible use of the waste and contributing to the generation of renewable energy.

In addition to biogas, by-products such as digestate are generated, which can be used as organic fertilizer. To obtain this digestate, the remaining material in the biogas reactor is sent to a dehydrator and a drying process, where the moisture is removed from this material, which can be used as fertilizer.

The individual analysis of the different processes that make up this plant has now been carried out. First, the needs and requirements of the hygenisation reactor were examined. Then, the anaerobic digestion reactor, which is in charge of sludge decomposition and biogas production, was studied. Finally, the characteristics and demands of the dehydrator and the drying process, whose function is to reduce the water content in the digestate, were explored. Through this detailed analysis, the aim is to understand and optimally design each of the processes necessary for the efficient and effective operation of the biogas plant, with special emphasis on the energy analysis.

It should be noted in relation to the thermal analysis of these reactors that the demand of each reactor will vary slightly with changes in ambient temperature. This is due to the fact that, at lower external temperatures, the reactor will have higher heat losses, which will have to be replaced by the residual energy of the SMR. In order to perform the most accurate and conservative study in terms of operability, the calculations have been carried out in the case where the ambient temperature is the lowest possible. In this way, it is studied in the case in which the thermal demand is higher, which will imply that, if the SMR is able to assume this thermal demand, it will also be able to do so in more favorable cases. Table 4 shows the climate and temperatures recorded in the Molde area according to “climate-data.org”[58].

Table 4 Climate and temperature data of the area of Molde (source climate-data.org)[58].

	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature °C (°F)	-1.4 °C (29.5) °F	-0.9 °C (30.4) °F	0.7 °C (33.3) °F	4.3 °C (39.7) °F	7.8 °C (46) °F	10.6 °C (51) °F	13.3 °C (55.9) °F	13.2 °C (55.8) °F	10.8 °C (51.5) °F	6.3 °C (43.3) °F	2.2 °C (35.9) °F	-0.6 °C (31) °F
Min. Temperature °C (°F)	-3.2 °C (26.2) °F	-3.1 °C (26.5) °F	-2.1 °C (28.3) °F	0.9 °C (33.6) °F	4.4 °C (39.8) °F	7.8 °C (46) °F	10.6 °C (51) °F	10.8 °C (51.4) °F	8.6 °C (47.4) °F	4.3 °C (39.7) °F	0.5 °C (32.8) °F	-2.4 °C (27.7) °F
Max. Temperature °C (°F)	0.3 °C (32.5) °F	1.2 °C (34.2) °F	3.4 °C (38.1) °F	7.3 °C (45.2) °F	10.8 °C (51.4) °F	13.1 °C (55.6) °F	15.9 °C (60.5) °F	15.8 °C (60.5) °F	13.3 °C (55.9) °F	8.4 °C (47.2) °F	3.7 °C (38.7) °F	1.1 °C (33.9) °F
Precipitation / Rainfall mm (in)	160 (6)	146 (5)	151 (5)	104 (4)	101 (3)	124 (4)	120 (4)	151 (5)	176 (6)	160 (6)	136 (5)	174 (6)
Humidity(%)	76%	79%	78%	77%	76%	79%	81%	83%	83%	82%	82%	79%
Rainy days (d)	13	12	13	11	12	12	12	13	12	13	11	13

Table 4 shows that the month with the lowest temperatures is January, reaching a minimum temperature of -3.2 °C. This will be the ambient temperature in which the biogas plant will be analyzed, and the energy demand of its different processes. On the other hand, the sludge temperature has been approximated to the minimum water temperature in the area of Molde, which is 4.9 °C. In relation to wind, the maximum speed recorded in the mold is 12.7 m/s[58].

5.9. Hygenisation reactor

The hygenisation reactor is one of the main components produced by Hyperthermics. In this reactor the salmon sludge is prepared to be treated more quickly, accelerating the whole process of biogas production.

As previously mentioned in section 5.8 "Biogas plant", this reactor contains a special bacterium, which are responsible for this treatment. These bacteria can be found in hot springs, volcanic areas, or in general those places on earth that are at a temperature above 45 °C. Life at temperatures above 45 °C is called thermophilic, and therefore these bacteria are qualified as thermophilic bacteria.

In the Hyperthermics reactor, the nominal temperature is 80 °C, and the sludge has to be kept inside the reactor for 8 hours. Knowing these data, it is possible to calculate the amount of sludge to be housed in each of the reactors, and therefore, the size of these facilities to accommodate all these sludges. To simplify the study, an approximation has been made considering that the shape of the reactor is similar to that of a cylinder whose height is 2.5 times its diameter. In addition, it has also been assumed that this reactor is made of stainless steel (k_{steel}=20 W/(m-K)), and that it has a thickness of 4 cm.

Due to the availability of large quantities of sludge, a study has been carried out to evaluate the possibility of implementing several reactors in the plant in order to reach the appropriate reactor size. The sizing of each reactor has been considered in case of opting for 1, 2, 3 or 4 reactors. Table 5 shows the amount of sludge to be treated, and the dimensions of each of these reactors in each case.

Table 5 Comparison between different number of hygenisation reactors installed.

Nº of reactors	Mass (tons)	Volume (m3)	Height (m)	Diameter (m)	Time (h)
1	51,95	49	7,31	2,92	8,00
2	25,97	24,5	5,80	2,32	4,00
3	17,32	16,33	5,07	2,03	2,67
4	12,99	12,25	4,60	1,84	2,00

Table 5 is used to make a comparison and select the number of hygenisation reactors to be installed in the project. In each case, the dimensions of each reactor are shown, in the different cases shown. In addition, the last column shows the time required to fill each reactor with a flow rate of 6.5 tons of sludge per hour. This time represents the interval between the filling of the reactors, i.e., the time required to fill a reactor with the available flow rate.

Having studied this comparison, it has been decided to implement 2 reactors, since a greater number of reactors would imply a greater economic effort without achieving an excessive reduction in the dimensions of the reactors. On the other hand, having only one sanitization reactor would imply a total stop of production in case it requires maintenance, whereas, with 2 reactors, even if one is inoperative, production would not be so affected.

Once the number of reactors has been chosen, the thermal demand of each reactor has been studied. In the case of the hygienization reactors, the thermal demand is based on raising the sludge temperature to 80 °C, in order to allow the thermophilic bacteria to act optimally. As explained in chapter 4 "CASEMETHOD" this thermal demand has been divided into two phases. The first phase is to heat the salmon sludge from ambient temperature (4.9 °C) up to the operating temperature of the reactor (80°C), and the second phase is to compensate the heat losses of this reactor, keeping it at the operating temperature. Eq 20 shows the energy required to raise the temperature of sludge that will later be introduced into a complete sanitization reactor.

$$Q = 7.583 \cdot 10^{6}\ kJ = 2106\ kWh \tag{20}$$

This will be the heat that will have to be extracted from the modular reactors every 4 hours to heat the salmon sludge that will enter the hygienization reactor. This energy is very small, since it can be extracted from the reactor in only 10.4 s. On the other hand, the power required to replace the heat losses of each reactor is shown in Eq 21.

$$\dot{Q} = 247.9\ kW/reactor \cdot 2\ reactors = 495.8\ kW \tag{21}$$

These losses have been calculated as presented in chapter 4 "METHOD". It should be noted that this also does not represent a large power compared to the residual energy of the reactors, accounting for only 0.07% of this.

5.10. Anaerobic digestion reactor

This reactor is the main reactor in any biogas production plant. In this reactor, organic matter, in this case salmon sludge, is converted into biogas through a controlled biological process. In this type of reactor, an anaerobic environment is created, i.e. without oxygen, which favors the activity of microorganisms called methanogenic bacteria. These bacteria decompose organic matter under low temperature conditions and in the absence of air, releasing methane (CH_4) and carbon dioxide (CO_2), the main components of biogas. In addition to biogas production, the anaerobic digestion reactor also produces other valuable by-products, such as digestate, which can be used as fertilizer.

The anaerobic digestion process is carried out in several stages within the reactor. In the initial stage, known as hydrolysis, complex organic molecules are broken down into simpler compounds, such as organic acids and sugars. Then, in the acidogenesis stage, the microorganisms convert the organic acids into simpler compounds, such as acetic acid and butyric acid. Subsequently, in the acetogenesis stage, the products of acidogenesis are converted into hydrogen acetate and carbon dioxide. Finally, in the methanogenesis stage, methanogenic microorganisms consume the hydrogen acetate and other compounds, generating methane and carbon dioxide, which constitute biogas[59].

Inside the anaerobic digestion reactor, an exothermic process takes place. This means that heat is released as a result of the chemical reactions that take place during the decomposition of organic matter. However, because it is necessary to maintain a constant and optimal temperature for the efficient functioning of the methanogenic bacteria, it is necessary to remove this heat from the reactor. Calculation of the heat generated in anaerobic digestion reactors can be performed using basic heat transfer principles and considering the thermophysical properties of the materials and flows involved. However, in order to study the most unfavorable case, the calculation of this generated energy is not within the scope of the project. For the development of the project, this energy has been neglected, which implies that the energy required to reach the operating temperature (52 °C) and maintain it throughout the process has to be matched only by the residual energy of the SMRs.

According to Hyperthermics, its process can be used with any anaerobic digestion reactor on the market, and therefore, its operating temperature can vary from one case to another. However, in their test plants they use reactors with an operating temperature of 52 °C, and the reactors take 30 days to perform the entire organic matter treatment process. Therefore, in this project it has been decided to incorporate these same reactors given their proven performance in previous installations. On the other hand, as in the case of the sanitization reactors, the structure of these reactors will be similar to a stainless-steel cylinder with 4 cm thick walls.

In the same way, once the most relevant parameters of these reactors and the processes to which they are subjected are known, the number of reactors to be installed in the Gossa biogas plant will be studied. In this case, different options from 1 to 20 reactors have been considered. Table 6 shows the different cases, and which would be the most relevant parameters of these reactors in the different situations.

Table 6 Comparison between different number of anaerobic digestion reactors installed

Nº of reactors	Mass (tons)	Volume (m3)	Height (m)	Diameter (m)	Time (h)
1	4675000	4410	32,74	13,10	720,0
2	2338000	2205	25,99	10,39	360,0
3	1558000	1470	22,70	9,08	240,0
4	1169000	1103	20,63	8,25	180,0
5	935014	882	19,15	7,66	144,0
6	779178	735	18,02	7,21	120,0
7	667867	630	17,12	6,85	102,9
8	584384	551	16,37	6,55	90,0
9	519452	490	15,74	6,30	80,0
10	467507	441	15,20	6,08	72,0
11	425006	401	14,72	5,89	65,5
12	389589	368	14,30	5,72	60,0
13	359621	339	13,92	5,57	55,4
14	333933	315	13,58	5,43	51,4
15	311671	294	13,28	5,31	48,0
16	292192	276	12,99	5,20	45,0
17	275004	259	12,73	5,09	42,4
18	259726	245	12,49	5,00	40,0
19	246056	232	12,27	4,91	37,9
20	233753	221	12,06	4,83	36,0

For the biogas plant of this project, it has been decided to install 10 anaerobic reactors. A smaller selection of reactors would have meant excessively large installations, and in addition, in this way, the interval between the filling of each reactor would be 3 days, giving a greater margin of maneuver in case maintenance is needed in these reactors. On the other hand, the selection of more reactors has been discarded since this would imply an excessive number of installations. However, in a future study, a greater or lesser number of reactors could be chosen, depending on the needs of the project.

After having evaluated and decided the configuration of anaerobic digestion reactors, the thermal demand of each reactor has been studied. In these reactors, a sludge temperature of 52 °C has to be obtained. To make the calculation, it has been assumed that the initial sludge temperature is the same as in the previous case (4.9 °C):

However, it will be higher, since the sludge has just been evacuated from the hygienization reactor, where it was at a higher temperature. In this project, it has been assumed that the sludge leaving the hygienization reactor is cooled to room temperature, until it reaches the same temperature it had before entering the hygienization reactor. In this way, a conservative decision is made to evaluate the thermal demand.

The same method used in section 5.9 "Hygenisation reactor" was used for this evaluation. Using this method, firstly, the energy required by each reactor to heat the sludge to operating temperature (52 °C) has been calculated. Secondly, the temperature of this reactor has to be kept constant, counteracting the heat losses occurring in the reactors. Eq 22 and Eq 23 show both parameters respectively.

$$Q = 8.560 \cdot 10^7\ kJ = 23778\ kWh \quad (22)$$

$$\dot{Q} = 503.86\ kW/reactor \cdot 10\ reactors = 5{,}238.6\ kW \quad (23)$$

It should be noted that the energy demand of these reactors is also very low. First of all, as regards the temperature rise of the initial sludge, this can be extracted from the reactor in 117.5 sec. On the other hand, as regards the constant energy supply to mitigate heat losses, it should be noted that this thermal power represents only 0.72% of the residual thermal power of the reactors.

5.11. Energy analysis of the installation

Taking into account the observations made, the energy feasibility analysis of the project is presented below, where the energy demand has been summarized by dividing it into its different applications. Table 7 shows the available electrical and thermal energy generated by the SMRs, and the energy demand of the gas processing plant and the biogas plant.

Table 7 Analysis of the different energy generation and demand in the project.

	Generation		Demand	
Electrical Energy [MW(e)]	SMR	240	Compressors	220
			Pumping Sludge	> 0,01
			Grid	20
Thermal energy [MW(th)]	SMR rest energy	728,4	Hygenisation Reactor	0,5
			Anaerobic digestion reactor	5,2
			Available Rest heat	722,7

In terms of electricity demand, the 3 SMRs would provide the power needed for the compressors at the Nyhamna plant, and there would be 20 MW left over that could be fed into the grid for use in nearby towns, or even at the Salmon Evolution facility.

On the other hand, regarding thermal energy, it is evident that the energy generated in the reactors is very abundant, and the constant thermal needs of the biogas plant only account for 0.8% of the total waste energy generated in the SMRs. After this use, the remaining thermal energy will be used to increase the temperature of the sludge as it enters the hygienization and anaerobic digestion reactors. The energy required to fill an entire tank in each case to operating temperature is shown in Eq 16 and Eq 18. With the available power, the hygienization reactor could be heated to operating point in 10.5 seconds, and in the case of the anaerobic digestion reactor, the sludge would be at the desired condition in 118.4 seconds.

This analysis demonstrates the capacity of the residual energy of these reactors to supply the thermal demand of this biogas plant by far. The study of the biogas production generated in this plant is presented below.

5.12. Biogas production

As seen above, biogas is a renewable fuel produced from the decomposition of organic matter in the absence of oxygen, in a process known as anaerobic digestion. The gas obtained from this process is composed mainly of methane (CH_4) and carbon dioxide (CO_2), although it may also contain small amounts of other gases such as nitrogen (N_2), oxygen (O_2) and traces of sulfur compounds. Therefore, the study of biogas production deals with the analysis of the amount of these gases that can be extracted from anaerobic digestion.

The calculation of biogas production in a biogas plant from salmon sludge is a complex process that depends on several parameters and variables. To perform this calculation, aspects such as the quantity and composition of the salmon sludge, the operating temperature, the efficiency of the anaerobic digestion process and the capacity of the system must be taken into account.

However, for this project, due to the lack of biogas composition data, and in order to simplify the calculation, as mentioned in chapter 4 "METHOD", an approximation has been used to get a general idea about the production. Eq 24 and Eq 25 show the potential methane and carbon dioxide extractable from salmon sludge according to Hyperthermics.

$$CH_4\,potential = 1.894 \cdot 10^6\,Nm^3/year = 1{,}244\,tons/year \qquad (24)$$

$$CO_2\,potential = 1.576 \cdot 10^6\,Nm^3/year = 3{,}115\,tons/year \qquad (25)$$

On the other hand, it is worth mentioning that a certain amount of hydrogen (H2) is also obtained at the Hyperthermics plant. Although it is not the main aspect of the project, due to the large capacities of this gas, it has been considered convenient to show the potential of hydrogen extractable by the plant (Eq 26).

$$H_2\ potential = 39{,}816\ Nm^3/year = 3.579\ tons/year \tag{26}$$

On the other hand, to put into perspective the amount of biogas generated, an estimation has been made about how many houses could be thermally supplied by this amount of biogas. To do this, first the amount of thermal energy that can be obtained from these amounts of biogas has been analyzed. From these biogas quantities, the biogas energy potential can be obtained. The result is represented in Eq 27.

$$Energy\ potential = 19.2\ GWh/year \tag{27}$$

From this, and taking into account that the average thermal demand in Norway is around 17,000 kWh per year, the number of dwellings that can be thermally supplied by the generated biogas is represented in Eq 28.

$$Dwellings\ supplied = \frac{19.2\ GWh}{17\ MWh} = 1{,}129\ dwellings \tag{27}$$

It is important to mention that the calculation of biogas production is an estimate and there may be variations in practice due to various factors, such as fluctuations in the composition of the salmon sludge, changes in operating conditions and process efficiency. Therefore, continuous monitoring and adjustments to the plant are recommended to optimize biogas production and maximize its performance.

6. DISCUSSION

Once the case of the present project has been developed, and the different aspects that compose it have been described, next, the discussion of the work is formulated. In this discussion, the main research questions surrounding the project will be addressed, analyzing different aspects of the installation of the modular reactors and the use of their residual energy for the production of biogas.

First of all, it should be noted that the main objective of the project has been achieved, which was to verify the possibility of supplying electricity to an industrial plant, taking the Nyhamna plant as a case study. This implementation has allowed a significant saving of 220 MW(e) from the conventional power grid. In addition, by using state-of-the-art nuclear reactors, it has been possible to diversify the energy matrix and generate electricity in a sustainable and GHG-free manner. This transition to a cleaner and more efficient energy source brings with it numerous additional advantages.

By implementing these modular reactors, dependence on fossil fuels is reduced and the carbon footprint of the industrial plant is reduced, which directly contributes to climate change mitigation. In addition, a reliable and stable energy supply is ensured, avoiding fluctuations in production due to variable weather conditions or limitations in the electrical infrastructure. Likewise, SMRs are characterized by their high efficiency and long-term generation capacity, resulting in greater profitability and long-term economic viability.

Moreover, the use of this technology promotes innovation and technological development in the energy sector, opening new opportunities and perspectives for future applications and improvements in the industry. In this context, this project paves the way for these modular reactors, validating their adaptability to virtually any environment and circumstance in which increased electricity generation is required. In summary, the adoption of these nuclear reactors has not only fulfilled the main objective of supplying electricity to the Nyhamna plant, but has also provided a number of additional advantages, both environmentally and economically.

On the other hand, another main objective of this project was the use of the rest energy generated by the modular reactors. In this sense, the feasibility of using this rest energy to feed the hygenisation reactors and the anaerobic digestion reactors in a biogas plant has been investigated and evaluated. As seen in chapter 5 "CASE", the hygienization reactors operate at 80 °C, while the anaerobic digestion reactors operate at 52 °C. This, coupled with the fact that the waste energy of the reactors is at 100 °C, allows for adequate heat transfer to meet the thermal requirements of the biogas plant reactors. In this way, the possibility of using this remaining energy to heat the biogas plant processes in an efficient and effective manner has been validated.

Furthermore, unlike the study developed by Lipka et al. [39] in the present project no pre-turbine steam extraction was required to heat the steam at the turbine outlet as shown in Figure 6 since the application temperature is already substantially lower than the turbine outlet temperature. This factor is due to the selection of HTGR. Due to the high temperatures of the steam, the energy from these reactors has a higher quality, which facilitates heat transfer without reducing the electrical output. This indicates that the available waste energy can be effectively harnessed to supply the thermal needs of the hygenisation and anaerobic digestion reactors. This waste energy reuse approach not only contributes to the energy efficiency of the plant, but also reduces the dependence on external heat sources, thus improving the self-sufficiency and sustainability of the system.

Despite the benefits obtained by using the rest energy from the nuclear reactors in the biogas plant processes, it is important to note that the portion of energy used is minimal compared to the total residual energy available. This comparison is reflected in Table 7, where it can be seen that only 0.8% of the residual energy generated by the three nuclear reactors is used on a constant basis. In addition to this demand, the reactors also have a punctual demand to heat the sludge at an initial instant. However, this demand only occurs every 4 hours for the hygenisation reactors and every 72 hours for the anaerobic digestion reactors. This punctual thermal demand would last 10.5 seconds in the case of the hygenisation reactors and 118.4 seconds in the case of the anaerobic digestion reactors.

In the development of this study, only waste heat has been used to heat the waste plant processes, although it should be noted that there are other alternatives in the area that should be studied if these reactors are implemented. One of these cases is the thermal demand of the Salmon Evolution facilities. With respect to this demand, the County Governor of More og Romsdal County requested the Norwegian Environmental Agency (Miljødirektoratet) to consider transferring the cooling water from the Nyhamna plant to Salmon Evolution's plant in Indre Harøy[60]. The demand of this plant is 45 GWh per year, which is only 2% of Nyhamna's cooling energy. However, after this news published in 2018, there have been no further breakthroughs in the project, so it could be about providing the energy required in this plant by SMRs. Anyway, this study has not been detailed exactly, although it is necessary to mention, that it would not change the excess amount of energy available at the turbine output, which still remains remarkably abundant.

This is mainly due to the large amount of residual energy available in these reactors, and the high temperature of the same. Therefore, it is important to emphasize that this energy use, despite being minor in comparison with the total produced rest energy, it could be very significant for the biogas plant, and in general for the country of More og Romsdal, since it allows carrying out all the sludge decomposition processes without the need to incorporate any other type of energy source, or without the need to burn part of the biogas generated. In this way, not only a greater amount of biogas is obtained, but also an outlet is provided for the salmon sludge that is currently sprayed into the fjord, polluting it. However, in order to achieve a greater use of the rest energy, two other options are proposed in this project, which, although they do not fall within the scope of the project, should be evaluated in future work.

One of the proposed solutions for using more of the waste energy generated by the SMRs and not used by the biogas plant is its application in district heating systems. As mentioned in chapter 3 "STATE OF THE ART", there are three main cities in the area where the biogas plant is located: Molde, Ålesund and Kristiansund. In the case of Molde, which is only 10 km from the plant, the utilization of waste thermal energy could have a substantial impact on reducing dependence on fossil fuels and contribute to the transition to a more energy sustainable city. On the other hand, Ålesund and Kristiansund, located at a distance of 50 km each, could also benefit from this solution, although it would require additional heat transport infrastructure, such as long-distance pipelines.

The implementation of a district heating system would allow the heat generated by the reactors to be channeled to the residential and commercial areas of these cities. The supply of heat from the nuclear plant could replace or supplement conventional energy sources currently used for heating, resulting in a significant reduction in GHG emissions and greater energy efficiency.

It is important to note that this study has not been carried out in depth due to the lack of specific data on the energy demand of these cities and because it has not been raised as a main objective of the research project. However, the implementation of a district heating system would be an interesting option to consider in the future, especially if a close collaboration between the biogas plant, local authorities and other stakeholders is achieved.

In addition to the environmental benefit, the application of waste thermal energy in district heating systems could also generate significant economic savings in the long term, in exchange for a non-negligible investment for the implementation of pipelines and ducts to transport the heat to the main consumption points. The use of a more sustainable energy source that is less dependent on fossil fuels could reduce heating costs for residents and businesses, while ensuring a stable and reliable supply.

The other solution put forward to achieve greater utilization of the wastewater from the SMRs is the possibility of increasing biogas generation at the plant by incorporating a larger amount of salmon sludge, as well as other waste such as wastewater generated in the cities of Molde, Ålesund and Kristiansund. This waste could be pumped to the biogas plant for further processing. Thus, with more organic matter to be treated, the energy required to carry out the different processes would increase, and a larger number of sanitization and anaerobic digestion reactors would need to be installed.

As mentioned above in chapter 5 "CASE", the energy required for sludge pumping is minimal. It should be noted that, in the case of wastewater from the cities mentioned, or in the case of sludge generated in other industrial activities, the pumping distance would be greater than in the case studied, which could lead to greater losses and require greater power. However, it is important to note that nuclear reactors generate a significant amount of additional electrical energy that could be used for this activity.

The availability of this additional power from nuclear reactors provides a unique opportunity to address the waste pumping activity. The power generated by the reactors is more than sufficient to cover the energy requirements of this additional process. This would allow for an increase in the amount of salmon sludge and wastewater treated at the plant, which in turn would result in an increase in biogas production.

As mentioned above, the use of salmon sludge and wastewater as additional substrates for biogas production would not only contribute to maximizing the plant's energy generation capacity, but would also provide a sustainable solution for the treatment of these wastes. By taking advantage of these resources, landfill disposal would be avoided and their environmental impact would be reduced.

The treatment of a larger amount of sludge makes it necessary to increase the number of reactors in the biogas plant, which implies a greater occupation of space and land requirements. However, this aspect does not represent a significant problem, since Gossa Island has large areas of undeveloped land that could be used for this purpose.

The reactors of the designed biogas plant occupy only 85 square meters, which is relatively small compared to the availability of land on the island. To put this in perspective, suffice it to mention that the plot adjacent to the Nyhamna plant has an area of 110.5 hectares, which is approximately 13,000 times the size of the biogas plant. This indicates that there are ample areas available for plant expansion and implementation of new reactors.

Increasing biogas production by treating more salmon sludge and other wastes has numerous benefits. First, it makes more efficient use of available resources, reducing environmental impact and optimizing energy efficiency. In addition, by increasing biogas production, it promotes renewable energy generation and reduces dependence on conventional and non-renewable energy sources.

This option is highly viable and scalable, meaning that it can be adapted and expanded according to future needs and demands. The modular design of the biogas plant allows the addition of new reactors in a flexible and gradual manner, ensuring sustainable growth as the amount of sludge and waste treated increases.

In conclusion, although the energy required for the operation of the biogas plant is initially limited, it is important to consider that there are different ways to take advantage of the capacity of this energy for the benefit of the community, being able to reach a point where the residual energy used acquires high and significant values. This translates into significant energy and economic savings, as well as the reduction of GHG emissions. Therefore, this project has proven the feasibility of using the residual energy from SMRs to carry out fuel synthesis, promoting the collaboration of nuclear energy together with renewable energies to advance towards the decarbonization of the energy sector.

On the other hand, it is important to note that this option could generate a larger amount of biogas. As we have seen in chapter 5 "CASE", from the 36,000 tons of salmon sludge per year, this biogas plant could produce enough fuel with zero net emissions to thermally supply 1,129 houses in Norway. This is a small amount, as it would be insufficient to supply the thermal demand of a city like Molde, for example.

However, there are other applications that could be given to this biogas to take better advantage of its energy capacity. One of these applications would be the use of this biogas in power generation plants as a peaker unit.

Plants that act as peaker units are power generation facilities designed to provide additional electricity during periods of high energy demand. These plants are designed to be flexible and capable of rapidly increasing their power output to meet fluctuations in electricity demand.

Peaker units use fast power generation technologies, such as gas turbines or internal combustion engines, which can start up quickly and reach full capacity in a short time. These units are activated when electrical demand peaks, whether due to extreme weather conditions, peak consumption hours or emergency situations.

Although peaker units can provide a reliable and fast source of power during peak demand, they are generally not designed to operate at full capacity on a continuous basis. This is because base generation plants, such as hydroelectric power plants, or nuclear plants, are more efficient and cost-effective for long-term, constant power production.

The use of peaker units has significant benefits, as it helps balance energy supply and demand, avoids overloading the power grid, and ensures a reliable supply of electricity during periods of high demand. In addition, being flexible and fast-responding units, they can be integrated with intermittent renewable energy sources, such as solar or wind power, to ensure greater stability in the power grid.

In this way, the biogas produced from the salmon sludge could be used in a plant of these characteristics, where large quantities of fuel are not necessary to have a very positive impact on the electricity grid, since these plants operate for short periods of time, only to meet peaks in electricity demand. However, it should be noted that the study of the capacity of the biogas generated to operate in these units is not within the scope of the project, and its possible implementation will have to be analyzed and evaluated in the future.

On the other hand, due to the lack of maturity of modular reactor technology, it is currently imprecise to perform an exhaustive economic study on their feasibility. Therefore, as presented in chapter 8 "FUTURE WORK", this analysis remains pending for future studies in which more information and concrete data on the performance and costs associated with these reactors will be available.

Regarding the Hyperthermics biogas plant, it is important to mention that it is a project in the process of analysis and development. At this time, there are no absolute certainties about its value and cost, as these aspects are subject to ongoing evaluations and adjustments as the project design and implementation progresses.

It is essential to understand that the economic evaluation of a biogas plant, especially when it involves emerging technologies such as modular reactors, requires a detailed and rigorous analysis. This implies taking into account aspects such as initial investment, operating costs, revenues generated, environmental benefits and other relevant factors to determine its long-term financial viability.

Therefore, more comprehensive and in-depth studies are needed in the future in order to more accurately determine the economic viability of modular reactors and to obtain a more accurate assessment of the value and cost of the project. These analyses will allow informed and informed decisions to be made regarding these technologies and projects in the area of biogas production from nuclear reactor waste energy.

Finally, it is of great importance for the current project to review the actions taken in relation to the Sustainable Development Goals. It is important to note that the objective of the project has not been to make a quantitative analysis of the contributions made to the SDGs, and therefore, this study has been done in a more qualitative way, looking at the different contributions globally.

As described in chapter 1 "INTRODUCTION", this project is mainly framed within the SDG number 7 that talks about ensuring clean and safe energy. In this sense, the implementation of the reactors and the biogas plant is a clear example of energy efficiency and represents a clear act against climate change, since it promotes energy generation away from sources with GHG emissions. Although it is true that this is only a feasibility study, this work serves to lay the foundations for a future project in which SMRs are required to be implemented near a point of high energy consumption.

In addition, significant contributions have also been made in relation to SDG 9, as it promotes the construction and implementation of a safe, modern and efficient plant. With regard to SDG 12, waste recovery is a sustainable way of producing and consuming resources in the area, and lastly, SDG 14, which deals with ocean conservation, has also been a central point of the project, preventing salmon sludge from being dumped into the fjord.

7. LIMITATIONS

This section focuses on analyzing the constraints that may affect the implementation and development of the present project. While diligent work has been done to design and plan each aspect, it is important to recognize that there are certain constraints and challenges that could influence its implementation and results. These constraints may range from technical and logistical aspects to economic, legal or environmental factors. Understanding and addressing these constraints effectively is crucial to assessing the feasibility and success of the project, and will enable informed decisions to be made to overcome obstacles and maximize the benefits gained.

As mentioned in chapter 4 "METHOD", one of the most significant limitations in the development of this project has been the scarcity of available data on the composition and properties of the sludge. The lack of accurate and detailed information on this organic matter has been a major challenge to perform the feasibility study, since this variable can introduce a large error in the results obtained. The composition of sludge is fundamental to understand its behavior in anaerobic digestion processes and to determine the efficiency and biogas production.

The composition of this kind of sludge can be very variable, as it depends on a large number of factors, such as the feeding of the salmon, the water temperature or the frequency of sludge removal. Therefore, the most accurate way to carry out this project is the particularized evaluation of this sludge, since, in this way, the composition of the sludge will be better known, and a better treatment will be carried out.

However, in this project, since there is no updated data available for the plant of Salmon Evolution, we have worked with the data collected in the study by N. Teuber et al.[46] which are shown in Table 1. These data might not particularly accurate for this project, but they are useful to carry out a general study, adjusting to the objective of studying the feasibility of installing these biogas plants powered by SMRs. However, it should be noted that, in the event of implementing a project of these characteristics in the future, the rigorous study of the raw material that makes it up is of vital importance.

Regarding sludge composition, for the purpose of simplifying calculations, and also as a consequence of the lack of data on the transformation processes, it has been assumed that sludge has the same properties throughout the different processes of the biogas plant. This is clearly uncertain, but data limitations have contributed to this decision. This parameter has a direct impact on biogas production, and to overcome this uncertainty, the company Hyperthermics has provided their expertise in the topic based on the experimental data obtained by their biogas production plant. As mentioned above, this company has years of experience in the biogas production sector, and therefore their valuable information has contributed to better estimate the capacity of the installed plant, despite the inaccuracies committed in the study when assuming the composition of the salmon sludge or other variables.

On the other hand, for the development of the project, other assumptions about the environment, such as ambient temperature or water temperature, have also had to be made. These parameters vary throughout the year and for this reason could not be studied in depth. Therefore, in order that the conclusions of the project are not greatly affected, a conservative approach has been taken placing the study at all times in the most unfavorable possible case.

Regarding the use of waste energy, as mentioned in chapter 3 "STATE OF THE ART", several alternatives have been explored, including the implementation of district heating systems. However, this proposal has had the limitation of having insufficient information on the thermal demand of nearby towns, such as Molde, Kristiansund and Ålesund, which could directly benefit from this energy source due to their proximity to the plant. Unfortunately, the lack of knowledge of the thermal demand of these locations has made it difficult to accurately assess the feasibility and benefits associated with this approach. On the other hand, it is important to note that this study has not been included in the scope of the current project, but it is recognized the importance of conducting a comprehensive assessment in the future in order to evaluate the feasibility and potential for implementing district heating systems that efficiently harness this waste energy.

Finally, it is important to comment on the status of the economic study. Currently, due to the immaturity of the reactors and the biogas plant of the Hyperthermics company, there is not enough information available, which has been an important limitation to carry out the economic study of this project. These technologies are in the process of being commercialized, but there is still no study available that precisely analyzes the implementation costs of a project of these characteristics. Therefore, this analysis remains to be carried out in the future, as discussed in chapter 8 "Future Work".

8. FUTURE WORK

The present feasibility study has been developed with the objective of validating the ability of SMRs to meet electricity demand in high demand areas, while harnessing waste energy to heat the processes of a biogas power plant. Through this analysis, a solid foundation has been established to continue with more detailed research to enable future implementation of this approach. In addition, several lines of research have been identified that need to be addressed before a project of this nature can be implemented. This chapter will detail the different studies and lines of research that have been left open, as well as the main objectives to be addressed in this further work. First, the issues related to the particular case have been addressed, and then a more general view of the project has been taken, and the different lines of research to be addressed have been proposed.

First of all, it has to be noted that in order to successfully implement this project, a more detailed study is needed, focusing on key aspects that have been generalized so far. Among these aspects, the precise composition of the sludge is of utmost importance, as it will determine the quality and quantity of biogas generated. Once this composition has been determined, a more precise thermal calculation of the plant can be carried out, taking into account the actual thermal demand of such a facility. This analysis will make it possible to evaluate the feasibility and efficiency of the use of the waste energy in an even more concrete way, and in this way more precise data will be available that will make it possible to estimate biogas production more accurately. After this study, the engineering design of the plant can begin, where special attention will be paid to the functionality of the processes and to optimizing the extraction of the waste energy in the most efficient way possible. These steps will be indispensable to achieve a successful implementation and maximize the use of available resources. However, as far as the Nyhamna project is concerned, there are other aspects that will need to be addressed.

One of the most important points to address regarding the project is the large amount of residual energy remaining in the reactor. According to the calculations presented in chapter 5 "CASE", the biogas plant only uses 0.8% of the waste energy generated in the reactor. This is a very low percentage, and although this demand is not exact and must be recalculated, thanks to the conservative approach of the study, it can be affirmed that the energy needed in the biogas plant in relation to the residual energy of the reactor is very low. For this reason, in order to make better use of this energy, and to obtain a higher energy efficiency, different alternatives have to be looked for. These alternatives have not been evaluated in the present project since it has been focused on the biogas plant, and on valorizing the waste from the Salmon Evolution plant. Therefore, these alternatives do not fall within the scope of this project. Nevertheless, the different alternatives proposed in this project to achieve a greater use of rest energy are shortly discussed below.

As mentioned in chapter 6 "DISCUSSION", one of the main alternatives could be to increase biogas production. To do so, the organic matter available in the area should be analyzed and its transport should be evaluated both logistically and economically. In this sense, for the present project, several options have been evaluated to complement the salmon sludge. The main organic matter that has been taken into account has been the wastewater from nearby cities. This option is of great interest because in this way it would be possible to take advantage of this waste, which is currently a problem due to the management it requires. Other alternatives that have been evaluated are the use of salmon sludge or sludge from other land-based fish farms, or the introduction of seaweed as organic matter. In the first case, it would involve pumping sludge from more distant plants. This idea is driven by the fact that this transport of this matter does not require a great expenditure of energy, and can be done in a reasonably simple way by means of a pipeline. In the case of the use of seaweed, this would require the construction of plots where these are cultivated for later exploitation, which would have an undesirable environmental impact. However, the use of these organic materials would expand the generation of biogas, and would take advantage of the rest energy of the reactor, while giving a valorization to these wastes.

Another alternative to increase the energy efficiency of the reactors would be the use of this thermal energy to heat other types of processes. In this sense, 3 different thermal energy demand points have been identified where this technology could be useful: the Nyhamna plant, the Salmon Evolution facilities, or the district heating of the nearest cities.

At the Nyhamna plant, in addition to natural gas compression, other types of treatments are also performed to process the gas and send it to the English coasts. These treatments require thermal energy, either directly or indirectly in the facilities, and this energy could be supplied by the SMRs. However, although one of the main objectives of the project has been to match the energy demand of the Nyhamna plant, given the lack of information about this thermal demand, it has not been taken into account in the development of this work, and its assessment should be carried out in future studies. As for the Salmon Evolution facilities, as mentioned in chapter 6 "DISCUSSION", this plant has a certain energy demand to carry out its activity. This demand is very small, only 45 GWh per year[60], but supplying it with thermal energy from the reactors would mean considerable energy savings for the salmon production company.

Finally, the possibility of using the waste heat from the SMRs for district heating in nearby cities has been considered. As mentioned in section 3.2 "District heating", this application is one of the most widespread in nuclear cogeneration. In this sense, the possibility of transporting the remaining thermal energy from the reactors through specialized pipelines to the nearest cities (Molde, Kristiansund and Ålesund) is proposed. In order to carry out this project, the district heating of these 3 cities should be analyzed, studying their needs and their actual status. It should be noted that these needs will depend on the season of the year, being higher in the winter months. After analyzing the energy demand of these cities, the feasibility of transporting this energy through specialized pipes should be studied, analyzing the different areas they would cross, and studying the heat losses to which they would be exposed. It should also be noted that these energy losses will be greater in those months when energy demand will be higher.

The implementation of any of these alternatives would contribute to energy efficiency, and would result in large savings for the community of Møre og Romsdal. Consequently, when implementing this project, these alternatives should be taken into account, and comprehensive studies should be conducted on the feasibility of each of them.

However, although the study has focused on analyzing the Møre og Romsdal area, and although the particular case of the Nyhamna gas processing plant has been studied, the ultimate goal of the study is to demonstrate the feasibility of this project, and to validate its adaptability to other areas. In this way, a feasible proposal has been made to generate electrical energy at points of high demand, while treating organic waste from the area to generate biogas. Having demonstrated the capacity of this project, other locations with similar characteristics should be studied to implement these facilities.

In this regard, the Mongstad area, located 50 km north of Bergen, is a candidate for such a project. Mongstad is a leading industrial cluster, home to more than 50 companies including Equinor, Schlumberger, Baker Hughes and the world's largest coal capture facility, TCM. In this industrial area, the possibility of installing a salmon farm has been considered. The real estate company Asset Buyout Partners, owned by Sweden's Balder, is expected to invest between NOK 2 billion and NOK 4 billion to take over a disused refinery and implement a fish farm, which is expected to produce around 42,000 tons of salmon per year[61]. Compared to Salmon Evolution, this amount of salmon would generate about 48,000 tons of sludge annually, 12,000 tons more than what is generated off the coast of Indre Harøy.

This fact opens up the possibility of implementing SMR technology to supply the electricity demand of the industrial plant, while at the same time taking advantage of the residual energy to treat the salmon sludge that will be generated at the Mongstad facility. In addition, being relatively close to one of the largest centers in the country, the city of Bergen, the possibility of using the wastewater generated in this city to generate biogas together with the salmon sludge could be analyzed, or the district heating of Bergen could be evaluated, to supply the city with the waste heat from the SMRs. Overall, if the project is developed, the incorporation of SMRs at the Mongstad plant presents itself as an option with significant potential. This option opens up new opportunities to improve the efficiency and competitiveness of the Mongstad plant, while contributing to the transition to cleaner and more sustainable energy sources, and should be explored in the future.

This is just one example of a location where such a project could be beneficial. However, future work should evaluate this option along with several others to study the feasibility of this project, following the guidelines shown in the current project.

In relation to the economic study, despite the advances and promising potential of SMRs and Hyperthermic's biogas technology, it is important to note that a precise analysis has not yet been possible due to the lack of concrete data on the costs of these facilities. Both SMRs and Hyperthermic's technology are in the process of being commercialized, which means that there are no reliable studies that provide detailed information on the costs of these facilities. However, the intrinsic nature of these technologies raises promising prospects in terms of cost reduction.

On the one hand, SMRs have the advantage of being modular, which allows for factory production, reducing costs compared to conventional nuclear facilities. This modularity also means greater flexibility and scalability, which can result in additional long-term savings. On the other hand, Hyperthermic's biogas technology aims to reduce the costs of conventional biogas plants. This technology allows for faster and more efficient treatment of organic waste, reducing the amount of waste treated in a single instant, and thus favoring the construction of smaller and less costly facilities.

In summary, while it is anticipated that both SMRs and Hyperthermic's biogas technology can offer significant reductions in costs, the lack of available information limits the ability to perform a detailed economic study in the present project. For this reason, future work with more robust and complete data will be necessary to adequately assess the economic viability of a plant incorporating these technologies.

Another line of research that has remained unresolved in the work is the use to be made of the biogas generated. This fuel has great potential, due to its renewable nature. However, as studied in section 5.12 "Biogas production", the amount of extractable fuel in the case of study is quite limited. This could change in case it is decided to increase the production of biogas, increasing the dimensions of the plant and treating other types of waste from the area, which would increase the capacity of action of this fuel. This is why, in the current project, the possible applications of this biogas have not been studied in depth, since it is a value that could fluctuate in the future, altering its capacity for action.

However, as mentioned in chapter 6 "DISCUSSION", it has been considered the possibility of using the biogas generated as a heat source to heat the homes in the area, as well as to use it as fuel in peaker units. These applications have great potential in terms of energy efficiency and emissions reduction. However, a more comprehensive and detailed study is needed in the future, especially regarding the feasibility and impact of peaker units. This analysis should focus on the current market, assessing the needs of the power grid and demonstrating the ability of these units to contribute to improving the quality and stability of the grid. To this end, it will be essential to consider factors such as the electrical demand of the area and the economic and environmental benefits that can be obtained from their implementation. In short, a rigorous and specific study is required to determine the potential and opportunities that these applications can offer in the current context.

Regarding the overall project, it should be noted that in the future the work done should be reviewed and updated with the advances in technology at the time of implementation. A clear example of this is the selection of the SMR. As mentioned in section 5.4 "Selection of the reactor for the project", the X-energy company's SMR, the Xe-100, has been chosen for the development of this project. This reactor currently presents a high degree of maturity compared to other fourth generation reactors, and has been selected for the development of the project due to its safety, its capacity to be incorporated next to the industrial plant, and its high temperature, which facilitates the recovery of waste heat.

On the other hand, SMR technology is constantly advancing, and every day there are countless eventualities that can change the course of this technology. For this reason, the different SMRs on the market must be constantly reviewed to ensure that the reactor selected is the right one for the project. In this sense, there are currently 2 very promising reactor technologies with great future potential, but due to their low maturity, they have not been evaluated in the current project: the Molten Salt Reactors (MSR) and the Liquid Metal-cooled Reactor (LMR).

These reactors are currently considered a promising alternative for power generation as a perspective of the thorium fuel cycle or to use spent LWR fuel. Moreover, in the case of MSRs, thanks to the use of salts, these reactors allow energy storage, which is a clear qualitative differentiator compared to other current designs. Although this aspect could be a revolutionary factor in the nuclear energy landscape, these reactors have been discarded in this project because they are a technology under development, which does not offer availability in the near future. However, it is worth mentioning the potential that these reactors could have in the future due to their ability to revolutionize the nuclear landscape in the coming years, and therefore, a detailed evaluation of these technologies should be carried out to verify their capability if the project is developed.

Finally, it is necessary to mention the SDGs, and the contribution of this project to the guidelines established in the Paris agreement[7]. It is clear that the current project is developed with the purpose of addressing climate change, proposing sources of energy generation free of GHG emissions. In this sense, it can be reasoned that the implementation of the facilities studied in this project would bring substantial progress to the 7th SDG. However, the study of the contribution of this project to the SDGs has not been the main purpose of the project. In order to know this contribution more precisely, it will be necessary to carry out a study based on the indicators established in the Paris agreement, analyzing the environmental impact of the plant and assessing its benefits and detriments of the project. This work is pending to be carried out in the future.

9. CONCLUSIONS

In conclusion, this study has comprehensively addressed the analysis and feasibility of the implementation of SMRs in areas of high electricity consumption, and the utilization of the remaining residual energy to heat the processes of a biogas plant. Throughout this work, it has been demonstrated that the incorporation of these reactors in the Nyhamna plant and the utilization of their rest energy are feasible and offer significant benefits in terms of electrical and thermal generation.

The main objective of the project, which was to supply electricity to the Nyhamna plant, has been achieved, thus reducing the demand on the power grid and contributing to the generation of energy free of GHG emissions. This plant requires 220 MW(e) to drive the compressors, and through the 3 SMRs implemented, an electrical capacity of 240 MW(e) has been installed. In this way, the demand of the compressors is fully supplied, and there would still be 20 MW(e) left over that can be used for other applications such as sludge pumping, or for the power supply of neighboring communities.

The X-energy company's reactors, the SMR Xe-100, have been chosen for power generation. These are fourth generation HTGR reactors, and have a high degree of maturity compared to other SMRs that are in the process of being commercialized. HTGRs are characterized by operating at higher temperatures compared to other SMRs, which provides greater safety in case of failures. In addition, this feature allows the rest energy to be extracted more efficiently, which is a factor of great importance in this project. By operating at higher temperatures, HTGR reactors offer advantages in terms of energy efficiency and waste energy utilization, helping to maximize the production of electricity and heat safely and reliably.

Thanks to this feature of the Xe-100 SMRs, the feasibility of using waste energy from the reactors to heat the processes of a biogas plant has been demonstrated. Through this innovative idea, it has been possible to obtain greater energy efficiency of the reactors, while at the same time valorizing the salmon sludge. Currently, this waste is dumped into the fjord, polluting the water and harming the fjord's marine life. In this way, not only is this waste treated, but biogas is obtained, a renewable fuel that is presented as a valuable alternative to other fossil fuels in the fight against climate change.

To develop the biogas plant, the technology and experience of the company Hyperthermics has been made available, which has resulted in great improvements in waste management and biogas production. This biogas plant consists of 2 main processes: the hygienization reactor and the anaerobic digestion reactor. These processes require certain stable conditions in terms of temperature over an extended period, 8 hours and 3 days respectively, and therefore the waste heat from the reactor has been used to maintain this stability.

Therefore, the project has consisted of the thermal study of this biogas plant, and the feasibility analysis to match this demand by means of SMRs. The results of the plant design have revealed the need to install 2 hygenisation reactors and 10 anaerobic digestion reactors. In this way, the thermal needs of all these reactors have been evaluated, and the rest energy capacity of the selected SMRs has been verified to meet these needs.

However, this project has shown that due to the limited availability of organic matter in Salmon Evolution's facilities, both the rest energy used and the biogas production are very low. In this sense, several opportunities for improvement have been identified and lines of research have been proposed for future studies to further optimize the use of residual energy and explore other potential applications. Among them, it has been proposed the inclusion of other organic materials in the biogas plant, such as wastewater from nearby cities, which would increase the production of biogas, using a greater amount of waste energy. Another proposal has been the use of waste energy for district heating in nearby cities. However, these proposals were not within the scope of the study and will need to be analyzed in the future.

Taken together, these results support the feasibility and importance of continuing the development and implementation of projects involving SMR power generation in the future, thus contributing to the transition to a more sustainable and efficient energy system by combining the strengths of nuclear and renewable energies in order to combat climate change.

10. REFERENCES

[1] United Nations, “Progress towards the Sustainable Development Goals,” 2022. [Online]. Available: https://unstats.un.org/sdgs/.

[2] United Nations, “Sustainable Development Goals,” 2015.

[3] United Nations Environment Programme, “Stockholm Declaration,” 1972.

[4] United Nations, “MULTILATERAL: Montreal Protocol on Substances that Deplete the Ozone Layer,” 1978.

[5] United Nations, “Rio Declaration on Environment and Development,” 1992. [Online]. Available : http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

[6] United Nations, “KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE UNITED NATIONS,” 1998.

[7] Unfccc, “PARIS AGREEMENT,” 2015.

[8] IEA, “World Energy Statistics and Balances,” 2020. http://www.iea.org/terms (accessed May 14, 2023).

[9] J. Twidell, *Renewable Energy Resources*. 1986.

[10] Energy Fact Norway, “Electricity Production Norway,” *https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/*, Nov. 05, 2021.

[11] V. Kumar Gupta and M. G. Tuohy, “Biofuel and Biorefinery Technologies Volume 6 Series editors.” [Online]. Available: http://www.springer.com/series/11833

[12] I. Renewable Energy Agency, *Biogas for Road Vehicles: Technology brief*. 2018.

[13] Z. Burivalova, “LETTER FROM SCIENTISTS TO THE EU PARLIAMENT REGARDING FOREST BIOMASS.”

[14] S. Glasstone and A. Sesonske, *Nuclear Reactor Engineering*. Springer US, 1994. doi: 10.1007/978-1-4615-2083-2.

[15] E. Latré, T. Perko, and P. Thijssen, “Public opinion change after the Fukushima nuclear accident: The role of national context revisited,” *Energy Policy*, vol. 104, pp. 124–133, 2017, doi: 10.1016/j.enpol.2017.01.027.

[16] J. Ataman, “France announces plans to build up to 14 nuclear reactors - CNN,” Feb. 11, 2022. Accessed: May 16, 2023. [Online]. Available: https://edition.cnn.com/2022/02/11/business/nuclear-power-france/index.html#:~:text=France%20has%20announced%20plans%20to%20bui

ld%20up%20to,study%20the%20possibility%20of%20commissioning%20a%20further%20eight.

[17] Isabeau van Halm, “Japan eyes return to nuclear power,” *Energy Monitor*, Oct. 03, 2022.

[18] Ministerstwo Klimatu i ´Srodowiska, “74% Polaków popiera budowę elektrowni jądrowych w Polsce,” 2021. Accessed: Jun. 26, 2023. [Online]. Available: https://www.gov.pl/web/klimat/74-polakow-popiera-budowe-elektrowni-jadrowych-w-polsce

[19] World Nuclear News, “Polish plans for large and small reactors progress,” Apr. 17, 2023. Accessed: Jun. 26, 2023. [Online]. Available: https://world-nuclear-news.org/Articles/Polish-plans-for-large-and-small-reactors-progress

[20] Reuters, “UK gives go-ahead for EDF’s Sizewell C nuclear plant construction,” Jul. 20, 2022. https://www.reuters.com/business/energy/uk-gives-development-consent-sizewell-c-nuclear-plant-2022-07-20/ (accessed Jun. 26, 2023).

[21] Ismail Shakil, “Canada commits C$970 million to new nuclear power technology,” *Reuters*, Oct. 25, 2022. https://www.reuters.com/business/energy/canada-backs-nuclear-power-project-with-c970-mln-financing-2022-10-25/ (accessed Jun. 26, 2023).

[22] Catherine Clifford, “Germany has shut down its last three nuclear power plants, and some climate scientists are aghast,” *CNBC*, Apr. 18, 2023. https://www.cnbc.com/2023/04/18/germany-shuts-down-last-nuclear-power-plants-some-scientists-aghast.html (accessed Jun. 26, 2023).

[23] C. DeBolt, “Nuclear Power Plant Ban Repeal Advances,” Jan. 2022. Accessed: Jun. 26, 2023. [Online]. Available: https://blog.wvlegislature.gov/house-committee/2022/01/24/nuclear-power-plant-ban-repeal-advances/

[24] World Nuclear Association, “Plans For New Reactors Worldwide,” May 2023. https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx (accessed Jun. 26, 2023).

[25] World Nuclear Association, “Emerging Nuclear Energy Countries,” Apr. 2023. https://world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx (accessed Jun. 26, 2023).

[26] New European Parliament, “Taxonomy: MEPs do not object to inclusion of gas and nuclear activities,” Jul. 06, 2022. https://www.europarl.europa.eu/news/en/press-room/20220701IPR34365/taxonomy-meps-do-not-object-to-inclusion-of-gas-and-nuclear-activities (accessed Jun. 24, 2023).

[27] BBC, “Finland’s plan to bury spent nuclear fuel for 100,000 years,” Jun. 14, 2023. https://www.bbc.com/future/article/20230613-onkalo-has-finland-found-the-answer-to-spent-nuclear-fuel-waste-by-burying-it (accessed Jun. 24, 2023).

[28] Hannah Ritchie, “What are the safest and cleanest sources of energy?,” *Our World in Data*, Feb. 10, 2020. https://ourworldindata.org/safest-sources-of-energy (accessed Jun. 25, 2023).

[29] A. Markandya and P. Wilkinson, “Energy and Health 2 Electricity generation and health,” *www.thelancet.com*, vol. 370, 2007, doi: 10.1016/S0140.

[30] B. K. Sovacool *et al.*, “Balancing safety with sustainability: Assessing the risk of accidents for modern low-carbon energy systems,” *J Clean Prod*, vol. 112, pp. 3952–3965, 2016, doi: 10.1016/j.jclepro.2015.07.059.

[31] United Nations. Scientific Committee on the Effects of Atomic Radiation., *Sources and effects of ionizing radiation: United Nations Scientific Committee on the Effects of Atomic Radiation: UNSCEAR 2008 report to the General Assembly, with scientific annexes.* United Nations, 2010.

[32] IAEA, “Small Modular Reactors: A new nuclear energy paradigm,” 2022.

[33] IAEA, “Considerations for Environmental Impact Assessment for Small Modular Reactors,” *IAEA TECDOS SERIES*.

[34] H. Safa, “Heat recovery from nuclear power plants,” *International Journal of Electrical Power and Energy Systems*, vol. 42, no. 1, pp. 553–559, 2012, doi: 10.1016/j.ijepes.2012.04.052.

[35] IAEA., *Opportunities for Cogeneration with Nuclear Energy.* IAEA, 2017.

[36] “Nuclear Process Heat for Industry,” *World Nuclear Association*, Sep. 2021, Accessed: Jun. 08, 2023. [Online]. Available : https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry.aspx

[37] G. Alonso, S. Vargas, E. Del Valle, and R. Ramirez, “Alternatives of seawater desalination using nuclear power,” *Nuclear Engineering and Design*, vol. 245, pp. 39–48, Apr. 2012, doi: 10.1016/j.nucengdes.2012.01.018.

[38] S. A. Ahmed, H. A. Hani, G. A. Al Bazedi, M. M. H. El-Sayed, and A. M. G. Abulnour, “Small/medium nuclear reactors for potential desalination applications: Mini review,” *Korean Journal of Chemical Engineering*, vol. 31, no. 6. Springer New York LLC, pp. 924–929, 2014. doi: 10.1007/s11814-014-0079-2.

[39] M. Lipka and A. Rajewski, “Regress in nuclear district heating. The need for rethinking cogeneration,” *Progress in Nuclear Energy*, vol. 130. Elsevier Ltd, Dec. 01, 2020. doi: 10.1016/j.pnucene.2020.103518.

[40] Atomenergi, *Ågesta Nuclear Power Station with district heating - Stockholm*. 1958.

[41] A. Teräsvirta, S. Syri, and P. Hiltunen, "Small Nuclear Reactor-Nordic District Heating Case Study," *Energies (Basel)*, vol. 13, no. 15, Aug. 2020, doi: 10.3390/en13153782.

[42] C. Tai, G. Tian, and W. Lei, "A water-heat combined supply system based on waste heat from a coastal nuclear power plant in northern China," *Appl Therm Eng*, vol. 200, Jan. 2022, doi: 10.1016/j.applthermaleng.2021.117684.

[43] X. L. Yan, S. Konishi, M. Hori, and R. Hino, "Nuclear Hydrogen Production: An Overview," 2011. [Online]. Available: https://www.ebsco.com/terms-of-use

[44] G. Becerra *et al.*, "Nuclear Technology & Canadian Oil Sands Integration of Nuclear Power with In-Situ Oil Extraction," 2005.

[45] K. Verfondern, "Potential for nuclear process heat application," 2009.

[46] N. Teuber, M. A. Alfaro, F. J. Salazar, and C. Bustos, "Sea salmon sludge as fertilizer: effects on a volcanic soil and annual ryegrass yield and quality," *Soil Use Manag*, vol. 21, no. 4, pp. 432–434, Feb. 2006, doi: 10.1079/sum2005352.

[47] Journal of Petroleum Technology, "Kongsberg To Build Digital Twin for Shell's Nyhamna Gas Facility." Accessed: May 26, 2023. [Online]. Available: https://jpt.spe.org/kongsberg-build-digital-twin-shells-nyhamna-gas-facility

[48] Reuters Staff, "Norway's Nyhamna gas plant cuts power consumption to 100 MW until Nov. 22," Nov. 19, 2018. https://www.reuters.com/article/norway-gas-outages-idUKO9N1JQ00O (accessed May 22, 2023).

[49] IAEA, "Advances in Small Modular Reactor Technology Developments A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2022 Edition." [Online]. Available: http://aris.iaea.org

[50] NuScale Nuclear Power, "VOYGR NuScale SMR".

[51] NuScale Power, "About NuScale Power." https://www.nuscalepower.com/en/About (accessed May 24, 2023).

[52] "X-energy." https://x-energy.com/ (accessed May 25, 2023).

[53] S. Patel, "Novel UAMPS-NuScale SMR Nuclear Project Gains Participant Approval to Proceed to Next Phase," *POWERMAG*, Mar. 02, 2023. Accessed: May 28, 2023. [Online]. Available: https://www.powermag.com/novel-uamps-nuscale-smr-nuclear-project-gains-participant-approval-to-proceed-to-next-phase/

[54] World Nuclear News, "NuScale, KGHM agree to deploy SMRs in Poland," Feb. 14, 2022. Accessed: May 28, 2023. [Online]. Available: https://www.world-nuclear-news.org/Articles/NuScale,-KGHM-agree-to-deploy-SMRs-in-Poland

[55] A. Duckett, “Dow goes nuclear: chemical firm will install reactors at US chemicals complex,” Aug. 11, 2022. Accessed: May 28, 2023. [Online]. Available: https://www.thechemicalengineer.com/news/dow-goes-nuclear-chemical-firm-will-install-reactors-at-us-chemicals-complex/

[56] FishfarmingExpert, “Salmon Evolution fish ‘still exceeding expectations,’” Nov. 16, 2022. https://www.fishfarmingexpert.com/norway-salmon-evolution/salmon-evolution-fish-still-exceeding-expectations/1453685 (accessed Jun. 02, 2023).

[57] Hyperthermics, “Hyperthermics’ technology will increase the biogas yield from the biomass and increase your biogas plant’s capacity.” https://www.hyperthermics.com/biogas-booster (accessed Jun. 20, 2023).

[58] Climate Data, “Data and graphs for weather & climate in Molde.” https://en.climate-data.org/europe/norway/m%C3%B8re-og-romsdal/molde-9909/ (accessed Jun. 05, 2023).

[59] V. Kumar Gupta and M. G. Tuohy, “Biofuel and Biorefinery Technologies Volume 6 Series editors,” 2018. [Online]. Available: http://www.springer.com/series/11833

[60] U. Lucasen, “Energi fra Nyhamna til nytt landbasert fiskeoppdrettsanlegg ved Indre Harøy,” Jun. 15, 2018. https://www.statsforvalteren.no/nb/More-og-Romsdal/Miljo-og-klima/Klima/Energi-fra-Nyhamna-til-nytt-landbasert-fiskeoppdrettsanlegg-ved-Indre-Haroy/ (accessed Jun. 20, 2023).

[61] Salmon Business, “New Nordic land-based salmon project aims for 42,000t capacity at disused refinery...,” Nov. 11, 2022. https://www.undercurrentnews.com/2022/11/11/new-nordic-land-based-salmon-project-aims-for-42000t-capacity-at-disused-refinery/ (accessed Jun. 29, 2023).