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Master's Programme in Manufacturing

Green Hydrogen Production Site Validation and Supply Chain Simulation and Analysis: a Case Study of Lough Ree Power Plant

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Master's thesis
2023

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Aalto-universitetet
Aalto University

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Title of thesis Green Hydrogen Production Site Validation and Supply Chain Simulation and Analysis: a Case Study of Lough Ree Power Plant

Programme Master's Programme in Manufacturing

Major Zero Defect Manufacturing for a Circular Economy

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Date 09.06.2023 **Number of pages** 77/62 **Language** English

Abstract

Green hydrogen is generated from electrolyzing water with electricity from renewable sources. Thus, green hydrogen production has no carbon emissions and it releases oxygen and water into the environment. It can be a replacement for fossil fuels and mitigates the energy demand. Although green hydrogen technology is still on a small scale or in the pilot phase, the demand for green hydrogen has grown in recent years.

This thesis study will be conducted on a closed coal power plant that is proposed for transformation into a green hydrogen production site to mitigate the hydrogen demand in Ireland. One of the aims of the study is production site validation by comparing selected sites with an Ideal production site model. The ideal site model has been developed from literature and comparison has been performed under location, social, and technical criteria. The result shows that discussed site is valid as a production site except it is far from wind firm, gas, and rail networks.

Another aim is to develop various supply chain scenarios and simulate them to measure the performance metric which will help to select the best scenario. The discrete event simulation approach has been used to simulate the scenarios in Anylogistix software. The basic model has one supplier, one producer, five distribution centers, and twenty-six counties as customers. The different scenarios have been generated by varying the distribution centers. The selected performance metric is ELT service level by orders which is measured for high, moderate, and low levels of safety stock. The model is sensitive to demand variation. However, the simulation result shows that the production site is capable to satisfy the demand of midland customers and west-side customers of Ireland. That scenario has performed over 90% of ELT service level by orders for every level of safety stock. Also, they performed well for long-term (3 years) simulation and it is more economical than other scenarios. Overall, the Lough Ree power plant can supply green hydrogen with acceptable ELT service level by orders to the customers of Cavan, Donegal, Leitrim, Longford, Monaghan, Roscommon, Westmeath, Clare, Galway, Mayo, Offaly, and Sligo counties.

Keywords Hydrogen, site location, supply chain, ELT service level by orders

Preface and Acknowledgments

First of All, I would like to thank Allah for blessing me with all the opportunities that I gained in this life. Alhamdulillah for everything.

I would like to thank my main supervisor Dr. Mika Salmi for his guidance through this thesis journey. His support and motivation helped me to work on a complex topic. Thank you for supporting me with proper direction and concepts. I also like to thank Dr. Pezhman Ghadimi for his guidance during the thesis.

I also want to mention Irene Nantongo from FDT Ireland. I appreciated your support with project information.
To my family, thank you all for your love and support.

Rafiqul Alam
Espoo, June 2023

Abbreviations

ABS	Agent-based simulation
CO_2	Carbon dioxide
CPLEX	IBM ILOG CPLEX Optimization Studio
DES	Discrete event simulation
e-	Electron
ELT	Estimated lead time
GIS	Geographic Information System
GW	Gigawatt
H_2	Hydrogen
H_2O	Water
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
Kt	Kiloton
KW/h	Kilowatt per hour
LSM	Lanthanum Strontium Manganite
LSCM	Lanthanum Strontium Cobaltite Manganite
MPa	Mega pascal
Mt	Megaton
O_2	Oxygen
OH-	Hydroxide anion
PPM	Particle per meter
PWR	Power-to-weight ratio
PEM	Polymer electrolyte membrane
ScSZ	Scandium-Stabilized Zirconia
SOEC	Solid oxide electrolyzer cells
SDS	System dynamic simulation
UK	United Kingdom
YSZ	Yttria-stabilized Zirconia

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1 Introduction

1.1 Background and Context

Due to the constant growth of technology and the standard of living, energy demand is increasing every year. But the natural energy sources reserves are limited compared to the current demand for energy. The other concerning fact is burning natural energies create high entropy on earth. That is resulting in massive pollution in the environment. Some examples of the pollution effect are changes in biodiversity, climate change, polar ice melting, etc [1]. As the world becomes warmer due to massive amounts of greenhouse gas emissions, the effort to protect the environment become people's concern. Therefore, people are moving to alternative energy sources from natural sources to protect the future of the earth.

However, shifting to other renewable energy sources have been started around a century ago. The most common options are capturing energy from wind, sun, biomass, etc. These sources are not fully capable of managing the overall demand. The output of most of those sources is electrical energy which is deposited in the storage cells. One of the main materials of energy cells is lithium. Due to the high mining of lithium, it is becoming rare in the world. Thus, the current option is either changing the battery design or shifting to other energy sources which can be stored more conveniently way than electricity. In this situation, hydrogen can be a suitable replacement for energy [2].

Hydrogen demand is increasing as a sustainable energy carrier. Hydrogen production has been done in various ways (more information in Table 1). Based on the current scenario, most hydrogen is produced using natural gas which is called gray hydrogen. Following that, there is another technique where hydrogen generates from bituminous and ignites. These types of specific hydrogen are called black and brown hydrogen. However, previous techniques are responsible for emitting carbon dioxide for producing hydrogen. Thus, scientists came up with a new type of hydrogen called blue hydrogen. It is a similar technique to gray hydrogen but the production system will be capable of capturing most of the emitted carbon. It is also called the low-carbon hydrogen production technique. It seems a better option yet natural gas is limited on earth. Therefore, green hydrogen technology has been introduced where hydrogen will produce from water splitting electrolysis process and release oxygen and water into the atmosphere. In such a way, there is no harmful effect on the environment. Currently, green hydrogen projects are going through the research and pilot phase.

Green hydrogen is having high priority in recent years due to zero emission priority. It is currently quite expensive due to the price of electrolysis technology. It is expected to be cost-competitive by 2030. In pre-2023, most counties are taking steps for developing a green hydrogen economy within their system. Some countries such as China, Denmark, Germany, etc. are in leading positions in the manufacturing and utilizing of green hydrogen [3]. For example, China has several green hydrogen plants around the country and they have more than 200 hydrogen refueling stations. Within 2025, China will introduce fifty thousand hydrogen fuel vehicles and reduce their carbon emission by at least 40%. However, Denmark is planning to build a high-capacity electrolysis plant by 2023 and they are planning to use hydrogen as a replacement for natural gas for several years [4]. Moreover, a multinational company called Siemens is working with the German government to produce hydrogen in Germany. Based on the information from last year's hydrogen energy statistics, Siemens is the largest hydrogen manufacturing equipment supplier in Europe [5]. Overall, the demand and investment in green hydrogen are increasing around the world. By 2023, the technology matures will likely be greater standardization of processes and components, which will make it easier to manufacture and maintain the equipment. This will help to reduce costs and increase reliability. Besides, advanced digitalization and automation will play a significant role in boosting the efficiency and capacity of green hydrogen electrolysis technology. These technologies will allow for real-time monitoring and control of the production process, as well as predictive maintenance and fault detection. Overall, while there are certainly challenges to be overcome, there are many reasons to believe that the stability of green hydrogen electrolysis technology will continue to improve in the coming years, paving the way for widespread adoption and use.

To start with the green hydrogen transition, it is required to have a well-planned structure to execute efficiently. The location of the production site needs to be well-designed in such a way that it can fit in the long-term green hydrogen supply chain. The things that need to be considered for the site location are the geographical position, transportation advantage, resource availability, community benefit, etc. Although it is not easy to find a suitable location with all the advantages, decision-makers can select a location with the maximum available advantages. Therefore, site location selection is a prime concern for green hydrogen projects.

However, a stable and scalable supply chain depends on the performance quality of the operation. The green hydrogen supply chain needs to be constructed in such a way that customers can get the best experience with the overall supply chain coordination. The system needs to have a better understanding and strong communication to achieve the success in supply chain. Simulation can be helpful to acknowledge the supply chain before real-life implementation. The shortcoming and issues can be identified easily with a simulation approach which reduces the risk in the actual supply chain. It is also useful for continuous improvement. Thus, it is important to simulate the green hydrogen supply chain in the planning phase of the actual supply chain.

1.2 Problem Statement and Research Scope

This thesis is conducted in collaboration with an engineering consulting company called FDT Ireland. FDT Ireland is a famous company that has experience consulting in biotechnology, food, beverage, pharmaceutical, water, and sustainability. Recently, they got a project to transform a closed coal power plant named Lough Ree. The location of the power plant is the midland of Ireland. The company has seen an opportunity to implement sustainable projects and started to evaluate the opportunities and options for that location. They had come up with a few possible solutions and a green hydrogen facility is one of them. FDT Ireland has noticed the current growth of renewable energy projects. Also, Lough Ree already has some power generation structure. Thus, it is more appropriate to conduct a feasibility study of green hydrogen generation at the Lough Ree power plant.

However, this masters degree major is mostly focused on logistics topics rather than technical topics. Therefore, this thesis will focus on the feasibility of production site location validation and supply chain modeling with performance metric measurement. Yet, there will be some information about the different hydrogen types, green hydrogen, green hydrogen production, and common storage technique in the state of the art. In such a way, the reader will get a better understanding of the aim of the thesis. Although there are some studies available about the supply chain of hydrogen for Ireland, there is no study conducted on green hydrogen supply chain performance metric measurement and site validation. However, FDT Ireland does not have any expertise in green hydrogen. This thesis will be a handbook for them to guide them through the green hydrogen supply chain modeling and production site validation.

1.3 Research Objective and Questions

As hydrogen can be a good alternative and clean energy source, Ireland should focus on implementing a hydrogen facility. This thesis objectives are the production site validation of hydrogen facilities and supply chain performance quality when the supplier is the Lough Ree power plant. The study is divided into two parts. The first part is the comparison between the Lough Ree characteristics with ideal production site characteristics including a discussion about the opportunities in the Lough Ree power plant. The second part will be modeling supply chain models with different scenarios and the performance metric measurement of the supply chain models which will help to decide the suitable model for the green hydrogen supply chain. However, supply chain modeling and performance measurement will be conducted with simulation method and a simulation software called Anylogistix will be used for the process. The performance metrics will be the ELT service level by orders which is a special type of service level for the supply chain. Therefore, the questions that this thesis will answer are as follows,

1. Is the Lough Ree power plant site valid as a green hydrogen production site?
2. Which regions of Ireland are suitable for supplying green hydrogen from the Lough Ree power plant?

2 Literature Review

2.1 Hydrogen

The chemical periodic table starts with hydrogen and it can be utilized in different forms to achieve energy. Hydrogen has colorless, scentless, and highly burnable gas. By weight, it is the lightest component as it requires only two molecules of hydrogen in gaseous form. Thus, hydrogen has a low density in normal environmental conditions. As a result, a massive amount of hydrogen needs to generate a minimum amount of energy.

Hydrogen has the highest power-to-weight ratio (PWR) although the density of hydrogen is quite low. Typically, a liter of gasoline can provide 14KW/h of useable energy whereas hydrogen offers 33.6 KW/h of useable energy per liter. It is around three times more energy. Following that, methene supplies 2.5 times less energy than hydrogen per liter [6]. It is also a similar situation if hydrogen is compared with propane. Therefore, hydrogen can be beneficial compared to other fuels regarding PWR.

2.2 Green Hydrogen

It is previously mentioned that there are color code-based criteria for remaking hydrogen based on how hydrogen is produced. The color code also denotes the possibility of emitting CO2 in hydrogen production. The process and energy source are presented in Table 1. This thesis will be conducted

Table 1: Hydrogen type based on production method and energy source

Color Code	Production method	Energy source
Gray	Steam Reforming	Natural gas
Black	Gasification	Coal
Brown	Gasification	Lignite
Green	Electrolysis	Renewable energy
Blue	Steam generation with carbon capture	Natural gas
Pink	Electrolysis	Nuclear energy
White	Industrial production	As byproduct
Yellow	Electrolysis	Solar Energy
Turquoise	Pyrolysis	Natural gas

based on green hydrogen. Green hydrogen generates from the water electrolysis process with electrical power. That electrical energy should be generated from renewable sources. As the process has zero carbon emission, it is stuck as a green hydrogen process. The difference between green and yellow hydrogen is that yellow hydrogen is made from only solar energy whereas green hydrogen can be produced from both solar and wind energy sources.

As green hydrogen offers clean energy, using green hydrogen can limit global warming agreed in the Paris Agreement's goal (2015) report [7]. According to that report, the most emission has happened in transportation, electrical power generation, industry, and temperature-controlled environment. Those specific sections are responsible for hampering the environment for years by using carbon-based energy sources. Especially, aviation, shipping, concrete, and manufacturing require massive energy and green hydrogen can meet their requirement to decarbonize those sectors.

Green hydrogen has some benefits over other fuels or energy sources. Green hydrogen is manufactured from water and electricity. Thus, it is more convenient to produce rather than mine or filter fossil fuel. Another advantage is storage flexibility. As hydrogen can generate three times more energy than fossil fuel, storing one kg of hydrogen will be more beneficial than storing one kg of fossil fuel. Despite that, large amounts of electrical energy cannot be stored for a longer period. But hydrogen can be stocked in large amounts for longer periods [8].

2.3 Electrolysis Technology

The electrolytic process is popular in industries to refine any pure chemical element with minimum cost. This process also prioritizes the purity of the final product. However, as a chemical element pure hydrogen can be generated from environmental substances by using an electrolytic process. The current demand for green energy increased the necessity of hydrogen in the modern era. As hydrogen-based fuel or energy offers carbon-free emissions, people are trying to adopt the hydrogen-based energy system to reduce their dependence on the fossil fuel-based energy system.

Producing hydrogen fuel by electrolysis process is not an innovation. It was first introduced by Zénobe Gramme in 1869. The main components of the process are two metal electrodes (as anode and cathode), storage with pure water, and electron flow with a small potential difference. First, the two electrodes are placed into the water and the electric circuit is connected to the two electrodes. The electrode connected to the negative point of the electric circuit is called the cathode and the other electrode attached to the positive point is called the anode. When there will be electron flow, the cathode reduces electrons to hydrogen ions in the water and creates hydrogen gas. At the same time, the anode absorbs (oxidization) from water and makes oxygen gas. Both reactions which are expressed in equation form are given below-

Cathode: $2\ H_2O\ (l) + 2e^- \rightarrow H_2\ (g) + 2\ OH^-(aq)$ (reduction)

Anode: $2OH^-(aq) \rightarrow \frac{1}{2} O_2\ (g) + H_2O(l) + 2\ e^-$ (oxidation)

2.3.1 Alkaline Electrolysis Process

There are various types of electrolysis processes are available for producing hydrogen. The Alkaline water electrolysis process is one of those processes. The electrolysis environment requires an alkene-hydroxide-based solution instead of water. The suitable temperature for the process is around 80 to 90 degrees Celsius and the pressure is around 3.2 MPa. The differentiation membrane between the two electrodes is quite thin and made from steel-based material. The construction cost of this process is cheaper than other processes but the operation cost is high. The reasons for costly operation are noble material electrodes, high temperature, and high pressure. To achieve better efficiency in the process, the electrolyzes should be precisely designed. If the electrical energy required for the operation is from renewable sources, then it can be a sustainable way to produce hydrogen [9].

2.3.2 Polymer Electrolyte Membrane Electrolysis Process

Another popular electrolysis process is Polymer electrolyte membrane (PEM). The basic construction of the process is a polymer bar placed between electrodes. The responsibility of the polymer bar is to help conduct protons, separation of output gases and avoid direct conduction between anode and cathode. This process works on high electrical current density compared to the Alkaline electrolysis process. The cost of construction is high but the operation cost is lower than the Alkaline electrolysis process. PEM technology can be operated under different pressure. Thus, it is easy to integrate with renewable energy sources. In spite of those advantages, the life cycle of PEM cells is shorter than Alkaline electrolysis cells [10].

2.3.3 Solid Oxide Electrolysis Process

Solid oxide electrolyzer cells (SOEC) are the latest technology compared to the previous two technologies. The construction is similar to other processes as it required an anode and cathode. The electrodes are made from mixed materials (solid oxide) such as YSZ, ScSZ, LSM, LSCM, etc. It requires a high temperature to operate (over 500 degrees Celsius) [11]. Still, this process operates on less electrical power. Thus, the operation cost is less than PEM. Moreover, the hydrogen production electrical efficiency of this process is

90%. This technology is not available in the market. However, the research on this process is still going on and it will be accessible to the consumer soon. SOEC will be a game changer for the hydrogen production industry.

2.4 Hydrogen Storage

As it is previously mentioned that hydrogen has a low volumetric energy ratio in normal temperature and pressure [12]. This specific nature of hydrogen is responsible for considering economical and efficient storage. The hydrogen-based supply chain requires hydrogen to be used for both stationary and onboard purposes. Stationary storage is more convenient than onboard storage as hydrogen is highly flammable. Thus, hydrogen density has less priority than the volume of stationary storage. For onboard storage, the hydrogen density and volume of the storage both have high priority, especially for transportation [13]. Moreover, other factors such as cost, safety, loading, unloading, operational condition, and entropy are also important for hydrogen storage construction [14,15]. There are some common practices of storing hydrogen which are compressed form, liquid form, cryo-compressed, metal hydrides, etc. These methods are popular in hydrogen supply chain operations.

2.4.1 Compressed Hydrogen Storage

Storing hydrogen as compressed gas is old technology. It is the most convenient for storing hydrogen as it required no extra energy for release [13,16]. But it has some issues such as it requiring a huge pressure which reduces the overall efficiency of hydrogen fuel. Also, the storage material needs to be capable enough to withstand the high pressure and diffusion of gas [17]. As a result, it is quite complex to store compressed hydrogen on board. Also, compressed hydrogen has safety issues. Still, compressed hydrogen storage is commercially used by some vehicle manufacturers [18]. Overall, it is more suitable to store compressed hydrogen in stationary storage. In some cases, hydrogen has been kept underground. In Europe, there is an underground hydrogen storage project called HyUnder where hydrogen is stored in a cave with salt [19].

2.4.2 Liquid Hydrogen Storage

Liquid hydrogen requires more space than the compressed form due to its high density. Also, it required a lower temperature (>-253 Celsius) as it will be solidified in high temperatures. Furthermore, it required a controlled temperature environment. Another disadvantage of the process, the conversion of hydrogen from gas to liquid form creates a loss of hydrogen up to 3% per day [20]. But, it required less pressure, and it can be stored in a thin container. But, the liquefication of hydrogen requires a massive amount of energy which increases the overall cost [21]. This is one of the main reasons to use this technology commercially where the cost factor is ignored. However, some experiments have been done using liquid hydrogen on board [22]. The result of those experiments is not satisfactory due to low temperatures and boil-off cases.

2.4.3 Metal Hydride hydrogen storage

Metal hydrides are the specific type of lattice where hydrogen bonds with metal. In such a way, the original metal lattice increased up to 30% [23,24]. This process can be done by direct reaction or electrochemical deformation of water. Also, it requires a certain amount of energy consumption or release based on formation and deformation. The biggest advantage of metal hydrides is their storage capacity which is less than liquid and compressed hydrogen storage by volume. Moreover, it required moderate temperature and pressure to store the hydrogen [22]. Overall, it is beneficial to use this process for stationary storage. But, hydrogen from metal hydride storage can not be used directly for onboard conditions. Some additional techniques will be required to use this storage system onboard.

2.5 Market Trend of green hydrogen

2.5.1 Green Hydrogen Economy

Hydrogen can be an asset to deal with huge energy demand which leads to planning a green hydrogen economy. Thus, many countries are focusing on the planning of implementation of the green hydrogen economy. Organizations are also considering the impact of hydrogen on their business and pointing out the shape of the future market opportunity. But there are other things to be considered rather than business risks and opportunities. However, A green hydrogen economy is expected to be a well-planned supply chain network. The supply chain plan includes producers, suppliers, consumers, etc. both directly and indirectly. Thus, it is important to evaluate the options of the supply chain to build and green hydrogen economy. Although the hydrogen energy system implementation plan consists of customer demand, production cost, construction of electrolyzers, location of the production site, and structure of the generation plant, this thesis will focus on the location of the production site and supply chain.

2.5.2 Hydrogen Production in the World

Based on the current market view, most hydrogen is produced by burning fossil fuels. Recently, the overall production amount has reached 90 Mt per year. If the production amount is classified based on feedstock, then, most of the hydrogen (around 59%) has produced from natural gas [25]. However, refineries systems produce hydrogen as a by-product around 21% of overall production. Moreover, coal-based hydrogen systems produce 19% of overall hydrogen in the world. Lastly, green hydrogen production is still on a very small scale compared to other hydrogen [25]. Based on the International Energy Agency (IEA) report in 2021, the largest user of hydrogen is the chemical industry and refining sector. They use hydrogen for treatment to remove impurities in the oil. Although hydrogen is used for decades to synthesize methane and ammonia. The chemical industry uses around 89 Mt of hydrogen every year. Other consumption of hydrogen is 18Kt. However, it is mentioned that hydrogen can contribute to the power grid and transportation. Some countries have already built hydrogen-powered transportation maps and power plants to replace fossil fuel uses [26].

2.5.3 Overall Hydrogen Demand

There are some predictions of future hydrogen demand that can be found in a report from the World Energy Council [27]. However, there is also another report published by the hydrogen council and McKinsey & Company which can be considered to discuss the demand from 2023 to 2050 [28]. In addition, another report from Acil Allen company also can be helpful to create the overall scenario of hydrogen demand.

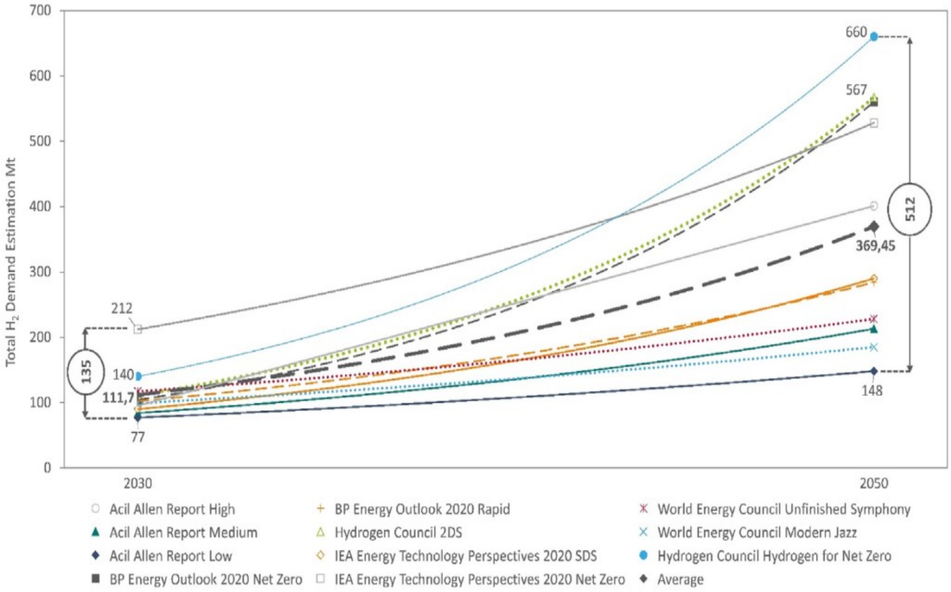


Figure 1: A combination of various studies of annual hydrogen demand in a megaton *(different colors denote each study performer and the timeline is between 2023 and 2050)* [29]

From Figure 1, it is predicted that hydrogen demand will raise from 77 Mt to 212 Mt. It can be seen that the difference between the demand for a certain year is increasing with time. As the different author has used various method and approach for generating data, the prediction becomes quite unsteady with time. However, the prediction in 2023, Hydrogen Council assumed the demand which is nearly twice the IEA prediction. In the report published by IEA, they considered mostly industries [30]. Yet, Hydrogen Council has considered more applications such as power grid and transportation, etc. Usually, demand should be considered with the more possible application rather than some specific sectors. However, these data are considered based on mostly assumption, it will be more appropriate to consider the value of the overall mean demand 110 Mt. Also, the mean value is nearly the current demand of the most authentic report. Although this demand is for overall hydrogen demand, there is no specific information about green hydrogen except the report from the International Renewable Energy Agency (IRENA) and Hydrogen Council. IRENA has predicted that demand will rise from 15 Mt to 95 Mt between 2023 to 2050. On the other hand, Hydrogen Council predicted that the hydrogen demand will rise to 140Mt in 2023, and by 2050, the demand will be 660Mt [30]. This report also indicates the rapid growth of the green hydrogen economy and projects. This is more reasonable to consider as it has considered energy transition and industrial sectors perspective. Altogether, it is quite understandable that the demand for green hydrogen will grow in the future.

To accomplish the target production and predicted demand, the government is working on mapping and strategies. There are around 27 countries have published their hydrogen strategies [28]. Among them, China, America, and Japan have developed a vast plan for the long-term roadmap of hydrogen. Japan even created a 'Hydrogen Society' in 2019 to implement the hydrogen roadmap with the collaboration of academia, industry, and government [31]. Currently, there are new policies about hydrogen is publishing almost every month around the world. However, the global temperature rising rate is 1.5 degree Celsius and world leaders are planning to limit the rate instead of rate increases to 2 degrees Celsius. Thus, the time frame to reach the carbon-free emission target has been set for 2045 instead of 2050. Although most countries have published their plans from 2030 to 2050, they are started working towards initiating more projects with hydrogen. However, hydrogen demand will rise sharply after 2030 based on estimated research [32]. Along with this, green hydrogen demand will also increase as it has the potential to generate hydrogen without carbon emission. Most countries have made their strategies based on all colors of hydrogen and some of them only focus on green hydrogen. Besides that, roadmap from some countries has defined how they will use hydrogen, self-sufficient, importer, and exporter. It is quite a beneficial approach for countries around the world as it will speed up the energy transition.

2.5.4 Hydrogen Demand and Production Projection in Europe

The hydrogen roadmap designed by the EU has made some predictions about renewable and clean hydrogen which indicates green hydrogen. They stated the importance of the water-based water electrolysis process and the energy transition opportunities. The prediction for the production of green hydrogen by the EU is 6GW by 2024 and 40GW by 2030 in overall Europe [33]. They also have a plan to import hydrogen if the production in Europe fails to meet the demand. However, Germany is planning to develop a 5GW electrolyzer system by 2030 and double its capacity by 2024. They estimated the demand for hydrogen in Germany will be 1.6Mt to 1.8Mt by 2030 [34]. That is quite higher than the predicted production. Thus, they are looking for a partner country to import hydrogen. Moreover, the government of Italy is aiming to construct the same capacity green hydrogen production system as Germany. However, the authority has planned to establish a minimum of 5GW electrolyzer to cover 2% of energy demand by 2030 [35]. Following that, Spain is taking steps to install 4GW capacity within 2030 by following the hydrogen roadmap [36]. Besides, Portugal is targeting to implement at least 2-2.5GW of electrolyzer within the targeted year (2030) [37]. In Finland, they are planning to transform their gray hydrogen production into green hydrogen production. They also researched the cost comparison between gray and green hydrogen. The result of the research is green hydrogen will be cheaper. They are predicting that Finland will generate 100 Kt to 150 Kt of hydrogen per year by 2030 [38].

2.5.5 Hydrogen Demand and Production Projection Outside of Europe

Outside of Europe, China is producing the largest share of green hydrogen. Although they made their hydrogen policy based on mixed-color hydrogen, they are highly focused on green hydrogen. The government of China has made a roadmap to establish 100GW of electrolyzers by 2030. Besides, the demand for green hydrogen will rise from 35Mt to 90Mt between 2030 and 2050. The authorities are encouraging people to use hydrogen power vehicles and implementing the hydrogen refueling station plan all over the country [4]. However, Chile has a massive amount of green energy sources. They project that they are capable of running a 1800GW electrolyzer facility. It will produce a large amount of renewable energy which can be utilized for the water electrolysis process. Hence, the cost of green hydrogen will be cheaper. The plan for implementing an initial capacity of 5GW within the next two years. With this amount of capacity, they will generate 360Kt of hydrogen per year. As they are capable of generating cheap hydrogen, they are aiming to become a global supplier of green hydrogen by 2030 [39]. However, New

Zealand built its green hydrogen strategies in 2019 and they use most of their renewable energy to produce green hydrogen. IEA predicted that New Zealand can generate 700Kt hydrogen per year. They can use nearly half of that energy to meet their demand. They can also be an exporter of hydrogen. They also made a deal with Japan and South Korea to export green hydrogen in 2018 [40]. In Africa, Morocco made a draft of generating green hydrogen which is only available in the French language. Morocco is capable of generating vast amounts of solar and wind energy which can be used to generate green hydrogen. They need to develop a proper plan with some generation capacity and generation capability of green hydrogen [41].

2.5.6 Hydrogen Demand and Production Projection in UK and Ireland

The UK also has made a plan to establish 10GW of the hydrogen production facility where 5GW will be for green hydrogen. A government official in the UK has predicted that the hydrogen demand in the UK will be between 147-474 Terawatt hours in 2050. They also have planned to increase green hydrogen production gradually. Along with this, they will also depend on gray and blue hydrogen [42].

Ireland Published their latest hydrogen strategy in 2022. The pathway to zero carbon emission in Ireland is reducing 7% emissions every year from 2021 [43]. Besides that, Ireland has a plan to generate green hydrogen and they will run more research programs and projects on green hydrogen. There was no specific number for demand or production prediction of green hydrogen. Bust researchers from Dublin City University estimated the demand for hydrogen will be 3219 tons per year in 2030 [44]. There is a refinery company and an industrial gas supply company that produces hydrogen for their internal uses and other industries. The industrial gas supply company named BOC supplies green hydrogen to three Bus Éireann hydrogen bus trail programs. Some other companies are applied for permission to install hydrogen facilities but the type of hydrogen was not specified in the report.

2.6 Green Hydrogen Production Site Selection

The implementation of a green hydrogen supply chain starts with selecting suitable production and construction of the plant. Green hydrogen technology is not been vastly produced before. Thus, the overall system of green hydrogen is complex and costly. Therefore, it is very important to select the best location for building production facilities.

Some previous studies have been done about the site selection of green hydrogen production facilities. A study in Algeria has considered two main criteria (economical and technical) for site selection. In economic criteria, they denoted distance from roads, railways, and power transmission networks and the technical equipment cost based on demand and production capacity [45]. Moreover, they also had some analysis of their water resources. Regarding China, researchers have considered natural, technical, and social factors. The natural and technical factors are similar to previous research. They also pointed out that if the production site can be connected to any large hub such as a gas network or railway connection, then it will be cheaper to supply that on-road medium. The social factor has defied from government and public co-operational view [46]. In Turkey, researchers have also analyzed the environment of the site location such as agricultural area, residential area, and designed area [47]. Besides that, some other researcher from Turkey has included socio-economic factors (policy and legal support, community benefit, and social acceptance) in selecting a suitable site for hydrogen production [48]. Following that, there is another study of site selection has done based in Alborz Province, Iran [49]. This study has been done mainly on distance from roads, airports, rivers, urban areas, etc. For this thesis study, the factors like natural resources, social, socio-economical, and environmental will be considered to conduct a site feasibility study for midland Ireland. As the path of the thesis will mostly focus on supply chain design and key indicator measurement, the technical factor of site location will not be discussed in detail.

2.7 General Supply Chain Design and their Limitations

Previously, researchers have done some supply chain modeling of the green hydrogen economy. Two researchers in 2014 performed an exploration of structural inspection of the general hydrogen logistics management. They also studied the pathway from production to end user of hydrogen. That study provides a logical view of a supply chain in many different structures [50]. The best way to approach the supply chain is by analyzing different options to settle on the most optimized path. However, another study has been performed on the cost optimization of the technological component in the supply chain. The authors have explained the cost structure which helps budget a supply chain [51]. But there were no findings about the quality of the supply chain in those studies.

Moreover, a research study has been done based on modeling the supply chain of hydrogen in the UK which contents with different model optimization, cost planning, and environmental factor [52]. That paper has minimum information about uncertainties in the supply chain but has not discussed and solution. However, another study was conducted on an approach to solve the hydrogen supply chain model and discussed three optimized approaches: cost, safety, and carbon emission level [53]. They also have not discussed the performance of the supply chain.

Some research also has been done some researches based on the Irish green hydrogen economy planning [54,55]. Yet, those studies have not shared any findings on the quality or performance level of the green hydrogen supply chain in Ireland.

2.8 Supply Chain Performance Metrics

Supply chain performance metrics are essential for measuring and evaluating the efficiency and effectiveness of supply chain operations. Performance metrics help organizations measure how well they are doing in various aspects of the supply chain, including delivery time, inventory turnover, and order accuracy. By tracking these metrics over time, decision-makers can identify areas where they are excelling and areas where they need to improve. Besides, performance metrics can also help organizations monitor the performance of their suppliers. By tracking metrics like delivery time and order accuracy, projects can identify which suppliers are performing well and which ones need improvement. Finally, performance metrics can be used to benchmark a project's performance against industry standards. By comparing their performance to other competitors in the same industry (for example, hydrogen over other energy sources), managers can identify areas where they are falling behind and take steps to catch up. This can help organizations make informed decisions about which suppliers to work with in the future. A variety of performance metrics have been developed in the literature, including service level, safety stock, on-time delivery, and supply chain costs.

2.8.1 Safety Stock

Safety stock is a term used in supply chain management to describe the extra inventory held to protect against uncertainties in demand and lead time. It is an essential component of inventory management and is used to ensure that there is always enough inventory on hand to meet customer demand [56]. The amount of safety stock needed depends on several factors, including lead time variability, demand variability, and the desired service level. Accurately calculating safety stock levels can be challenging, as it requires a detailed understanding of demand and supply variability. There are a variety of methods for calculating safety stock levels, including using statistical models, simulation, and heuristic approaches [57]. Safety stock can have a significant impact on supply chain performance and profitability, as it affects inventory holding costs and stockout risk.

2.8.2 On-time Delivery

On-time delivery calculates the percentage of orders that are shipped to customers on or before the agreed deadline. On-time delivery is an important metric because it reflects the potential of a company to fulfill customer demand to manage its supply chain operations effectively. Measuring on-time delivery performance involves comparing the actual delivery date of orders with the promised delivery date [58]. A company can track on-time delivery performance using various methods such as customer surveys, order tracking systems, and performance dashboards. On-time delivery performance can have a significant impact on customer satisfaction, repeat business, and overall profitability. Decision-makers who consistently meet or exceed customer expectations for on-time delivery are more likely to retain customers and gain a competitive advantage in the marketplace [59]. Overall, on-time delivery is a critical performance metric in supply chain management, and companies should strive to continuously improve their on-time delivery performance to meet customer expectations and enhance their competitive advantage.

2.8.3 Supply Chain Cost

Supply chain cost is associated with all activities involved in the production and delivery of goods or services, including raw materials, labor, transportation, and inventory holding costs. Measuring supply chain cost performance involves tracking and analyzing all costs associated with the supply chain operations, such as procurement, production, transportation, warehousing, and distribution. Managers can use various methods such as cost accounting systems, activity-based costing, and cost-benefit analysis to measure supply chain cost performance. Supply chain cost performance is critical because it directly impacts a company's profitability, cash flow, and financial performance. By optimizing their supply chain costs, organizations can improve their competitive position, increase their profitability, and enhance their long-term sustainability. However, lean and green supply chain practices can lead to cost reductions and improved supply chain performance [60]. As cost efficiency is positively related to supply chain performance, it increases customer satisfaction and profitability. Therefore, supply chain cost is a critical performance metric in supply chain management, and companies should strive to continuously improve their cost performance to optimize their operations and enhance their overall supply chain performance.

2.8.4 Service Level

Service level is an important performance metric for supply chain management. It measures the ability of a company to meet customer demand by ensuring that orders are delivered on time. A high service level can help companies improve customer satisfaction, increase sales, and maintain a competitive edge in the market. Several studies have investigated the factors that affect service levels in supply chains. Researchers have found that inventory management practices, such as safety stock and order quantity, have a significant impact on service level [61]. Besides that, service level transportation mode and delivery lead time can also affect service level [62]. In addition to these factors, several other factors can impact service level, such as order processing time, production lead time, and supplier reliability. Improving supply chain visibility, implementing lean manufacturing practices, and using advanced analytics and technology to optimize inventory and production planning. Current studies prove that advanced analytics and simulation tools can significantly improve service levels in supply chains [63].

Lead time is another important metric of the supply chain and it helps to define the service level more efficiently. Lead time is the cycle time from order to delivery of the product. It can explain the more responsive and exact measurement of supply chain performance. The service level combined with the actual lead time is called the estimated lead time service level or ELT service level. ELT service level can be defined as-

$$\text{ELT service level} = \frac{Number\ or\ product\ or\ value\ of\ on\ time\ order}{number\ or\ product\ or\ value\ of\ outgoing\ order} \qquad \text{(i)}$$

ELT service level can be measured for orders or products or revenue. When the ratio is taken for the number of orders, it measures the percentage of on-time orders to the overall outgoing orders. Similarly, it calculates the ratio of product and revenue. The values are mostly calculated in percentages.

2.9 Performance Metric Selection

The performance metric called service level for the green hydrogen supply chain is crucial for several reasons. It provides insights into customer satisfaction, helps differentiate from competitors, mitigates disruption risks, facilitates accurate inventory planning, and ensures the effective design of the supply chain. Prioritizing service level over other performance indicators allows for better adaptation to customer expectations, market trends, and demand uncertainty, leading to a successful and efficient green hydrogen supply chain implementation. while traditional service level measures the demand fulfilled within a given time frame, it fails to consider the lead time, which can impact customer satisfaction. The Estimated Lead Time (ELT) service level, on the other hand, takes into account the lead time and provides insights into inventory levels, safety stock, and bottlenecks affecting system performance. Measuring ELT service level can lead to increased customer satisfaction, cost reduction, and improved profitability. It is more beneficial to measure ELT service level by orders rather than by product or revenue, as it accurately captures variations in lead time for individual orders. Therefore, in this study, ELT service level by orders will be used as the metric for measuring the performance of the green hydrogen supply chain.

2.10 Supply Chain Simulation Approaches and Effect of Performance Metrics

Simulation of supply chain models can be a powerful tool for optimizing supply chain operations and improving performance. The process starts with creating a simulation model in software considering different simulation techniques. The model includes different supply chain components such as suppliers, distribution centers, routes, modes of transportation, product, etc. Following that, sample data are used for different components of the supply chain. Then, the different conditions are determined for the model which can provide different scenarios of the supply chain. The next step is executing the simulation process and collecting data for analysis. Finally, the model will be updated and improved based on data analysis. It is a continuous process and it can help to build a proper supply chain model instead of investing in the actual model. Several simulation approaches are commonly practiced for analyzing supply chains. Those are also used for measuring service levels and ELT service level by orders. A summary of different simulation approaches for performance measurement is documented in Table 2. However, there are very few research papers available on ELT service level by orders measurement. Thus, literature has been performed on both service level and ELT service level by orders measurement to get an idea of most simulation approaches.

Table 2: Summary of the previous work on measuring the service level and ELT service level of the green hydrogen supply chain

Reference no.	Simulation technique	Affecting factors on supply chain performance
[64], [65],[66]	Discrete event simulation	Agreements, demand, safety stock, system delay
[67]	System dynamic simulation	Policies and demand uncertainty
[68],[69]	Agent-based simulation	Government policy
[70]	Hybrid simulation	Natural disasters, accidents
[71]	Monte Carlo simulation	Cost, reliability, and environmental impact

The most popular simulation approaches are discrete event simulation, agent-based simulation, system dynamic simulation, hybrid simulation, Monte Carlo simulation, etc.

2.10.1 Discrete Event Simulation

Discrete event simulation (DES) is a simulation approach that is used to design a simulation model in which events occur at discrete points for a specific period. Generally, this type of simulation model represents a set of interconnected components or modules, and events trigger changes in the state of the system. DES is commonly used in modeling manufacturing, logistics, and service systems. Research has investigated the impact of lead time variability on the performance of a hydrogen supply chain [64]. The authors used a discrete event simulation model to evaluate the performance of the supply chain under different lead time scenarios and found that ELT service level by orders was a useful performance indicator for assessing the impact of lead time variability on system performance. Besides, a group of other researchers used a discrete event simulation model to analyze the performance of a hydrogen refueling station under different operating conditions [65]. The authors used ELT service level by orders as a performance indicator to evaluate the impact of different factors, such as queue length, safety stock, and customer demand, on system performance. In another study, the authors investigated the impact of logistics and operational factors on the performance of a hydrogen supply chain [66]. The authors used a discrete event simulation model to evaluate the performance of the supply chain under different scenarios and used ELT service level by orders as a performance indicator to assess the impact of delays in delivery on system performance.

2.10.2 System Dynamic Simulation

It is a technique used to model systems in which feedback loops exist. The system is represented as a set of stocks and flows, and feedback loops are used to model the dynamics of the system. System Dynamic Simulation (SDS) is commonly used in modeling economic, environmental, and social systems. Some researchers developed an SDS model to evaluate the impact of demand uncertainty on the green hydrogen supply chain's performance [67]. The model was used to identify the optimal inventory policies for different levels of demand uncertainty. The results showed that inventory policies that took into account demand uncertainty led to better performance and reduced risk of stockouts.

2.10.3 Agent-based Simulation

This simulation is also known as ABS. ABS is a technique used to model systems in which agents interact with each other and the environment. The system is represented as a set of autonomous agents that have their behaviors and decision-making processes. ABS is commonly used in modeling social and ecological systems. A study has been done with the agent-based simulation model to analyze the service level and cost analysis of a green hydrogen supply chain in China [68]. The output of the study showed that government policy interventions can improve the performance and cost structure of the supply chain. In another study, an agent-based simulation model has been developed to study the integration of renewable energy sources in green hydrogen supply chains [69]. The authors use the simulation model to analyze the impact of renewable energy integration on service levels and evaluate different supply chain strategies. They highlight the importance of accurate service level measurement in evaluating the performance of green hydrogen supply chains and provide recommendations for improving service levels through coordinated decision-making among different agents.

2.10.4 Hybrid Simulation

Hybrid simulation approaches combine two or more simulation techniques to model complex systems. For instance, combining DES and SDS techniques can be used to model systems that have both discrete events and feedback loops. A study with the hybrid simulation risk assessment model for the green hydrogen supply chain has incorporated various risk factors, including natural disasters, accidents, and supply chain disruptions [70]. The model was used to identify the most critical risk factors and develop risk mitigation strategies.

2.10.5 Monte Carlo Simulation

Monte Carlo simulation is a complex and widely used simulation technique that involves generating multiple random samples of input parameters to simulate the behavior of a system or process. It is quite complex and used for the evaluation of the effect of certain changes in the supply chain. A study has proposed an improved model with various objectives to design a green hydrogen logistic management network under variable conditions [71]. The authors used a genetic algorithm coupled with Monte Carlo simulation to generate a group of multi-objective optimization scenarios that provide a relationship between cost, reliability, and the effect of natural disasters. The conclusion of the study showed that the improved model can be used to design a logistic network and it can point out the investment opportunities that can significantly improve the supply chain's reliability.

2.10.6 Sensitivity Analysis of Hydrogen Supply Chain

Sensitivity analysis is commonly known as the effect on output based on input variable variation [72]. It is one of the approaches for understanding the supply chain model behavior and the robustness of the analysis. There are a few parameters considered for sensitivity analysis which are demand, cost, adaptability, uncertainty, etc [73]. Among them, demand is considered the most important parameter in the hydrogen supply chain [74]. The demand parameter is quite helpful for scenario analysis. It is highly used for hydrogen market research and new supply chain planning [75]. Thus, demand variation sensitivity analysis will be an important tool for green hydrogen supply chain modeling.

3 Methodology

3.1 Methodology Overview

Based on the research questions, the thesis has been divided into two parts. The first part will be a site feasibility study of the Lough Ree power plant. The second part will be green supply chain modeling and analyzed with performance metric measurement when Lough Ree is considered the main green hydrogen production site.

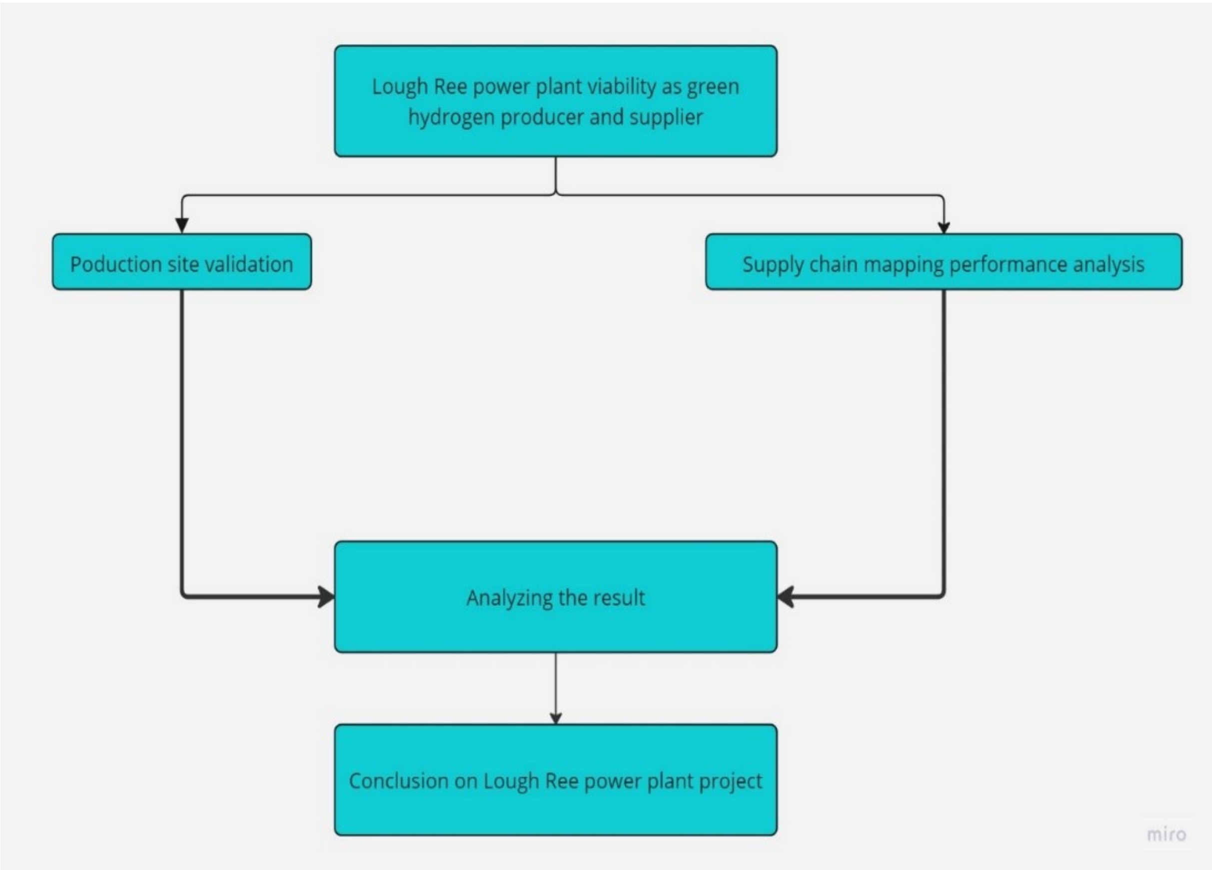


Figure 2: Diagram of the thesis methodology (*the study will focus on production site validation for green hydrogen and supply chain performance analysis based on certain characteristics*)

3.2 Location Validation Methodology

As it is previously mentioned that it will be a validation study. The study will be a comparison-based discussion between Lough Ree site characteristics and standard site characteristics.

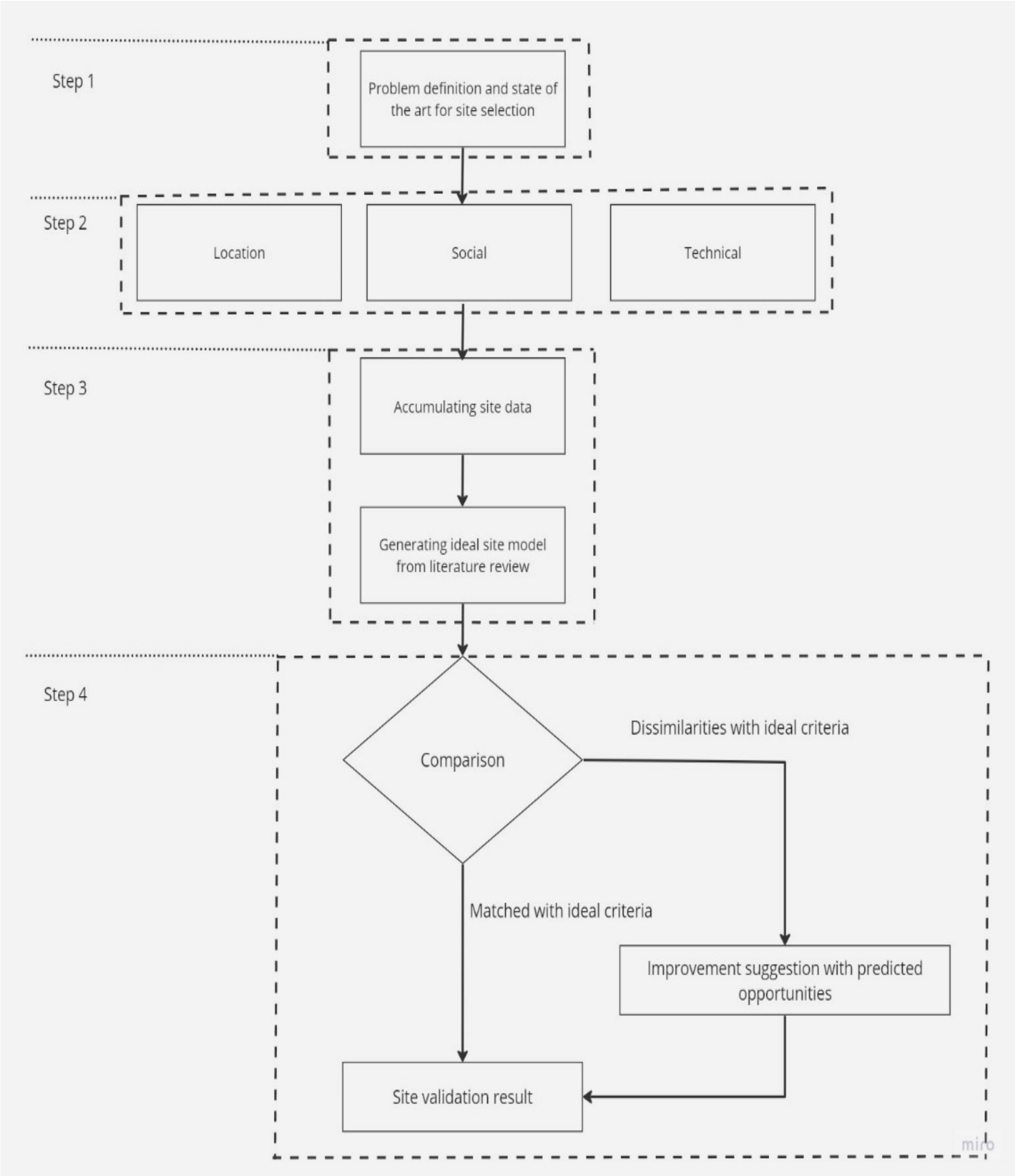


Figure 3: Implementation plan for location validation (*the comparison will be done based on various sections of three main factors*)

Step 1: The target of the validation study is verifying the site location in a structured way. At the beginning of the validation study, the primary goal is to understand the core approaches of the study. Therefore, a literature review has been done in section 2.6. However, the validation study is a minor part of the overall study. Thus, this study will be done based on comparison rather than technical approaches such as MCDM, mathematical modeling, etc. During the literature review, some scopes of the feasibility study have been found which are economical, site placement, social, GIS, technical and environmental, etc. Analyzing the amount of information available for the Lough Ree power plant, the site placement/location, and social and technical scope are selected for the site validation study.

Step 2: The next step is analyzing the deep of the selected scope criteria and sub-criteria. There are three main sub-criteria has been selected which are location factor, social factor, and technical factor. For example, site location criteria consist of distance from road, waterbody, etc. All the criteria and sub-criteria are presented in Figure 6 (chapter 4). The structure of the criteria is designed from various previous studies and selected based on the relatable information on the study site.

Step 3: This step is making the framework for the comparison study. The available data of the Lough Ree site are accumulated and categorized for comparison study. Similarly, ideal site characteristics are documented in Table 7 (chapter 4). These ideal characteristics will be compared in the study site characteristics which will be done in the next chapter.

Step 4: In this step, the comparison will be done based on selected criteria (section 4.3). If the characteristics of the study site match with the ideal site, it will provide a positive result in the conclusion of the validation study. If some characteristics are failed to meet the ideal site properties, then possible improvements for the study site will be highlighted with future opportunity scopes (section 5.1).

3.3 Supply Chain Modelling Methodology

To answer the second question of the thesis, a supply chain of green hydrogen will be designed from the Lough Ree power plant for different regions in Ireland. Then, it will be simulated for various conditions.

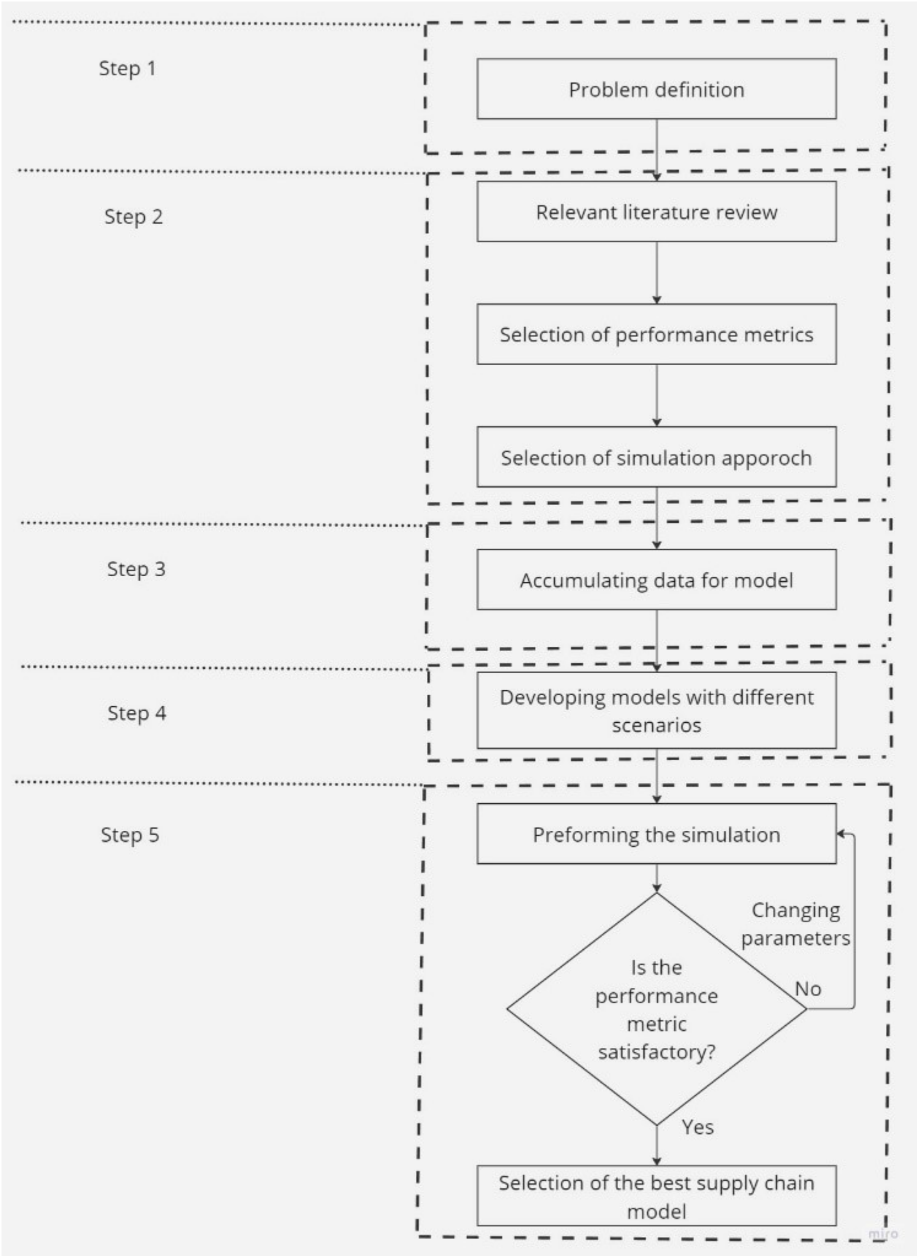


Figure 4: Implementation plan for supply chain key performance metric measurement (*this section will be done in five steps and the finding will depend on different scenarios and parameters*)

Step 1: This step is defining the goal and aim of the simulation study. The goal of the simulation study has been defined in chapter one. The simulation study aims to find the best supply chain model of the green hydrogen supply chain when the production site is the Lough Ree power plant.

Step 2: This step has been done in chapter two. In this step, the state of the art has been on green hydrogen production, storage, and demand. These insights have provided some overview of green hydrogen and steps taken by counties around the world to implement a green hydrogen economy. Following that, there are some findings have been explained to understand the supply chain key metrics in section 2.8, and a literature review has been done on five different supply chain simulation approaches in section 2.10.

To answer the research question, a simulation model approach is required which is flexible and capable of analyzing different scenarios in dynamic conditions. DES allows to implementation of complex systems and offers various interaction input options. Thus, single input can change the entire system which is desirable to observe the dynamic impact of the supply chain. Besides, DES modification is quite simple and easy. Therefore, it is suitable for new products or policies. However, it also offers detailed information about any changes in the supply chain. Finally, DES can be used to simulate different scenarios and assess the impact of those effects on the system. Thus, DES can be a powerful tool to model and analyze the green supply chain for this study.

Step 3: This step will be explained in chapter three. This step starts with accumulating data for the simulation. The major data for the experiment was the demand for individual areas in Ireland. As there was no exact demand data about green hydrogen, demands are projected from the historical data on the consumption of natural gas. Besides that, some other data such as generation capacity and cost are taken from the additional data of the project.

Step 4: This step consists of developing the simulation model with various scenarios. The primary simulation model will be based on the whole of Ireland. After that, the models will be generated based on small groups of counties to justify different angle views of the green supply chain. This approach will be helpful to get more deep study of the green hydrogen supply chain. A demand variation sensitivity analysis will be performed in this step to understand the effect of demand uncertainty. As this step is a part of the implementation, it will be found in chapter four (section 4.4).

Step 5: The last step of the study is generating different scenarios and simulating them with different levels of safety stock. For every run of the simulations, the ELT service level by orders will be observed. The model with the best service level will be considered the desired model for the study with specific parameters. The simulation will be performed in chapter four (section 4.5) and the final discussion will be documented in chapter five (section 5.2).

3.4 Introduction of the Simulation Software (Anylogistix)

Anylogistix is a supply chain logistic simulator and it is used by many companies around the world. It can be used for designing the supply chain network with various components and optimizing different parameters of a supply chain. It is a simple software with an easy interface where users do not need to deal with complex equations and formulas. With just a few clicks, the users will get the desired information about their needs.

Working principle

The supply chain model works based on both qualitative and quantitative analysis. Simulation modestly provides decisions on quantitative parts. The first step for the software is collecting data and constraints. The next step is converting the problem into a mathematical problem. When the model is developed, it will be solved by the existing algorithm or simulation techniques. The final step is providing the result with possible suggestions for different scenarios. Anylogistix uses CPLEX which is a professional solver tool. It is capable of solving liner problems and mix integer problems. An example of solving a problem can be finding a suitable factory location. The first step is inputting the customer location, demand, and quantity. In the next step, it will take more data such as cost and period, etc. and when the model has sufficient data it will convert into a mathematical problem. Then, it will perform network analysis and simulation and will provide the result.

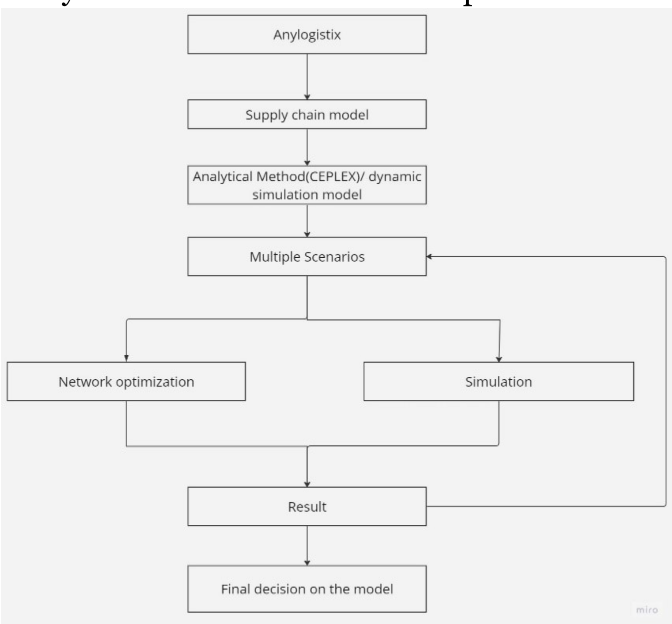


Figure 5: Analytical and Simulation Methods in AnyLogistix (*it works based on the iteration process and makes the best possible solution for the simulation model*)

3.5 Case Studies on Lough Ree Power Plant

The case studies on this project have some information that can be helpful to answer the second research question. Previously, the project will mainly focus on producing hydrogen from electrolysis and steam methane reforming (carbon capture utilization and storage can be an optional feature). The aim for storing and distributing hydrogen is in 3 different forms. Hydrogen can be kept as gas by compassing under certain temperatures and pressure. Another option is storing hydrogen as a cryogenic liquid in extremely cold temperatures. Lastly, hydrogen can be chemically transformed and it can be stored in liquid tanks. The final application of hydrogen will be mostly the replacement of gas in appliances, industrial feedstock, and fuel cells. However, the transportation sector is responsible for emitting more carbon than other sector. Therefore, a pilot project can be initiated by transforming the transportation sector with a hydrogen-based fuel system.

3.5.1 Advantages of the location

The authority can use the expertise from previous coal power plant for developing the infrastructure in the Lough Ree power plant. They can source renewable electricity from the nearby wind farm or the proposed wind farm. However, there are some industries near the proposed location. Hydrogen can be used to fuel up industrial trucks. It also can be used as a replacement for industrial oil for heating. Hydrogen can be fed up to 20% into the gas network near Athlone. Lastly, the location has good accessibility.

3.5.2 Targeted consumers

Long-route trucks are one of the targeted sections for feeding hydrogen. There is a significant haulage industry in the region, with numerous fleets of different sizes located near Lanesboro (e.g., DPD trucking fleet of 120 in Athlone). Hydrogen is a better replacement for electricity. The batteries require a long time to charge. The electrical energy-based engine has poor milage and low payload capacity. Hydrogen can reduce all those issues and offers an efficient experience in the supply chain.

However, there is no direct gas line in the heart of Roscommon and Longford counties. Therefore, industries need to depend on heavy heating fuel for heating. This chemical is not only less efficient but also quite risky to use. Hydrogen can be used for heating in those industries. Some examples of using hydrogen for heating have been seen around the world. For example, The HyNet Industrial Fuel Switching Project is currently testing the firing of hydrogen in various blends up to 100% for industrial gas boilers in North West England and SAACKE also operates several hydrogen-fired industrial turbines and boilers around the world.

3.5.2 Cost and generation capacity projection

Cost and generation capacity projection is calculated based on different scenarios. The two main scenarios are estimated before 2030 and one of them is post 2030. The overall projection is documented in Table 3.

Table 3: Cost and capacity projection of the Lough Ree power plant [76]

Renewable energy	Scenario	Hydrogen Demand(kg)	ELectrolyzer capacity (MWs)	Production cost(max)	Production cost(min)	Transportation cost
70% renewable energy	Transportation (50 trucks)	400,000	2.5	€3.00/kg	€4.80/kg	€0.40/kg
	Industrial heat (50% fuel usage)	1,800,000	11	€2.70/kg	€4.50/kg	€0.30/kg
	National grid injection (20% blend /vol)	21,000,000	125	€2.40/kg	€4.20/kg	N/A**
100% renewable energy	Wind farm (Sliabh Bawn 58MW)	400,000	3	€2.70/kg	-----	-----
100% renewable energy (post-2030)	Transport (100 Trucks)	960,000	52	€2.50/kg	€4.30/kg	€0.40/kg
	Industrial heat (100% FO Usage)	3,600,000				
	Local grid injection (100% H2 Grid)	4,300,000				

**Given this scale, a dedicated hydrogen pipeline would be built from Lanesboro to Athlone

3.6 Data Selection and Generation

To perform the thesis experiment, it is required to have some data for building the simulation model. But there is no exact data for green hydrogen in Ireland. There are some projected values of overall demand and production capacity. In the supply chain, only overall country data is not enough. It is necessary to have some data about the production site, distribution center, and customer. Regarding those specific elements, the model needs data about demand, inventory policy, cost structure, and production capacity. Cost structure and capacity are projected by the project team. More details of the simulation model construction will be explained in the next chapter.

To assume the demand of every county in Ireland, the value of gas consumption is considered from both the residential and non-residential sectors. It is more appropriate to relate gas with green hydrogen as natural gas use can be replaceable by green hydrogen. However, gas consumption data is taken from the website called www.cso.ie. This website is run by the central statistics office of Ireland.

The first approach for data selection was figuring out the latest data on consumption in both residential and nonresidential sectors. The latest data on the website was from 2021. There is also an issue with the data of Donegal, Leitrim, and Sligo. As there is no gas network in that area, there is no data on gas use in the central statistics of Ireland. Thus, uses of those places are assumed baes on their population. Then, the consumption of the uses for every county is converted into a percentage of the total consumption. Finally. The percentages of every county are applied to the assumed hydrogen demand which results in the assumption of the individual country hydrogen demand in Ireland.

Table 4: Mean consumption of gas in every county in Ireland (in 2021)

County	Uses of Gas in Kw/h	Percentage
Carlow	7,379	1.024%
Cavan	1,751	0.243%
Clare	5,335	0.740%
Cork	88,652	12.300%
Donegal	100	0.014%
Dublin	415,426	57.640%
Galway	7,950	1.103%
Kerry	77	0.011%
Kildare	36,847	5.112%
Kilkenny	7,643	1.060%
Laois	8,390	1.164%
Leitrim	80	0.011%
Limerick	28,236	3.918%
Longford	15	0.002%
Louth	25,786	3.578%
Mayo	1,373	0.191%
Meath	27,879	3.868%
Monaghan	1,399	0.194%
Offaly	1,978	0.274%
Roscommon	83	0.012%
Sligo	90	0.012%
Tipperary	8,549	1.186%
Waterford	18,488	2.565%
Westmeath	4,059	0.563%
Wexford	81	0.011%
Wicklow	23,083	3.203%
Total	720,729	100.000%

Table 5: Assumption of mean hydrogen demand of every county in Ireland

County	Demand for hydrogen in kgs
Carlow	32956.91
Cavan	7820.51
Clare	23827.77
Cork	395947.42
Donegal	446.63
Dublin	1855421.79
Galway	35507.17
Kerry	343.91
Kildare	164570.17
Kilkenny	34136.02
Laois	37472.35
Leitrim	357.30
Limerick	126110.76
Longford	66.99
Louth	115168.30
Mayo	6132.25
Meath	124516.29
Monaghan	6248.37
Offaly	8834.36
Roscommon	370.70
Sligo	401.97
Tipperary	38182.49
Waterford	82573.16
Westmeath	18128.76
Wexford	361.77
Wicklow	103095.86
Total	3219000

Instead of gas user data, demand can be projected from fuel consumption data. But gas user data are more appropriate as some industries are using hydrogen for heating by replacing gas. Although there is a pilot project on hydrogen buses, industries consume more hydrogen than the transport section. Besides, the gas heating system in the household can be replaced by hydrogen. Thus, gas data will provide more accurate insights than fuel data.

4 Implementation and Result

4.1 Site Validation Criteria and Sub-criteria

As previously mentioned in the implementation plan a model needs to be developed to perform the site validation. After going through the previous work of the researchers a hydride model has been implemented. It was the second step of the implementation plan. The model is represented in Figure 6.

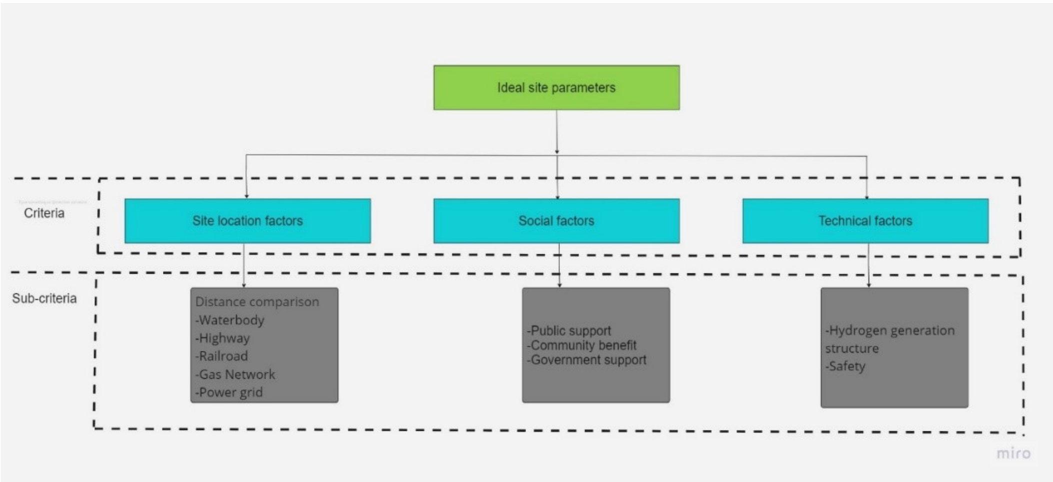


Figure 6: Criteria and sub-criteria for validation study (*each section will be used to compare with Lough Ree site data*)

Major three criteria are already explained in the state of the art. However, green hydrogen production sites need to have certain location-wise advantages for production and supply chain. Thus, distance from different places such as waterbody, highways, power grids, etc. has been considered for the study. Besides, data for those ranges are also available for the Lough Ree site. Following that, social factors such as public and government support, benefits, etc. should be considered to build a new plant and Lough Ree power plant circumstances can be relatable to those sub-criteria. Lastly, some technical factors are also discussed to get a more concrete idea about site validation.

4.2 Ideal Site Model

To continue with the site validation study, it is needed to develop an ideal site model. This is the third step of the implementation plan. An ideal site characteristic has been documented in Table 6. It is a hydride model state of the art.

Table 6: Ideal hydrogen site features [43,48,49]

Factors	Sub-factors	Value/ Status
Site location factor	Distance from water-body	<1000m
	Distance from highway	<=500m
	Distance from railroad	<=500m
	Distance from the gas network	<=1500m
	Distance from the power grid	<=1000m
	Distance from the wind farm	<=500m
Social factor	Public support	Highly important
	Community benefit	Engaging more locals in operation
	Government support	Needed for transition
Technical factor	Hydrogen generation structure	Depending on cost
	Safety	Highly important

This framework will be used to examine the circumstance of the Lough Ree power plant to be a green hydrogen power plant.

4.3 Site Validation Implementation

It is the final step of the site validation where Lough Ree power plant data will be compared with the ideal site data.

4.3.1 Description of Lough Ree power plant

Lough Ree region is an area surrounded by a lake in midland Ireland that is commonly placed between county Longford and county Roscommon. The lake is one of the major branches of the River Shannon. Based on the name of the lake the area around the lake is called Laugh Ree region. The Lough Ree power plant is on the bank of the lake and is placed on the border of two counties. The power plant was operated with coal. The power generation capacity of the plant was 100MW. The coal power plant principle is burning coal to generate steam which will flow on the turbine. When the turbine starts to rotate, it generates electrical power. However, the plant was connected to the national grid. Due to burning coal, a massive amount of carbon was released into the environment, and the authority planned to stop the Laugh Ree power plant in December 2020. It was a great initiative towards protecting the environment. But it affected the people around the area. As most people's livelihoods depended directly or indirectly on that power plant. Thus, the power plant has some pre-existing potential and opportunities which will be discussed in the flowing sub-sections.

4.3.2 Site location factors

As it is previously mentioned that the site is near a lake, which will be a big advantage for green hydrogen production. A report from Environmental Protection Agency concluded that the water from the site location has no issues with high contamination or high ppm (particle per meter) [77]. Thus, it will not be required to use an expensive filter to prepare the water from the lake to produce hydrogen. However, the distance from the lake to the site is around 800m. Thus, it can be considered that the site is suitable in terms of the availability of water.

In terms of transportation, the Lough Ree power plant is around 220 meters away from N63 main highway. However, a study suggested that hydrogen production facilities should be located within a 500-meter distance from the main highway [78]. Therefore, Laugh Ree has the advantage of easy transportation access.

However, rail communication is also important for the hydrogen production site. The ideal distance between the rail communication line and the production site should be not more than 1km [49]. But, the nearest railway station to Laugh Ree station is Roscommon which is 17km away. Moreover, Longford station is nearly the same distance as Roscommon from the site. But the Longford station is the geographically more suitable position to become a common hub for supplying hydrogen. A common hydrogen refueling station can be developed in the Longford and a pipeline can be developed from the site to that common hub. It will be costly but it will be beneficial for the long-term goal.

Besides, the production site should have a minimum distance of accessibility to the power grid and gas network. As it was a coal power station, it had easy access to the power grid. But the main gas pipeline is nearly 20km away from the production site. The main gas pipeline is in Athlone and thus it will be required to build a network from the production site. It can be beneficial in the same way as like rail communication plan.

Finally, the green electricity generation site needs to be located near the green hydrogen production site. The nearest wind firm (Sliabh Bawn) is about 14 Km away. But it was previously mentioned that a certain amount of wind power in Ireland is not utilized every year. Thus, a transmission line can be developed from that renewable energy site that can supply electricity to produce green hydrogen.

4.3.3 Social factor

Laugh Ree power plant was operated for more than half of the decade to produce electricity. Most of the people around the Laugh Ree region were directly or indirectly involved with this power plant. Due to the end of the operation, a huge amount of people lost their jobs and were out of their business. Thus, the new project in Laugh Ree will create new jobs and businesses that will benefit the community. However, it is a key requirement to get public acceptance of a new site [47]. Laugh Ree is an old power plant and it has a reputation in the community. It will be easier to introduce the new project to the community.

Governmental support is another important factor for green hydrogen production. The Irish authority has initiated some necessary steps to increase the production of green hydrogen [43]. Among those initiatives, Shannon Estuary Economic Taskforce is one of them. The purpose of the task force is to analyze the potential of wind power from the Estuary region which is 25km from the Lough Ree power plant. It will boost the planning and production of green hydrogen. However, there are no specific places that have mentioned green hydrogen production sites in the policy but the government is highly interested in developing production sites in the country. Thus, it will be massive support from the government to transform Laugh Ree into a green hydrogen production site.

4.3.4 Technical Factor

The major equipment of green hydrogen production is electrolyzers. As it is a new project, infrastructure investment will be costly. But coal power plant also requires clean water to operate. Therefore, the water filters are already in the existing structure of the Laugh Ree. A couple of powerful electrolyzers can be installed to start the green hydrogen project. The investment in infrastructure will be returned with profit over the years [48].

Another technical factor is safety. As hydrogen is highly flammable, it should be handled appropriately. In coal power plants, coal is burned to achieve energy. Thus, there are some fire protection facilities available in Laugh Ree. Investment in safety features will be cheaper than a new site in the Laugh Ree power plant.

4.4 Supply Chain Modelling

4.4.1 Initial Modeling

To answer the second research question of the thesis, the first three steps of the implementation plan are completed in the previous chapters. This section will be an overview of supply chain modeling for green hydrogen.

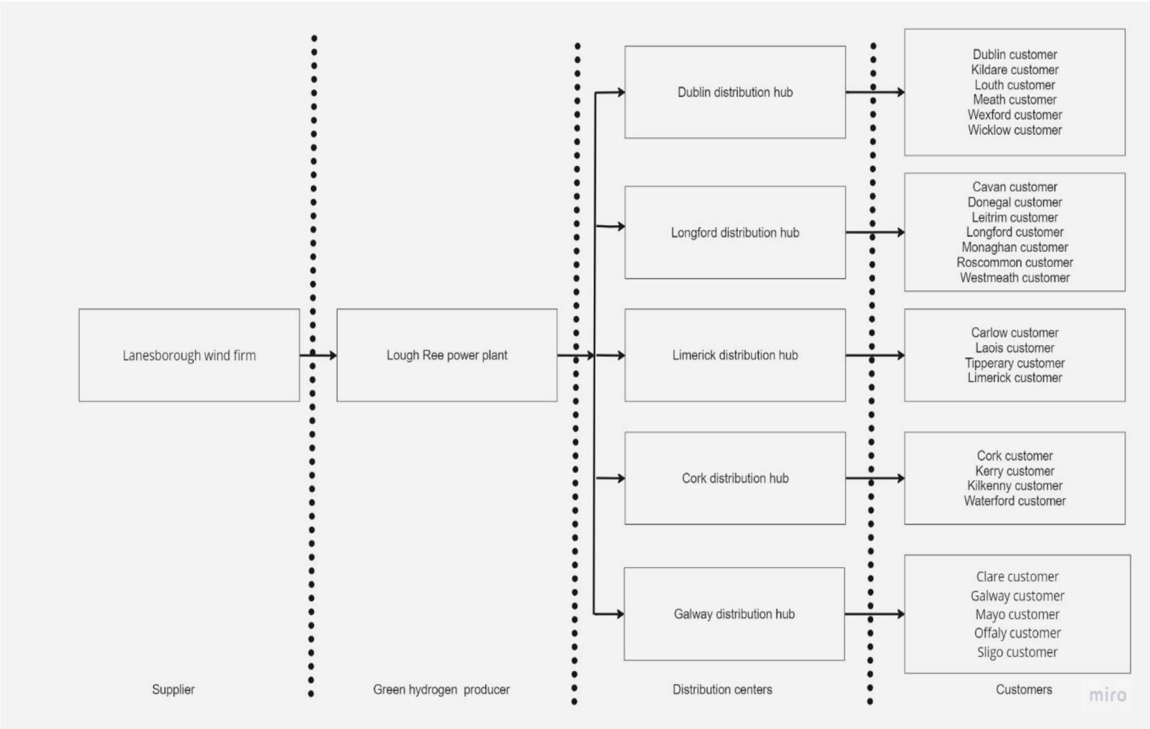


Figure 7: Primary model of the supply chain of green hydrogen (*this plan is constructed to supply green hydrogen all over the Ireland from Lough Ree power plant*)

In Figure 7, the main model of the supply chain has been drawn. The supply chain has divided into four main participants which are the supplier, producer/factory, distributor/ distribution center, and customer/consumer. Generally, there is another percipient in the supply chain which is the retailer. In the primary phase of energy products, the retailer has been ignored, as it will be centrally controlled and the distribution center can manage the role of the retailer. However, this is the initial model and it will be modified later for different scenarios. However, the producer, distributor, and customer will be explained in this section. The supplier will be explained in the additional parameters section.

Green Hydrogen Producer

It is previously stated that the Lough Ree power plant will be the production site. A few assumptions need to be made for the production site. In this supply chain modeling the capacity of the electrolyzers has considered 52Mw projected by the project company(post-2030). Typically, a single Mw of electrolyzer can make 400kg of hydrogen. Thus, 52MW electrolier will make around 20,800 kg. Due to any loss or risk, the production of green hydrogen per day is assumed around 20,000 kg. This data will be used for the simulation.

However, the assumption for the electrolyzer type will be an Alkaline electrolyzer (explained in sub-section 2.3.1). It is suitable for producing mass amounts of hydrogen which is mentioned in the state of the art. PEM electrolyzer is for a small amount of production and Solid Oxide electrolyzer is still in the research phase. Following that, the demand for hydrogen is projected from the actual user data of natural gas. Thus, it is obvious that hydrogen will be a gas replacement, and hydrogen in the gas form will be the main product of this supply chain. Therefore, the storage system in the production site and distribution center will be compressed hydrogen storage which is mentioned in sub-section 2.4.1.

Distribution Center and Customers

There are five distribution centers are selected for the model and every county is considered customers. Among all of the counties, Dublin has the highest demand as it has the highest population and industrial area. Dublin will also serve hydrogen in the other six counties which are nearby Dublin. Following that, Limerick and Cork also have industrial areas. Thus, a massive amount of hydrogen demand has been created there for industrial heating. Thus, they also have been selected as distribution centers. As those two counties are quite close to each other by distance, they will supply hydrogen to four different counties from each distribution center. However, Galway is situated on the west coast of Ireland. It is a growing city with several large industries, including medical devices and technology. therefore, it also has a great demand for hydrogen. Galway is considered the distribution center for the west side of Ireland. Lastly, there is a high demand for hydrogen in the midland of Ireland. Although Longford does not have that much demand, Longford is chosen as the distribution center of the midland due to its geographical position and distance from other counties in the midland.

4.4.2 Different Scenarios

The primary model is already defined. The model will be replicated by varying the distribution centers to understand the change in the service level of the supply chain model. The replication scenarios of the model are presented in Table 7.

Table 7: Model replication scenarios

Scenario No.	Distribution centers
1	All distribution centers (base model scenario)
2	Cork, Limerick, Galway, Longford
3	Longford, Dublin
4	Longford, Cork
5	Longford, Limerick
6	Longford, Galway

In these six different models, Longford county is common in all models. As the production site is in Longford, this county is considered in all scenarios. However, these models will be simulated separately in Anylogistix software.

4.4.3 Parameter Selection

In Anylogistix software, it is required to define some other parameters for the simulation. The main components of green hydrogen production are electricity and water. The electricity will be supplied by the Landsborough wind firm. To produce 1kg of hydrogen, 50KW of electricity is required [79]. The price of that amount of green electricity in Ireland is 0.138 euros [80]. However, the production site required 9 liters of water to produce 1kg of green hydrogen [81]. As the production site is near the river, the water supplier has been ignored in the model.

However, the inventory policy is required to define the distribution center and factory. The min-max policy has been considered for distribution centers as the hydrogen storage system is costly. Thus, it is required to define a specific range for the inventory in distribution centers. For the factory, the order-on-demand inventory policy is selected as it is more economical to get electricity from the supplier when it is needed rather than storing electricity.

For defining the min-max policy in Anylogistix, there are certain rules for defining them. The minimum level of the inventory policy will be twice the average demand of the distribution center. The maximum level of the inventory policy will be five times the average demand. To find the average demand for each distribution center, equation (ii) has been used.

$$\text{Average Demand} = \frac{\textit{Sum of all the counties avarge demand under distribution center}}{\textit{Number of counties under each distribution center}} \quad \text{(ii)}$$

All of the inventory policy has been documented in Table 8

Table 8: Inventory policy for the model scenarios

Distribution center/ factory	Average demand(kg)	Minimum Level(kg) (2* Average demand)	Maximum Level(kg) (5* Average demand)
Production site	--	Order-on-demand	Order-on-demand
Dublin	10790.57	21581.13	53952.84
Cork	3513.70	7027.40	17568.51
Galway	409.33	818.67	2046.67
Limerick	1607.69	3215.38	8038.44
Longford	130.88	261.76	654.389

The selling price and the production price of green hydrogen have been taken from the additional project data. The production price of green hydrogen is considered 2.4 euro/kg and the selling price is assumed 3.5 euro/kg. The transportation mode will be trucks with 50km/h speed. Besides, the estimated lead time for all scenarios is 30 days. Overall, these data are sufficient to run the simulation.

4.5 Supply Chain Performance Measurement Implementation

In this section, supply chain simulations will be performed on the supply chain model. At the beginning of the simulation, there was a very poor score of ELT service level by orders achieved. The issue is that the production per day is lower than the demand of the distribution center combination. Thus, an additional parameter is required to use for the models which is the safety stock in the factory. In the state of the art, it was pointed out that safety stock can be used to mitigate higher demand [64]. It means the production site will make some stock products before delivering them to the distribution centers. It is always advised to keep the safety stock level high to achieve a better service level [82]. For this supply chain model, the high safety stock is considered 400,000 kg of hydrogen which is nearly five times the maximum level of the all-distribution centers. In other words, the production site will start supplying after producing the green hydrogen for 20 days. There are two other levels (moderate and low) of safety stock have been considered which can be found in Table 9.

Table 9: Safety stock inventory level in the production site

Safety stock amount(kg)	Level of safety stock
400,000	High level
200,000	Moderate level
100,000	Low level

If any combination can achieve more than 90% ELT service level by orders, then the safety stock level will be reduced and will be simulated again. The model will be simulated till it reaches an ELT service level by orders lower than 90% to check the minimum safety stock of each scenario. A minimum 90% ELT service level by orders is the standard for most industries especially for the energy supply chain [83].

Another option for improving the service level is the increment of the production capacity. It will be more costly to increase the capacity than to increase the storage system. Therefore, the safety stock will be a better option than the capacity increment in this study.

Scenario 1

This scenario consists of a single supplier, a single production site, five distribution centers, and twenty-six customers. The supplier has an unlimited inventory of electricity and the Lough Ree production site is responsible for the production of green hydrogen which is distributed to all the distribution centers. The Longford distribution center has the highest number of customers as Longford distribution center is positioned in the midland of Ireland. However, the Cork and Limerick distribution centers are near to each other by distance and they supply four customers each for their operation. However, the highest demand is generated in the Dublin distribution center and the lowest demand is in the Longford distribution centers. The simulation period is 1 year. The overall operation has been displayed in Figure 8.

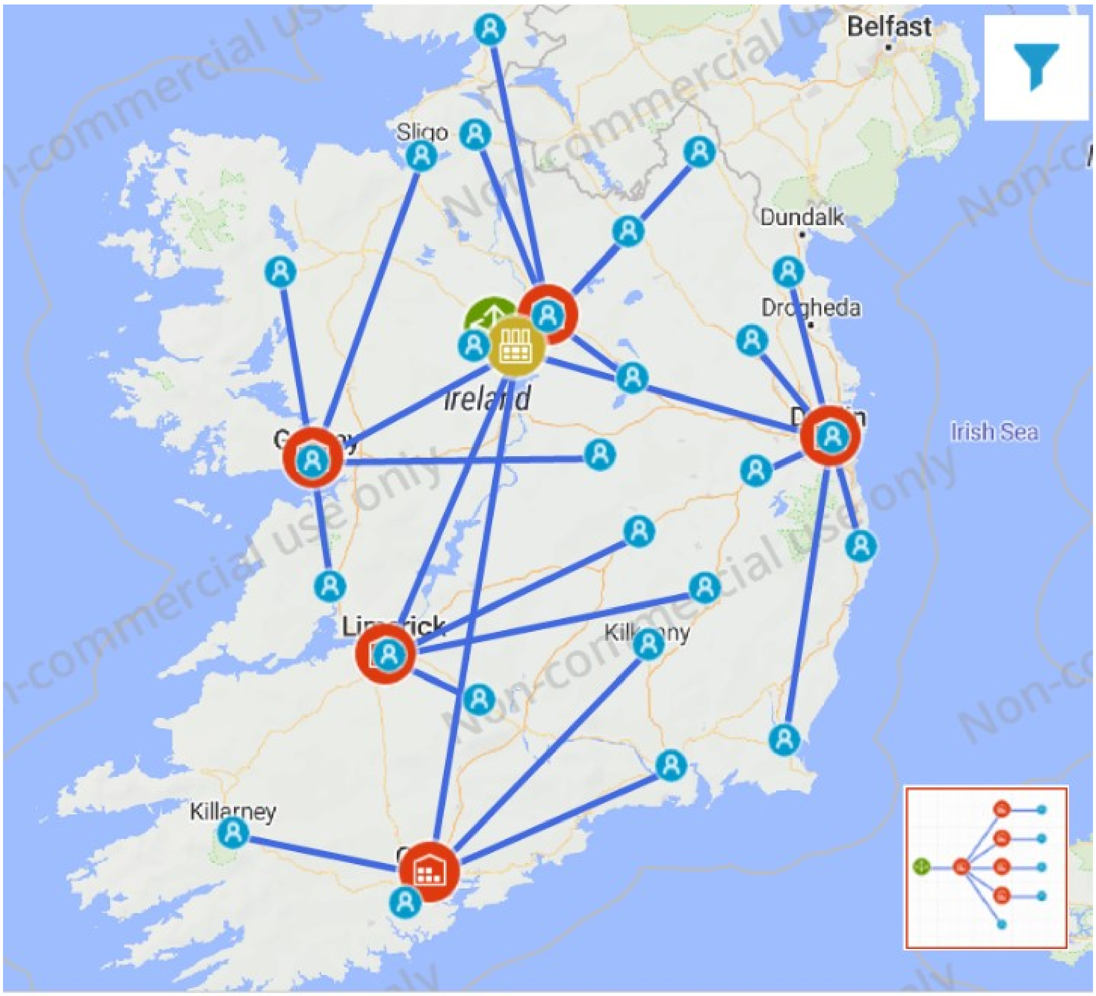


Figure 8: Map view of the all-distribution center scenario with routing connection

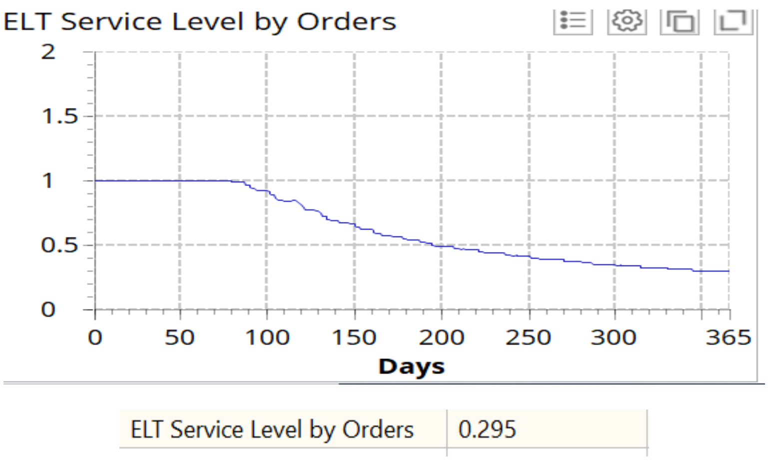


Figure 9: Service level of all distribution center scenario (*when the safety stock is 400,000 kg*)

After simulating all distribution centers scenario, the score of ELT service level by orders is .295 or 30%. That means only 30% of the orders have been fulfilled within 30 days of the expected lead time and the other orders get delayed or never completed within a single year of the timeline. It is a very disappointing result for the energy supply chain. However, the safety stock level was maximum for the simulation operation and it fails to achieve more than 90%. Therefore, it will not be simulated for any other safety stock inventory level.

Scenario 2

For this scenario, the Dublin distribution center was removed from the simulation operation. It is previously mentioned that Dublin shares more than 50% of the overall demand. The ideology of this scenario is to check if it is possible to satisfy the demand for all distribution centers except for Dublin. The supplier and the production site are the same as in the previous scenario. The number of distribution centers has reduced to four and the number of customers has limited to twenty. Here, the highest demand is from Cork and the lowest demand is from Longford. The simulation period is the same as the previous scenario. The scenario has been presented in Figure 10.

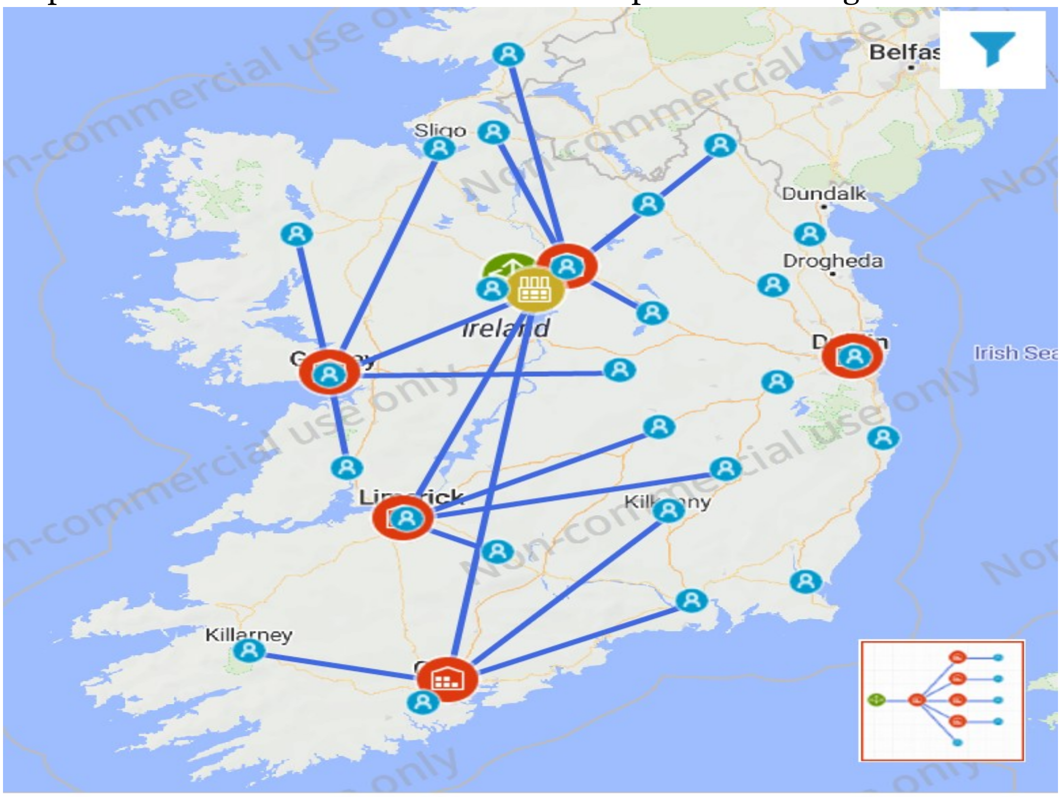


Figure 10: Map view of the Cork, Limerick, Longford, and Galway scenario with routing connection

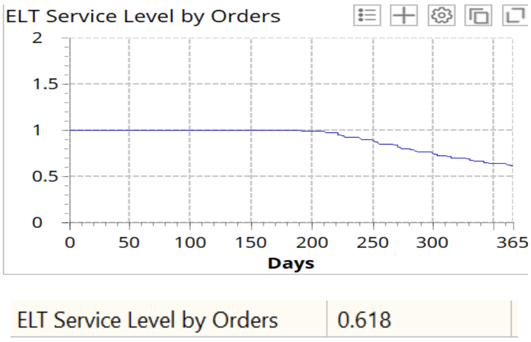


Figure 11: Service level of the Cork, Limerick, Longford, and Galway scenario (*when the safety stock is 400,000 kg*)

The ELT service level by orders without the Dublin distribution center is quite better than the previous score. The result is .618 or 62% which is nearly double the previous scenarios for expected lead time. Although the score has improved from the previous scenario, it is still not a satisfactory score for the hydrogen supply chain. Besides, this scenario also failed for the high level of safety stock and it will not be tasted for moderate level and low level of safety stock.

Scenario 3

The third scenario is testing the system from another angle by removing Galway, Limerick, and Cork from the main scenario. This scenario has two distribution centers and thirteen customers. The number of customers and distribution centers has been reduced more than the previous scenario. Thus, there will be less use of transportation for the supply chain. The demand is from the Dublin customer and the least demand is from the Longford customer. The timeline for the simulation is the same as the previous one. The map view of the scenario has been presented in Figure 12.

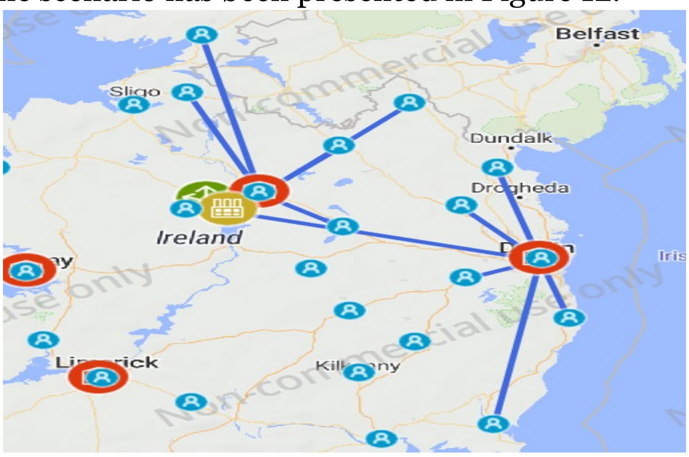
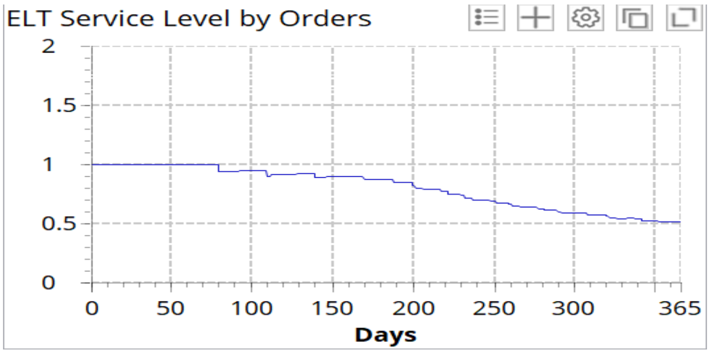


Figure 12: Map view of the Longford and Dublin scenario with routing connection



ELT Service Level by Orders	0.515

Figure 13: Service level of Longford and Dublin scenario (*when the safety stock is 400,000 kg*)

The ELT service level by orders for Longford and Dublin combination becomes lower than in the previous scenario. The score becomes .515 or 52% for 30 days of expected lead time. Although the scenario is simple than any previous scenario, the massive demand in Dublin has impacted the ELT service level score. However, the score indicates nearly half of the overall orders are failed which is a disappointment for new products. The scenarios also failed to fulfill the threshold of the high level of safety stock.

Scenario 4

This scenario has been created from the last scenario by replacing the Dublin distribution center with the Cork Distribution center. The Longford distribution center is constant due to the production site being in Longford. In this scenario, the highest demand is from Cork as Cork has more municipalities and industries in the area. The lowest-demand customer is the same as the previous one. The supplier, timeline, and production site are unchanged. Although the number of distribution centers is the same as before, the number of customers has been reduced to eleven. Cock has fewer customers than Dublin. The supply chain model with routing for this scenario is illustrated in Figure 14.

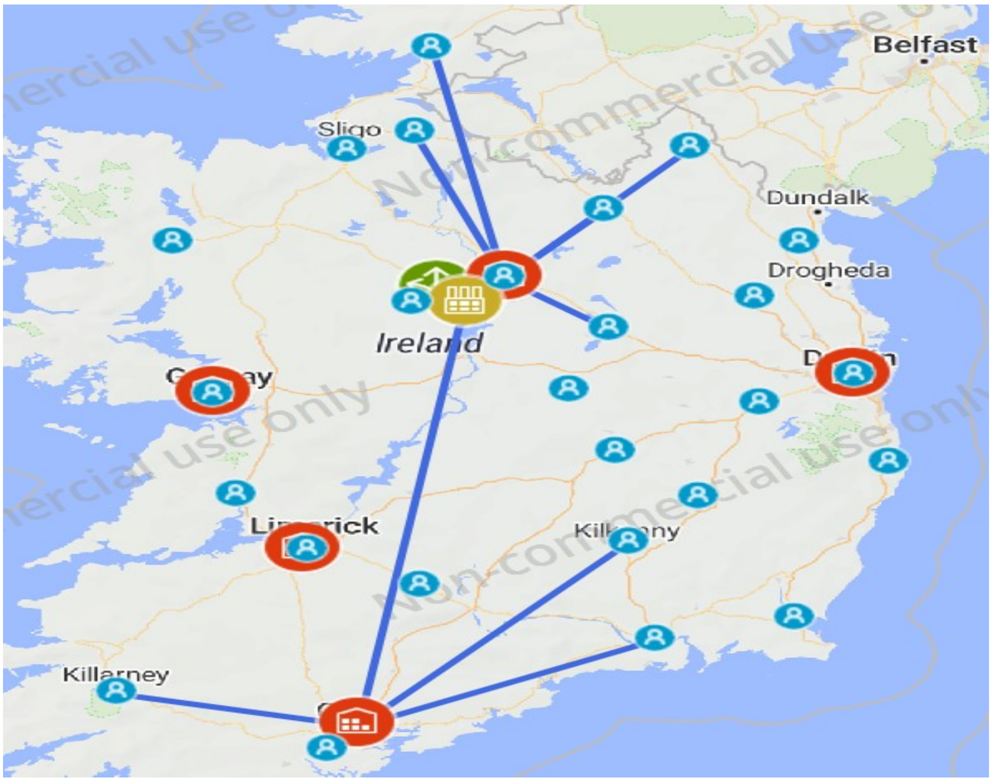


Figure 14: Map view of the Longford and Cork scenario with routing connection

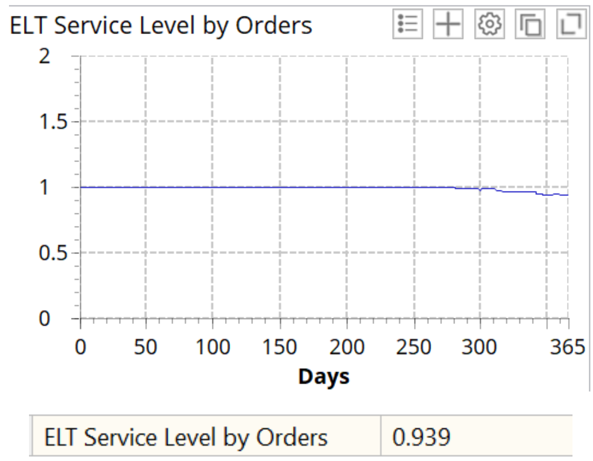


Figure 15: Service level of Longford and Cork scenario (*when the safety stock is 400,000 kg*)

The combination of Longford and Cork has achieved around .939 or 94% of the ELT service level by order. Thus, most of the orders are fulfilled within 30 days of the expected lead time. It is a good and acceptable service level. The service level also indicates that only 6% of orders are lost. The service level is still acceptable for the energy supply chain. This simulation is executed for the high level of safety stock and it has satisfied the threshold of the safety stock assumption. Therefore, the simulation will be executed again with a moderate level of safety stock (200,000kg) for a one-year timeline.

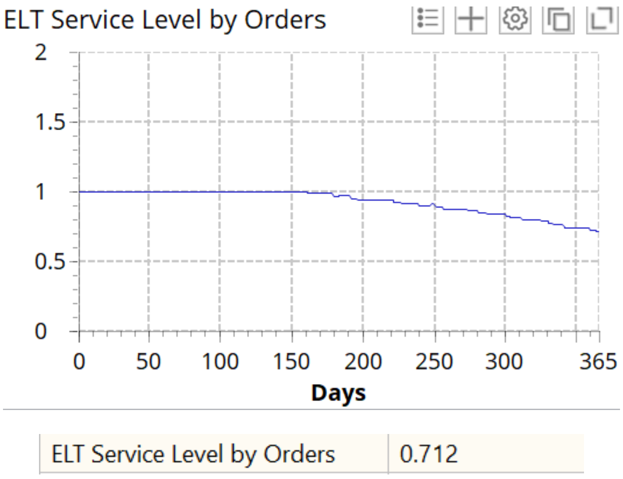


Figure 16: Service level of Longford and Cork scenario (*when the safety stock is 200,000 kg*)

When the safety stock has become half of the previous simulation, it reduces to around .33 or 33% of the previous score. Thus, this supply chain model can complete .712 or 71% of the orders in 30 days of expected lead time. It is not the desired service level. But this model can provide the desired service when the safety stock is high.

Scenario 5

This scenario has massive similarities with the last model. Here, the number of distribution centers and customers are the same. But Cork distribution center is replaced by Limerick distribution center. The customers are also different but the total number of customers are same. The total demand for this combination is nearly half of the previous combination as the customers of Limerick have less demand than Cork customers. This simulation period is also for one year. The visualization of the model is presented in Figure 17.

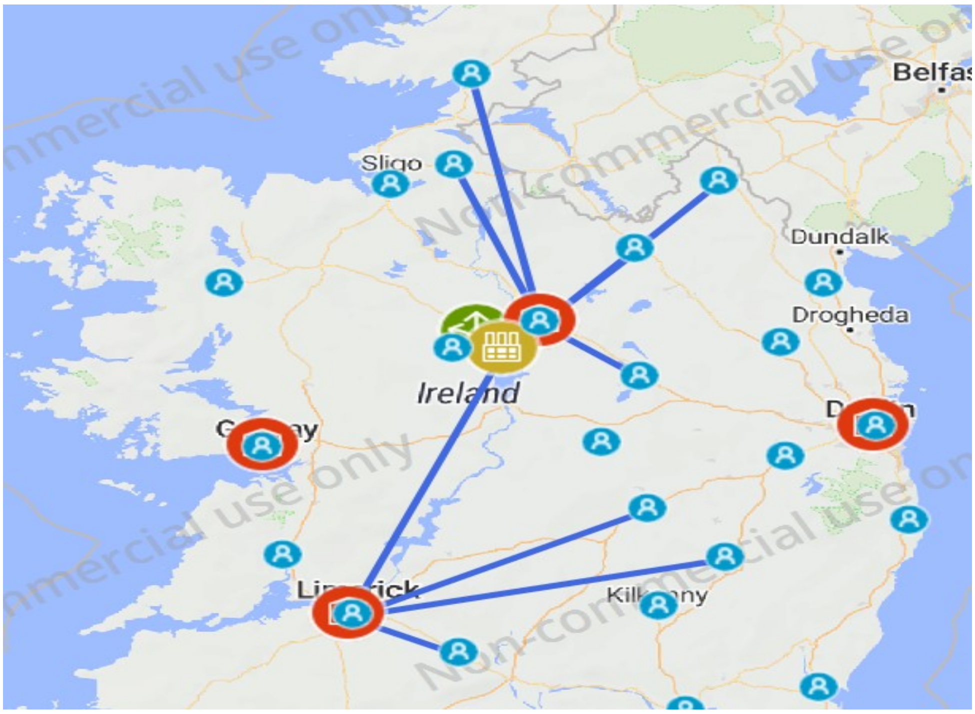


Figure 17: Map view of the Longford and Limerick scenario with routing connection

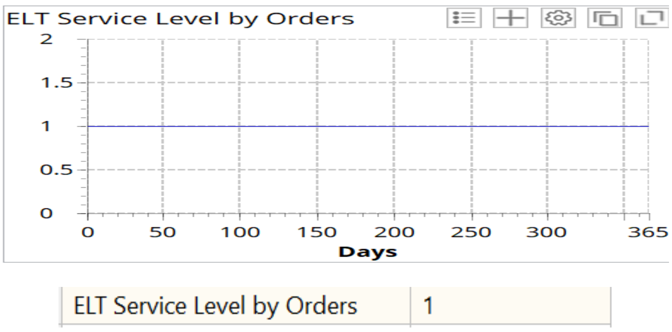


Figure 18: Service level of Longford and Limerick scenario (*when the safety stock is 400,000 kg*)

The ELT service level by orders for Longford and Limerick combination is 1 or 100% which is a perfect score for the energy supply chain. Thus, this model is capable of coping with all customers for the expected lead time under those two distribution centers. This combination has been simulated for the high level of safety stock inventory level and it has passed the threshold. Therefore, it will be simulated again for the moderate level of safety stock at the same timeline.

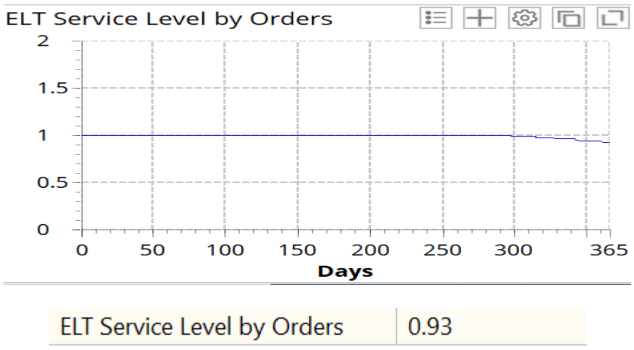


Figure 19: Service level of Longford and Limerick scenario (*when the safety stock is 200,000 kg*)

When the safety stock becomes half, the supply chain combination is still working well. The score of ELT service level by orders is .93 or 93% which is still acceptable for the energy supply chain. Thus, this combination can perform well while having a moderate safety stock inventory level too. As per the model assumption rules, this model will be simulated again for low safety stock level.

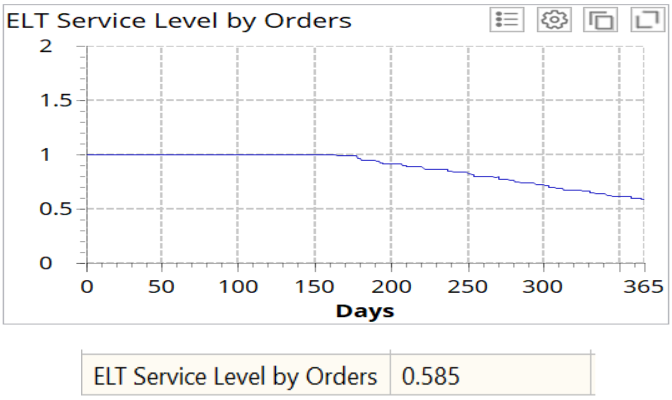


Figure 20: Service level of Longford and Limerick scenario (*when the safety stock is 100,000 kg*)

By reducing the safety stock more, the distribution center combination starts to have a downfall in performance. The service level becomes .585 or 59% by lowing the safety stock level. Thus, Longford and Limerick combination can perform well when the safety stock inventory level is either high or moderate.

Scenario 6

The final scenario for the study consists of Longford and Galway distribution centers. It has twelve customers which is more than the last scenario. The highest demand is from Clare customers. The lowest demand is the same as the last scenario. The two distribution centers are quite near to each other and they are responsible for serving the mid-west-north of Ireland. The simulation timeline for this scenario is 1 year. The scenario has been shown in Figure 21.

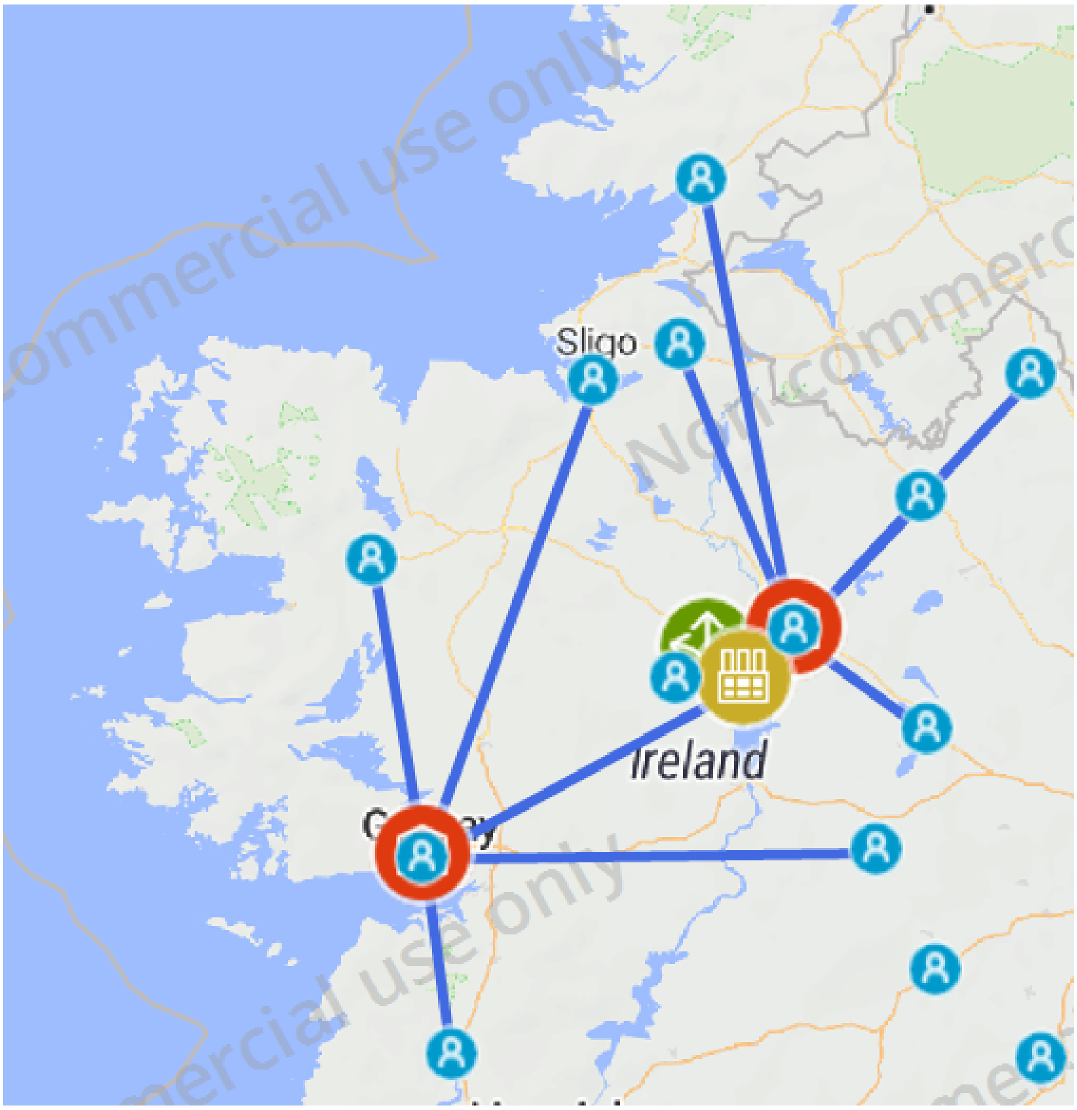


Figure 21: Map view of the Longford and Galway scenario with routing connection

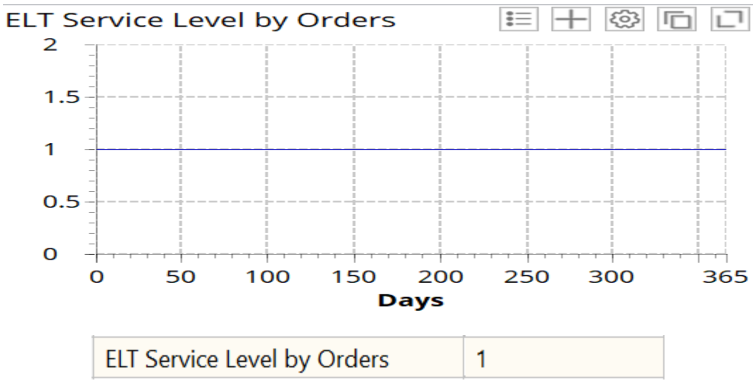


Figure 22: Service level of Longford and Galway scenario (*when the safety stock is 400,000 kg*)

For the Longford and Galway combination, the ELT service level by orders is 1 or 100% when the safety stock is 400,000 kg hydrogen. Thus, this combination can satisfy the order of all customers in the expected lead time with the current parameter of the production site. As this scenario has passed the desired ELT service level by orders score, it will be simulated again with moderate safety stock for one year period.

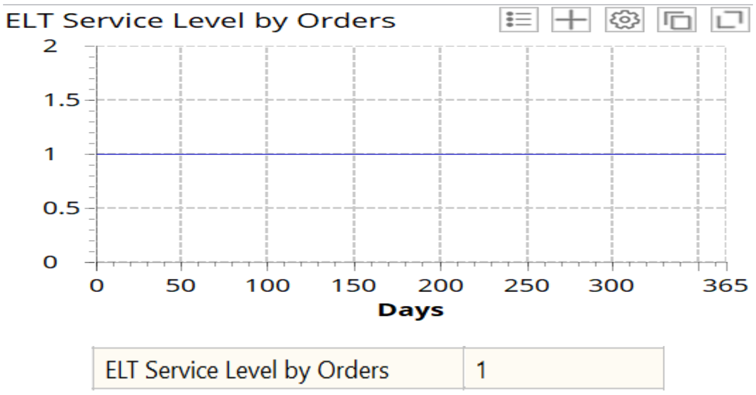


Figure 23: Service level of Longford and Galway scenario (*when the safety stock is 200,000 kg*)

When the safety stock inventory level is moderate then the Longford and Galway combination performance has no change. Thus, it is possible to serve these customers with a moderate level of safety stock on the production site. As per the rules of safety stock assumption of this study, the scenario will be simulated a third time with low safety stock.

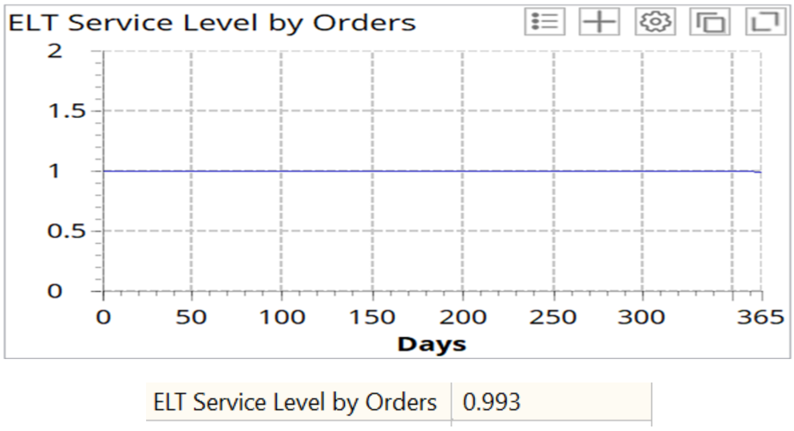


Figure 24: Service level of Longford and Galway scenario (*when the safety stock is 100,000 kg*)

After lowering the safety stock inventory level more, the current network combination can serve their customer at a 94% service level for 30 days of expected lead time. In energy supply change, it is an acceptable service level. Thus, the production capacity and the safety stock are a good fit for the demand in Longford and Galway regions.

4.5.1 Model Sensitivity Analysis

Previously the simulations have been done with various levels of safety stocks which are from the production side. If the variation happened on the end user side, there are possibilities to understand the sensitivity of the model. To accomplish the end user variation, demand has been chosen as the variation parameter as this model has demand data as only end user data. The demand data can be varied by probability distribution techniques. There are various types of probability distributions are available and most of them require different parameters of data for implementation. As this model has only mean demand data, uniform distribution is the more appropriate approach for experiments compared to other probability distributions. The uniform distribution works by considering two points (maximum and minimum).

The minimum point= $\frac{Mean}{2}$ (iii)

The maximum point= $Mean + \frac{Mean}{2}$ (iv)

The Demand variation with uniform distribution is documented in Table 10

Table 10: Demand Variation with uniform distribution

County	Mean Demand	Minimum point	Maximum point
Carlow	32956.91	16478.46	49435.37
Cavan	7820.51	3910.255	11730.77
Clare	23827.77	11913.89	35741.66
Cork	395947.42	197973.7	593921.1
Donegal	446.63	223.315	669.945
Dublin	1855421.79	927710.9	2783133
Galway	35507.17	17753.59	53260.76
Kerry	343.91	171.955	515.865
Kildare	164570.17	82285.09	246855.3
Kilkenny	34136.02	17068.01	51204.03
Laois	37472.35	18736.18	56208.53
Leitrim	357.30	178.65	535.95
Limerick	126110.76	63055.38	189166.1
Longford	66.99	33.495	100.485
Louth	115168.30	57584.15	172752.5
Mayo	6132.25	3066.125	9198.375
Meath	124516.29	62258.15	186774.4
Monaghan	6248.37	3124.185	9372.555
Offaly	8834.36	4417.18	13251.54
Roscommon	370.70	185.35	556.05
Sligo	401.97	200.985	602.955
Tipperary	38182.49	19091.25	57273.74
Waterford	82573.16	41286.58	123859.7
Westmeath	18128.76	9064.38	27193.14
Wexford	361.77	180.885	542.655
Wicklow	103095.86	51547.93	154643.8

By using this demand data, scenario simulation has been repeated and the result of the simulation can be found in Table 11

Table 11: Simulation result with demand variation

Scenarios	Safety stock level	ELT service level by orders
Scenario 1	High	37%
Scenario 2	High	63%
Scenario 3	High	77%
Scenario 4	High	95%
	Moderate	70%
Scenario 5	High	100%
	Moderate	89%
Scenario 6	High	100%
	Moderate	72%

The result shows some changes from the previous simulation. When the safety stock level is high, the ELT service level by orders result is higher than the previous result. When the safety stock level has reduced, the service level has also dropped. The demands are determined from the uniform distribution by simulation software. It can be assumed that software is triggering the demand levels when safety stock is low and vice versa. Overall, demand variation has a high effect on the output of the simulation model.

5 Discussion and Conclusion

5.1 Discussion on Production Site Validation

For the first part of the thesis, a comparison has been done between the ideal site location and the Lough Ree power plant. The study result indicates that the Lough Ree site is generally well-located regarding location, social and technical factors (Table 10). Some shorts comings are contrasted with Ideal

Table 12: Summary of the production site validation study

Factors	Sub-factors	Ideal site value/status	Lough Ree site value /status
Site location factor	Distance from water-body	<1000m	<800m
	Distance from highway	<=500m	220m
	Distance from railroad	<=500m	1700m
	Distance from the gas network	<=1500m	2000m
	Distance from the power grid	<=1000m	Direct access
	Distance from the wind farm	<=500m	1400m
Social factor	Public support	Highly important	Higher chances of support
	Community benefit	Engaging more locals in operation	Created jobs and business
	Government support	Needed for transition	Positive support
Technical factor	Hydrogen generation structure	Depending on cost	Pre-structure available
	Safety	Highly important	Protocols practiced in site

site location. The first dissimilarity is denoted that the distance from the rail communication system. The rail connection is connected from midland to all over Ireland. Our literature suggested that it is transporting hydrogen by rail is cheaper and has the possibility of less carbon emission. The decision-makers should consider this shortcoming with high priority at the time of green hydrogen production site development.

The distance from the gas network is considered an advantage by the project company. Yet, the distance between the production site and the gas network is quite long and it will increase the cost of green hydrogen transportation. Another noticeable factor that has been figured from the second part of this study is that the gas network in the midland of Ireland is not properly constructed to reach the maximum number of customers. Thus, it is quite important to build a proper gas network in midland for connecting the production site and customers. Thus, study findings suggest that greater investment in expanding the gas network could be necessary to facilitate the growth of the green hydrogen industry.

Another key issue figured out from the comparison study is that the distance from the wind farm to the production site is not ideal. Thus, it will be required to build a long electrical transmission line for connecting the renewable energy source to the production site. Although the production site is near to lake where the wind gust is high. It will be more appropriate to build an inhouse wind firm that can be modified later based on the capacity of the production site. Moreover, there will be less transmission loss of electrical power.

Regarding social factors, they matched with the ideal site factor. People from that region were highly dependent on power plants. A large number of people have migrated to other places due to the shutdown of the coal power plant. Thus, developing a new production site can create new jobs and businesses which will benefit the community. People can earn their livelihood in their hometown rather than migrating to other places. Besides, there will be no carbon emissions on the production site. Thus, locals will highly appreciate the new project in their town. However, the government already has published strategies to boost the green hydrogen economy. The decision-makers should present a well-structured plan to the government to request support to build a green hydrogen production site in Lough Ree. The findings of this study will help decision-makers to make an in-depth plan. Besides, the main products of the production site will be changed from electricity to hydrogen, there will be some investment is required to transform the technical factors. Most of the funds will be needed for electrolyzers.

Overall, the study provided valuable insight to validate the production location in a structured way. The findings suggest that careful consideration of the factors is necessary for developing the green hydrogen production facility in the Lough Ree power plant and the investment in infrastructure is essential for the growth of the green hydrogen industry.

5.2 Discussion on Supply Chain Performance Measurement

The second phase of the thesis is supply chain design for different scenarios and finding the best regions to supply green hydrogen from the Lough Ree power plant. For the experiment, different scenarios have been created by varying the number of distribution centers. The supplier and the producer

Table 13: Summary of modeling and performance measurement (ELT service level by orders)

Scenario	ELT service level by orders (high level of safety stock)	ELT service level by orders (moderate level of safety stock)	ELT service level by orders (low level of safety stock)
All distribution centers	30%	--	--
Cork, Limerick, Galway, Longford	62%	--	--
Longford, Dublin	52%	--	--
Longford, Cork	94%	71%	
Longford, Limerick	100%	93%	59%
Longford, Galway	100%	100%	94%

are the same for all scenarios. The performance metric for all scenarios is ELT service level by orders where the expected lead time is one month. Initially, the results are very low, and different level of safety stock is introduced to improve the value of the performance metrics. It was also stated in the literature review that safety stock can improve performance. It is also proved in the simulation experiment. Some scenarios are performed very well with safety stock. The summary of the result can be found in Table 11.

The ELT service level by orders is calculated for the number of orders fulfilled within the expected lead time and a score of 90% or above is considered an acceptable score. The first three scenarios are failed to reach the threshold of ELT service level by orders for the high level of safety stock. The fourth scenario (Longford and Cork) has passed the high level of stock inventory level. However, the production site produces 20,000 kg of green hydrogen every day. If the production site wants to supply green hydrogen to the customer under Longford and Cork for satisfactory ELT service level by orders, it needs to produce green hydrogen for 20 days to make the required safety stock. Following that, Longford and Limerick scenario has satisfied the required ELT service level by orders rate for the high and moderate levels of safety stock. Thus, the production site needs to stock green hydrogen for a minimum of 10 days to supply the fourth scenario. The final scenario which consisted of Longford and Galway has passed the desired ELT service level by orders all the levels of safety stock. Therefore, the production site needs to stock green hydrogen for a minimum of 5 days to supply the customer corresponding to those regions.

For a long-term plan, another simulation can be performed on Longford and Galway scenario. The assumption of the long-term is 3 years and the safety stock assumption is 300,000kg of green hydrogen (100,000kg for each year). Other parameters are kept constant.

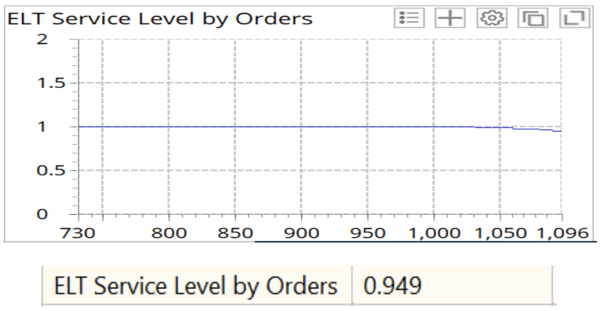


Figure 25: Service level of Longford and Galway scenario (*when safety stock is 300,000 for 3 years*)

The result of the simulation has presented in Figure 25. The ELT service level by orders score is slightly better than the single-year simulation. Thus, the system can fulfill .949 or 94% of orders for 30 days of expected lead time. The production site needs to stock green hydrogen for a minimum of 15 days to serve the customer under Longford and Galway region.

Another approach can be implemented to get a better understanding of the simulation analysis result which is cost analysis. The cost of each scenario has been documented in Table 14.

Table 14: Overall cost of all supply chain scenarios

Scenarios	Total cost (in euros)
All Distribution centers (400,000kg)	22,077,921
Cork, Limerick, Galway, Longford (400,000kg)	3,644,062
Longford, Dublin (400,000kg)	16,033,445
Longford, Cork (400,000kg)	1,210,400
Longford, Cork (200,000kg)	2,749,230
Longford, Limerick (400,000kg)	1,179,418
Longford, Limerick (200,000kg)	589,709
Longford, Limerick (100,000kg)	1,356,890
Longford, Galway (400,000kg)	5,454,454
Longford, Galway (200,000kg)	2,727,227
Longford, Galway (100,000kg)	84,141
Longford, Galway (100,000kg, 3 years)	3,522,255

The result of the cost analysis shows that Longford and Galway combination is economical compared to other scenario combinations. As this project will be the first green hydrogen project in Ireland, it is important to spend less in the pilot phase. However, the long-term plan of Longford and Galway is cheaper than Cork, Limerick, Galway, and Longford scenarios. Thus, Longford and Galway scenario is more suitable in this context based on this research result.

Regarding the sensitivity analysis, uncertain demand can change the output performance of the supply chain. The experimental result has a significant difference from the static demand result. Thus, safety stock is helpful to reduce the uncertainty of the demand effect as a higher level of safety stock was resulting a better output value. Proper planning of safety stock can reduce the uncertain disruption of the green hydrogen supply chain.

5.3 Limitations

In the comparison study, there was no exact data was found about the cost of technical development was found in the literature review. There was various cost assumption from different parts of the world. Also, neighboring countries such as the UK, etc. are in the development phase with green hydrogen.

Thus, it was not possible to discuss the exact cost of technical development for the new sites. However, the data about Lough Ree was also limited as it is a government site leased by a private company. Thus, some data used in the thesis can be varied from the actual data.

For the supply chain modeling, the demand data was assumed from the gas user data, and it is not the exact data of hydrogen demand. Due to less availability of data, the scenarios for the coming decade were not possible to determine. However, the simulation software used for the experiment was the free version. If the paid version could be used for the experiment, the simulation can also determine different routes possible routes for the scenarios. However, the is no option for simulating a gas pipeline in the Anylogistix software. Thus, the truck is used as the only transportation mode for the scenarios. Moreover, there is no option for defining peak time in the software. It will be more appropriate

5.4 Future work

As the demand for green hydrogen will grow in the future, there is massive scope for research into this specific field.

- There is a tool called Greenfield Analysis in the paid version of Anylogistix software. It helps to determine the production facility location and distribution center. This study will contribute more to finding a suitable location for the green production site.
- Another scope of future work is running simulations on the supply chain with accurate data. Accurate data can be gathered by interviewing engineers from different industries and people from hydrogen-based appliance suppliers. They can explain more about the exact demand that they are expecting in the energy sector.
- Simulation of the scenarios can be taken place in software where it is possible to define peak time for the energy demand. Using this specific feature will provide more accurate performance measurements of different scenarios.

5.5 Conclusion

The first question of the thesis is: Is the Lough Ree power plant site valid as a green hydrogen production site? A comparison-based study has been done to analyze the Lough Ree power plant site characteristics. Most of the characteristics have been matched with the ideal green hydrogen production site characteristics. The comparison has been done based on three criteria and eleven sub-criteria. In the Location factor criteria, few improvements are required to connect the Lough Ree site with the rail network, gas network, and wind firm. These areas are quite far from the green hydrogen production location and connecting those areas will benefit the production and supply network of green hydrogen. However, decision-makers can take the steps to build a wind firm for the production site. In such a way, there will be less transmission loss of electricity and the firm capacity will be modified based on the production site demand. However, the Lough Ree power plant has public and government support. Previously, this site has contributed to the community by offering jobs and businesses. It will be capable to do the same if it becomes a green hydrogen production site. Regarding technical criteria, improvements are required to transform the site. As it was a coal power plant before, the transformation will be cheaper compared to constructing a production site. Overall, the Lough Ree power plant is valid for developing a green hydrogen production site with few improvements. The main idea of the study is to validate the Lough Ree site characteristics with practiced green hydrogen production site characteristics.

The second question of the thesis is: Which regions of Ireland are suitable for supplying green hydrogen from the Lough Ree power plant? The discrete event simulation technique has been used to simulate different scenarios consisting of different regions in Ireland. The simulation has been performed in software called AnyLogistix. The selection of the region was based on ELT service level by order score of every scenario. The idealogy of this scoring method is to observe the number of completed orders within the estimated lead time which was assumed 30 days. To achieve more meaningful results, the safety stock is used as an additional parameter. Customers from Cavan, Donegal, Leitrim, Longford, Monaghan, Roscommon, Westmeath, Clare, Galway, Mayo, Offaly, and Sligo can get the green hydrogen from the Lough Ree power plant with an acceptable ELT service level by orders score. These customers are distributed under Longford and Galway distribution centers. The production capacity of the Lough Ree was taken from the assumption of the project for a 100% renewable electricity source in post-2030. However, the selected customer regions have been simulated under different levels of safety stock. The simulation result has passed all the levels of safety stock. Thus, those customers will be satisfied with the minimum amount of safety stocks and the production site can make those stocks within minimum days compared to other scenarios. The Longford and Galway scenarios also simulated for three years with the low level of stock inventory for each year. The result of the ELT service level by orders score was 95% which means only 5% of orders is failed within the expected lead time. Thus, the Lough Ree power plant is capable of supplying green hydrogen to the regions under Longford and Galway distribution centers. Besides, it is quite economical compared serve other regions. Moreover, the model is highly sensitive to demand variation. Strategic planning of safety stock can reduce the disruption risk of the model.

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