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MASTER'S PROGRAMME IN INNOVATIVE SUSTAINABLE ENERGY ENGINEERING

GIS-Based Site Suitability Assessment for Green Hydrogen Production in Norrbotten County

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Author Gargi

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Thesis supervisor Prof. Mika Järvinen, Associate Professor, Aalto University

Thesis advisor(s) Prof. Jagruti Ramsing Thakur, Assistant Professor, KTH Royal Institute of Technology; Anna Adolfsson, Project Manager, SSAB

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Abstract

The swift industrial transformation in Northern Sweden is closely linked to the huge potential for green hydrogen utilisation. With the hard-to-abate and carbon-intensive iron and steel industry championing the utilization of green hydrogen towards achieving fossil-free iron and steel production in the region, Norrbotten County has emerged as the pioneer for promoting potentially large green hydrogen projects and a market across various industries which includes the marine and transportation sector along with the main iron and steel industry. Furthermore, the rich availability of resources such as land, water, renewable energy potential and locally produced green electricity brings down the cost in the region potentially making it geographically and economically ideal to establish large-scale green hydrogen projects. These are the key motivators for this study.

To enable such a transition and scalability, it is crucial to analyse multiple geographical factors influencing the decision-making for establishing green hydrogen projects , mainly renewable potential in the vicinity, proximity to key resources and demand points, existing grid support, underground geology suitability for storage and proximity to restricted and protected zones. The study primarily generates a site suitability map using a GIS-based Multi-Criteria Analysis (MCA) which is expected to provide reasonably good pointers for making viable green hydrogen business cases mainly to cater to the iron and steel industry and also to other potential beneficiaries in the county. Once the site suitability is established, a thorough green hydrogen demand analysis is undertaken considering theoretical hydrogen demand estimations, electrolyser efficiency, and associated electricity and water requirements to achieve the envisaged fossil-free transformation. The study also forecasts the sufficiency of surface water resources and highlights the need for additional electricity provision plans to meet the growing green hydrogen demand in Norrbotten County.

Keywords Green hydrogen, renewable electricity wind energy, water, sponge iron transformation, Norrbotten County, Multi-Criteria-Analysis, Site Suitability

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Units and Abbreviations

Units

Mt	Megatons
kWh	Kilowatt hours
GW	Gigawatt
Mm^3	Million cubic meters
TWh	Terrawatt hours

Abbreviations

HYBRIT	Hydrogen Breakthrough Iron-Making Technology
BOF	Blast Oxygen Furnace
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
MCA	Multi-Criteria Analysis
AHP	Analytical Hierarchy Process
GIS	Geographic Information System
MCWOA	Multi-Criteria Weighted Overlay Analysis
RBD	River Basin District
OECD	Organisation for Economic Co-operation and Development
WDPA	The World Database on Protected Areas
IEA	International Energy Agency

1. Introduction

Norrbotten County is the northernmost and largest county in Sweden covering a quarter of the country by area. It is further divided into 14 municipalities as represented in Figure 1, with Luleå being the capital of the county. The county's rich resources like surface water, renewable potential (hydroelectricity and wind), land availability, timber and minerals (especially high-grade magnetite iron ore) have played a key role in Sweden's industrialisation [1]. A majority of the resources are also the key inputs for green hydrogen production and are currently driving several large-scale green hydrogen projects in the County. Green hydrogen, produced using renewable electricity to split water into hydrogen and oxygen, offers a clean and versatile energy carrier with its applications having the potential to span across several sectors such as hard-to-abate industries, heavy-duty transportation, heating/cooling and long-term energy storage to balance intermittent renewable energy sources like wind and solar power. It makes for a crucial component in the transition to a low-carbon economy as its production process generates only water and oxygen with zero direct greenhouse gas emissions.

The most prominent of them is the HYBRIT (Hydrogen breakthrough-making Technology) initiative which aims towards commercialization of fossil-free sponge iron production by utilizing green hydrogen as a fuel in place of the fossil-fuel-dependent BOF (Blast Oxygen Furnace) route to reduce iron ore into the metallic form of iron [2]. The pilot project having been set up in Luleå was commissioned in 2020 and which happens to be the world's first fossil-free steel production initiative and is now aiming for a large-scale production at Gallivare by 2027 [2]. Several other projects in the county are also in the pipeline and expected to be operationalized in the years to come.

H_2 Green Steel has initiated establishing the first fully integrated fossil-free steel production in Boden, Gallivare and is expected to commence production from 2025 onwards. Power 2 Earth is a unique project that is said to be the first industrial-scale, emission-free ammonia and fertilizer plant that is expected to be operational in 2026 with the potential of producing 1500 tons of e-methanol per day [3]. This initiative is an international collaboration with Grupo Fertiberia's decarbonization efforts in Spain which leverages the exceptional conditions in the Norrbotten region. The green ammonia produced thereby is expected to help the decarbonization of maritime transport, the mining sector and the fertilizer industry in Sweden. Furthermore, the Port of Luleå, ABB and Uniper plans to develop a regional hydrogen hub enabling the production of 12000 metric tons of green hydrogen annually in Luleå in order to contribute to fossil-free supply chains in the region and also to the country's export [4]. Also, there are ongoing plans to establish hydrogen refuelling stations to support heavy road transportation. All put together, these pipelines highlight the region's significant demand for green hydrogen and this has laid the foundation for studying the future expansion of green hydrogen production in the county.

Towards this, the study aims to analyze the geographical suitability and availability of associated resources in Norrbotten County to cater to future green hydrogen projects using a GIS-based Multi-Criteria Analysis. Considering the envisaged fossil-free transformation in the county, green hydrogen plays a crucial role in realizing this. Therefore, the study period for assessing the green hydrogen demand and the associated resources has been taken as 2027 – 2045 in the backdrop of the Swedish National Mission to achieve net zero by 2045 [5] and various de-carbonization initiatives including the hard-to-abate iron and steel industry in the county which are expected to come to fruition from 2026 or 2027 onwards.

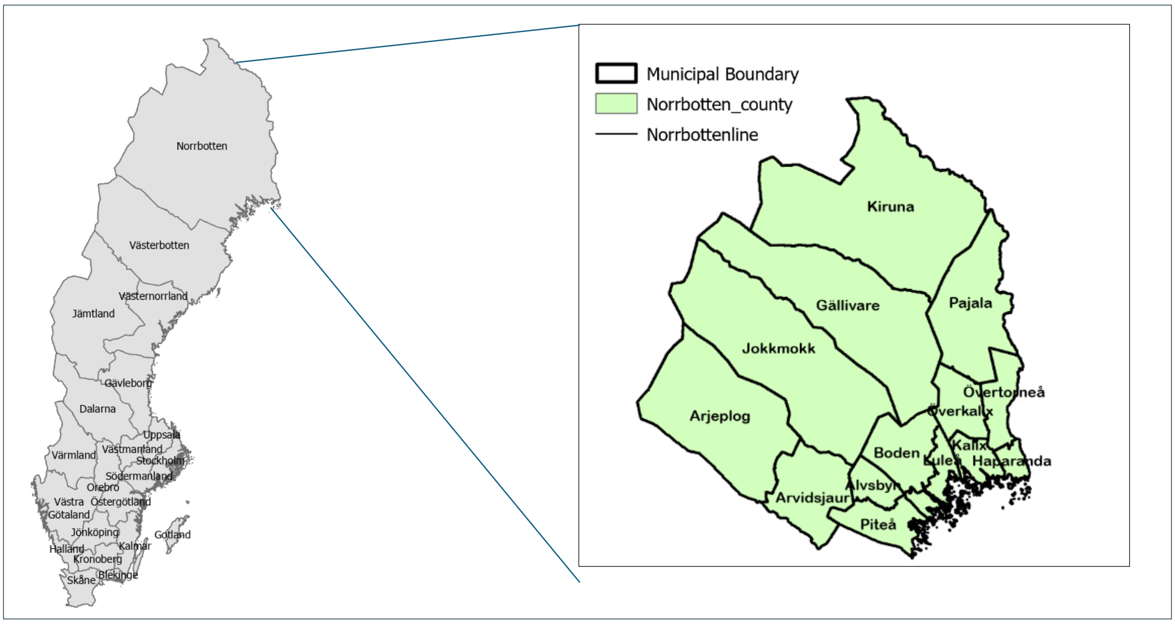


Figure 1 Norrbotten County divided into 14 municipalities

2. Literature Review

This section dives into the research's fundamental blocks, laying the groundwork for a comprehensive understanding of the study. It elucidates the core concepts that underpin the work, providing essential context and background information. By establishing this foundation, the significance of the study's objectives and methodologies followed by the identification of gaps in current research methodologies can be established and better appreciated in the following detailed analysis and discussions.

At present, a total of 41 governments have a hydrogen strategy in place with some early movers updating their original strategies and raising national ambitions [6]. These strategies comprise production, import and export plans aiming to cater to a diverse range of end-use sectors such as oil refining, ammonia, methanol, Iron and Steel, mobility, power, grid injection, CHPs, domestic heating, biofuels, and synfuels. Towards this, water electrolysis currently plays a significant role and has been anticipated to continue doing so given its reliance on green energy sources and using water with emissions limited to water vapour and oxygen only. Despite its tremendous potential, low-emission hydrogen today accounts for less than 1% of global hydrogen production and would potentially need to scale up greater than 100-fold by 2030 to achieve the NZE (Net Zero) Scenario.

A clear and stable regulatory framework is key to streamlining licensing and permitting processes and enhancing coordination among the various stakeholders and authorities involved to accelerate the development of green hydrogen projects [7]. IRENA suggests the critical role that resource assessment plays in the development of green hydrogen projects [8]. Furthermore, they could potentially compel developers to align their projects with a clear and stable regulatory framework thereby initiating expansion efforts and facilitating smoother, faster, and more sustainable project implementation. Resource assessment is fundamental in this context, as it helps identify, prioritize and evaluate the key resources by determining their availability and adequacy, thereby establishing the associated regulation standards towards the sustainable utilization of resources that hold an influence over decision-making to establish green hydrogen projects.

The availability of these resources for green hydrogen production is inextricably linked to their harnessing potential, accessibility and distribution which are further influenced by several factors such as the presence of anthropogenic infrastructure including power lines, road networks, potentially large-scale natural storage facilities, demand points and spatial constraints such as proximity to restricted and residential areas. These factors can potentially ensure decisions on site selection, resource optimization, cost efficiency, risk mitigation, environmental protection and regulatory compliance. For instance, it can be beneficial to understand the proximity to power lines, road networks, and storage facilities for the logistical planning of hydrogen production and distribution and also to understand the zoning laws and conservation regulations to reduce the risk of legal challenges.

Several studies that exist today revolve around the assessment of natural resources that are required for green hydrogen potential including renewable energy, water resources as well as the critical raw materials required for the manufacturing of the production technology [9]. This certainly is a critical step to quantify the resources. Following this, particularly in countries with ambitious targets, the next crucial phase involves assessing and analyzing and analysing the accessibility and suitability of sites for implementation. Towards this, a method termed as GIS-based MCA is an important tool with the potential to enhance project management and site selection by visualizing, assessing and identifying opportunities for added value [10]. Its main objective stems from the need to make geographic and spatial information more relevant for identifying and analysing preferred spatial data and resources for planning and management. Furthermore, factoring in a spatial perspective to management and decision-making strategies and policymaking could potentially bridge the gap between spatially perceived and actual availability, assessment and practical utilization of the resources.

GIS enables data visualization by mapping various geographical features and urban elements and assessing the geographical features and resources based on their position on the Earth's surface. MCA is a method for evaluating and selecting several decision alternatives based on conflicting and incommensurate criteria [11]. In a typical multi-criteria problem, one or more policy/project options that hold influence over decision-making are assessed against several different choices and quantified, for which a set of criteria is identified as a fundamental step. Each of the several criteria is further weighed in comparison to the various objectives and criteria and is identified by a standard scaling system to determine the best possible alternative that further enables decision-making. In the context of green hydrogen production.The GIS-based MCA approach factors in several criteria that are geographically assessed and evaluated based on prioritisation.

Several studies have been referred to gain a comprehensive understanding of the most important criteria consideration and the associated reasoning to cater to site selection for green hydrogen production in different regions globally. For example, Emmanuel [12] elucidates upon establishing the green hydrogen production potential in South-Eastern Nigeria by wind resource availability and further highlight upon the utilisation of wind energy potential map on GIS for site selection. Similarly, it highlights the utilization of the solar energy potential map for site suitability assessment of green hydrogen production. These studies use spatial data on wind speeds and solar irradiance, combined with MCA, to identify regions with the highest potential for renewable energy generation for green hydrogen production. Furthermore, research by Stepanov et al. [13] shows the utilization of GIS in mapping the electrical grids to identify locations for new hydrogen production facilities. It further suggests that the closer the proximity to powerlines the better the accessibility and efficiency of power transmission. Moreover, a study by the African Development Bank Group [14] emphasizes the importance of the closer proximity to freshwater sources to identify suitable sites for green hydrogen production near rivers and lakes. The study by Emmanuel et al. [12] further highlights the importance of considering closer road proximity using GIS as that would lead towards reduced transportation costs and improved logistics support for green hydrogen production. Furthermore, it explores the connectivity of potential sites to roads, electricity grids, and industrial zones using GIS. A study by Ali et al. [15] integrated various spatial datasets as listed, including restricted zones inclusive of natural reserves, national parks and other areas of national/cultural interest to ensure that the selected sites do not overlap with conservation efforts, urban planning, or national security interests. Lastly, demand points also play a significant role in criteria identification and assessment for site suitability as they help determine the suitable proximity requirement and accessibility of green hydrogen production sites to potential markets such as transportation networks, industrial hubs and urban areas. This has the potential to further ensure the economic viability of the projects by reducing the associated transportation costs.

Site suitability assessment for green hydrogen production involves evaluating various key criteria, which could vary significantly on a global scale. In this context, various studies highlight distinct combinations of these criteria. A study on the GIS-MCA decision-making approach for site suitability analysis for hydrogen production in the Valencian Community of Spain [16] considered 11 factors which were evaluated to identify optimal areas for hydrogen generation. This study takes into consideration energy potential from various renewables like solar and wind and also transmission lines to evaluate the overall renewable energy potential as well as distribution capacity. Apart from several industrial demand points such as the ceramic, fertiliser and chemical industries, the study also factors in potential demand from the transportation sector like railways, airports and seaports as they continue to rely on fossil fuels and electrification of these sectors proves challenging. An interesting aspect of this study is that it accounts for a variety of water resources such as large rivers, several lakes and dams that are suitable for water extraction. Furthermore, desalination plants are also considered as a potential source for supplying purified water for electrolysis. All put together, a total of three potential locations were determined to further deep-dive into the resource availability surrounding the pin-pointed site.

Similarly, a site suitability analysis of solar-powered hydrogen production in the Souss-Massa Region, Morocco [17] considered 10 factors grouped into technical and economic categories which were evaluated to identify optimal areas for hydrogen generation, with environmental factors set as the constraints. Furthermore, this study factors in only the western region of Morocco, leveraging the high solar potential for solar-based hydrogen projects. The ten criteria considered are as follows; solar potential, groundwater resources, proximity to the shoreline, slope, elevation, proximity to roads, industries, agricultural areas and power lines and lastly protected areas. It can be observed in this study that water resources considered in this case for hydrogen production are groundwater resources and seawater, the reason being limited rainfall harvesting due to reduced rainfall rates in the region. The topography has also been considered in the study to identify the level of terrain for development. Interestingly the study also considers the proximity to agricultural land for potential distribution of nitrogen fertiliser through green ammonia. Several other studies were also referred to such as the GIS-MCA that assessed hydrogen production potential in Argentina, based on the Atlas of Solar Energy of Argentina [18] and other proximity factors as enlisted previously.

It can be observed from the studies that a varied set of criteria have been considered towards the same objective of site suitability assessment for green hydrogen production. The criteria have been identified and evaluated based on region-specific renewable potential, water availability, topography and potential demand from various industries. Therefore, it can be challenging to establish and evaluate a pre-defined set of criteria on a global-level basis to assess potential sites for green hydrogen production as each region poses unique characteristics and challenges. Local regulatory frameworks, stakeholder engagement, and logistical considerations further challenge the development of a universal assessment standard.

Using the same approach, this study first aims towards identifying and evaluating several criteria that influence green hydrogen production in The Northern County of Sweden. As established in Chapter 1, several green hydrogen projects are already underway or in the pipeline in Norrbotten County with pre-decided locations and electrolyzer capacities. Furthermore, an increase in the green hydrogen demand has been anticipated in Norrbotten County to cater primarily to the fossil-free industrial transformation, primarily the iron and steel sector [19]. Underground storage potential has also been envisaged to play a significant role towards the transformation. In this regard, no studies currently exist that focus on assessing the site suitability of the region, while also accounting for the underground storage potential. Therefore, the study aims to address this gap by evaluating site suitability to support the scaling up of green hydrogen projects.

3. Research Objectives

The objective of this study is to analyze specific geographical criteria towards generating a site suitability map for the potential green hydrogen projects in the Norrbotten County, Sweden. The study subsequently aims to analyze in detail the availability of key resources, quantify the green hydrogen demand in the county and establish the adequacy of resources vis-a-vis demand.

3.1 Research Questions

In line with the background presented above, the thesis work aims to answer the following critical questions:

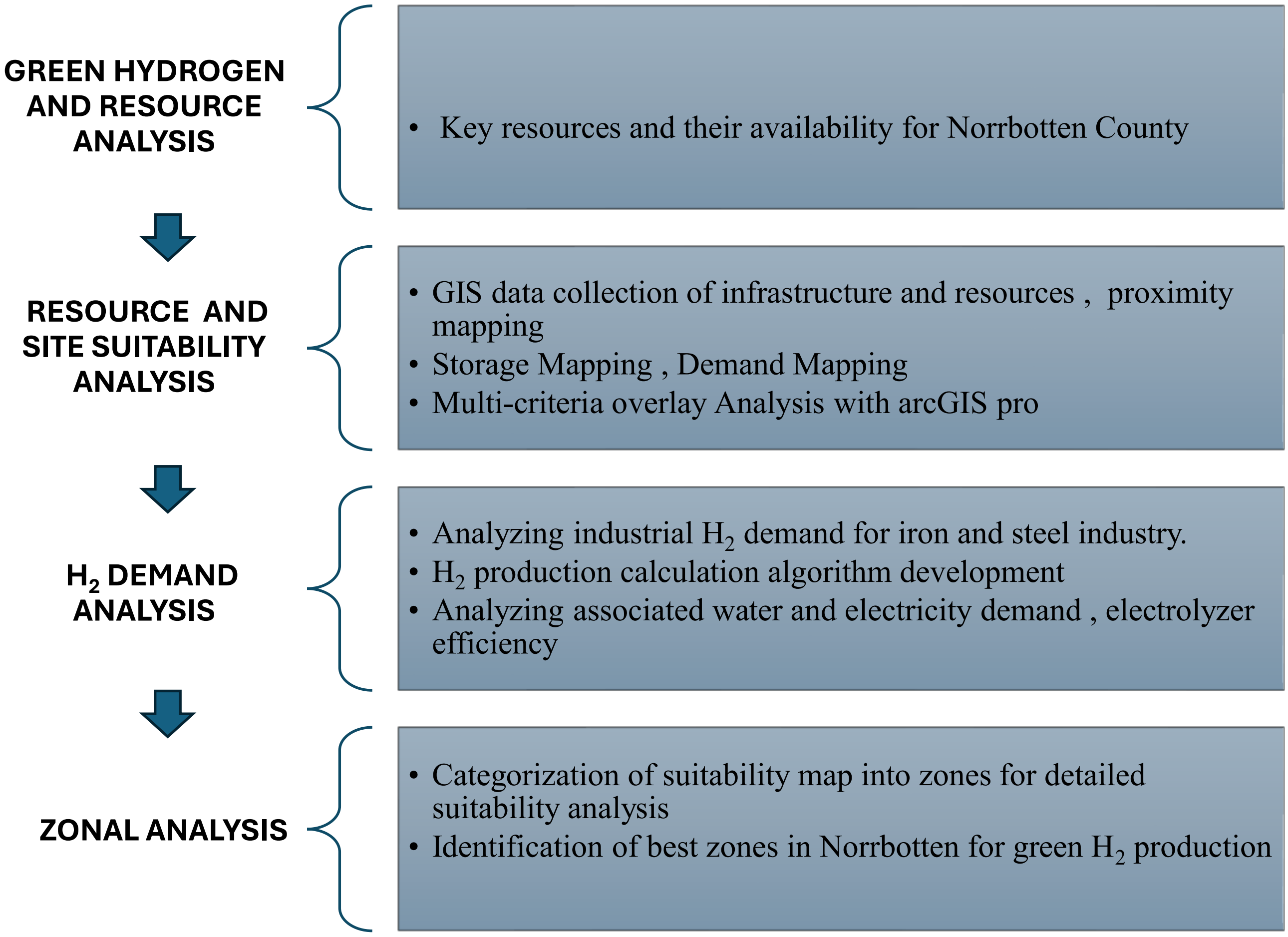
1. What are the most suitable locations for establishing green hydrogen production facilities to cater to the fossil-free transformation in Norrbotten County by 2045?
2. What is the annual hydrogen demand, additional renewable capacity required and also the adequacy of water resources to support this transition in Norrbotten County?

3.2 Scope and Limitations

The project mainly focuses on evaluating the green hydrogen production potential in Norrbotten County taking a cue from the potential demand of the industries therein. The time period that is considered for this study (2027 – 2045) is based on facts and data provided online which may differ in reality. Moreover, the research is based on theoretical work and interpretations which may be subject to errors/change. Hence, the methodology and results could be interpreted as a source of foundation and motivation to further develop the work to address real-world challenges. The green hydrogen storage potential mainly with respect to bedrock/cavern storage has been analyzed only at a fundamental geographical level which studies the suitable bedrock availability in the County. However, a thorough geophysical analysis has been recommended at the end to further study the potential of underground cavern storage.

4. Methodology

The methodology adopted in this project as represented in Figure 2 is a blend of a thorough literature review, data acquisition, company references and facts for the identification and analysis of suitable sites for green hydrogen production.



- Key resources and their availability for Norrbotten County

- GIS data collection of infrastructure and resources , proximity mapping
- Storage Mapping , Demand Mapping
- Multi-criteria overlay Analysis with arcGIS pro

- Analyzing industrial H_2 demand for iron and steel industry.
- H_2 production calculation algorithm development
- Analyzing associated water and electricity demand , electrolyzer efficiency

- Categorization of suitability map into zones for detailed suitability analysis
- Identification of best zones in Norrbotten for green H_2 production

FIGURE 2 DETAILED FLOWCHART FOR STUDY

The study begins with a brief context on the key resources required for green hydrogen production. Zooming in further, the key resources which are water and electricity and their availability in Norrbotten County are analyzed.

The study further delves into the site suitability assessment on GIS. This comprises several steps which begin with mapping on ArcGIS pro, the several geographical criteria influencing green hydrogen production such as existing and planned wind farms, power lines, water resources, major residential and commercial urban establishments, hydrogen demand points, underground cavern storage and protected natural areas following which proximity maps are generated. These maps are then assigned weights based on a scale using the Analytical Hierarchy process which is integrated and overlayed on the software to obtain the final suitability map.

Furthermore, the annual demand analysis with respect to the hydrogen demand by the iron and steel industry during the period 2027 – 2045 is analyzed. This includes several steps including a thorough review of the replacement of a Blast Oxygen Furnace (BOF) by hydrogen-based Direct Reduced Iron (H_2 -DRI) which is the technology utilized by the HYBRIT initiative [2]. This is followed by a detailed upstream analysis that assesses the associated green hydrogen demand year-on-year resource demand including water and electricity to cater to the HYBRIT expansion in Norrbotten County.

As an extension to the site suitability map obtained previously, a zonal analysis is performed to assess the suitability statistics of several zones created on the map and identify a set of zones that is recommended for further analysis that also factors in the closest proximity to mines. Lastly, an analysis is conducted to assess the H_2 demand from other potential beneficiaries of green H_2 and map them on the suitability map obtained for further observations.

4.1 Key Resource Assessment for Green Hydrogen Production in Norrbotten

This section aims towards assessing the two key resources for green hydrogen production i.e., water and electricity in Norrbotten County , Sweden between the period 2027-2045. This is crucial to gain quantified insights on the availability and accessibility to reflect upon analysing these resources' demand requirements.

4.1.1 Water

To produce 1 kg of hydrogen theoretically via electrolysis, 8.94 kg of water is needed [20]. The chemical reaction is as follows:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (1)$$

This implies 1 mol H_2 requires 1 mol of water. Factoring in the atomic weight of each molecule: 1 $mol\ H_2O$ = 18.015 $g\ H_2O$ and 1 $mol\ H_2$ = 2.016 $g\ H_2$. The resulting average water consumption rate is 18.015/2.016 = 8.94 kg H_2O/kgH_2.

This section aims to assess the water availability in Sweden, primarily in the study period 2027-2045. Sweden has abundant water resources including streams, freshwater and lakes of which their total water withdrawal represents only 1% of all available freshwater resources, which is among the lowest intensity of water use in the Organisation for Economic Co-operation and Development (OECD) [21]. This gives Sweden the advantage in terms of freshwater availability for green hydrogen production for the potential industrial demand in the following decades. For the same reason only surface water is considered within the scope of the study and groundwater has been excluded as there have been said to be political disagreements with regard to utilizing groundwater for hydrogen production as stated by SSAB [22] .

Sweden is divided into five water districts based on the borders of the major sea basins and catchment areas which are intended to be the management units for water resources as represented in Figure 3. They in turn cover 10 river basin districts (RBDs) reported under the Water Framework Directive (WFD) [23] . One county administrative board in each water district is appointed as the River Basin Water District Authority to ensure the coordination of the work within each district and ratify the Program of Measures and the River Basin Management Plan. The five main water districts in Sweden are the Bothnian Bay, the Bothnian Sea, the North Baltic, the South Baltic and Skagerrak and Kattegat. Table 1 represents the 10 RBDs inclusive of the main ones that are star-marked and the subcategories represent their international borders. This study primarily focuses on analyzing the water availability in the Bothnian Bay River Basin District as it comprises the whole of Norbotten County.

Table 1 River basin districts of Sweden [24]

River Basin District	Name	Countries sharing RBD
SE1**	Bothnian Bay	FI,NO
SE1TO	Bothnian Bay (International district Torne River)	FI,NO
SE2**	Bothnian Sea	-
SE3**	North Baltic Sea	-
SE4**	South Baltic Sea	NO
SE5**	Skagerrak and Kattegat	NO
SE1102	Bothnian Sea (International RBD)	NO
SE1103	Bothnian Bay (InternationalRBD)	NO
SE1104	Bothnian Bay (International RBD)	NO
SE5101	Skagerrack and Kattegat (International RBD)	NO

Figure 3 Geographic division of 5 main River Basin Districts of Sweden [24]

To forecast surface water availability for the study period, a regression analysis has been performed. Renewable freshwater primarily including surface and groundwater resources is replenished by precipitation that ends up as runoff to rivers and recharge to aquifers, and by surface waters and groundwater flowing in from neighbouring countries (inflow) [25]. Therefore, precipitation is a crucial factor in replenishing freshwater sources such as rivers, lakes, and aquifers. This analysis is undertaken following four steps. First, the annual precipitation in the Bothnian Bay is forecasted for the period 2027-2045. Following this, the freshwater availability for the same period is forecasted by virtue of a regression analysis that considers two independent variables: forecasted annual precipitation (2027-2045) and the time period. Lastly, with estimations on the % availability of surface water relative to groundwater in Sweden, the availability of surface water resources in Norrbotten County is estimated. Finally, to make estimations on the total available surface water for utilization by future demand sectors an analysis of the annual surface water abstraction from other sectors is taken into consideration.

Forecasting Precipitation for the period 2027-2045

An increase in annual precipitation over Northern Europe between 10 and 40% in the last century with the strongest increases was observed in Scandinavia and Western Russia [26]. It was also found that the trend towards increasing precipitation in Northern Europe would continue at a rate of 1 to 2% per decade. Taking a cue from this, the precipitation data from Eurostat for the last two decades was studied in the Bothnian Bay River district [27]. A pattern with respect to increasing precipitation within the decades 2001-2010 and 2011-2020 and the increase from 2021 was observed subsequently based on the average precipitation in each period.

The average precipitation in Bothnian Bay from 2001-2010 amounts to 113390 Mm^3, 2011- 2020 amounts to 114483 Mm^3 and the value for 2021 provided is 116787 Mm^3 The % change in these average values amounts to 0.96% between the first 2 decades and 2% between the second and third decades which can be corroborated by the increase in precipitation rate in Northern Europe. Therefore, an average estimate of a 1.5% increase in precipitation has been considered for the period between 2031-2040 and 2041-2050 although values up to 2045 are required. The values for 2022-2030 remain the same as provided for 2021. The annual forecasted precipitation for the period 2027-2045 is as presented in Table 4 and Figure 5.

Forecasting availability of freshwater resources (2027 -2045)

Data from Eurostat with regards to freshwater resources from the period 2012-2021 was first obtained for the Bothnian Bay River Basin District (RBD) [27]. To perform the regression analysis the precipitation data from 2012 onwards is utilized to match with the fresh water data availability. With the two important datasets obtained, the Excel toolbox is utilized to perform the regression analysis. The dependent variable is considered to be freshwater resources and the two dependent variables are time and precipitation. The period 2012 – 2021 is considered for the regression model. The output suggests an 82% correlation i.e., the r square value implying that roughly 82% of the variability of y (freshwater resources) can be explained by the entire set of independent variables in this case which are time and precipitation. The multi-linear regression equation is as follows where X_t represents the time variable and X_p represents the precipitation variable and is used to calculate avg freshwater resources from 2022-2045. Tables 2 and 3 represent the statistical results obtained.

$$y = -2291 - (43.77X_t) + (0.722X_p) \tag{2}$$

TABLE 2 REGRESSION ANALYSIS COEFFICIENT OUTPUTS

	Coefficients
Intercept	-2291.808369
Time	-43.77094106
Precipitation (Mm^3)	0.722712618

TABLE 3 REGRESSION ANALYSIS R^2 OUTPUT

Regression Statistics	%
Multiple R	0.909116043
R Square	0.826491979
Adjusted R Square	0.776918258
Standard Error	5382.364173
Observations	10

Equation 2 has been further utilized to quantify the freshwater resources for the period 2027-2045 as observed in Table 4**.**

Surface Water Availability (2027 – 2045)

Further, these estimations are used to calculate the surface water availability year on year. With insights from the WISE data catalogue [28], the total number of surface water and total area occupied by it accounts for close to 87% of the total freshwater in the Bothnian Bay RBD. This however does not quantify the volume of surface water available annually. Therefore, further analysis from the AQUASAT Dissemination study [29] suggested that the average annual surface water availability in Sweden amounts to 173 Bm^3 and groundwater 20 Bm^3. This implies that approximately 89% of the volume of freshwater resources is accounted for by surface water bodies only indicating that there is more surface water in volume as compared to ground water resources. The same estimation of 89% has been considered to determine the availability of surface water in the period 2027-2045 as represented in Table 4 and Figure 4. For instance, from 2027 onwards, 89% of the freshwater resources amount to 73 Mm^3 of surface water on an average.

TABLE 4 FORECASTED PRECIPITATION, AVAILABLE FRESHWATER AND SURFACE WATER IN THE PERIOD 2027-2045 (MM^3)

Time	Precipitation (Mm^3)	Freshwater resources (Mm^3)	Surface water resource (Bm^3)
2027	116787	81139	72
2028	116787	81096	72
2029	116787	81052	72
2030	116787	81008	72
2031	119123	82646	74
2032	119123	82603	74
2033	119123	82559	73
2034	119123	82515	73
2035	119123	82471	73
2036	119123	82428	73
2037	119123	82384	73
2038	119123	82340	73
2039	119123	82297	73
2040	119123	82253	73
2041	121505	83925	75
2042	121505	83881	75
2043	121505	83837	75
2044	121505	83794	75
2045	121505	83750	75

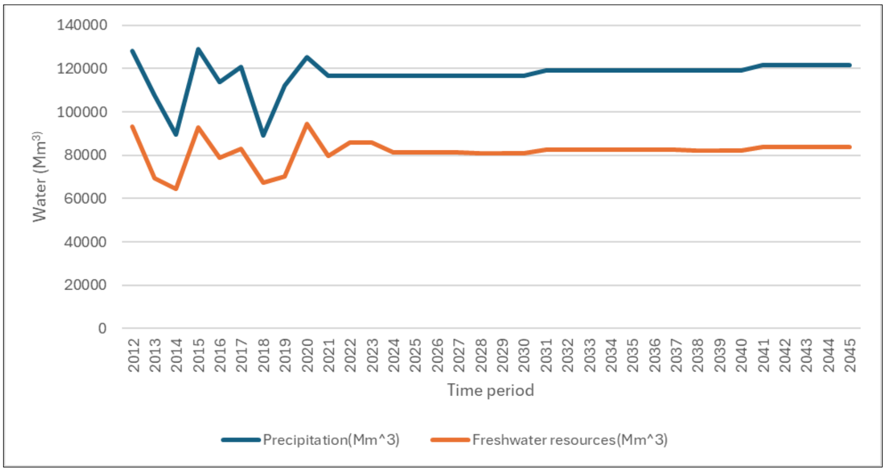


FIGURE 4 INCREASE IN PRECIPITATION AND SURFACE WATER AVAILABILITY IN THE BOTHNIAN BAY RBD (Mm^3)

Estimation of Surface Water Consumption from other sectors

It is also crucial to account for potential surface water consumption from the as-is surface water users to estimate the final water availability in the time period for potential consumers. The surface water consumption data per river basin district every five years since 2000 has been considered from Statiskdatabasen [30] as the basis for the analysis as represented in Table 5. Performing regression analysis does not provide accurate results in this case as it provides a low R^2 value representing a poor correlation between the variable's time and abstraction of surface water every 5 years. An inconsistently fluctuating pattern of low and surface water withdrawal was observed in the period. Therefore, an average estimate of the water withdrawal from the as-is users in the last 20 years was considered and projected up until 2045 to factor in water withdrawal from other sectors with 253 Mm^3 was determined to be the average estimate projected for the period 2027- 2045.

TABLE 5 SURFACE WATER WITHDRAWAL IN 1000 CUBIC METERS IN THE BOTHNIAN BAY RBD EVERY 5 YEARS (2000 – 2020)

Year	2000	2005	2010	2015	2020
Surface Water Withdrawal (1000 cubic m)	254297	259002	276786	227473	249114

4.1.2 Electricity

Under perfect conditions with 100% efficient conversion of electrical energy to chemical energy, the production of 1 kg of hydrogen requires 39.4 kWh/kg which represents the higher heating value (HHV) of hydrogen [31]. The higher heating value (HHV i.e., 39.4 kWh) has been considered in this study as it provides a more realistic estimate of the energy content available from a fuel or a chemical process which also accounts for the heat released when the water vapour produced during combustion is condensed back into liquid water, hence representing the maximum amount of energy that can be obtained from the complete combustion of a fuel. However, in reality, the electricity requirement for producing 1 kg of H_2 ranges from 50-55 kWh which is around 4.5-5 kWh/Nm^3.

Sweden's rich supply of moving water and biomass contributes to the country’s substantial renewable energy output. Hydropower accounts for approximately 45% of Swedish electricity generation and nuclear 30%, together laying the foundation of the Swedish electricity system [32]. Assessments of future electricity demand point to around 200 TWh in 2040 of which wind power has the potential to deliver at least 120 TWh [33]. Moreover, Sweden is expected to generate 60 TWh of wind electricity by 2030 and 120 TWh by 2040 to cater to the escalating need for electrification in the country and enhance the flexibility of the power system. These plans however solely reflect the national objectives and initiatives. Sweden is divided into 4 electricity price areas namely, SE1, SE2, SE3 and SE4 bidding zones as shown in Figure 5a. This section aims towards assessing the forecasted electricity demand and installed capacity of renewables in the SE1 bidding zone during the period 2027-2045 to cater to the increasing demand for electricity for increasing the green hydrogen production to enable the fossil-free transformation in Norrbotten County given that the SE1 bidding zone accounts for the whole county as represented in Figure 5b.

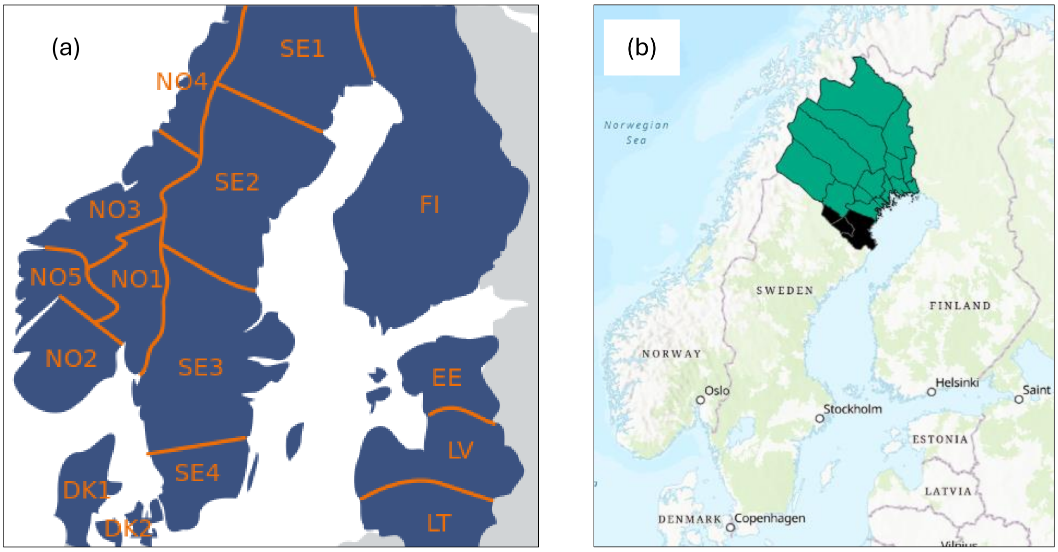


FIGURE 5 A)FOUR ELECTRICITY BIDDING ZONES IN SWEDEN SE1 , SE2 , SE3 , SE4 [60] ; B) NORRBOTTEN COUNTY REPRESENTED IN SE1 BIDDING ZONE

Future Electricity Demand and Installed Capacity of Renewables in SE 1

The goal is to study the future demand for electricity and forecasted installed capacity in the SE1 bidding zone in the given study period. The assumptions, calculations and estimations have been carried forward here from the previous study [34] for the period 2024-2040 which are outside the scope of this thesis. The electricity demand for various sectors including industry, commerce, household and transport as marked in orange has been arrived at considering the forecasted Gross Value Added (GVA) and the energy intensities (I) of each of these sectors as shown in Figure 6. However, this study analyzes the period up to 2045, hence, certain estimations have been made for the period 2041-2045. Taking into account an accelerated growth in the electricity demand from the period 2036-2040 from the referred study, a simple linear regression analysis has been performed taking time as the independent variable and the electricity demand as the dependent variable. Consequently, an R^2 value of 99% was obtained suggesting a fairly good estimation. Equation 3 represents the regression equation where D represents the electricity demand and x_T represents the time period 2041-2045. The output suggests a 99% correlation i.e., the r square value implying that roughly 99% of the variability of D (electricity demand) can be explained by the entire set of independent variables in this case which is time. The complete forecasted electricity demand in SE 1 bidding zone is marked in orange as represented in Figure 6 with an estimated total demand of 30 TWh by 2045.

$$D = -1014.32 + (0.511x_T) \qquad (3)$$

TABLE 6 REGRESSION ANALYSIS COEFFICIENT OUTPUTS

	Coefficients
Intercept	-1014.322
X Variable 1	0.511

TABLE 7 REGRESSION ANALYSIS R^2 OUTPUT

Regression Statistics	
Multiple R	0.999978938
R Square	0.999957876
Adjusted R Square	0.999943834
Standard Error	0.006055301
Observations	5

Furthermore, the cumulative forecasted installed capacity of power generation in SE1 has been obtained from the same study for the period 2024-2040. The forecast is based on today's electricity market and electrical power system, as well as on decisions on future actions planned for the Swedish energy system. Following this, the calculated share of installed capacity in the SE1 bidding zone based on municipality data is considered. This capacity expansion represents business cases from different markets, which is concluded by calculating the net present value (NPV). The forecasted increase in the installed capacity of renewables capacity is also represented in Figure 6. As calculated for the electricity demand , factoring in the accelerated growth observed in installed capacity from the period 2036-2040 from the referred study ,a simple linear regression analysis has been performed taking time as the independent variable and the installed renewable capacity as the dependent variable. Consequently, a R^2 value of 88% was obtained suggesting a fairly good estimation. Equation 4 represents the regression equation where C is the installed capacity and y_T represents the time period 2041-2045. The output suggests an 88% correlation i.e., the R^2 value implying that roughly 88% of the variability of C (Installed renewable capacity) can be explained by the entire set of independent variables in this case which is time. The complete forecasted renewable installed capacity in SE 1 bidding zone is marked in green as represented in Figure 6 amounting to 80 TWh by 2045.

$$C = -4173.48 + (2.08y_T) \tag{4}$$

TABLE 8 REGRESSION ANALYSIS COEFFICIENT OUTPUTS

	Coefficients
Intercept	-4173.48
X Variable 1	2.08

TABLE 9 REGRESSION ANALYSIS R^2 OUTPUT

Regression Statistics	
Multiple R	0.941263199
R Square	0.885976409
Adjusted R Square	0.847968545
Standard Error	1.362350909
Observations	5

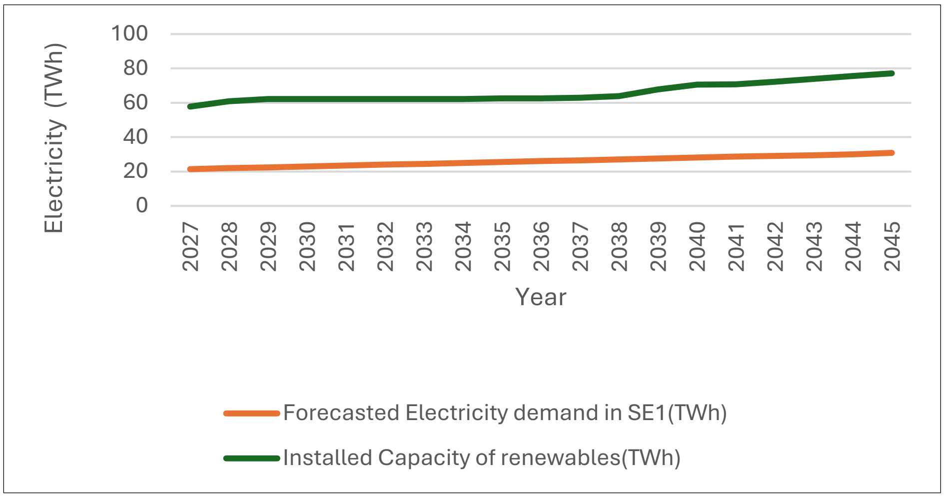


FIGURE 6 FORECASTED ELECTRICITY DEMAND VS INSTALLED RENEWABLE CAPACITY (2027 – 2045)

Transmission Capacity Addition in SE1

To meet the large power requirement of the industry in bidding zone SE1, Svenska kraftnät has created a programme named Fossilfritt Övre Norrland (FÖN) [35] that is further categorized into two investment packages called Norrlandkusten and Malmfälten respectively. These packages aim towards an accelerated completion of transmission networks away from the normal 10-year span in order to meet the industry's demand. Figure 7 shows a map with the initiatives included in the Norrlandskusten and Malmfälten packages. The sole purpose of expanding grid networks is that the new electricity-intensive industries demand abundant electricity that the regional grid power lines cannot efficiently support.

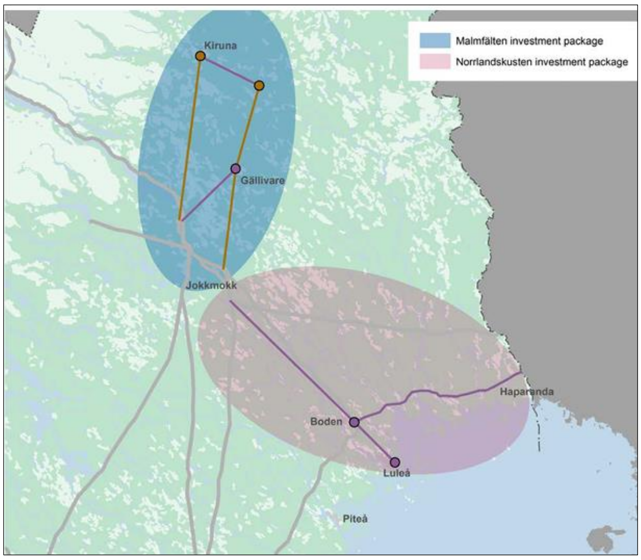


FIGURE 7 MALMFALTEN AND NORRLANDSKUSTEN TRANSMISSION INVESTMENT PACKAGES [35]

The Norrlandkusten investment package as highlighted in Blue in Figure 7 aims to cater to large-scale and electricity-intensive industries along the northern Norrland coast around the cities of Piteå, Skellefteå , Boden, Kalix and Luleå. The package is inclusive of three new systems reinforcing 400 kV power lines, and 400 kV substations.

The Malmfalten initiative as highlighted in blue in Figure 7 particularly will cater to LKAB's continued electrification of mining and iron ore processing at its industrial facilities outside Gällivare, Svappavaara and Kiruna. A new 400 Kv line from Vitafors – Gallivare between the Porjusberget–Naalojärvi substations is underway as illustrated in Figure 7 (marked in purple), close to the HYBRIT demonstration plant planned to be commissioned in 2027. Furthermore, the project aims to build four new 400 kV power lines in the Kiruna Svappavara and Gallivare regions. These are currently under consideration and are anticipated to be commissioned from 2030 onwards. The same has been considered for the GIS analysis that follows. A project is classified as being under consideration when there is an ongoing investigation to assess suitable conditions for possible investments. Furthermore, upon discussion with a representative from Svenskakraftnat [22], implications were made that the requirement for additional transmission lines would arise upon potential hydrogen infrastructure locations in the future. Moreover, any restrictions to transmission capacity building could be potentially compensated by utilising hydrogen storage.

4.2 GIS based MCA analysis

Taking forward the detailed assessment of the key resources within the county for the period 2027-2045 from the previous section, this section studies the geographical availability and accessibility of associated resources that influence decision-making to cater to green hydrogen projects. It is categorized into multiple steps. Firstly it involves a thorough analysis of the criteria and the geographical factors influencing green hydrogen production for which data obtained are in the form of spatial layers such as point, line and polygon files, each representing approximate locations, boundaries and areas of the criteria taken into consideration. Following this, a Multi-Crietria Overlay analysis is performed by assigning weights to the criteria to further develop a site suitability map on ArcGIS Pro. Multi-criteria weighted overlay analysis [11], amongst several applications, is widely utilised in spatial decision-making by evaluating several criteria that hold a favourable or opposing influence over the suitability of the site identified. Therefore, this methodology transforms and combines geographic data and value judgments to obtain information for decision-making by allocating weights to every criterion taken into consideration that renders their relative importance over each other. As a next step, these criteria when spatially overlayed upon each other, result in an integrated geographic map that indicates all regions having high suitability to cater to a particular goal.

4.2.1 Criteria Consideration

The study has factored in ten important criteria that influence the site selection for green hydrogen production. A thorough literature review has been conducted under this segment following which the latest data sets were obtained and the same has been summarized in Table 10 which is inclusive of the source from which it was obtained. The same has been represented in Figures 8 -17. For industries and bed-rock storage data points were developed from scratch and subsequently extracted as compared with the other layers for which data formats were readily available. Moreover over all the data obtained are in the vector format and were individually transformed to raster data sets except the wind power density map which was readily available in the raster format.

TABLE 10 COMPILATION OF GIS CRITERIA DATA

Data	Source
Wind Power density	[36]
Surface Water Bodies	[37]
Planned wind power	[38]
Existing Wind Ppower	[38]
Potential Storage sites	[39]
Restricted zones	[40]
Urban Centers	[39]
Power lines	[39]
Industrial demand points	[41]
Road Networks	[39]

Firstly, the wind power density map has been taken into consideration that can be evaluated for the potential development of wind farms in the future as represented in Figure 8.

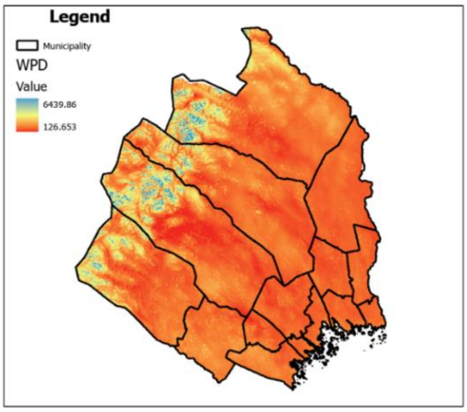


FIGURE 8 WIND POWER DENSITY MAP (W/M²)

Furthermore, nine proximity layers have been considered to evaluate the acceptable distance a particular criterion must hold from the desired location. Since most of the data obtained are in the vector format, it is converted into a raster format.

Each pixel (or cell) in the raster grid has a value which represents some attribute or characteristic of the corresponding location on the ground. This allows to maintain a uniform grid structure and allows for a continuous representation of proximity values across the study area. Since the proximity maps are created based on the criteria, the raster format is beneficial as each pixel value would essentially represent the distance to the nearest feature of interest. Following this conversion, all the raster layers are transformed into proximity maps using the Euclidean distance tool. The distance has been set to metres and is consistent throughout the analysis. This is a crucial step whose results are an input for the suitability analysis. The set of Figures 9 - 17 represents the vector outputs of each criterion alongside the proximity map after conversion using the Euclidean distance tool. It can observed from each figure that the vector map indicates either a point/line/polygon and from the proximity maps, the regions in green indicate closer proximity while the regions in red indicate greater proximity. The same has been associated with a scale of 0-5 where 0 indicates closer proximity and 5 indicates farther proximity. However, only in the case of the wind density map, the original raster format is retained as it stores the values of wind density in each pixel.

Proximity to existing wind power plants, planned wind farms and power lines represent the electricity provision layers as represented in Figures 9, 10 and 11. The red encirclement in Figure 9 also indicates the planned transmission capacity as discussed in section 4.1.2.

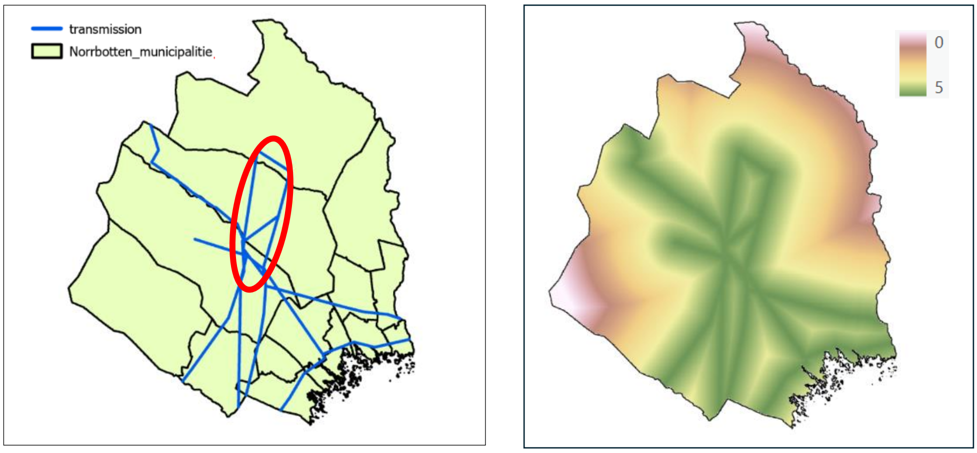


Figure 9 Transmission network (vector and proximity maps)

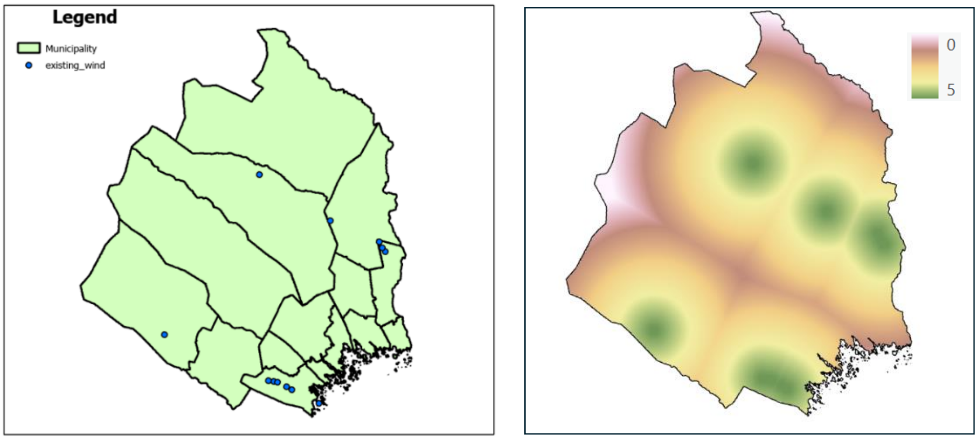


Figure 10 Existing wind power farms (vector and proximity maps)

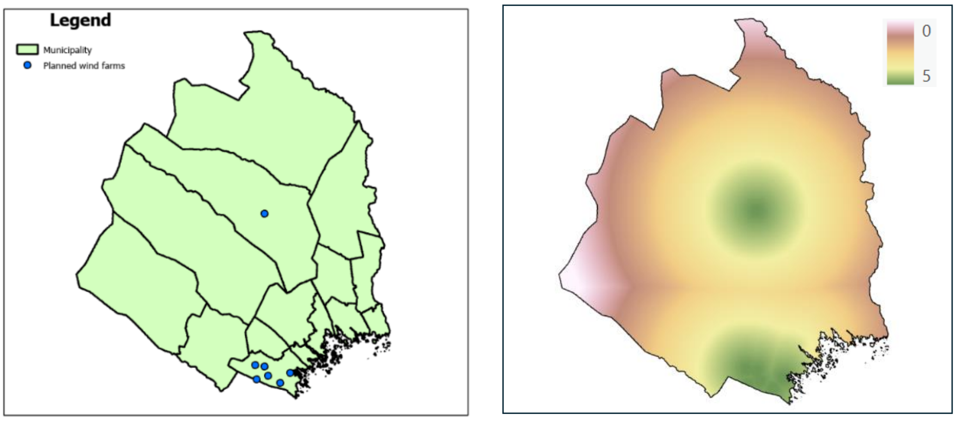


Figure 11 Planned wind farms (vector and proximity maps)

The proximity to surface water bodies Figure 12 is also one of the crucial requirements for green hydrogen production hence having it placed closer to the facility holds high importance.

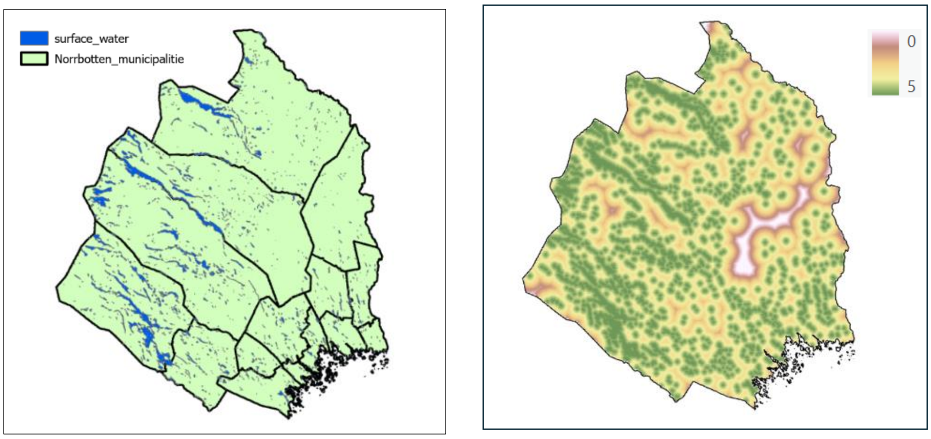


Figure 12 Surface water bodies (Vector maps and proximity maps)

In addition, the proximity to urban areas (Figure 13) and protected areas (Figure 14) represent layers that must be carefully assessed as they are required to be maintained at an acceptable and safe distance from the production facilities. The areas are inclusive of Strict Nature Reserves, wilderness areas, national parks, natural monuments, habitat/ species management sites, protected landscape/ Seascape and managed resource-protected areas. Additionally, the layer also comprises military zones and air-strips.

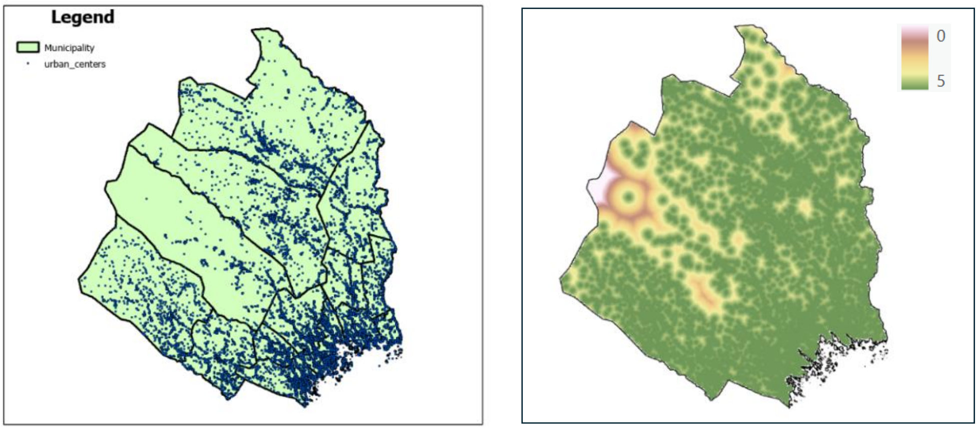


Figure 13 Residential and Commercial urban centres (vector and proximity map)

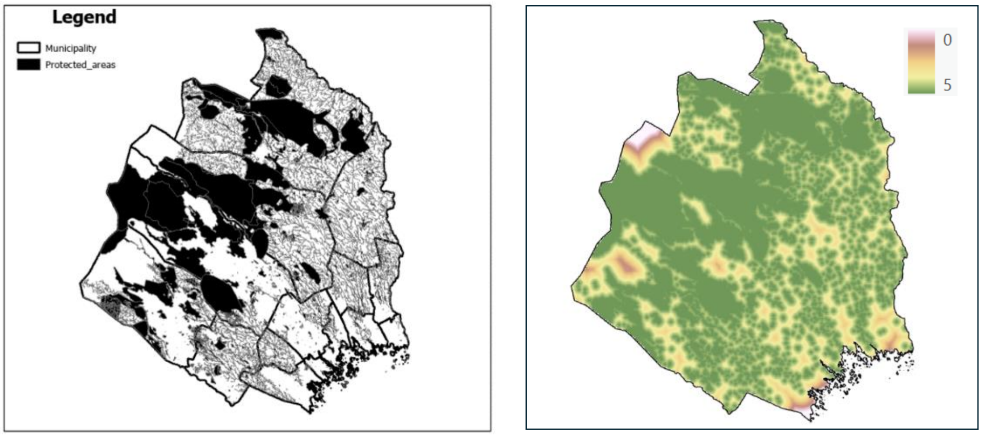


Figure 14 Restricted Areas (Vector and Proximity maps)

Furthermore, proximity to suitable bedrock storage Figure 15 represents all the regions having the potential to store the green hydrogen gas on a larger scale. This criterion in particular takes into consideration only the geographical availability of suitable rock types. The analysis of future cavern hydrogen storage relies fundamentally on the type of geological characteristics of the bedrock, including its stability, permeability, and porosity. The following suitability of bedrock type for storage has been considered to be most suitable for underground H_2 storage potential [42]. Intrusive igneous rocks like granite, granodiorite, diorite, gabbro, syenite, peridotite, and pegmatite groups are considered to be massive, and homogeneous with very low porosity and permeability. Similarly, sedimentary rocks like shales and siltstones are considered to be the most favourable sedimentary lithologies as a result of low permeability and easy excavation. Lastly, metamorphic rocks such as non-foliated metamorphic rocks (quartzites and marbles) are considered to occur in large masses and are suitable for caverns as they are usually homogeneous and show high strength. To corroborate this information, the pilot green hydrogen storage facility in Luleå was studied to have similar geology [43]. The geographical data extracted for such bedrock types has also factored in 1 km of buffer zones around deformation zones such as severely cracked zones, strongly cracked zones and heavily foiled zones. Though it does not account for detailed geophysical characteristics and capacity, the type of bedrock serves as the foundation for evaluating the potential suitability of a site for cavern storage. It forms the basis upon which further assessments can be performed to determine the viability and feasibility of establishing underground caverns for hydrogen storage.

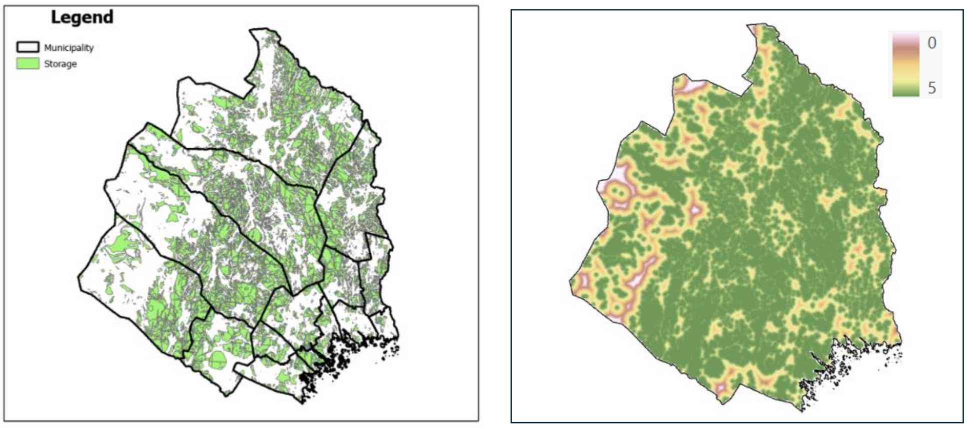


FIGURE 15 SUITABLE BEDROCK TYPE FOR STORAGE (VECTOR AND PROXIMITY MAPS)

The proximity to roads as represented in Figure 16 aims towards giving a certain level of importance to hydrogen transportation and potentially indicates how accessible a location is. Areas that are closer to roads are typically easier to reach and may have better transportation infrastructure, which can be crucial for various activities.

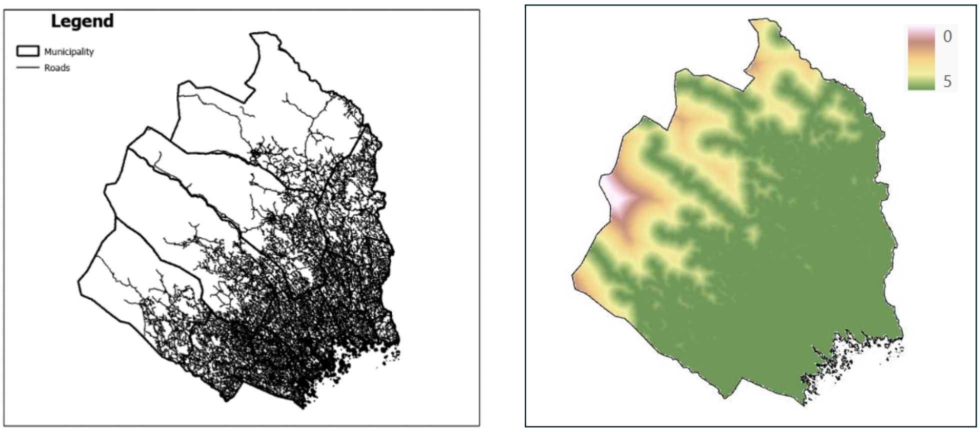


FIGURE 16 ROAD NETWORKS (VECTOR AND PROXIMITY MAPS)

Most importantly the proximity to industries (Figure 17) with the potential to use green H_2 is considered to establish an approximate spatial demand. The primary demand points under consideration in this study are the 3 iron ore mines namely; the Kiirunavaara Mine located in Kiruna, the Malmberget Mine located near Gällivare and the Svappavara Mine also located in Kiruna in Norrbotten County as the study aims towards catering to the iron and steel industry which is discussed in detail in section 4. As addressed in the previous sections, plans to achieve a complete fossil-free transformation of the iron industry by 2045 essentially imply the complete transformation of extracted iron ore into sponge iron before supplying it to the Swedish steel industry (SSAB) and for export purposes. Towards this, the three iron ore mines have been considered as the demand points and the same is represented in Figure 17.

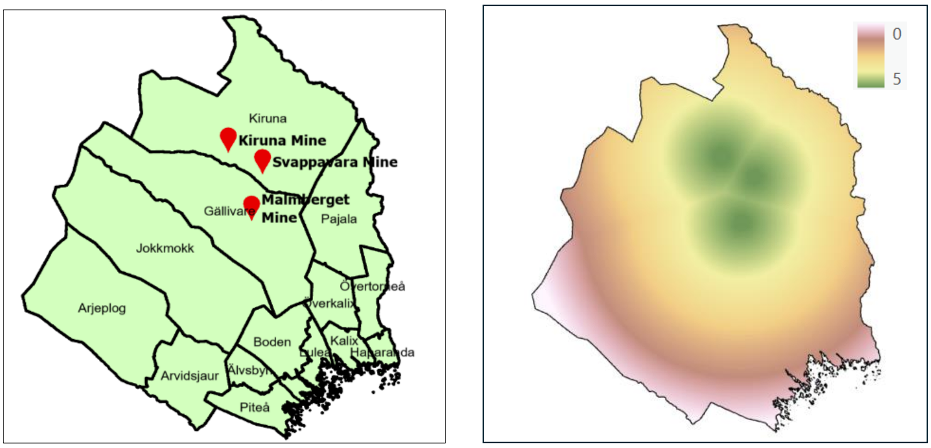


FIGURE 17 IRON ORE MINES (VECTOR AND PROXIMITY MAPS)

4.2.2 Multi-Criteria Analysis

To undertake the MCA analysis, the AHP (Analytical Hierarchy process) [44, 59] has been particularly utilized to assign the weights to each criterion. Saaty's 9-point scale [11,16] as represented in Table 11 is used to assign the weights following which the criteria are compared pairwise and a priority matrix is obtained which in turn is fed into the GIS systems to perform the suitability analysis.

TABLE 11 SAATY'S 9 POINT WEIGHTING SCALE

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over the other	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another.
7	Very strong importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals	If activity I has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i	

These weights in turn help obtain the pairwise comparison matrix as represented in Table 12 [59]. The matrix is in the form of a square matrix in which the rows and columns represent the criteria that have been taken into consideration. This method is used to analyze multiple criteria in pairs to determine their importance over each other, thereby analyzing the level of preference. The diagonal in the matrix is always set to 1 whereas the values falling under the diagonal are the reciprocal values of the values above the diagonal and visa-versa. The pairwise comparison matrix is filled comparing each layer to the other where each cell in the matrix represents the importance of each row layer in correspondence to the column layer. These weights are assigned as a result of a survey conducted that highlights a subjective approach where expert opinion and academic judgement, hold the key. Interestingly, the responses remained more or less similar in each case which benefitted the analysis.

TABLE 12 PAIRWISE COMPARISON MATRIX

	Wind Power existing	**Wind Power Planned**	**Proximity to roads**	**Proximity to surface water**	**Proximity to urban areas**	**Proximity to restricted areas**	**Proximity to storage**	**Proximity to planned industries**	**Proximity to power lines**	**Wind power density**
Wind Power existing	**1**	2	3	1/4	1/2	1/5	1/3	5	1/4	1/3
Wind Power planned	1/2	**1**	2	1/5	1/2	1/5	1/3	1/2	1/7	1/3
Proximity to roads	1/3	1/2	**1**	1/6	1/3	1/5	1/5	1/2	1/7	1/2
Proximity to surface water	4	5	6	**1**	4	4	3	5	1	5
Proximity to urban areas	2	2	3	1/4	**1**	1/2	2	3	1/5	3
Proximity to protected areas	5	5	5	1/4	2	**1**	4	4	1/3	5
Proximity to storage	3	3	5	1/3	1/2	1/4	**1**	4	1/3	4
Proximity to existing industries	1/5	2	2	1/5	1/3	1/4	1/4	**1**	3	6
Proximity to power lines	5	3	5	1	3	3	1	1/3	**1**	2
Wind power density	1/3	1/5	1/5	1/6	1/4	1/5	1/6	1/5	1/8	**1**

To fill the pairwise comparison matrix and obtain the priority matrix the following submissions have been made. Surface water resources and proximity to the power lines have been given a higher degree of importance (a value of 1 as shown in Table 12) given that they are the primary requirements and equally important for the production of green hydrogen and the establishment of its infrastructure. It can be also noticed that power lines are given more importance than the existing, planned wind power production facilities and wind power density maps. Power production may not be centralized for the sole purpose of green hydrogen production due to several geographical constraints in Norrbotten County hence transmission lines become crucial for providing electricity from distant renewable energy facilities to the hydrogen production sites. This also facilitates in balancing supply and demand potentially reducing costs associated with energy transportation. Next, it can be observed that protected areas or restricted zones have been given the highest priority as they are considered to be off-limits from any establishment of green hydrogen infrastructure. However, power lines and surface water still hold more preference over the restricted zones given that they are the key requirements and do not directly impact the environment but rather utilize resources that have to be transported to the desired location. Similarly, locating hydrogen production facilities too close to densely populated urban areas can raise concerns about safety and public acceptance, therefore areas that are sufficiently distant from densely populated regions are prioritised. The proximity to potential storage sites, in this study, engineering rock caverns, is given a high preference as they can potentially enhance the feasibility and cost-effectiveness of hydrogen production projects.

Moreover, the proximity to industrial demand interestingly has been considered to hold lower importance over several criteria like the proximity to surface water, urban areas, restricted zones and potential storage sites. This is the case as these important criteria are inclusive of aspects pertaining to production, storage, socio-environmental acceptability as well as potential pipeline transfers however the former only looks from the consumption point of view. It is interesting to note that these demand points considered are primarily the iron ore mines in North Sweden and there is a possibility to have sponge iron factory setups distributed across the county rather than having them centralized near the mines themselves.

Following the completed pairwise comparison matrix, the criteria weights also known as the priority values (principal eigenvector) are determined. In this method [11], all the entries per row from Table 12 are multiplied. Following that, the nth root of each product is then computed (where n is the number of criteria) and is summed across all rows. To ensure that the sum of the principal eigenvector elements equals one, normalization is applied, yielding the priority matrix, which essentially represents the criteria weights as shown in Table 13.

TABLE 13 PRIORITY MATRIX

CRITERIA	FINAL WEIGHTS
Wind Power existing	0.0562
Wind Power planned	0.0345
Proximity to roads	0.0269
Proximity to surface water	0.2716
Proximity to urban areas	0.0980
Proximity to protected areas	0.1739
Proximity to storage	0.1042
Proximity to existing industries	0.0625
Proximity to power lines	0.1525
Wind power density	0.0192

The last step involves determining the consistency ratio (CR) which provides a means ensure the accuracy of the matrix and robustness of the decision or judgement that has been made. A consistency ratio of <0.1 or 10% indicates a reasonable level of consistency in the pairwise comparisons [11].To obtain the CR, firstly values from each column of the pairwise comparison matrix are multiplied with the corresponding criteria weight or priority matrix to obtain a new normalized matrix as observed in Table 14 .Row-wise values are summed up which are then divided by the corresponding priority value for each criterion. This then helps determine the λ_{max} (which has been considered to be the average [11] of the new vector obtained based on the method used).

TABLE 14 NORMALIZED MATRIX

0.05624	0.06907	0.08081	0.06792	0.04902	0.03479	0.03476	0.31259	0.03815	0.00642
0.02812	0.03453	0.05387	0.05433	0.04902	0.03479	0.03476	0.03126	0.02180	0.00642
0.01875	0.01727	0.02694	0.04528	0.03268	0.03479	0.02086	0.03126	0.02180	0.00963
0.22497	0.17267	0.16162	0.27166	0.39219	0.69572	0.31283	0.31259	0.15259	0.09632
0.11249	0.06907	0.08081	0.06792	0.09805	0.08697	0.20856	0.18756	0.03052	0.05779
0.28121	0.17267	0.13468	0.06792	0.19609	0.17393	0.41711	0.25007	0.05086	0.09632
0.16873	0.10360	0.13468	0.09055	0.04902	0.04348	0.10428	0.25007	0.05086	0.07706
0.01125	0.06907	0.05387	0.05433	0.03268	0.04348	0.02607	0.06252	0.45776	0.11558
0.28121	0.10360	0.13468	0.27166	0.29414	0.52179	0.10428	0.02084	0.15259	0.03853
0.01875	0.00691	0.00539	0.04528	0.02451	0.03479	0.01738	0.01250	0.01907	0.01926

This is further utilized to calculate the CR which is defined as the ratio of the consistency index (CI) and the random index (RI) as represented in Table 15 [11], which has been derived from the Saatys book in which a set of judgements is used for the corresponding value from large samples of matrices for the computation of CR. It can be observed based on this study that with n=10 the RI is 1.49.

TABLE 15 RANDOM INDEX[34]

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

In this case, $\lambda_{max} = 11.241$

Once the principal eigenvalue is obtained, the CR is calculated as follows:

$$C.I = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

$$\frac{11.24-10}{10-1} = 0.137$$

Therefore the consistency ratio $(C.R) = \frac{CI}{RI}$ (6)

$$\frac{0.137}{1.49} = 0.093$$

Given that the value 0.093 is less than 10%, the pairwise comparison matrix indicates reasonable consistency to proceed with the suitability analysis on GIS.

4.2.3 Multi-Criteria Overlay Analysis on GIS

With the weights obtained through the AHP pairwise comparison methodology, the multi-criteria overlay analysis is then performed on the Arc-GIS software. Using the built-in suitability analysis tool on the Arc-GIS software, the suitability analysis is performed by feeding in the proximity raster maps and assigning the weights previously determined.

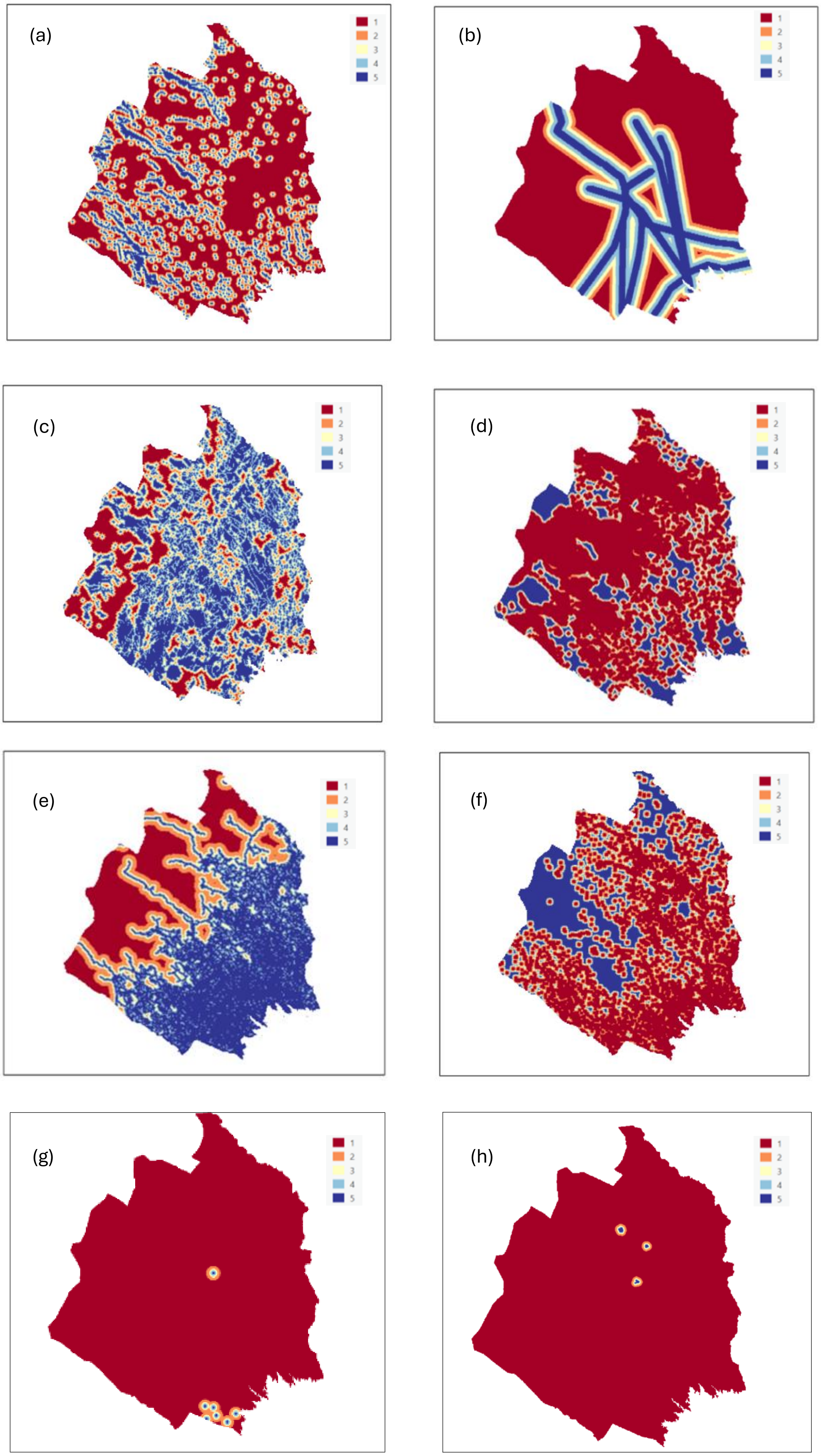
In the ArcGIS software, the Suitability Analysis tool assesses the suitability of several locations for specific activities, applications, land uses or purposes based on a set of criteria or factors. The suitability scale in ArcGIS refers to the range of values used to represent the suitability of locations within the study area. The suitability scale in this study is set from 1-5 with 1 representing low suitability and 5 representing high suitability. Furthermore, the analysis has been conducted on the basis of weights by % as the priority matrix represents the percentage importance one criterion holds over the other.

Next, all the proximity layers are added into the tool against which the weights that were determined earlier as assigned respectively. Each layer is then re-classified against the 1-5 suitability scale. To do so, the suitability scores for each layer are assigned in the form of proximity ranges. This score represents the degree to which the location meets the criteria specified by the input factors. This score is then assigned for all the criteria based on discussions with industrial experts and individual analysis. Table 16 represents the same. As it is observed, for some criteria like proximity to wind power plants, the closer it is to the location of interest the better hence is assigned a suitability score of 5. Whereas, in the case of restricted zones, the further it is from the location of interest, the higher the suitability and is an example of reverse scaling. Similarly, the proximity ranges have been established for all criteria as observed in Table 16.

TABLE 16 SUITABILITY SCORE MATRIX FOR EACH CRITERION

SCORE	Wind Power existing (km)	Roads (km)	Power lines (km)	Surface water (km)	Urban areas (km)	Restricted areas (km)	Storage (km)	Industry (km)	Wind power planned (km)	Wind density (W/m2)
5	<2	0.5 - 1	<5	0.5 - 1	>6	>6	<1	<0.5	<2	>800
4	2 - 4	1 - 2	5 - 10	1 - 2	5 - 6	5-6	1 - 2	0.5 - 1	2 - 4	600 - 800
3	4 -6	2 - 4	10 -15	2 - 3.5	4 -5	4-5	2 - 3.5	1 - 2.5	4 -6	400 - 600
2	6 -10	4-10	15 - 20	3.5 - 5	3 - 4	3-4	3.5 - 5	2.5 - 5	6 -10	200 - 400
1	>10	>10	>20	5 - 10	<3	<3	>5	>5	>10	<200

The proximity ranges and the respective suitability scores assigned are used to transform the proximity maps obtained section 4.2.1 into the maps as represented in Figures 18 (a-j). These maps store the respective suitability scores that have been assigned to each proximity range as represented in Table 16. Regions in blue represent the maximum suitability score of 5 whereas the red region represents the least suitability.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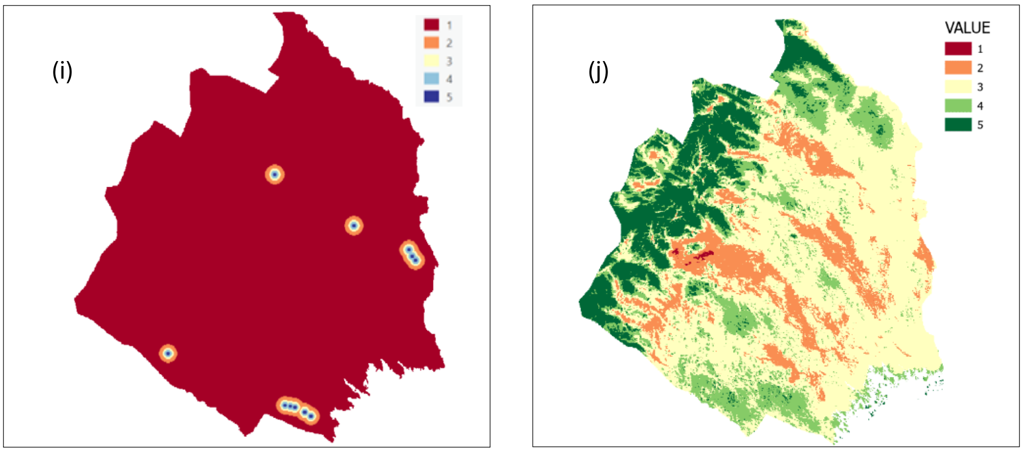

Figure 18 Transformed maps obtained based on assigning the suitability scores.a) Surface water b)transmission lines c) Storage d) Restricted Areas e) road networks f) urban centres g) planned wind farms h) iron ore mines i) existing wind power farms j) wind power density

Following the integration of all the above transformation maps, the final suitability map is obtained on Arc GIS which is discussed in detail in the results section.

4.3 Hydrogen Demand Analysis

Having done the site suitability assessment in the previous section, this section focuses on estimating the potential green hydrogen demand in Norrbotten County taking the iron and steel sector as the primary beneficiary owing to its high dependency on fossil fuels. This will in turn help in estimating the annual water and electricity required to cater to the potential demand of green hydrogen.

As a prelude to analyzing the hydrogen demand for the envisioned study period 2027 - 2045, it is crucial to understand the key process that is on the verge of complete transformation. As HYBRIT has been found to neutralize the adverse effects of the BOF reduction process, the study revolves around the reduction of iron ore into sponge iron production using green hydrogen. This transformation to sponge iron alone has been estimated to demand a significant quantity of green hydrogen as compared to other sectors within the county.

The iron used in the steelmaking process is currently chemically reduced from iron ore using the blast furnace route through the use of fossil resources, mainly coal or natural gas. In this process, carbon combines with the oxygen from the iron ore thereby producing metallic iron and CO_2 [45] and the same is represented in Equation 7 below according to the following simplified chemical reaction:

$$2Fe_2 O_3 + 3C \rightarrow 4Fe + 3CO_2 \tag{7}$$

Figure 19 represents the detailed processes that are involved in the BOF Route of manufacturing steel. As observed, the raw iron ore is first mined and processed into pellets which are small balls consisting of a mix of upgraded iron ore, oxides and additives with iron concentrations lying between 66.7 and 67.8 per cent. They are further transported to the steel manufacturers who utilize the raw iron ore pellets to produce molten metal via BOF reduction using coke that is further processed alongside scrap into different steel products.

The green steel pathway, which is also the foundation of the HYBRIT initiative has gained tremendous recognition given its potential to de-carbonize the iron and steel industry. In this pathway, green hydrogen is utilized to directly remove (reduce) the oxygen content in the raw iron ore to produce sponge iron [45] that retains its solid form and wastewater as the by-product. This is then further processed in an Electric Arc furnace for the production of green steel. It is further transported to the steel manufacturers where they are fed into the Electric Arc Furnace (EAF) alongside scrap to produce molten steel that is subject to further processing. This process is known as Direct Reduced Ironmaking (H_2 - DRI). The following Equations 8 and 9 represent the same:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \tag{8}$$

$$FeO + H_2 \rightarrow Fe + H_2O \tag{9}$$

\

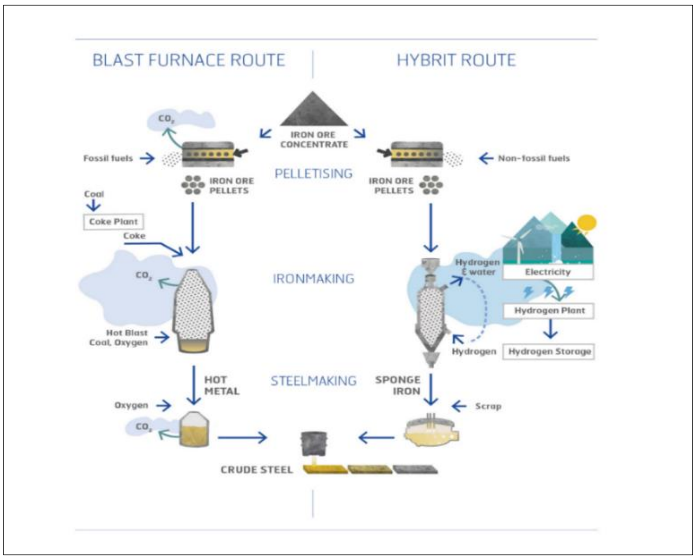

Figure 19 Blast Furnace Route of reducing iron ore vs HYBRIT Route [46]

Towards this, the annual green hydrogen demand for the given study period 2027-2045 has been estimated using the following steps:

1. **Iron Ore Extraction**: Estimation of annual iron ore extracted in Norrbotten County.
2. **Sponge Iron ore Capacity Building**: Estimation of sponge iron production potential from the iron ore extracted.
3. **Theoretical H2 demand estimation**: Quantifying the associated theoretical hydrogen demand to cater to the reduction process.

4.3.1 Iron Ore Extraction

There exist 3 iron ore mines in the country namely, Kiirunavaara Mine located in Kiruna, Malmberget Mine located near Gällivare and Svappavara Mine also located in Kiruna, all within Norrbotten County as represented in Figure 20. Each of the three mines has anticipated future iron ore extraction potential, extraction period and the scheduled iron ore extraction per year under Proven and Probable Mineral Reserves [47 ,48] which is represented in the Table 17.

Table 17 Scheduled quantity[8], extraction period and average annual extraction of iron ore (Kiruna, Svappavara and Malmberget mines) from Proven and Probable mineral reserves

	KIRUNA	MALMBERGET	SVAPPAVARA
Quantity (Mt)	757	284	97
Extraction period (years)	2023 - 2048	2023 - 2041	2023 - 2035
Scheduled Avg annual extraction (Mt/y)	29	17 up to 2033 and 15 thereafter	7.4

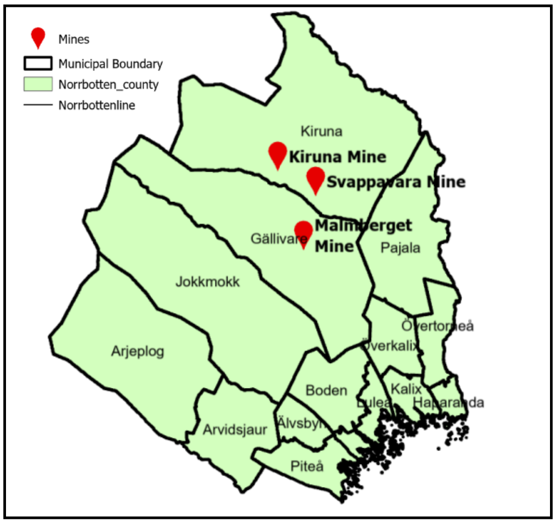

Figure 20 Iron ore mines in Norrbotten

It can be observed that the final year of the extraction period in each of the mines is inconsistent and is not representative of the extraction period required for this study i.e., 2027-2045 in the case of Malmberget and Svappavara.In order to study the iron ore extraction potential in the two mines after 2041 and 2035 respectively, data on mineral resources classified as Measured, Indicated and Inferred [47, 48] are considered in addition to the proven and probable Mineral Reserves which are essentially the next step to iron ore extraction from the mines and the same is represented in Table 18. In this case, only the quantity was provided using which the average annual extraction was estimated as follows. Firstly, using Tables 17 and 18, the time taken for extraction by the measured and indicated iron ore reserves (t_m) is estimated by considering the Quantities of measured and indicated iron ore (m_q) extracted, proven and probable mineral reserves (p_q) and the time taken for extraction by the proven and probable mineral reserves (t_p). Following that, the scheduled average annual extraction from each mine (E_{mine}) is calculated by considering the quantity of measured and indicated iron ore (m_q) and the time taken for extraction by those reserves (t_m).

$$t_m = \frac{m_q \times t_p}{p_q} \tag{10}$$

$$E_{mine} = \frac{m_q}{t_m} \tag{11}$$

Table 18 Scheduled quantity, Estimated Extraction period and estimated average annual extraction of iron ore (Kiruna, Svappavara, Malmberget mines) from Measured Indicated and Inferred mineral reserves[8]

	KIRUNA	MALMBERGET	SVAPPAVARA
Quantity (Mt)	799	1196	688
Extraction period (years)	2049 onwards	2042 onwards	2036 onwards
Scheduled Avg annual extraction (Mt/y)	29	15	14

Similarly, the calculations were made for the Svappavara mine. With this, the average annual extraction of iron ore for the entire study period has been established. This further aids in calculating total iron ore extraction year on year. Further, it is then important to estimate the sponge iron production potential from the extracted iron ore as represented in Equation 12 [49].

1 ton of sponge iron requires ~ 1.5 tons of iron ore (12)

This conversion rate is used to estimate the sponge iron production potential based on the cumulative iron ore extracted from all 3 mines year-on-year which is represented in Table 19.

TABLE 19 AVERAGE ANNUAL EXTRACTION OF IRON ORE FROM 3 MINES, TOTAL EXTRACTION CAPACITY OF IRON ORE AND SPONGE IRON PRODUCTION POTENTIAL YEAR ON YEAR

Year	Avg annual iron ore extraction from Malmberget (Mt)	Avg annual ore extraction from Kiruna (Mt)	Avg annual iron extraction from Svappavara (Mt)	Total Extraction Capacity (Mt)	Sponge iron production potential (Mt)
2027	17	29	7.4	53	35.2
2028	17	29	7.4	53	35.2
2029	17	29	7.4	53	35.2
2030	17	29	7.4	53	35.2
2031	17	29	7.4	53	35.2
2032	17	29	7.4	53	35.2
2033	17	29	7.4	53	35.2
2034	15	29	7.4	51	33.9
2035	15	29	7.4	51	33.9
2036	15	29	14	58	38.3
2037	15	29	14	58	38.3
2038	15	29	14	58	38.3
2039	15	29	14	58	38.3
2040	15	29	14	58	38.3
2041	15	29	14	58	38.3
2042	15	29	14	58	38.2
2043	15	29	14	58	38.2
2044	15	29	14	58	38.2
2045	15	29	14	58	38.2

4.3.2 Sponge Iron Production Capability Building

In this step, the additional requirement of sponge iron factories' capacity to be built is established within the study period to enable the complete transformation of their processes. The development of the first demonstration plant of 1.35 Mt sponge iron capacity [14] is already underway and has been set to commission in early 2027 following which a full-scale plant twice the capacity of the demonstration plant of 2.7 Mt/y is scheduled for operation starting in early 2030 as stated by SSAB and LKAB [14].

Taking a cue from this time interval, an addition of sponge iron capacity takes place every 3 years and has also been considered a reasonable estimation by SSAB and LKAB. Furthermore, the increase in capacity is such that, in 2030 the sponge iron factory is said to have double the capacity of the demonstration plant (1.35 Mt/y), therefore in 2033 the capacity added is assumed to be 3 times the capacity added in 2027 and so on and so forth, every 3 years until the years 2045 as presented in Table 20**.** It can be observed that in 2045 the cumulative sponge iron capacity factories added amounts to a total of 38 Mt of sponge iron capacity to achieve the complete conversion of all their iron ore extracted by 2045.

TABLE 20 SPONGE IRON CAPACITY BUILDS UP ONCE IN 3 YEARS AND CUMULATIVE CAPACITY YEAR ON YEAR

Year	Sponge iron Capacity Built (Mt)	Cumulative sponge iron capacity built (Mt)
2027	**1.35**	**1.35**
2028	0	1.35
2029	0	1.35
2030	**2.7**	**4.05**
2031	0	4.05
2032	0	4.05
2033	**4.05**	**8.1**
2034	0	8.1
2035	0	8.1
2036	**5.4**	**13.5**
2037	0	13.5
2038	0	13.5
2039	**6.75**	**20.25**
2040	0	20.25
2041	0	20.25
2042	**8.1**	**28.35**
2043	0	28.35
2044	0	28.35
2045	**9.90**	**38.25**

The sponge iron production potential from the iron ore extracted helps to determine the theoretical hydrogen that is required in the conversion process which has been evaluated in the results section.

4.3.3 Theoretical H2 Demand Estimation

The stoichiometric consumption of hydrogen for reducing ~1.5 ton hematite (Fe_2O_3) is estimated to be 54 kg [50,52] . As benchmarked in the previous section that 1.5 tons of iron ore is required to produce 1 ton of sponge iron, it can be inferred that 54kg of H_2 is theoretically required for the production of 1 ton of sponge iron. However, LKAB extracts high-grade magnetite [51] having the chemical notation (Fe_3O_4).To calculate the hydrogen demand to reduce magnetite per ton of sponge iron, the calculations are as follows:

The chemical equations that comprise the reduction reaction of iron oxides to iron

Hematite ore : $Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$ (13)

Magnetite ore : $Fe_3O_4 + 4H_2 = 3Fe + 4H_2O$ [12] (14)

The H_2 required for magnetite ore (M_{H_2}) is estimated by utilizing the stochiometric coefficients for magnetite (S_m) and the hematite (S_h) ore and also the hydrogen required to reduce the hematite ore i.e., 54 kg.

$$M_{H_2} = \frac{S_m}{S_h} \times 54 \quad (15)$$

$M_{H_2} = \frac{4}{3} \times 54 = 72\ kg\ of\ H_2$

Building upon the previous step, the associated annual hydrogen demand (D_{H_2}) is determined by applying Equation 16 to the projected growth in sponge iron capacity (Sn, where n denotes the year) as established in Table 20.

$$D_{H_2} = M_{H_2} \times S_n \qquad (16)$$

For instance, from Table 20 , in 2027, the calculation is as follows,

$72 \times 1.35 \sim 97\ kt\ of\ H_2$

Similarly, the annual hydrogen demand based on this calibrated incorporation of sponge iron factories through the study period has been calculated as presented in the results section.

5. Results and Discussions

Reflecting on the main research questions, the results delve into the estimation of annual hydrogen demand, calibrated electrolyser capacity and efficiency required followed by final electricity and water adequacy in Norrbotten County to cater to this demand. Furthermore, the results from the suitability analysis have also been presented and discussed to locate the most suitable sites to cater to this green hydrogen expansion.

5.1 Theoretical H_2 Demand

The method in section 3.3.2 is utilized to further calculate the annual theoretical hydrogen demand required for the sponge iron production as represented in Table 21. It can be observed that 97 kt is demanded annually in the period between 2027-2029 given there is no additional sponge iron capacity in the given period. However, an additional capacity of 2.7 Mt sponge iron capacity can be observed in 2030 from Table 20 due to which the cumulative capacity of sponge iron in 2030 is observed to be 4.05 taking into account the 1.35 sponge iron capacity which amounts to a cumulative hydrogen demand of 292 kt. Similarly, the cumulative theoretical hydrogen demand is calculated year-on-year and suggests a total hydrogen demand of 2.7 Mt for the production of 38.25 Mt of fossil-free sponge iron from 2045 onwards.

TABLE 21 ESTIMATION OF THEORETICAL H_2 DEMAND FOR SPONGE IRON PRODUCTION

Year	Cumulative sponge iron capacity (Mt)	Cumulative theoretical H2 demand (kt)
2027	**1.35**	**97**
2028	1.35	97
2029	1.35	97
2030	**4.05**	**292**
2031	4.05	292
2032	4.05	292
2033	**8.1**	**583**
2034	8.1	583
2035	8.1	583
2036	**13.5**	**972**
2037	13.5	972
2038	13.5	972
2039	**20.25**	**1458**
2040	20.25	1458
2041	20.25	1458
2042	**28.35**	**2041**
2043	28.35	2041
2044	28.35	2041
2045	**38.25**	**2754**

The estimations on the hydrogen demanded further can be used to arrive at the required electrolyzer efficiency to meet the theoretical demand for hydrogen that has been previously established year on year. The system efficiency is assumed to include stack efficiency, auxiliary power consumption, stack energy losses, and electrical losses in the installations. Furthermore, the operation hours per year (h) for an electrolyser are said to fall between 2000 and 7500 hours [53], therefore this study considers the maximum number of hours it could potentially run i.e., 7500 hours. A 700 MW electrolyser (E_{cap}) has been planned for the 1.35 Mt sponge iron factory in 2027 [1,14] which theoretically demands 97 kt of H_2. As a first step, the minimum electrolyzer efficiency (η_{min}) to meet this demand of 97 kt (D_{H_2}) is determined to set a baseline requirement. The formula utilized to determine this is as follows;

$$D_{H_2} = \frac{E_{Cap} \times h \times \eta_{min}}{HHV_{H_2}} \tag{17}$$

$$97 = \frac{700 \times 7500 \times \eta_{min}}{39.4}$$

Therefore the minimum electrolyzer efficiency to meet the theoretical demand for hydrogen for the sponge iron transformation is 73%. In reality, however, there is potential for an increase in the electrolyzer efficiency within the time period 2027-2045. In that case, electrolyzers will have the potential to produce more hydrogen which they can cater to other beneficiaries apart from satisfying the theoretical hydrogen demand for the sponge iron transformation depending on the quantity demanded.

This further aids in the estimation of the required capacity of electrolyzers in the period 2027-2045. Given that a 700MW (E_{cap}) electrolyzer facility has been planned for a 1.35 Mt sponge iron factory (S_{year1}) in 2027 with a minimum electrolyzer efficiency requirement of 73%, the total electrolyzer capacity required (E_{tot}) for the production of 38 Mt of sponge iron (S_{tot}) which is the total amount to be transformed by 2045 amounts to approximately 20 GW using Equation 18.

$$E_{tot} = \frac{E_{cap} \times S_{tot}}{S_{year1}} \tag{18}$$

$$E_{tot} = \frac{700 \times 38}{1.35} \sim 20\ GW$$

5.2 Electricity and Water Requirement

With the annual hydrogen demand estimated in the previous section, this section further determines the associated electricity and water demand from the process and evaluates any potential deficit in resource availability to cater to the demand as discussed in Section 3.1.1 and 3.1.2.

5.2.1 Electricity Component

It has been established that 1 kg of hydrogen has a higher heating value of 39.4 kWh/kg. Therefore this value also suggests that an electrolyzer of 100% can entirely convert this electrical energy stored per kg of hydrogen into chemical energy using 39.4 kWh/kg of power. With this ideal assumption, the electricity demand has been first determined year on year as determined annually and the same is represented in Table 18. To determine the electricity demanded (ED), Equation 19 has been utilized.

$$ED = \frac{D_{H_2} \times HHV_{H_2}}{1000} \tag{19}$$

$$ED = \frac{97 \times 39.4}{1000} \sim 3.8\ TWh$$

Similarly, the electricity demand in an ideal case has been determined annually. The cumulative electricity demand by 2045 amounts to 108 TWh which has also been corroborated by LKAB [14].

The next step is to determine the electricity demand with the realistic efficiencies factored in and in this case is considered to be 73% as determined previously to obtain the theoretical hydrogen demanded by the process. The ideal electricity demand to convert 1.35 Mt sponge iron annually requires 3.8 TWh of electricity (E_{output}) as determined in Equation 19. However, with an electrolyzer efficiency of 73%, the electricity demanded (E_{input}) is calculated as represented in Equation 20 for the year 2027.

$$E_{input} = \frac{E_{output}}{\eta_{electrolyzer}} \tag{20}$$

$$E_{input} = \frac{3.8}{0.73} \sim 5.2\ TWh$$

Similarly, calculations are done over the time period to estimate the annual electricity demand with an electrolyzer efficiency of 73% and the same can be represented in Table 22. The cumulative electricity demanded amounts to ~148 TWh indicating 40 TWh additional electricity demanded as compared to the ideal scenario. In reality, however, there is potential for an increase in the electrolyzer efficiency within the time period 2027-2045 which can potentially reduce the electricity demand. Schneider Electric [54] states that the current electrolyzer efficiency is approximately 50%. The report further emphasizes that industries should aim to achieve at least 75% efficiency by 2050, indicating that electrolyzer efficiency may range between 50% and 75% until then. Factoring this in Table 22, a new scenario is created where the electrolyzer efficiency equals 73% in the first 9 years of the study period and 75% from 2036-2045. This would result in a few TWh less of the cumulative electricity requirement by 2045 ~ 144 TWh however is in the ballpark range of 150 TWh of electricity. This is a major engineering challenge and efforts to accelerate the efficiencies are crucial to lower the electricity demand.

TABLE 22 ESTIMATION OF ANNUAL IDEAL VS ACTUAL ELECTRICITY DEMAND TO ACHIEVE HYDROGEN DEMANDED

Year	Cumulative theoretical H_2 demand (kt)	Ideal Electricity demand (TWh)	Minimum Electricity demand with 73% electrolyzer efficiency (TWh)	Electricity demand with 73% and 75% electrolyzer efficiency (TWh)
2027	**97**	**3.8**	**5.2**	**5.2**
2028	97	3.8	5.2	5.2
2029	97	3.8	5.2	5.2
2030	**292**	**11.5**	**15.7**	**15.7**
2031	292	11.5	15.7	15.7
2032	292	11.5	15.7	15.7
2033	**583**	**23.0**	**31.5**	**31.5**
2034	583	23.0	31.5	31.5
2035	583	23.0	31.5	31.5
2036	**972**	**38.3**	**52.5**	**51.1**
2037	972	38.3	52.5	51.1
2038	972	38.3	52.5	51.1
2039	**1458**	**57.4**	**78.7**	**76.6**
2040	1458	57.4	78.7	76.6
2041	1458	57.4	78.7	76.6
2042	**2041**	**80.4**	**110.2**	**107.2**
2043	2041	80.4	110.2	107.2
2044	2041	80.4	110.2	107.2
2045	**2754**	**108.5**	**148**	**144**

All the data put together from the electricity analysis in Chapter 4.1.2, including the forecasted electricity demand, installed renewable capacity and the electricity demand for sponge iron transformation estimated in Table 22 have been plotted as shown in Figure 21. The figure illustrates the deficit between the forecasted installed capacity and the expected demand in the SE1 bidding zone through the sponge iron transformation. It is observed that from the year 2039 onwards, there is a year-on-year deficit in the forecasted demand for electricity as established in section 4.1.2 vs the electricity demand purely to cater to the HYBRIT expansion (representing scenario 2 with 73% and 75% efficiencies) which is represented in the grey shaded region. This deficit is equivalent to 115 TWh as observed in Figure 21 and could be made good by an additional wind capacity of 28 GW, assuming that 8 TWh reflects 2 GW of wind power capacity [33].

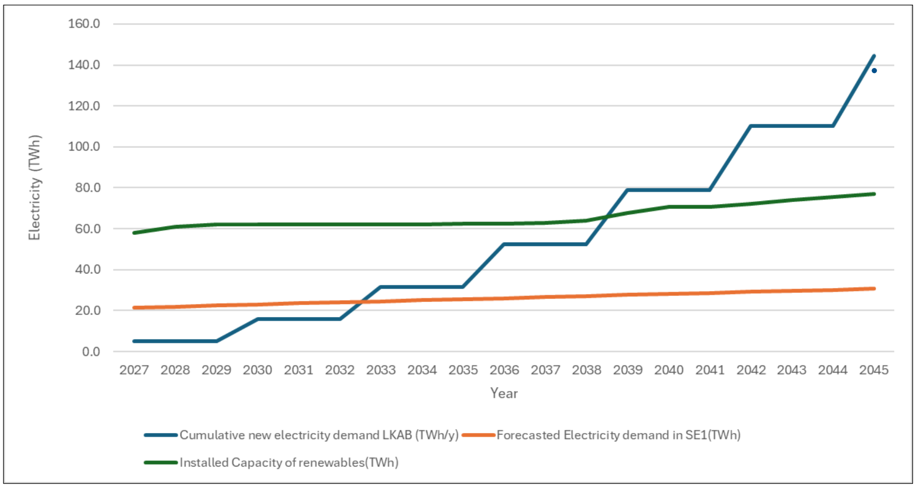

FIGURE 21 ANNUAL DEFICIT IN THE FORECASTED ELECTRICITY DEMAND TO MEET THE CALCULATED ELECTRICITY DEMAND FOR THE HYBRIT EXPANSION

5.2.2 Water Component

The efficiency of the electrolyzer primarily affects the amount of electrical energy required to produce a certain amount of hydrogen, but it does not directly impact the stoichiometry of the electrolysis reaction which determines the amount of water consumed per unit of hydrogen produced. This means that the amount of water consumed is fixed based on the stoichiometry of the reaction and the quantity of hydrogen produced. Therefore, regardless of the efficiency of the electrolyzer, the amount of water consumed per kilogram of hydrogen produced remains constant based on the chemical reaction itself and is not directly affected by the efficiency of the electrolyzer. However, in reality, a higher quantity of water is required to factor in the losses as some water may not potentially end up as hydrogen and oxygen and leave the system unprocessed. For the purpose of calculations, an average water consumption of 10 l/kg of hydrogen has been considered.

Using this conversion, the water consumption in the time period has been determined annually taking into consideration the theoretical hydrogen demand and amounts to a cumulative requirement of 28 Mm^3 by 2045. The same is represented in Table 23.

TABLE 23 ESTIMATION OF ANNUAL WATER DEMAND

Year	Cumulative theoretical H_2 demand (kt)	Water demand(Mm^3)
2027	**97**	**1**
2028	97	1
2029	97	1
2030	**292**	**3**
2031	292	3
2032	292	3
2033	**583**	**9**
2034	583	9
2035	583	9
2036	**972**	**10**
2037	972	10
2038	972	10
2039	**1458**	**16**
2040	1458	16
2041	1458	16
2042	**2041**	**23**
2043	2041	23
2044	2041	23
2045	**2754**	**28**

The surface water availability is estimated in context with the surface water analysis performed in 4.1.1 after accounting for the surface water consumption by other sectors. To assess the total surface water available for use (T) to cater to the HYBRIT expansion and other projects in Norrbotten County , the total surface water resources available annualy in the Bothnian Bay RBD (S_{tot}) has been considered alongside the total annual surface water abstraction (SA_{tot}). The total surface water abstraction is estimated by taking the average figure as presented in section 4.1.1.

$$T = S_{tot} - SA_{tot} \tag{21}$$

In that case , $75Bm^3 - 253Mm^3 = 74.74\ Bm^3$ of water available for use in 2045.

The results from the analysis imply that water demand purely for the sponge iron transformation amounts to approximately 28 Mm^3 by 2045. This implies approximately 0.05% of the total surface water available in the study period 2027-2045 will be consumed for the purpose of this envisioned sponge iron transformation as observed in Figure 22 where the red segment represents the same. This is based on the assumption that 1kg of H_2 would require 10 L of water alongside anticipating an increase in precipitation and resulting freshwater resources every decade in Northern Sweden.

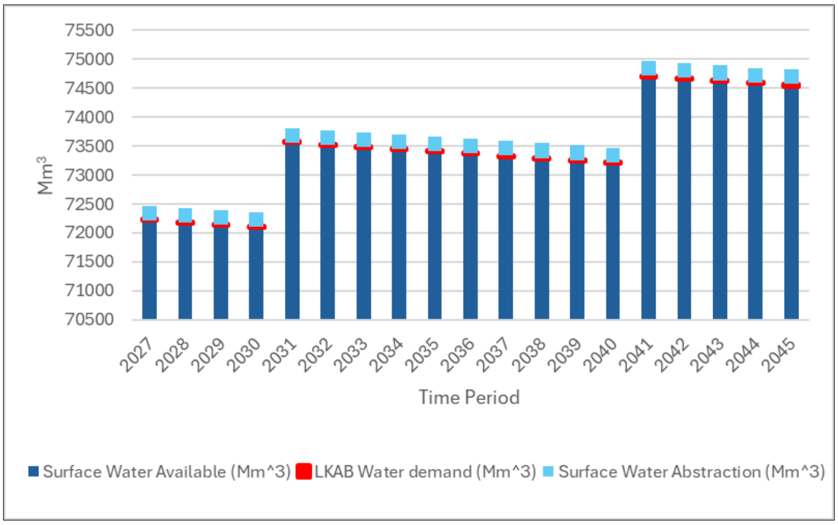

FIGURE 22 ANNUAL SURFACE WATER DEMAND PROPORTION VS AVAILABILITY

5.3 Suitability Maps

Figure 23a represents the final suitability map that has been obtained through the Multicriteria Overlay Analysis via the Suitability Analysis Modeller on ArcGIS Pro. This has been created after integrating all the transformed maps as observed in section 4.2.3. It can be observed that the green areas represent high suitability up to 4.32, yellow areas represent moderate suitability and the red regions represent low suitability and are as low as 1.06. Furthermore, Figure 23b overlays the restricted zones on the suitability map to provide better clarity on whether the suitability analysis has been performed correctly. It indicates that the prominent green areas have not been impacted or overlapped by the restricted zones implying a good level of accuracy in the suitability analysis. Moreover, it indicated the areas that are completely off-limits for the establishment of green hydrogen projects. The following segment discusses in more depth the selection and statistics of individual locations for ease of analysis.

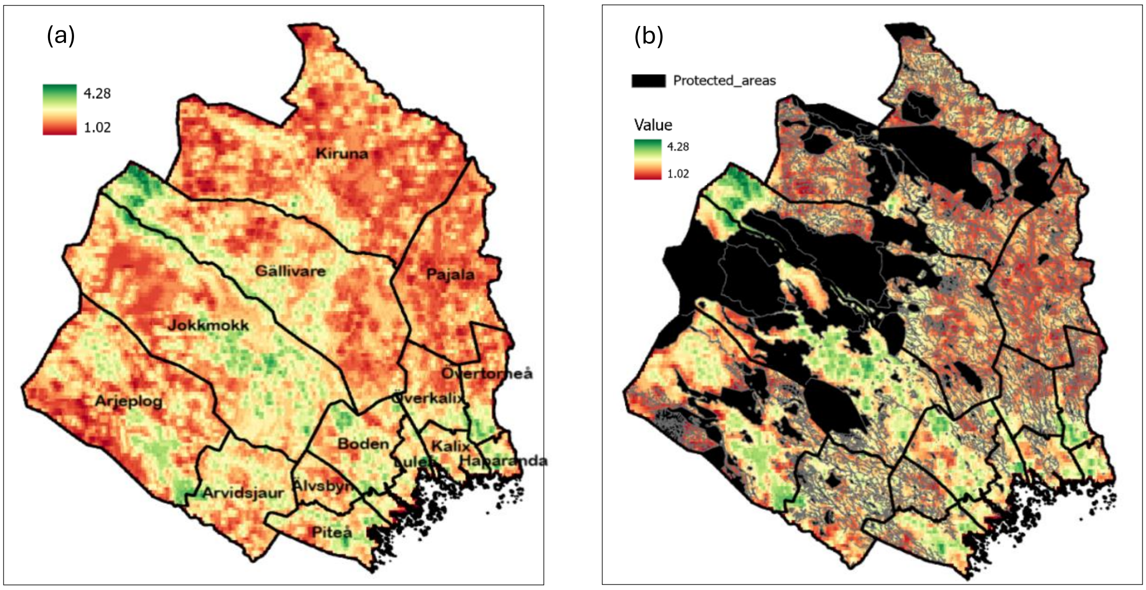

FIGURE 23 A) FINAL INTEGRATED SUITABILITY MAP B) SUITABILITY MAP OVERLAYED WITH THE RESTRICTED ZONES

5.3.1 Zonal Analysis

This segment aims is to further analyze the most suitable locations for the development of the sponge iron capacity within the period 2030-2045. Since the demonstration plant of 1.35 Mt sponge iron capacity has already been decided for establishment in the Malmberget, Gallivare municipality in 2027, the GIS analysis takes into consideration all plans post 2030. Most suitable locations will be analyzed in depth and the best locations will be recommended based on higher suitability score % and the proximity to the mines. This can be quantified via the pixel count within each of these regions given that the value of the suitability score is stored within each pixel on the suitability map that has been generated. Therefore, areas with a higher percentage of a desired suitability score will be identified and extracted as further recommendations for surveying.

To do so Norrbotten County is first divided into 110 zones having a cell size of 100×100 planar sq km each. The same can be represented in Figure 24, with each cell corresponding to a zone. Next, the % of suitable pixels in each zone is studied. To perform this analysis the suitability map is first transformed into a binary raster using a raster based on three specific suitability score scenarios. The first scenario considers a value of 2.6 (the average of the lower and upper band value i.e., 1.01 and 4.28) and uses the raster calculator by assigning pixels with suitability scores > 2.6 as 1 and the rest as 0. Similarly, a binary raster is created to determine the pixels with suitability scores greater than 3 and greater than 3.5. Figures 25 a,b and c represent the binary maps obtained with suitability scores greater than 2.6, 3 and 3.5. It can be observed that the number of zones with higher suitability decreases with the increasing suitability score.

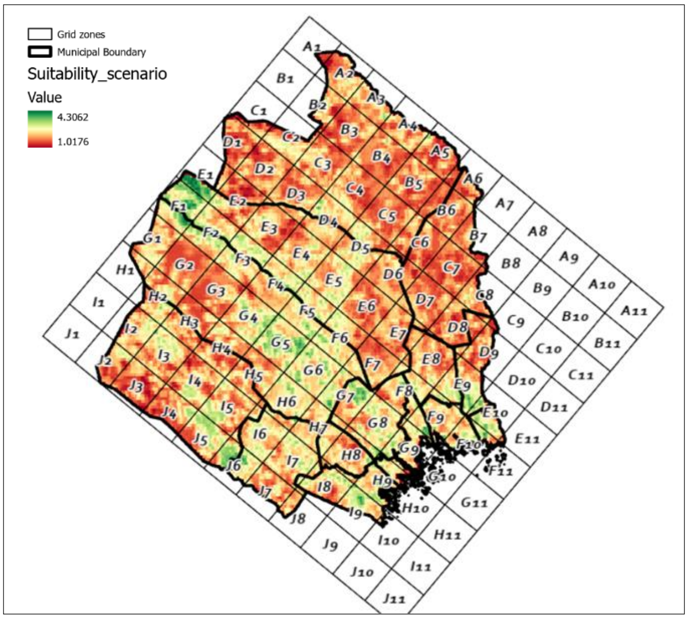

FIGURE 24 DIVISION OF SUITABILITY MAP INTO ZONES

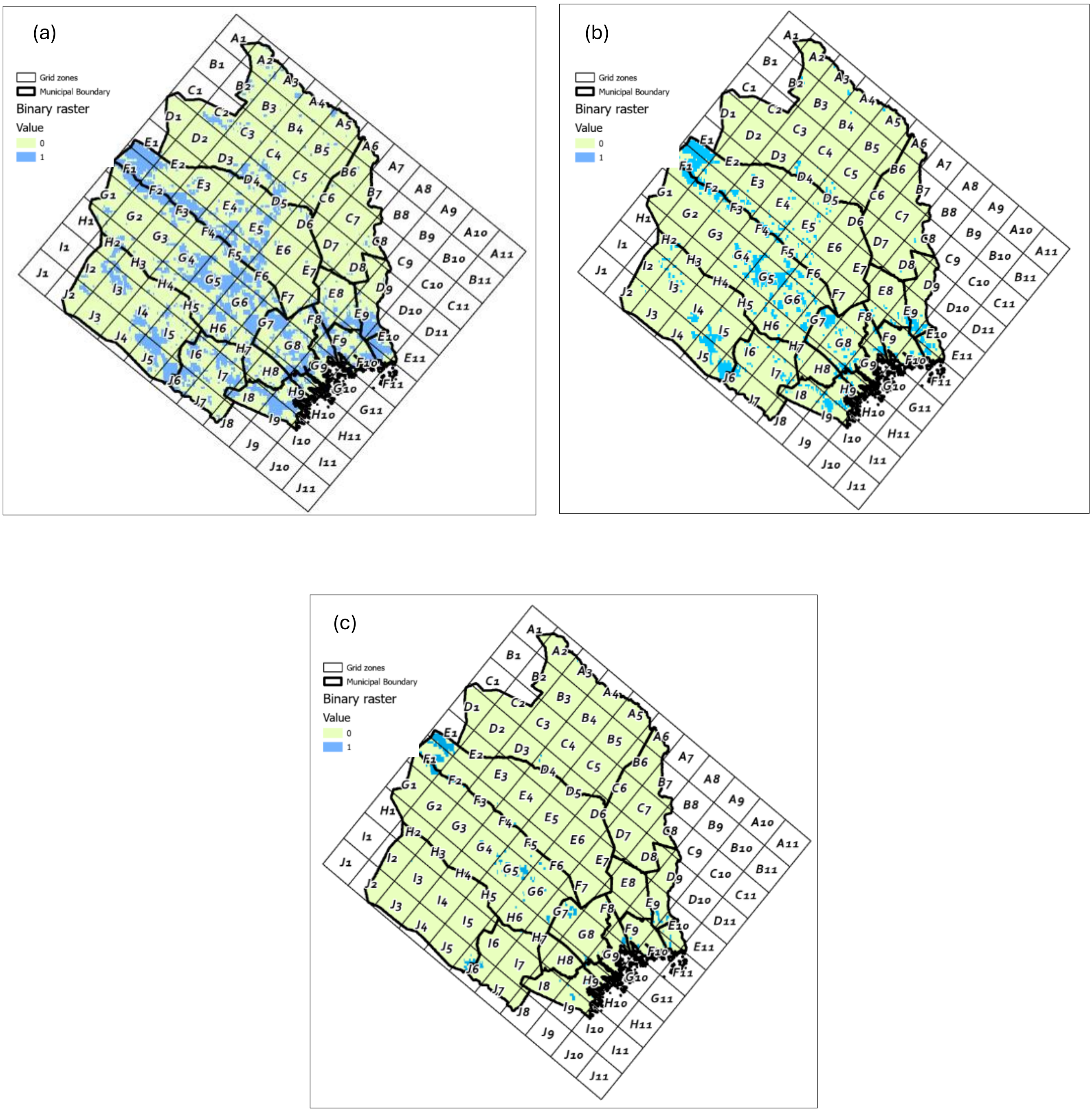

FIGURE 25 A) BINARY RASTER FOR SCENARIO 1 WHERE PIXELS WITH SUITABILITY SCORES > 2.6 ASSIGNED 1 AND THE REST 0 , B) BINARY RASTER FOR SCENARIO 3 WHERE PIXELS WITH SUITABILITY SCORES > 3 ASSIGNED 1 AND THE REST 0 , C) BINARY RASTER FOR SCENARIO 2 WHERE PIXELS WITH SUITABILITY SCORES > 3.5 ASSIGNED 1 AND THE REST 0

Table 24 represents the detailed percentage of suitability scores of 22 zones suitability score having more than 30% of the pixels with a suitability score greater than 2.6. Setting 2.6 as the baseline suitability score for this study, the zones in the instant case have been further studied to determine the percentage of pixels having suitability scores greater than 3 and 3.5.

TABLE 24 REPRESENTATION OF PERCENTAGE OF SUITABILITY SCORES FROM THE 3 SCENARIOS IN 22 ZONES

Grid	% of suitable pixels > 2.6	% of suitable pixels > 3.0	% of suitable pixels >3.5	Max suitability score
J5	42.6	22.74	0	3.47
J6	59.6	39.53	14.16	3.97
I6	35.2	5.66	0	3.26
I7	35.7	7.8	0	3.35
I9	61.1	28	5.9	4.09
H9	49.7	27.78	5.28	3.95
G4	43.1	21.11	3.41	3.76
G5	**62.4**	**43.49**	**13.03**	**3.95**
G6	**51.3**	**22.59**	**2.72**	**3.89**
G7	**49.7**	**26.29**	**7.87**	**3.95**
G8	38.3	11.32	0	3.44
G9	51.5	13.59	0.65	3.68
F1	**72.9**	**55.22**	**23.88**	**4.15**
F5	45.4	15.2	0.43	3.72
F6	**36.8**	**9.45**	**1.26**	**3.63**
F8	30.0	5.95	0.82	3.68
F9	35.2	12.8	3.43	3.95
F10	52.5	20.8	5.43	4.02
E1	70.8	67.53	51.3	4.31
E5	33.5	6.22	0	3.29
E9	50.5	22.73	7.27	3.95
E10	**54.5**	**27.5**	**6.5**	**3.84**

5.3.2 Selected Zones

To further narrow down the best-suited zones, the proximity to the demand points is further analyzed as presented in Table 25. Zones F1, G5, G6, G7, G8, E10 and F6 have been selected as shown in Figure 28 as a result of these zones having a high % share of suitability score greater than 2.6 and are also visibly the best locations to further study the potential of green hydrogen production due to their proximity to the mines as compared to the other zones observed on the map.

Zones D4, D5 and E5 comprise the mines, however, the study suggests that these zones indicate a lower suitability score to accommodate larger capacities of electrolyzers due to the presence of numerous restricted zones in the vicinity, thereby serving as a limitation. It can also be observed from Figure 26 that G5 – G7 zones primarily lie in Jokkmok County suggesting a high potential for geographical availability and accessibility to major resources for green hydrogen production followed by zones F1 and F6 concentrated in Gallivare.

TABLE 25 PROXIMITY OF THE MOST SUITABLE ZONES FROM THE IRON ORE MINES

	Kiruna (km)	Gallivare (km)	Svappavara (km)
F1	<150	<200	<200
F6	<150	<75	<135
G5	<150	<100	<150
G6	<175	<100	<150
G7	<200	<140	<180
G8	<250	<200	<150
E10	<300	<200	<250

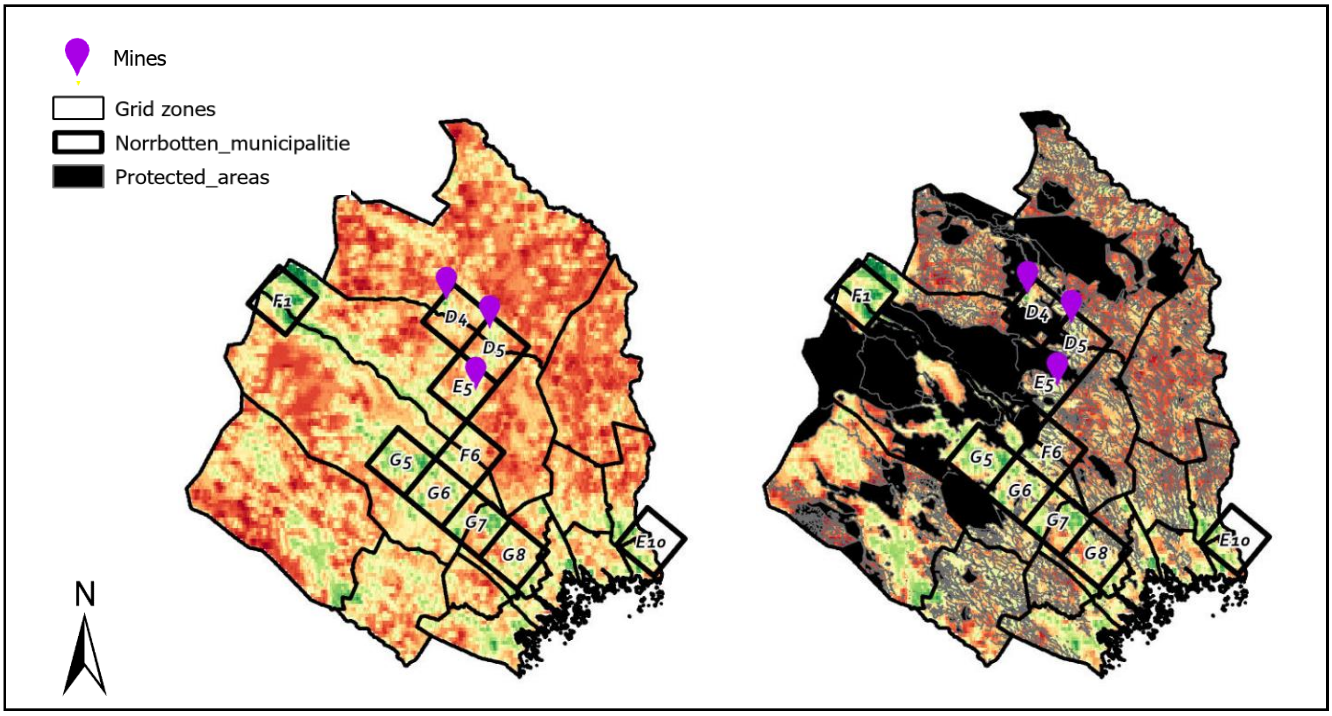

FIGURE 26 EIGHT SELECTED ZONES : F1 , F6 , E10 , G5 , G6 , G7 , G8

5.4 Hydrogen demand from other potential beneficiaries

The suitability map obtained has the potential to be utilized for the establishment of green hydrogen projects to cater to other beneficiaries in the county. Even as the green hydrogen demand from other beneficiaries merits a separate comprehensive study, an effort has been made here to assess and evaluate a few of the possible beneficiaries for better appreciation.

Biogenic emissions from the Swedish pulp and paper industry and combined heat and power plants (CHPs) could serve as significant feedstock for e-methanol production, as suggested by Uniper [14]. E-methanol is a clean liquid fuel to cater to the transportation sector that is produced by combining green hydrogen and captured carbon dioxide. An interview during this thesis work with Uniper corroborates this potential and highlights the long-term impact on e-methanol production. An advantage of using CO_2 emissions from the pulp and paper industry over CHPs is the stability of emissions production. Furthermore, the pulp and paper industry was suggested to have more potential as it typically relies on a consistent supply of wood or pulp as its primary feedstock and operates year-round, resulting in a predictable combustion process and stable emissions throughout the year. In contrast, CHP plants may experience fluctuations in emissions due to varying energy demands, as they adjust production based on electricity requirements.

Moreover, it has been suggested by Uniper that at least 100 kt of CO_2 is required to establish one e-methanol plant. Subsequently, the emission volumes [55] from the respective pulp and paper mills / CHPs individually as well as the combined volumes have been obtained and have been observed to meet the minimum demand thereby suggesting the potential for e-methanol establishments in the county. The associated e-methanol production potential and green hydrogen demand from the emission volumes as represented in Table 26 have been estimated based on equation 22 [56].

$$1.373\ t\ CO_2 + 0.188\ t\ H_2 = 1\ \text{ton e-methanol} \tag{22}$$

TABLE 26 H2 DEMAND ESTIMATION FROM OTHER BENEFICIARIES

Plant Type	Plant Name	Total CO_2 Emissions (kt)	E -Methanol Production Potential(Mt)	H2 Demand (kt)
Pulp and Paper Mills	Billerud Karlsborgs bruk SCA Munksunds pappersbruk Smurfit Kappa Kraftliner Pitea	2677	1.9	365.096
Combined Heat and Power	Bodens varmerverk Kiruna vameverk Luleå kraftvarmeverk	1999	1.5	272.6
	All	**4676**	**3.4**	**637.696**

From Table 26, it can be further observed that 637 kt is the estimated combined H2 demand, if all the biogenic emissions from both pulp and paper mills as well as combined heat and power plants are considered. This translates approximately into 4.6 GW of electrolyzer capacity required to cater to the same that has been estimated using Equation 23 [57] and corroborated by the assumptions made in section 5.1. This could potentially result in an emission reduction of 4.7 Mt of CO_2 emissions.

$$1\ \text{MW electrolyzer produces} \sim 400\ \text{kg}\ H_2\ \text{day} \tag{23}$$

With the potential increase in the efficiency of the electrolyzer over time with technological advancements for sponge iron production, there could be an increase in hydrogen output. Centralizing electrolyzers to cater to the requirements of both sponge iron and e-methanol production plants could be feasible if the green hydrogen is assumed to be transported to the CHPs and paper and pulp plant locations given that the electrolyzer capacity required to cater purely to e-methanol production is 4 times less than the 20 GW required for sponge iron production as established in section 5.1. This could avoid the need for setting up new infrastructure solely for e-methanol, requiring additional resources. With a suitability map developed for the sponge iron transformation, the same locations can be utilized to study the potential development of centralized green hydrogen production infrastructure for the above-discussed other beneficiaries. If a location/site is close enough to serve sponge iron and e-methanol production it could make economic sense. For instance, the pulp and paper mills and the CHPs in the county are plotted in

Figure 28 which indicates its proximity to zones G5 - G8 and E10 which can be further explored for green hydrogen production.

Now that the zones have been established, it is crucial to delve into the sustainability implications of the methodology. This would uncover the broader environmental, economic, and social impacts affected by the methodology and provide insight into how these factors interplay within the context of green hydrogen production.

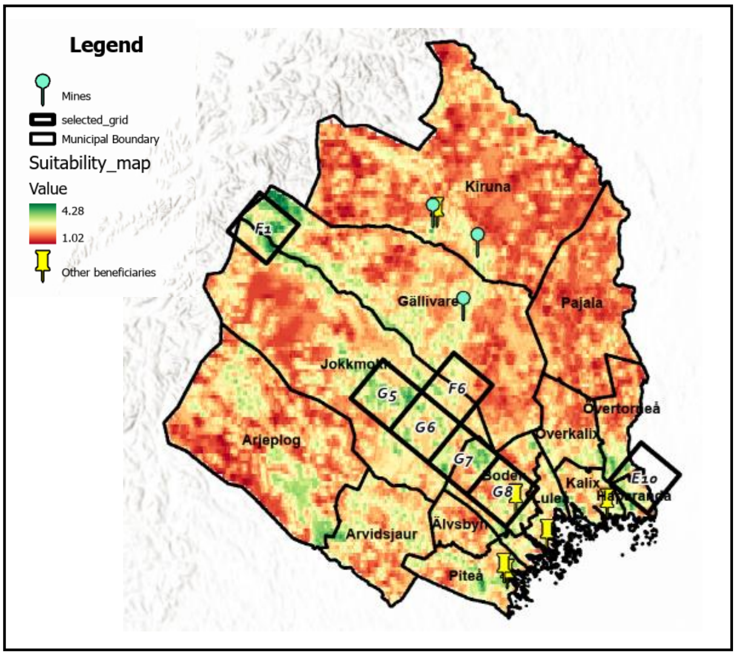

Figure 27 Suitability map with selected zones and representation of the pulp and paper mills and CHPs in the county

5.5 Sustainability

The spirit of sustainable Development (SD) is an integral part of this study considering the ambitious goals for sustainability set by the Swedish government including going fossil-free by 2045 and 100% renewable energy. This transition calls for a major transformation of energy-intensive industries particularly the hard-to-abate sectors such as the one chosen for this research ie the iron and steel industry while ensuring environmental integrity, and intragenerational and intergenerational equities. This study primarily concentrates on the goal towards achieving a 100% fossil-free sponge iron transformation by 2045 while preserving the natural resource base aligning with the national sustainability goal. Norrbotten County being the target region of this research, factors in environmental integrity during the multi-criteria analysis of the resources required for this ambitious transformation. The shift from traditional fossil-fuel-based dependency on energy-intensive industries to harnessing the incredible potential of green hydrogen is slowly but surely becoming a game changer in terms of scalability to support the national mission to mitigate climate change while aligning with Sweden's ambitious sustainability goals. Also, this research maps the technological, economic and environmental factors while taking into account the needs of other beneficiaries as they are critical to the sustainable scalability of this transformation. This could potentially attract local, national and foreign collaboration and investments, thereby enhancing the region's economic resilience and breeding innovation culture and could also generate employment opportunities, enhance skill and knowledge besides achieve energy security.

The site suitability assessment towards expansion of green hydrogen production capacity being core to this research to achieving fossil-free industrial transformation in Norrbotten County, considers various factors such as proximity to renewable energy sources, surface water availability, land use, environmental impact, and logistical aspects. This approach is expected to bring all the concerned stakeholders at the regional and national levels onto the same page to appreciate the big picture, frame/tweak policies and make informed decisions by right balancing of environmental, economic and social priorities impacting the environmental integrity and equity (Intergenerational and Intragenerational). Establishing the right mix of renewable sources to cater to the Green H_2 capacity expansion, decisions associated with creating industrial clusters in the region towards achieving economies of scale, supporting energy market stability, and reducing overall costs by competitive distribution networks and other key infrastructure are some of the foreseeable outcomes that could be derived from the research. Furthermore, establishing and standardizing buffer zones around restricted areas and areas of cultural importance, while involving local communities and the public in the decision-making process, can help identify regions that should be off-limits for large-scale green field projects. The estimated 20 GW of electrolyzer capacity and the associated large-scale expansion in electricity, requirements must be approached by factoring all three facets of sustainability to allow for a swift and smooth transition.

Currently, as per the UN SD Transformation Centre's 2024 report [58], Sweden ranks second globally with an SDG score of 85.7 only after Finland (86.35). This research template and methodology if replicated in other energy-intensive and fossil fuel-dependent sectors, potentially have a far-reaching impact (impact quantification is outside the scope of this research) on Sweden's Nationally Determined Contributions (NDCs) and its commitment to UN SDGs primarily addressing SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy to all), SDG 13 (take urgent action to combat climate change and its impact). The research outcomes could also indirectly address SDG 9 (building resilient infrastructure, promoting inclusive, sustainable industrialisation and fostering innovation) and finally SDG 17 (strengthening the means of implementation and revitalising the global partnership for sustainable development).

6. Conclusions

This study has analyzed in detail, the year-on-year capacity expansion of the sponge iron production facilities and the associated resource requirements (electricity, water and an electrolyzer of desired efficiency) which match the theoretical hydrogen demand. These results are beneficial for several reasons; firstly knowing the calibrated capacity expansion of sponge iron facilities year-on-year facilitates informed decision-making, resource planning and procurement of electrolyzer of appropriate capacity, aids in strategising production plan over time, streamlining supply chain upstream management and forecasting required investments more effectively.

The study further estimates a 20 GW addition of electrolyzer capacity to cater to the 100% sponge iron transformation that requires a substantial amount of electricity thereby necessitating swift and timely action to meet such large-scale demands. Although the path to decarbonizing the steel industry requires substantial resources, it is crucial to prioritize this goal early on to motivate and impel other steel industry players worldwide. To realize the green field projects of such large capacities, it is essential to assess the geographical availability and accessibility to resources. Subsequently, the study thoroughly applies the MCA to determine the most suitable locations in Norbotten County where the three mines are currently located. In conclusion, it is evident from the analysis that there are suitable locations that are concentrated in the Jokkmok and Gallivare counties which finds strong recommendations. In this regard, the future scope of this work revolves around conducting a more in-depth assessment of the identified zones to evaluate the potential and quantify the available resources in the given regions. Furthermore, evaluating the optimal mode of transportation would shed additional insight into logistical costs and the feasibility of establishing storage/pipeline networks. Lastly, assessing the economic viability of establishing the entire infrastructure will be crucial for determining the overall feasibility of the project.

Additionally, while the study under the established scope, evaluates Norrbotten County comprehensively, there is a plethora of scope for future study that could add significant value to the scalability and decarbonisation mission of SSAB, LKAB and Vattenfall through the HYBRIT. These may involve and not limited to conducting similar studies of other counties in Sweden, other SSAB locations in Finland and the USA, analysing safety and risk involved in transportation and storage, the necessity of centralizing and integrating hydrogen clusters, overall potential environmental impact analysis, thorough geophysical analysis of underground cavern storage and subsequent Cost-Benefit analysis/economies of scale of this envisioned green hydrogen transition. This approach could enable the prioritization of high-impacting business cases in maximizing the user base and economic value derived from green hydrogen potential.

7. Bibliography

[1] Sustainable Materials.Invest in Norrbotten. [n.d]. Available at: https://www.investinnorrbotten.se/sustainable-materials/.

[2] Direct Reduction with H_2 on a demonstration scale.HYBRIT.[n.d].Available at: https://www.hybritdevelopment.se/en/a-fossil-free-development/direct-reduction-hydrogen-demonstrationscale/.

[3] Grupo Fertiberia establishes itself in Norrbotten, invests over 10 billion. Luleå Business Region.[n.d]. Available at : https://Luleåbusinessregion.se/nyhetsarkiv/grupo-fertiberia-investerar-10-miljarder-i-norrbotten/.

[4] Hydrogen Projects.Luleå University of Technology.[Cited 2024]. Available at: https://ltu.instante.se/V%C3%A4tgas/HydrogenProjects_20240205.html.

[5] Sweden's Climate Act and Climate Policy Framework. Naturvårdsverket. [n.d.]. Available at: https://www.naturvardsverket.se/en/topics/climate-transition/sveriges-klimatarbete/swedens-climate-act-and-climate-policy-framework/ .

[6] Executive summary – Global Hydrogen Review– Analysis. International Energy Agency (IEA). [Cited 2023]. IEA. Available at: https://www.iea.org/reports/global-hydrogen-review-2023/executive-summary .

[7] *Hydrogen - IEA*. [n.d.]. IEA.Available at: https://www.iea.org/energy-system/low-emission-fuels/hydrogen .

[8] A Guide to Policy Making - Green Hydrogen for Industry. IRENA.[Cited 2022]. Available at: https://www.irena.org/publications/2020/Nov/Green-hydrogen.

[9] Tleubergenova, A., Abuov, Y., Danenova, S., Khoyashov, N., Togay, A., and Lee, W. 2023. Resource assessment for green hydrogen production in Kazakhstan. International Journal of Hydrogen Energy. Vol 48(43) 16232-16245. Available at: https://doi.org/10.1016/j.ijhydene.2023.01.113.

[10] Greene, R., Devillers, R., Luther, J. E., and Eddy, B. G. 2011. GIS-Based Multiple-Criteria Decision Analysis. Geography Compass. Vol. 5(6) 412–432. Available at: https://doi.org/10.1111/j.1749-8198.2011.00431.x .

[11] Department of Mechanical Engineering, Faculty of Engineering, Delta State University.2019. Weighting Methods for Multi-Criteria Decision Making Technique. Vol. 23 (8) 1449-1457.Available at: https://dx.doi.org/10.4314/jasem.v23i8.7

[12] Francis Emmanuel .2022.Land Suitability For The Placement Of Green Hydrogen Infrastructure In South-Eastern Nigeria.Dissertation.Hochschule Neubrandenburg University of Applied Sciences.Germany. URN: urn:nbn:de:gbv:519-thesis 2022-0253-2.Available at: https://digibib.hs-nb.de/resolve/id/dbhsnb_thesis_0000002930.

[13] Stepanov, A.S.; Kalina, R.A.; Stepanova, A.A. Analysis of power and energy loss based on long line equations. Russ. Electr. Eng. 2016, 87, 30–34. Available at : [Google Scholar]

[14] Potential Role of Green Hyderon.African Development Bank Group.[Cited 2022]. Available at: https://www.afdb.org/sites/default/files/documents/publications/20102022_potential_role_of_green_hydrogen_003.pdf.

[15] Ali, F., Bennui, A., Chowdhury, S., and Techato, K. 2021. Suitable Site Selection for Solar-Based Green Hydrogen in Southern Thailand Using GIS-MCDM Approach. Sustainability.Vol 14(11) 6597.Available at: https://doi.org/10.3390/su14116597

[16] Alberto Romero Boix .2023. Site suitability assessment for green hydrogen production in the Valencian Community (Spain).Dissertation.KTH Royal Institute of Technology.Stockholm.Available at: http:// urn:nbn:se:kth:diva-334553

[17] Taoufik, M., and Fekri, A. 2023. A GIS-based multi-criteria decision-making approach for site suitability analysis of solar-powered hydrogen production in the Souss-Massa Region, Morocco. Renewable Energy Focus.Vol 46 385-401.Available at: https://doi.org/10.1016/j.ref.2023.08.004.

[18] Sigal, A., Leiva, E., and Rodríguez, C. 2014. Assessment of the potential for hydrogen production from renewable resources in Argentina. International Journal of Hydrogen Energy.Vol 39(16) 8204–8214. Available at: https://doi.org/10.1016/j.ijhydene.2014.03.157.

[19] Just Transition Fund helps Sweden move towards climate neutrality. European Commission.[Cited 15 Nov 2023].Available at: https://ec.europa.eu/regional_policy/whats-new/panorama/2023/11/15-11-2023-just-transition-fund-helps-sweden-move-towards-climate-neutrality_en.

[20] Sea water electrolysis: a hydrogen revolution or an economical dud. World Economic Forum(WEF). [Cited 29 Sep 2023].Available at: https://www.weforum.org/agenda/2023/09/seawater-electrolysis-a-hydrogen-revolution-or-technological-dead-end-here-are-the-numbers/.

[21] Sweden and the OECD.Organisation for Economic Cooperation and Development(OECD).[Cited 2024].Available at : https://www.oecd.org/sweden/.

[22] Discussions with industry experts

[23] CoR - Sweden - Water Management. European Committee of the Regions [n.d.]. Available at: https://portal.cor.europa.eu/divisionpowers/Pages/Sweden-Water-Management.aspx.

[24] European Commission.Second River Basin Management Plans – Member State: Sweden.European Commission. [Cited 26 Feb 2019].Available at : https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019SC0057

[25] Water resources. European Environment Agency. [n.d] . Available at : .https://www.eea.europa.eu/help/glossary/eea-glossary/water-resources.

[26] Amelung, B. and A. Moreno, 2012. Costing the impact of climate change on tourism in Europe: results of the PESETA project. Climatic Change 112:83–100. Available at: https://link.springer.com/article/10.1007/s10584-011-0341-0

[27] Freshwater resources by River Basin District. European Commission.Eurostat Data browser [Cited 27 July 2023].Available at: https://ec.europa.eu/eurostat/databrowser/view/env_watres_rb/default/table?lang=enandcategory=env.env_wat.env_rwat.

[28] European Commission. Surface water bodies: Number and size, by category. [Cited June 8 2021]. https://water.europa.eu/freshwater/resources/metadata/dashboards/delineation-of-water-bodies/surface-water-bodies-number-and-size-by-category.

[29] AQUASTAT - FAO's Global Information System on Water and Agriculture. [n.d.]. https://www.fao.org/aquastat/en/.

[30] Statistikdatabasen. Total water withdrawal by type of water and region. Every fifth year 1970 - 2020-Statistikdatabasen. [Cited 2024]. Available at: https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__MI__MI0902__MI0902D/VattenUttag/.

[31] World Nuclear Association. Hydrogen Production and uses.[Cited May 1 2024].Available at: https://world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.

[32] Nuclear Power in Sweden - World Nuclear Association. [Cited 25 Mar 2024].Available at: https://world-nuclear.org/information-library/country-profiles/countries-o-s/swed

[33] Swedish Wind Energy Association. Roadmap 2040 Wind power: combating climate change and improving competitiveness.[Cited Jan 2021].Available at: https://swedishwindenergy.com/wp-content/uploads/2021/01/Roadmap-2040-ENG-rev-2020.

[34] Emma Nedstrand.2024. The potential of a bidding zone reconfiguration to foster an expansion of renewable energy production capacity in Sweden. Dissertation.Uppsala University.Uppsala.Available at: http:// urn:nbn:se:kth:diva-334553.

[35] Grid Development Plan 2024-2033. Svenskakraftnat.[Cited 2023]. Available at: https://www.svk.se/siteassets/om-oss/rapporter/2024/grid_development_plan_2024-2033.pdf.

[36] *Global Wind Atlas*. Available at: https://globalwindatlas.info/en/area/Sweden.

[37] *Länsstyrelsernas WebbGIS*. Vatteninformationsystem Svierge (VISS).Available at : https://ext-geoportal.lansstyrelsen.se/standard/.

[38] *Global Wind Power Tracker - Global Energy Monitor*. [Cited Feb 6 2024]. https://globalenergymonitor.org/projects/global-wind-power-tracker/.

[39] *Geodataportalen*.Available at: Lantmateriet.se. https://www.lantmateriet.se/sv/geodata/Geodataportalen/.

[40] The World Database on Protected Areas (WDPA) . Protected Planet. Available at: https://www.protectedplanet.net/en.

[41] Google Earth.Available at: https://earth.google.com/web/.

[42] Matos, C. R., Carneiro, J. F., and Silva, P. P. 2019. Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. Journal of Energy Storage.Vol 21 241-258. Available at: https://doi.org/10.1016/j.est.2018.11.023

[43] HYBRIT: A unique, underground, fossil-free hydrogen gas storage facility is being inaugurated in Luleå. [n.d.]. SSAB.Available at : https://www.ssab.com/en/news/2022/06/hybrit-a-unique-underground-fossilfree-hydrogen-gas-storage-facility-is-being-inaugurated-in-lule.

[44] T. L. Saaty, Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, Inc, 1980. [Online]. Available: https://archive.org/details/analytichierarch0000saat.

[45] Shahabuddin, M., Brooks, G., and Rhamdhani, M. A. 2023. Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and techno-economic analysis. Journal of Cleaner Production, 395, 136391. Available at : https://doi.org/10.1016/j.jclepro.2023.136391 .

[46] Blast furnace process and HYBRIT-process.HYBRIT. Available at: https://www.hybritdevelopment.se/en/media/blast-furnace-process-and-hybrit-process/ .

[47] Future Supplier of CO2-free sponge iron. LKAB. Available at: https://lkab.com/en/what-we-do/our-transformation/carbon-free-sponge-iron/.

[48] A summary Technical report on the mineral resources and reserves of LKAB, Sweden – Svappavara, Kiruna and Malmberget Mines. LKAB. [Cited 2022]. Available at: https://lkab.mediaflowportal.com/documents/folder/231556/.

[49] Li, B., Sun, G., Li, S., Guo, H., and Guo, J. 2020. The Preparation of High-Purity Iron (99.987%) Employing a Process of Direct Reduction–Melting Separation–Slag Refining. Materials, 13(8). Available at : https://doi.org/10.3390/ma13081839.

[50] Patisson, F., and Mirgaux, O. 2020. Hydrogen Ironmaking: How It Works. Metals.Vol 10(7), 922. Available at : https://doi.org/10.3390/met10070922.

[51] Magnetite iron ore similarities and differences. LKAB. [Cited 2019]. Available at: Magnetite, iron oxide, iron ore similarities and differences - LKAB Minerals.

[52] Heidari, A., Niknahad, N., Iljana, M., and Fabritius, T. 2021. A Review on the Kinetics of Iron Ore Reduction by Hydrogen. Materials.Vol 14(24), 7540. Available at: https://doi.org/10.3390/ma14247540.

[53] Kanellopoulos, K., Blanco Reano, H. 2019.The potential role of H2 production in a sustainable future power system: An analysis with METIS of a decarbonised system powered by renewables in 2050. Available at: https://ec.europa.eu/jrc.

[54] Pieces that need to fall into place to make green hydrogen viable. Schnieder Electric. [Cited May 15 2023].Available at: Pieces that need to fall into place to make green hydrogen viable | Schneider Electric Global (se.com).

[55] Environmental Report .Lansstyrelsen Stockhom.[Cited 2024].Available at : smp.lansstyrelsen.se

[56] Innovation Outlook: Renewable Methanol. International Renewable Energy Agency -IRENA and E-methanol Institute.[Cited 2021].

[57] Developing a Green Hydrogen Project Course. Renewable Energy Institute.[Cited 2023].

[58] Sachs, J.D., Lafortune, G., Fuller, G. [2024]. The SDGs and the UN Summit of the Future. Sustainable Development Report 2024. Paris: SDSN, Dublin: Dublin University Press. 10.25546/108572. Available at: https://sdgtransformationcenter.org/reports/sustainable-development-report-2024

[59] N. Mahmoody Vanolya, M. Jelokhani-Niaraki, and A. Toomanian.[2019].‘Validation of spatial multicriteria decision analysis results using public participation GIS’, Applied Geography. Vol. 112. Available at : doi: 10.1016/j.apgeog.2019.102061.

[60] Electricity Price Area.Wikipedia.Available at:
https://en.wikipedia.org/wiki/Electricity_price_area.