UiT The Arctic University of Norway

Faculty Engineering Science and Technology

Department of Electrical Engineering

Optimization of industrial power grid of Narvik

Optimal development of power generation and distribution network for hydrogen production industry plan at Kvandal and Narvik region

MD Nafis Ul Hoq Khan

Master’s thesis in Electrical Engineering…ELE-3900… [May 22 2023]

Abstract

The objective of this study is to review a comprehensive plan for optimization framework for the industrial power grid. Few factors considered such as power generation, transmission, distribution, energy storage solutions, cost development. The aim targets an overview of planning and optimization for a hydrogen production plant in Narvik region. It will improve the overall efficiency, stability, transmission, and distribution of the projected plan.

Aker Horizons is planning a large-scale hydrogen production facility at their site Kvandal. The region currently has a surplus of power production due to grid bottlenecks. The result is the lowest power prices in Europe, making way for interest from power intensive industries. However, Statnett has made reservations for all the 1150 MW surplus capacity. Additional capacity is dependent on grid developments or new generation. Aker Horizons has 230 MW reserved capacity in Kvandal but needs a minimum of 400MW for the project to be economically feasible. The municipality has developed several potential sites for new onshore wind power generation. Solar PV might be possible and/or Energy storage solutions can increase the potential for industrial users.

To achieve the objective, the study involves advanced optimization technic, simulation on the optimization plan, maximum power and energy density, regulations of the local government and geological location assessment. Some environmental impacts are also discussed along with a proposed energy storage for industrial grid. Furthermore, the study increases involvement of renewable energy in Northern Norway region. By optimizing renewable resources such as wind and hydro electrical energy industrial grid of Narvik can be beneficial asset for future development of Norway. Based on planned projects, potential projects, cost development of power generation, industrial and regional importance the most tecno-economic development of industrial offtake and generation was the expected outcome.

Acknowledgement

I would like to praise to Almighty for letting me the chance to pursue this thesis. Special thanks to my supervisor associate professor Charu Sharma for her endless support and motivation who always gave the guidance I needed to complete the journey. She continuously motivated me and steered me in the right direction with her valuable knowledge. I learned a lot from her.

I would also like to thank Mr. Jørn Eldby and the supportive person from Aker Horizon, Mr. Håkon Hjelstuen. The department of Electrical Engineering owns my respect for the immense journey.

The thesis was not possible without endless support from my wife Jannatul Ferdows Jui who was always behind me to encourage and support.

I dedicated the thesis to my mother who was the person who always wanted me to get a higher degree from a reputed university like UiT.

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1 Introduction

There is a critical role of optimization of industrial power grid in powering the city's various industries and to ensure that the energy supply is uninterrupted. The demand for power is increasing as well as the industrial demand of sustainable energy solution. To fulfill the demand and being able to secure the uninterrupted energy supply optimizing the power grid is the main challenge. Optimization requires a comprehensive approach that involves improvement of grid infrastructure, secure transmission and distribution network, integration of renewable energy resources and advanced energy management systems.

The power grid of Narvik is essential for powering the industries and maintaining continuous energy supply. Most of the energy comes from hydroelectric power as Norway has significant number of mountains, lakes and rivers which are required for the water flow to drive the turbines. Another important source of energy is wind farms. Narvik is connected to the national power grid which ensures that electricity generated in different regions can be transmitted and distributed to the consumers and the industries as needed. The transmission and distribution of electricity are operated by regional grid operators and distribution system operators (DSOs). These organizations are responsible for maintaining the power lines, distribution, transformers, and other infrastructure required for the efficient delivery of electricity to homes, business, and industrial areas.

2 Assessment of existing system

For the purposes of optimization, it is very important to know about the existing power grid and gather the necessary data regarding it. After understanding well, the existing system, it will be easier to understand if it needs to be expanded or new network is required for the optimization purposes.

2.1 Current power grid

The power grid in northern Norway is integrated in the larger Norwegian power grid. The main serving point is northernmost regions of Norway which includes Troms og Finnmark, Nordland and a few parts of Nord-Trøndelag. In this region the power grid is designed in such a way to supply electricity to residential, commercial, and industrial customers. Narvik as a city of northern Norway is facilitated with renewable energy. Two major sources of power are hydropower and wind power. As an interconnected grid with neighboring regions, it allows export of electricity. The facility enables the combination of demand and supply balance.

Narvik as well as northern Norway places a strong emphasis on transitioning of cleaner energy solution. From this region more than 8-9TWh is transferred to other regions as a surplus annually. It can be considered as a starting point for industrial development. Annually 950GWh of electricity is produced every year only from Narvik energy. So, there is huge potential for an industrial hub in Narvik region. [1]

2.2 Hydropower in Narvik

The most significant source of energy in Norway, including the Narvik region. Numerous rivers and mountain terrains are situated nearby Narvik that are well suited for hydro power generation. Hydropower generation uses the energy of continuous flowing water to generate electricity. The nearest hydropower plant produces about 25 MW of electricity. It benefits the local power supply. [4]

2.3 Wind Power in Narvik

Significant wind energy potential can be found in Narvik region. The reasons behind are coastal location and mountain terrains. The wind farm located near Narvik has installed capacity of 32 MW of electricity. Nygårdsfjellet wind farm has 14 turbines from where all of them are functional. [4] On shore wind farms depend on several factors. Such as environmental conditions, geo location, laws and regulations and technological aspects etc. [5]

2.4 Grid stability and backup

To ensure stable and reliable energy supply incorporate measures are taken. The measures include backup power systems such as diesel generators and energy storage. As a part of the green energy solution hydrogen power cells are also integrated into the backup power system. The system provides electricity during emergencies or in disruptions to the preliminary power sources.

2.5 Transmission Network

Over 3000 km transmission line in the north region is already developed. Among them Narvik consists of 420 kV high voltage transmission lines. Typically, the transmission lines are facilitated by 132 kV to 420 kV range. The red lines show the central grid line interconnected in this region. [2]

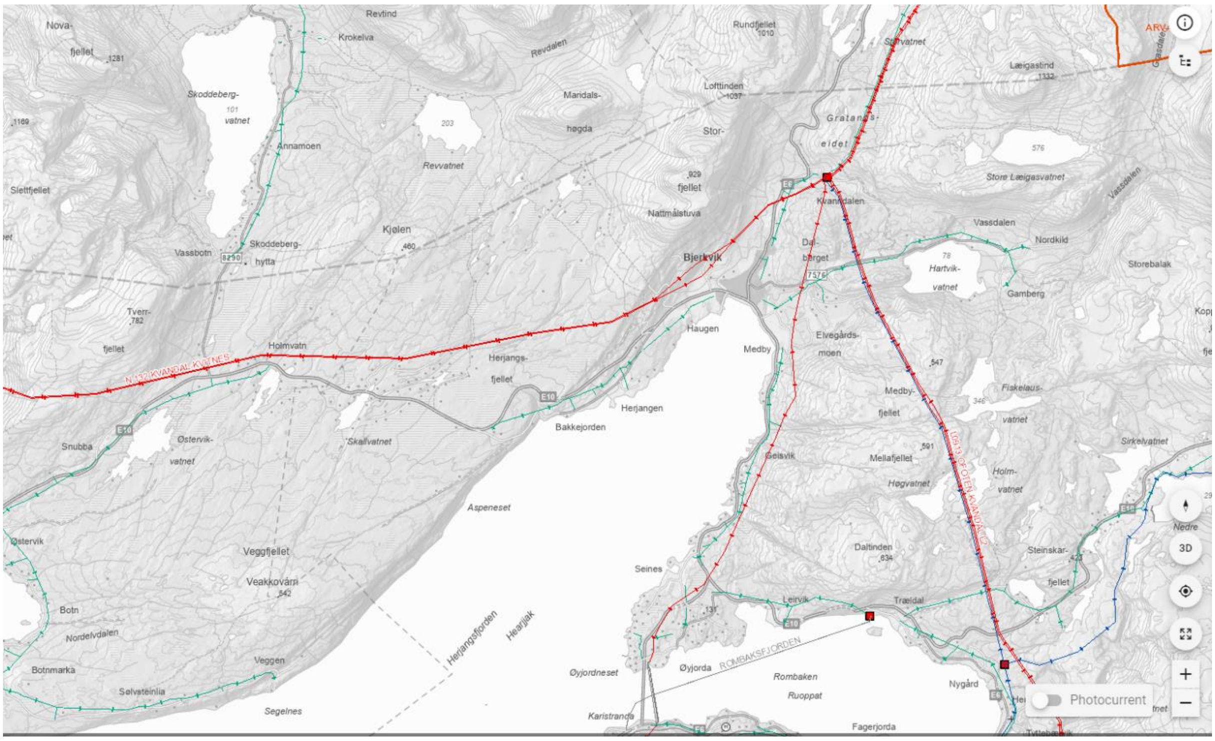

Figure 1: Central grid line connected throughout Kvandal, Narvik and Bjervik [5]

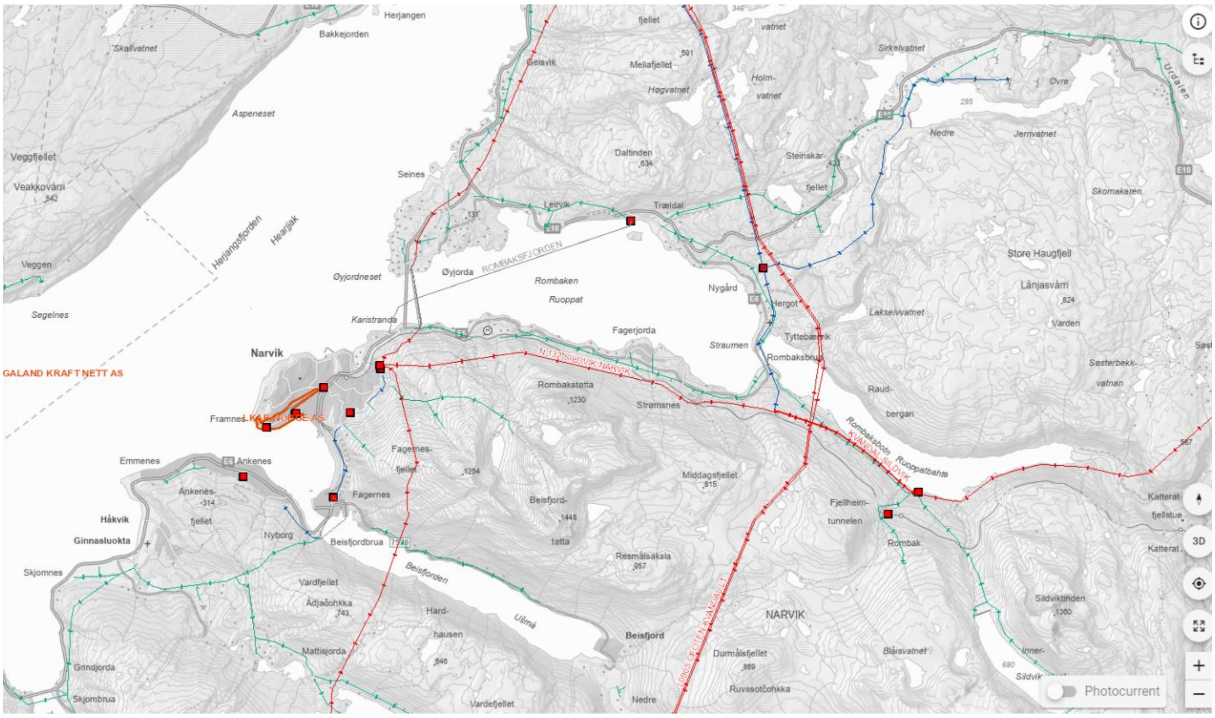

Figure 2: Central grid line in Narvik region [5]

2.6 Substations and grid monitoring

The substations are strategically located in this area. For efficient transmission of electricity in different voltage level substations are modified. The substations and other equipment are designed in such a way that transmission networks can be monitored and controlled 24/7. Various parameters such as voltage level, power flows, system stability are monitored continuously. To address any issues promptly and to secure the optimal grid operation real time data are analyzed. The dotted reds in figure 2 are situated substation in Narvik region.

3 Future industrial growth

There is a huge possibility of industrial revolution in Narvik region. One of the main reasons of growth of industries are Narvik which is in northern Norway is equipped with cheap electrical energy compared to the rest of the regions in Norway. Industries like hydrogen production, battery production, soft iron production are already in the planning stages. The industrial plan for Narvik region is establishment of those industries within 2030. So, for better understanding some aspects and requirements of the industries as well as locating the sites are reviewed in this section.

3.1 Power consumption patterns

For optimization, it is very important which kind of industries are going to be targeted for locating in the region and what are power consumptions and requirements. There is a possibility of sponge iron (DRI) based on hydrogen and iron ore, production of hydrogen, battery production industry in Narvik. To estimate the consumptions some previous industries are considered. In India, the DRI production which is coal based usually consume nearby 94.4KWh/ MT. As the DRI production planned here is based on hydrogen and iron ore, its consumption pattern is quite different. Including electrolysis, the usual consumption will be nearby 0.0004025 MW/t pa where normal size from 1.5-2.5mtpa DRI. Hydrogen production requires a lot of heat. [3] Usually, the operating temperature of hydrogen production is 1065°c. According to Bangladesh Council for Scientific and Industrial Research (BCSIR) on January 20th, 2021, they found that 51KWh/ kg electric power is consumed. [6] They found the number in a laboratory test for a pilot project. On average, electric power consumption for battery production is about 11.6KWh/ kg where anode production consumes 6KWh/ kg. These numbers are taken after many studies and based on them the load profiles, total consumptions and other determinates are going to be determined. The numbers are taken according to some recent developments in the industries. [7]

Table 3.1.1 – Load Profile and production forecast

INDUSTRY	LOAD PROFILE	OVERALL PRODUCTION
HYDROGEN	400 MW	88 Ton

3.2 Site location

For selecting the location of the industries and substations and distribution network, the availability of power and grid transmission lines are considered. The national grid is widespread in this area. From Bjerkvik to Kvandal where the national grid relates to an area of 4.23 km. It is equipped with a 420 kV high voltage transmission line. Where from Kvandal to Narvik the transmission line is around 18 km. In Kvandal site there is a huge possibility of an industrial hub. For power generation if onshore wind production is considered, Neverfjellet is the best possible area for establishing an onshore wind farm. Some important factors which eliminate the possibility for an onshore wind farm are wind speed, location of glaciers, cities, approach zones, heritage location, airports, aircraft radar, weather radar, and some natural elements like birds, reindeer, coastal health etc. Some other obstacles are conservation area, building plan, construction etc. These are classified as hard and soft exclusions. In figure 3 exclusions areas are indicated in bold color. Neverfjellet has none of these obstacles.

Figure 3: Hard and soft exclusion areas [5]

Another important factor is the cost of production. For study LCOE is considered. LCOE stands for levelized cost of energy used as a metric to evaluate and compare the cost of electrical energy generation cost for various power generation plants and technologies. Some important factors which are considered to determine LCOE are cost of building, operation cost, maintenance cost, future upgradation cost etc. It is calculated by dividing the total cost, which includes capital cost, fuel cost, operation, and maintenance cost by the total energy production over lifespan. It is a very critical factor as it defines the cost of one unit production. Though LCOE only provides simple metric ignoring all the complexity in energy system. According to nve catalog the LCOE which determines cost of production is comparatively lower than the Nygårdsfjellet wind farm. In figure 4 and figure 5 a comparative representation is provided. According to the NVE the LCOE is 30-32 öre/kwh in the Neverfjellet area. On the other hand, in the Nygårdsfjellet area the LCOE is 36-42 öre/kwh. [5]

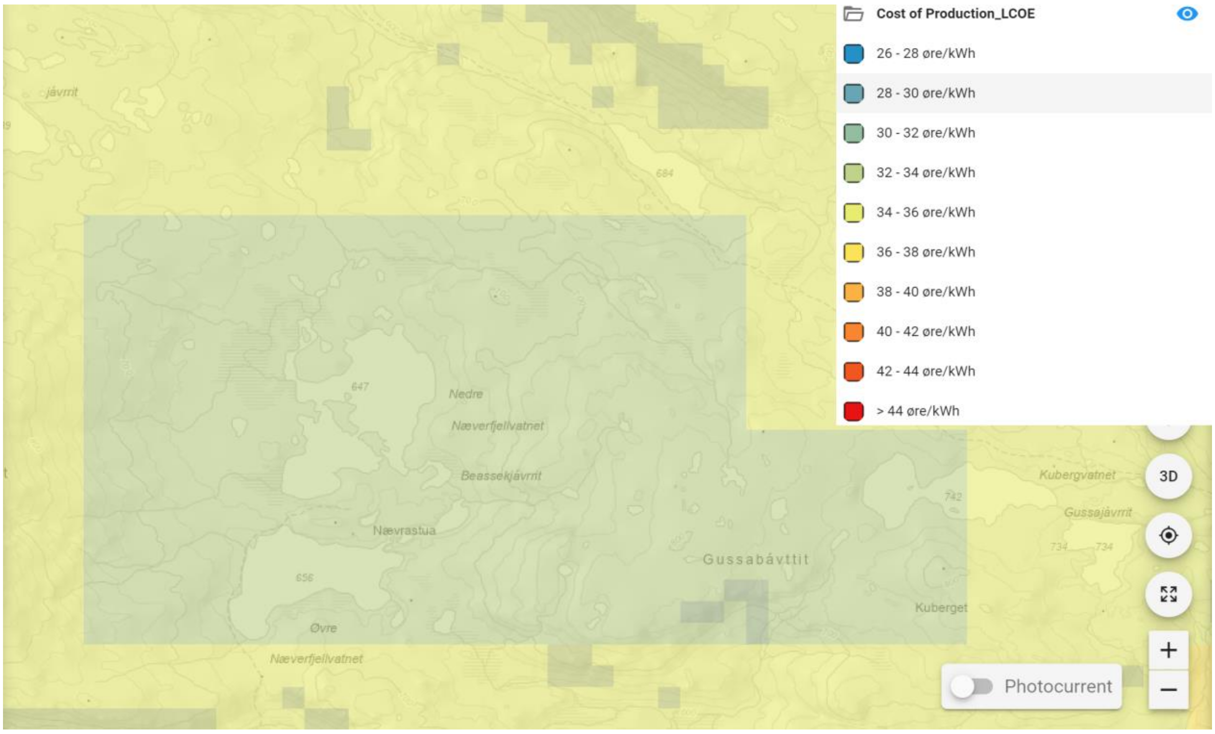

Figure 4: LCOE in Neverfjellet [5]

The LCOE is also an important factor in determining cost development. It is a simplified metric and not necessarily enough to determine all the complex calculations. Some complex factors such as impact on environment, policy intensives, grid integration cost can influence the value and viability of the energy source. LCOE is important in this study to understand the basic comparison of recent developments of wind farms in Norway.

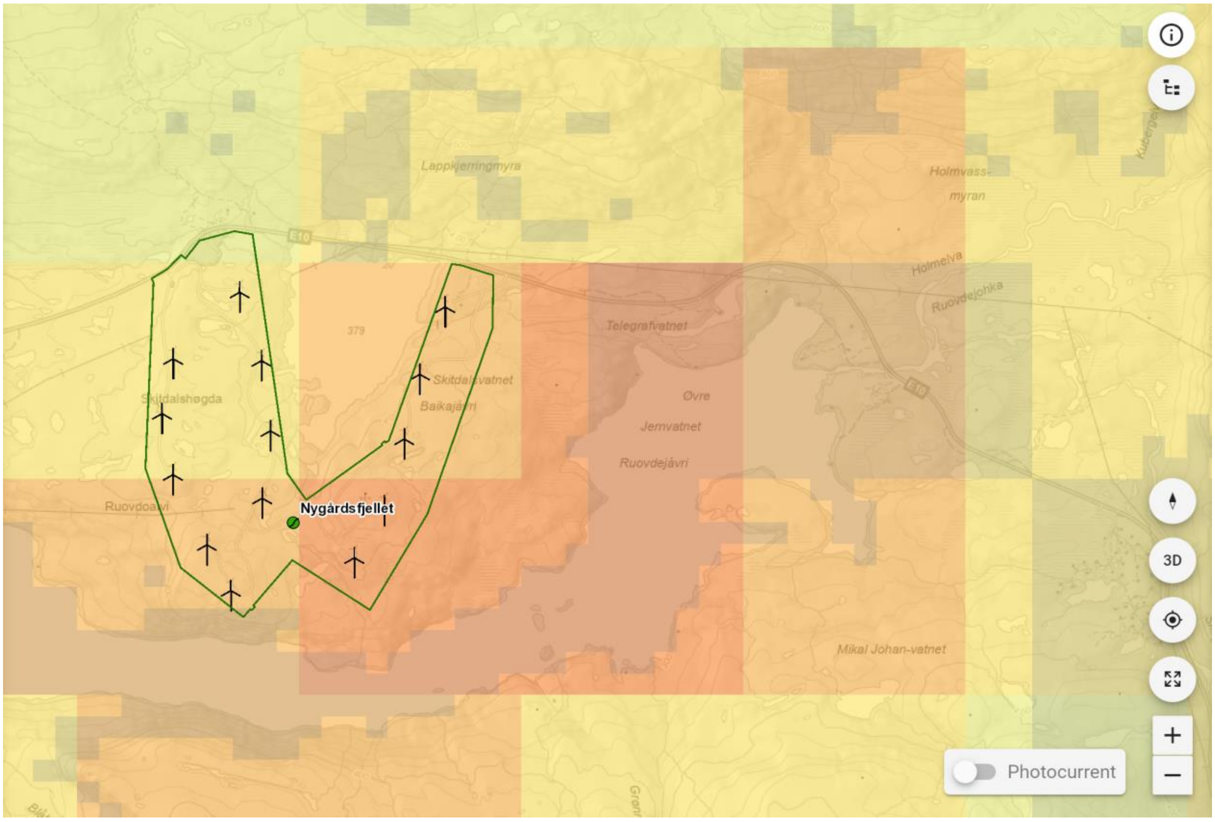

Figure 5: LCOE in Nygårdsfjellet [5]

4 Optimization process

The optimization process requires some phase-by-phase steps. In primary stage the expansion and development with grid, transmission infrastructure, different aspects of requirements such as regulation of authority and management system are discussed. In secondary stage, the plan of the power generation, technical requirements, modeling, grid connection, expansion of distribution and transmission networks with necessary development are discussed. Optimization requires proper investigation and analysis to get a full picture of the plan.

4.1 Primary stage

4.1.1 Pre-plans on grid interconnection

Collaborating with the grid operators such as TSO and DSOs, wind farm developers must initiate some study. This study usually concerns the capacity and stability of the existing grid infrastructure to determine if grid expansion is feasible or if it can accommodate additional power transmission and distribution. Some considerations such as capacity of the grid, stability of voltage, potential for reinforcement requirements etc. The nearest regional network is located near Nygårdsfjellet which is 132 KV line. If it is required to establish a new transmission and distribution network, it is required to examine the distance between the site and wind farm. [9]

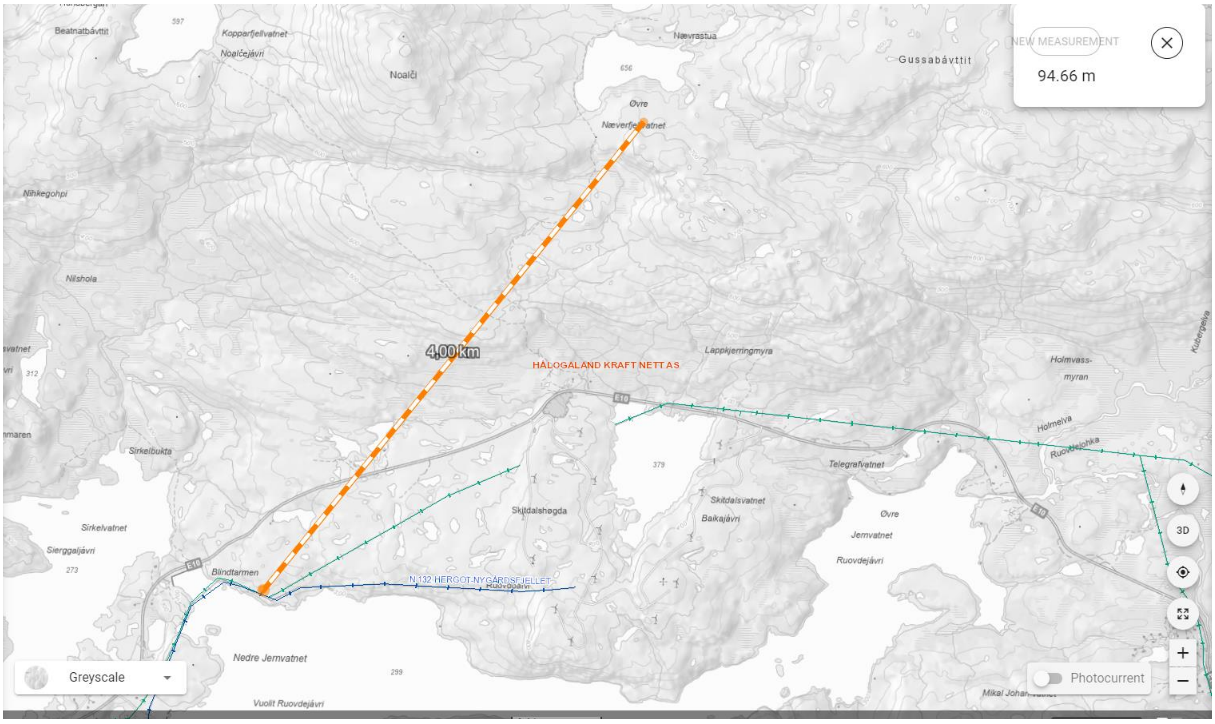

Figure 6: Distance of wind farm from existing grid connection [5]

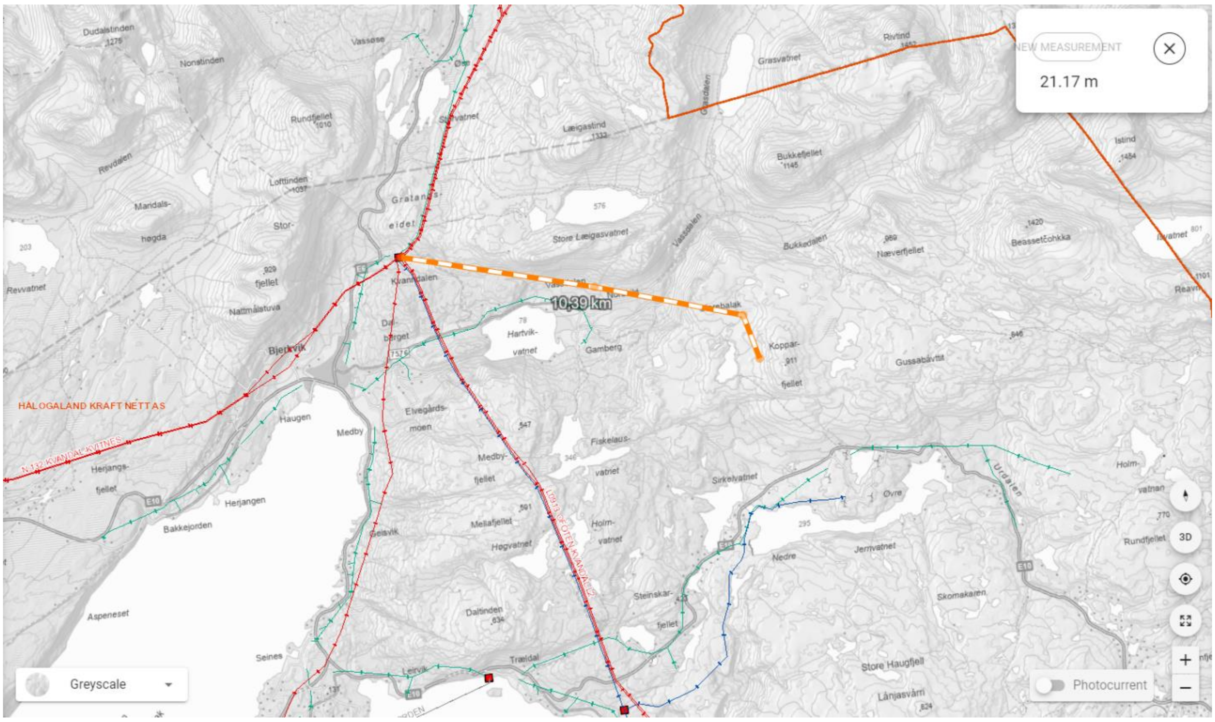

Figure 7: Required Path of new transmission and distribution network of wind farm from Kvandal site. [5]

4.1.2 Grid interconnection agreement

After the study on grid connectivity, grid operators and wind farms are into approval of a grid interconnection agreement. The agreement involves technical requirements, responsibilities, pre- conditions for interconnection from wind farms to grid infrastructure.

4.1.3 Power plant controller and protection system

Incorporating power plant controller systems with the wind farms is required to regulate protection systems for entire grid conditions. It is also required to ensure safe operation of power generation and disconnection of grid in case of faults.

4.1.4 Requirements by regularities authority

The requirements vary from one country to another. It depends on the power system characteristics and network topology where they are being applied. In Norway a Nordic grid model was simulated. According to grid code, wind farms shall be able to operate at limited power output, this is not like stated that wind farm shall operate at a bounded power output. It will result in an active power reserve which means loss of energy. This ability of wind farms to limit active power can be useful in case of grid congestion. The turbine must be equipped with frequency control functions to actively contribute to the frequency response. Some few other requirements are about environmental impact, energy potential of the area, special, time and vertical wind variation throughout the year etc. Some technical requirements for transmission line are provided in table 2. These technical requirements are found from technical data sheet from recent onshore wind power developed in Norge. [9] Some recommendations are:

1) Varying grid frequency at operation (normal: 49-50 Hz, Limited: 47-51Hz)
2) Varying grid voltage
3) Operation facilitated with active power control.
4) Facility of reactive power control
5) In case of grid faults and abnormal voltage operation facility with slow recovery
6) Characteristic properties verification

Table 4.1.2 – Load Profile and production forecast [10]

REQUIREMENTS	**NOMINAL VALUE**
CABLE TYPE	TSLF

NOMINAL VOLTAGE	87/150 KV
MAX ADMISSIBLE VOLTAGE	170 KV
CONDUCTOR CROSS SECTION	800 mm2
METAL OF CONDUCTOR	Aluminum
CONDUCTOR TYPE	Circular
CONDUCTOR DIAMETER	35.10 mm
CONDUCTOR THICKNESS	1.20 mm
INSULATION THICKNESS	17 mm
INSULATION DIAMETER	71.50

4.1.5 Operation and grid management

After the wind farm is interconnected with the grid, it gets involved with the overall grid system. The operators of grid, transmission, and distribution. To ensure stability, supply and demand balance, grid congestion management, integration into grid management is necessary.

4.1.5.1 Responsibility of TSO (Statnett)

The responsibilities of TSO are to operate and maintain complete transmission systems. Few responsibilities are:

1. Operation and Maintenance: TSO is responsible for the operation and maintenance of the high voltage transmission all over Norway. The responsibility regarding reliable and secure transmission is also included.

2. Grid Development and planning: TSOs planning, and development must take place in any case of development or expansion of grid considering few factors like future demand, integration of renewable energy, cross border connection etc.
3. Market Operation: TSOs operate the Norwegian power market facilitating the trade of electricity among market competition. Fair and transparent market operation and management of supply and demand is their optimal responsibility.

4.1.5.2 Responsibility of DSO

1. Distribution grid operation: The DSOs in Norway are responsible for the operation and maintenance of low and medium voltage distribution grid in different regions. Safe and reliable delivery of electricity to end users like residential, commercial, and industrial customers is their responsibility.
2. Connection and Metering: The process of handling new customers to the distribution grid and managing the metering process of new customers are the responsibility of DSO. Proper installation, maintenance, and functionality of meters are included in DSOs duty.
3. Grid planning: Planning and development of distribution grid are DSOs responsibility. Analyzing the future customer demands, accommodation, energy resource integration, ensuring grid stability are some of the responsibilities.
4. Customer service: Addressing the inquiry of the customers, interacting directly, handling service disruptions are some of the responsibilities.

4.2 Secondary stage

4.2.1 Measurement related to wind speed.

Usually for wind farms located in a different atmosphere and heat must experience different wind speed. For representing desired wind speed, an input signal wind speed module needs to be provided. For that purpose, an aerodynamic model is prepared to check wind speed and power relation. Test runs were provided at different wind speeds. Wind speed of 15 m/s was found to create the highest real power as shown in Table 3. The real power increases very slowly as wind speed increases, until it reaches 15 m/s. At that point, maximum power of 1.5 MW. After that, power P starts to deviate and drop beyond the rated wind speed because this model is not facilitated by pitch control.

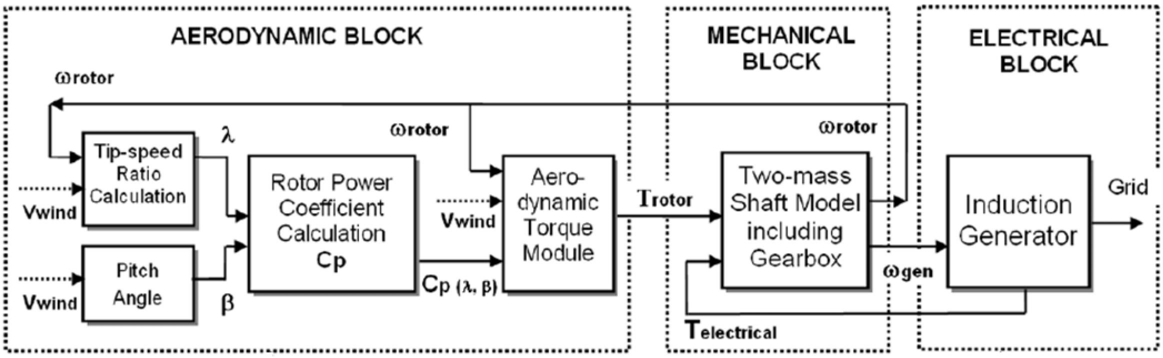

Figure 8: Block diagram of a wind turbine mechanism [10]

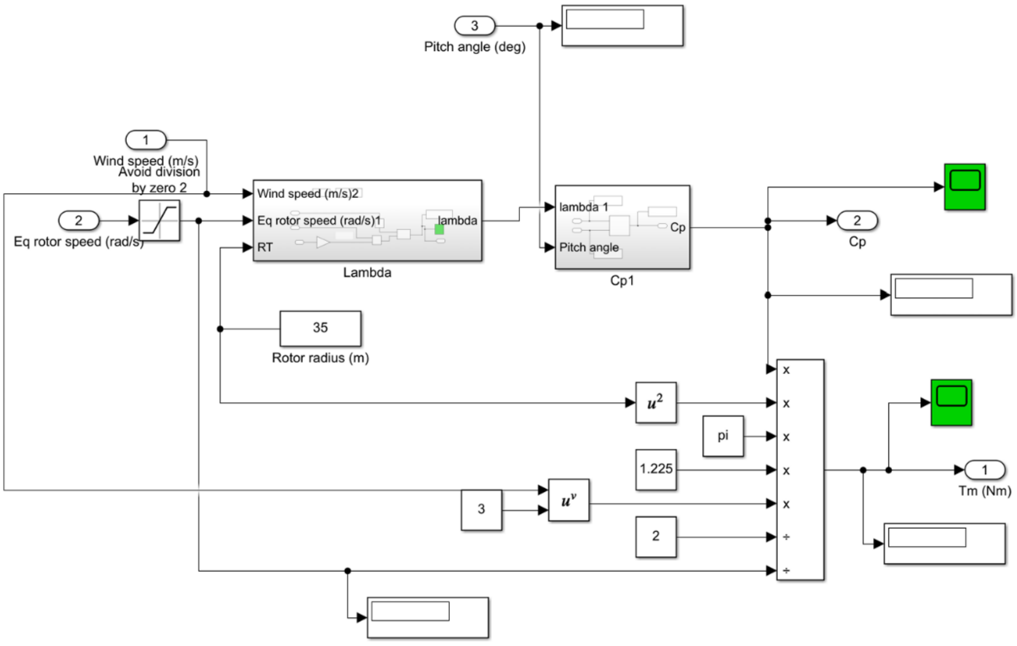

Figure 9: MATLAB Simulink model representation of aerodynamic block of a wind turbine. [10]

Table 4.2.3 – Wind speed vs real and reactive power [11]

WIND SPEED	REAL POWER (MW)	REACTIVE POWER (MVAR)
5	7.24e-5	0.3208
6	0.1324	0.3978

7	0.3121	0.4003
8	0.5401	0.4185
9	0.8228	0.4582
10	1.107	0.5064
11	1.298	0.5491
12	1.401	0.5769
13	1.463	0.5948
14	1.508	0.6145
15	1.5	0.6224
16	1.434	0.5891
17	1.403	0.5767
18	1.301	0.5508
19	1.259	0.5477
20	1.209	0.5248

4.2.1.1 Simulation result

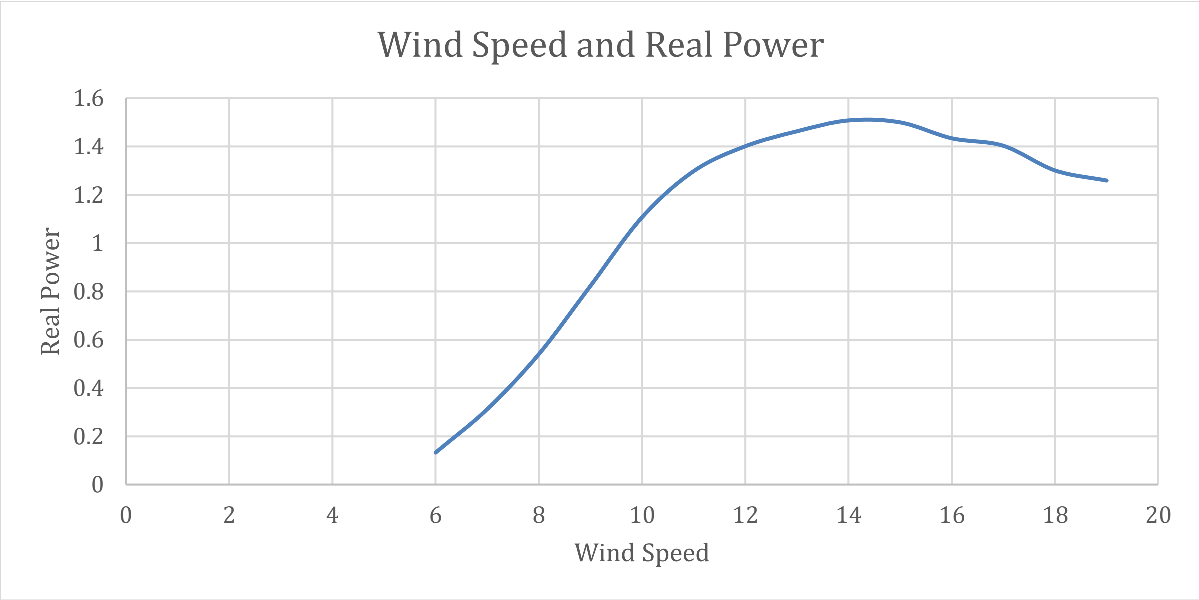

Figure 10: Relation between wind speed and real power

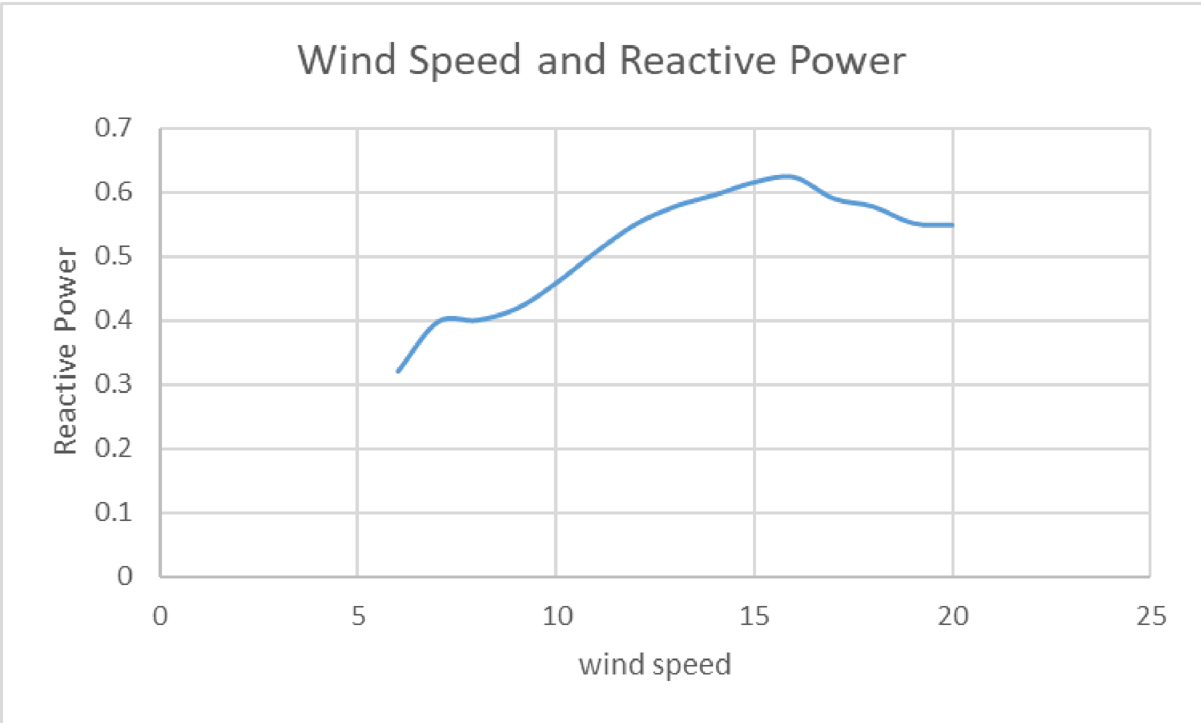

Figure 11: Relation between wind speed and reactive power

4.2.2 Grid connection and infrastructure development

After considering the location of wind farm, the next important task is to plan the connection to the grid with main grid line or transmission and distribution network. It is required to plan the connection to the existing grid infrastructure for transmission of the generated electrical power. For assessing the proximity to substations or transmission network, the distance between the wind farm and nearest developed network can be measured. It is required to ensure a reliable and efficient connection. The regional network near Neverfjellet is 132kv line. For connection to the distribution network with the wind farm an IEEE 9 BUS 3 machine system is planned.[8]

4.2.2.1 Transmission and distribution network development

For optimal power transmission and distribution, a benchmark power system is IEEE 9 BUS 3 machine design. This system is performed as the wind farm and the site in Kvandal is under study and planning process. The system consists of 9 nodes and with 9 nodes (BUSes) 3 synchronous machines are connected through transmission line. The IEEE 9 BUS 3 machine system is used widely to test and evaluate various power systems. As an example, load flow analysis, voltage stability, transient stability etc. It is represented by one line diagram which provides BUSes, generators, transformers, transmission lines, along with electrical parameters. To introduce each BUS, numbers are used. Generators are introduced as G1, G2, G3. It provides a simplified representation of a power system. In figure 12 IEEE 9 BUS 3 machine system is represented by a single line diagram. [14]

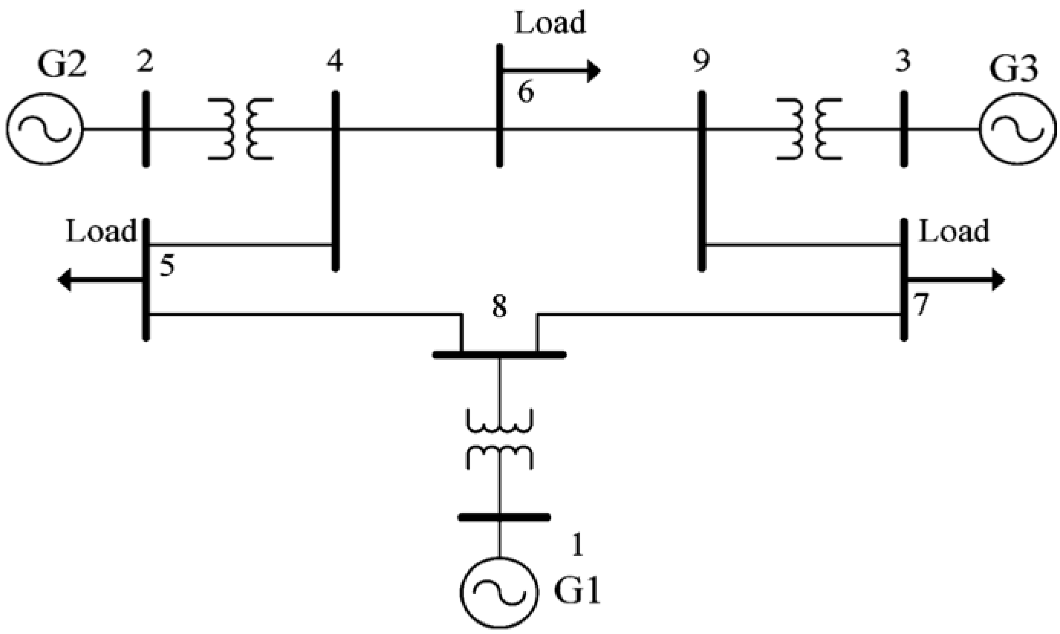

Figure 12: IEEE 9 BUS single line diagram [10]

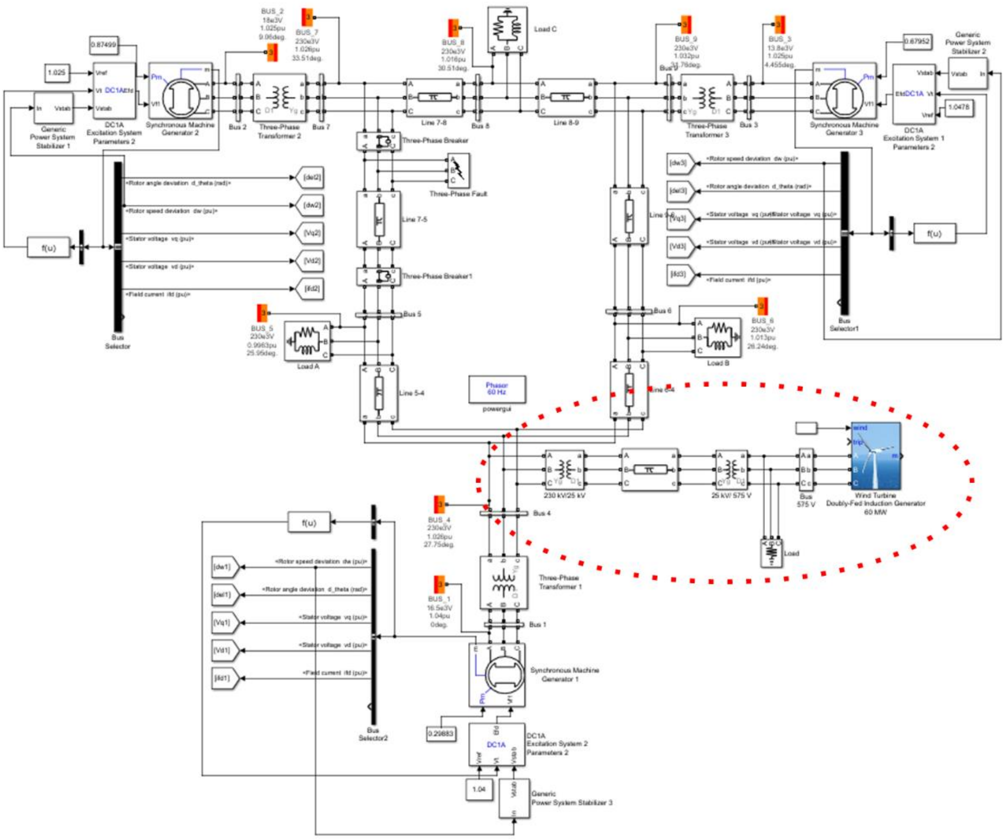

Figure 13: Diagram of IEEE 9 BUS system with integration of Wind farm (11)

4.2.3 Load flow analysis

Simple load analysis is performed. For simulation purpose parameters such as transformers, loads, transmission lines are chosen from MathWorks example. For reference, three synchronous generators are taken 3. The power system is operating under 50 Hz frequency. Load flow analysis is done to check whether the system parameters remain in designated load conditions. The listed parameters are V_lf which is load flow reference voltage, Q_lf is reactive power and and P_lf is active power. A wind turbine is integrated in BUS 4 to check the load analysis.

Table 4.3.4 – Load flow analysis results

BUS	V_LF (PU)	P_LF (MW)	Q_LF (MVAR)
1	1.075	71.19	26.96
2	1.028	164.0	6.39

3	1.0240	85.00	-10.69
4	1.0267	0.00	0.00
5	0.992	126.00	51.00
6	1.0121	91.1	30.00
7	1.0269	0.00	0.00
8	1.0159	100.00	35.00
9	1.0324	0.00	0.00

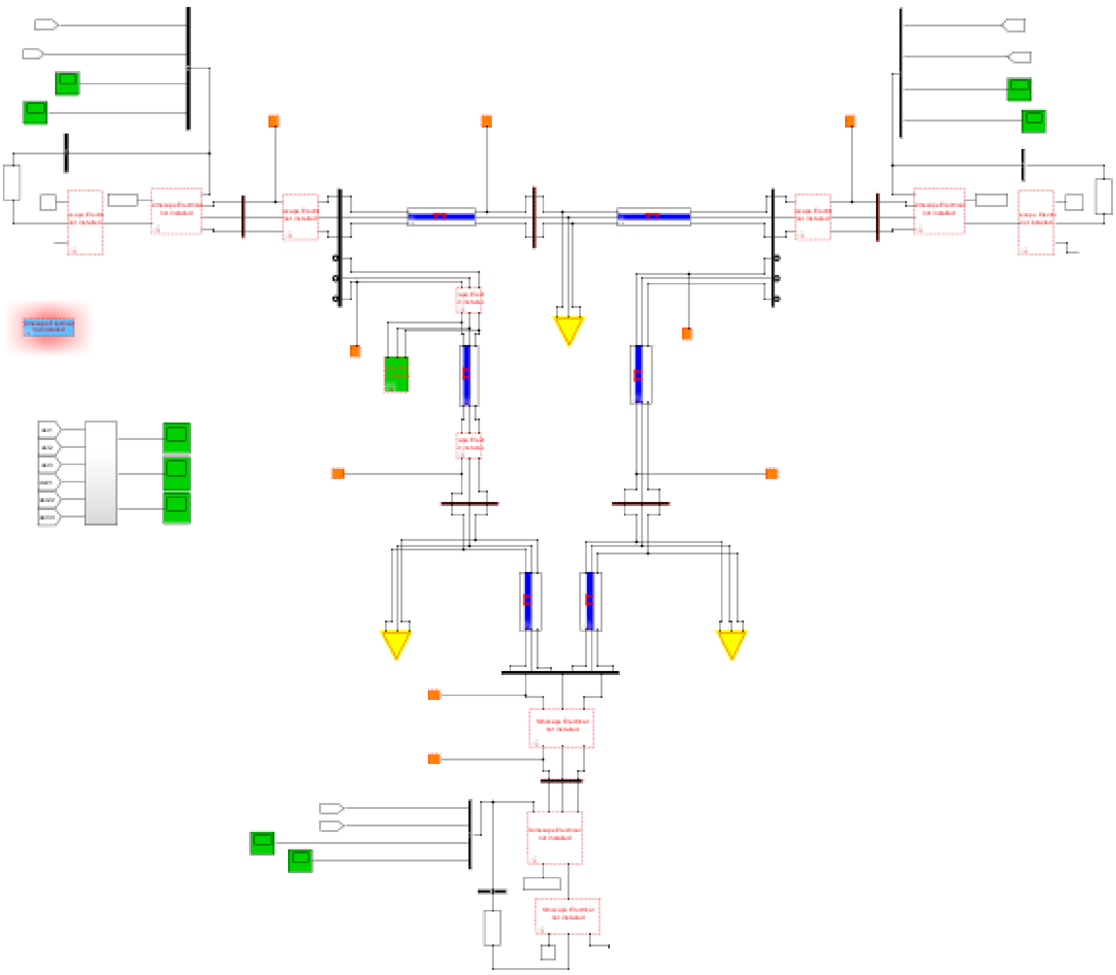

Figure 14: Simulink model of wind turbine model integrated in IEEE 9 BUS system.

4.2.4 Transient stability analysis

For simulation, a 400 MW capacity wind farm is placed to identify the suitable location of IEEE 9 BUS system. It is done on the MATLAB/ Simulink R2019a software. In two different situations of Wind turbine such as Double fed induction generator and Power system stabilizer were considered to investigate. Table 3 below shows the two variable scenarios with measured parameters of determining peak value of reactive power by setting time. The maximum reactive power found is in the case wind turbine integrated with double fed induction generator. The power system stabilizer shows some significant contribution to get stable network. Simulated results with and without power system stabilizer integrated with double fed induction generator decreases value of setting time. Figure 15 and 16 shows the overview of relative power angle with time based on highest peak values. In figure 15 is shown Wind turbine integrated with double fed induction generator and in figure 16 integrated with double fed induction generator with power system stabilizer. [12]

Table 4.4.5 – Setting time with DFIG

SETTING TIME	RELATIVE POWER ANGLE
22.15	129.25
22.75	129.55
17.28	140.42
18.11	134.54
19.05	132.64

Table 4.5.6 – Setting time with DFIG and PSS

SETTING TIME	RELATIVE POWER ANGLE
6.55	127.87
7.11	127.29
7.98	128.95

7.91	140.29
8.87	136.64
8.72	133.09

4.2.4.1 Simulation result

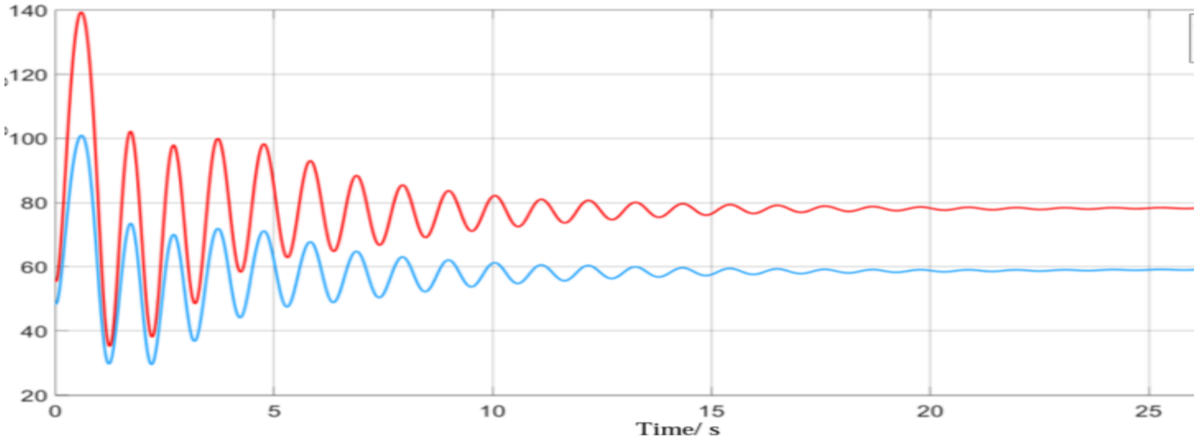

Figure 15: Wind turbine integrated with Double Fed induction generator.

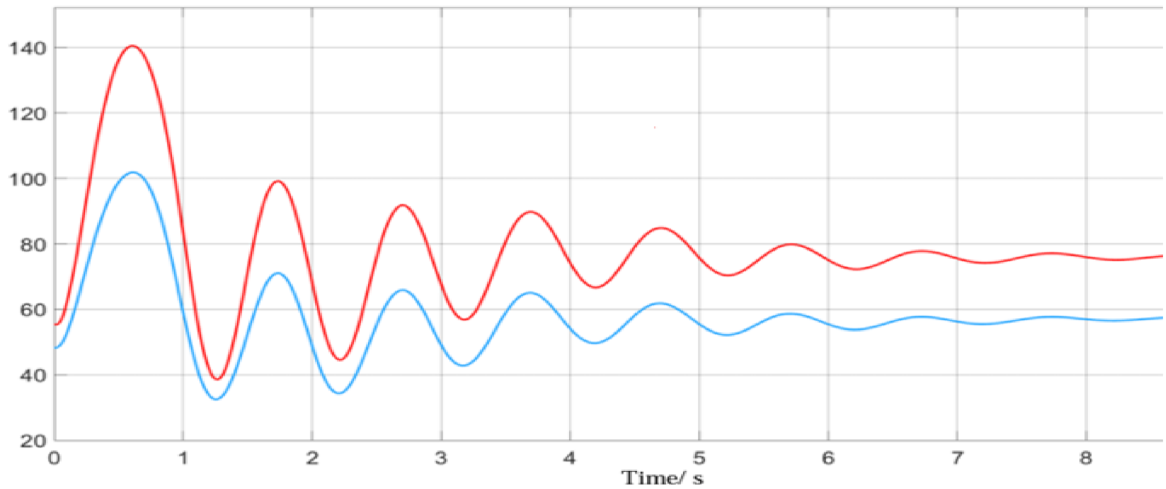

Figure 16: Wind turbine integrated with DFIG and Power system stabilizer.

5 Energy Storage

Industrial energy storage requires large scale facility to store electrical energy on an industrial or commercial stage. It ensures the supply of electricity in case of intermittent and variability related to industrial energy resources. It is mainly subjected to provide backup power in time of grid outage or even in peak demand situations. Some different forms of storage system discussion along with selection of suitable storage system is required to analyze.

5.1 Battery storage

Capacitors and batteries can store electrical energy. Natural energy storage devices like batteries can store energy in high density and voltages. Various types of batteries are now available, such as lithium ion (Li-ion), sodium sulfur (NaS), nickel-cadmium (NiCd), lead acid (Pb-acid), lead carbon batteries etc. As short storage capacitors deliver energy electronically. Some energy storage systems are reviewed, and suggestions provided for low cost and highest efficiency, energy density storage for industrial purposes. [13]

5.2 CAES

CAES is also known as compressed air energy storage system where air is compressed and stored in an underground cavern or an abandoned mine. Depending on energy demand, the compressed air can be released to a turbine which will generate electrical energy. Cavities such as aquifer strata can be provided, or caverns can be drilled in rock formation or in salt. It requires such a kind of geological formation which is not available everywhere. As an alternative, large still tanks which are equipped to handle high pressure air can be installed underground. It has a higher system cost. It can be economically feasible due to capacity and shift time of energy use.

5.3 Thermal energy storage

Thermal energy storage is known as storage of heat or cold in a storage medium. The system is usually equipped with a storage medium with an injection facility of heat or extraction to/ from the medium. The structure of the medium can be naturally found, or it can be made artificially established. Thermal energy storage has three different modes: sensible, latent, and thermochemical.

5.4 Pumped hydro energy storage

PHES, which stands for pumped hydro energy storage, is a facility that is resource driven in hydraulic potential energy by providing an electric pump to move water from a water source in lower level and to a higher-level water reservoir. If energy discharge is needed the system allows the water to flow through hydro turbine from higher to lower levels. A generator is connected to the turbine to produce electrical energy. As Northern Norway is completely undergone with renewable energy, PHES can be the best suitable options for renewable energy storage. The pumped hydro energy storage can provide 70-80% efficiency. It can even have a capacity of 1000-1500 MW. Near site Kvandal there is plenty of water resource which can provide water for reservoir. So, a hydro power plant can be integrated with wind turbine in the form of electrical energy storage in case of outage or as a backup energy source. [15]

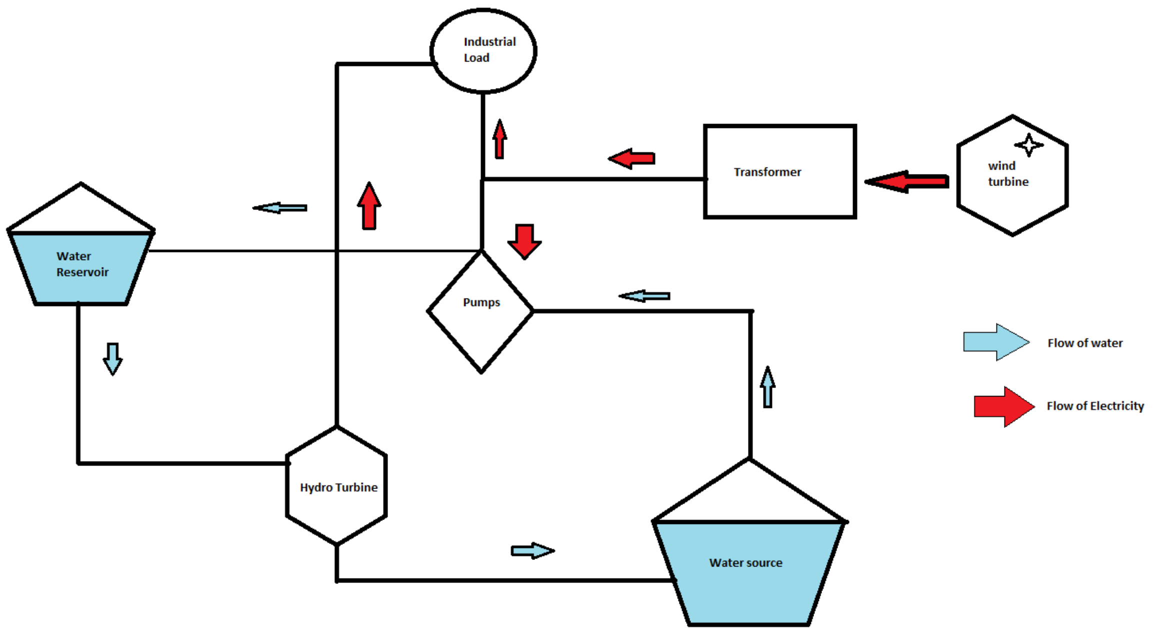

Figure 17: Pumped hydro energy storage integrated with wind turbine.

5.5 Technical Performance of storage systems

From a technical perspective, storage technologies are reviewed for better understanding the performance of the chosen energy storage system. To define the characteristics of the system some aspects such as power density, energy density, cycle efficiency, lifespan can be considered. Some technical characteristics are summarized in the table below. It is confirmed that energy storage with higher power density can be operational for the short term. On the other hand, higher energy density has a long duration of operation. It also needs to be mentioned that power storage like PHES can be beneficial for applications like renewable energy load shifting and long-term power outage.

Table 5.1.7 – Technical characteristic [15]

TYPES OF STORAGE	POWER DENSITY (KW/M3)	ENERGY DENSITY (KWH/M3)	CYCLE EFFCIENCY (%)	LIFE-TIME (CYCLE)

BATTERY STORAGE	1300-10000	300-750	85-98	500-10e4
CAES	0.2-0.6	2-6	41-75	>10e4
THERMAL	0.5-2	0.5-1.3	70-96	>10e4-10e5
PHES	0.1-0.2	0.2-2	70-80	>0.5*10e4

5.6 Advantage and disadvantage of different storage system

5.6.1 PHES advantages and disadvantages

Table 5.2.8 – PHES characteristics

	ADVANTAGES	**DISADVANTAGES**
	Maturity of technology	Constraints of location
PHES	High amount of energy storage capacity	Higher cost of installation
	Longer life span	Energy density and power are low
		Impacts on environments

5.6.2 CAES advantages and disadvantages

Table 5.3.9 – CAES characteristics

	ADVANTAGES	**DISADVANTAGES**
	Maturity of technology	Variation in efficiency
CAES	High amount of energy storage capacity	Leakage in system

		Issues concerning safety
		Constraints of location

5.6.3 Battery advantages and disadvantages

Table 5.4.10 – Battery energy storage characteristics

	ADVANTAGES	**DISADVANTAGES**
	Energy and power density higher in amount	Depending on discharge life cycle varies
BATTERY STORAGE	Shorter response time	Material consumption
		Li-ion batteries impacts on environment

6 Cost development

To determine the cost of developing industrial grid includes some cost analysis like cost of wind turbines, site development, cost of transmission lines, infrastructure cost and regulation of local govt on costing. Also, the cost development includes the cost of energy storage and expansion on the grid system. Some cost development breakdown is discussed to get an overview. This assumption might vary according to development and associated changes. The amounts taken from the LCOE found from nve and some recent developments of onshore wind power plants, PHES development. The cost developed in this study can be redone with more detailed cost analysis. [13]

6.1 Turbine and equipment cost

The highest amount of cost required for any wind farm is the procurement and installation of wind turbines. Per turbine cost usually varies according to factors such as turbine size, rated capacity, height of the hub, diameter of rotor etc. Technological improvement and economic scale improvement in wind turbines enhanced the price reduction. The cost of turbines makes up significant amounts of total cost. Recent developments indicate some assumption of per MW cost of wind turbines. The lowest cost for per MW production of energy is nearly 13,725,000 NOK. (12)

6.2 Site development

Cost of site development includes selection of site, size of the project, feasibility of the site, lease or acquisition of land, investigation on geotechnical issues, assessment of environmental, licensing from Norwegian government, approvals etc. This type of cost can be varied according to how complex the site is and local regulations from authority.

6.3 Infrastructure of electrical equipment:

From development of infrastructure to connection to grid, onshore wind farms require some cost to develop. For this purpose, the cost of construction of transmission and distribution networks, transformers, switchgear equipment, substations, connecting lines and many more are included. This kind of cost depends on distance and capacity.

6.4 Civil structure cost

The cost regarding building the towers and ensured stability is included in civil structure cost. The civil structure cost consists of preparations of structural development, access road construction, foundation installation, required landscaping etc.

6.5 Connection to grid and network cost

The cost of connecting the wind farm with the transmission and distribution network as well as grid mostly depends on the distance between the connection point of the grid and the infrastructure of the grid in the respective region. It also includes the cost of studies on grid, grid reinforcement, installation of grid equipment etc. This kind of expense ensures proper integration of the grid along with the power plants and energy storage.

6.6 Project Management

The cost regarding project management, engineering and project design, research and development on planning, permission and licensing, financial study, and other development expenses.

6.7 Energy storage management cost

For energy storage a PHES system is integrated which nearby costs a high amount like a hydroelectric power plant. It is a renewable energy resource, and it has a long lifetime. So, expenses on this kind of storage are feasible for long term development. The cost of PHES is also considered for the cost development.

6.8 Cost development including LCOE

Above mentioned development costs and other expenses are usually classified into two categories. Such as CapEx and OpEx. Capital expenses such as construction of infrastructure, grid, equipment, energy storage is Capital Expenses known as CapEx. The operational costs like management cost, engineering design and maintenance cost are defined as OpEx. The table below shows the cost development and including CapEx, OpEx and LCOE. (13)

Table 6.1.11 – LCOE and cost development breakdown

PARAMETERS	UNIT	UNIT SCALE	DISTRIBUTED AMOUNT FROM SINGLE TURBINE AND UNIT
WIND TURBINE RATING	MW	2.8	100
CAPEX	NOK/KW	14710	42140
FIXED CHARGE RATE	%	5.88	5.42
OPEX	NOK/KW/Year	40	35
NET ANNUAL ENERGY	MWh/MW/yr	3.775	2.486
ENERGY STORAGE	NOK/KW	17250	64213
TRANSMISSION COST	NOK/km	18300000	37270000
LCOE	NOK/KWh	34	94

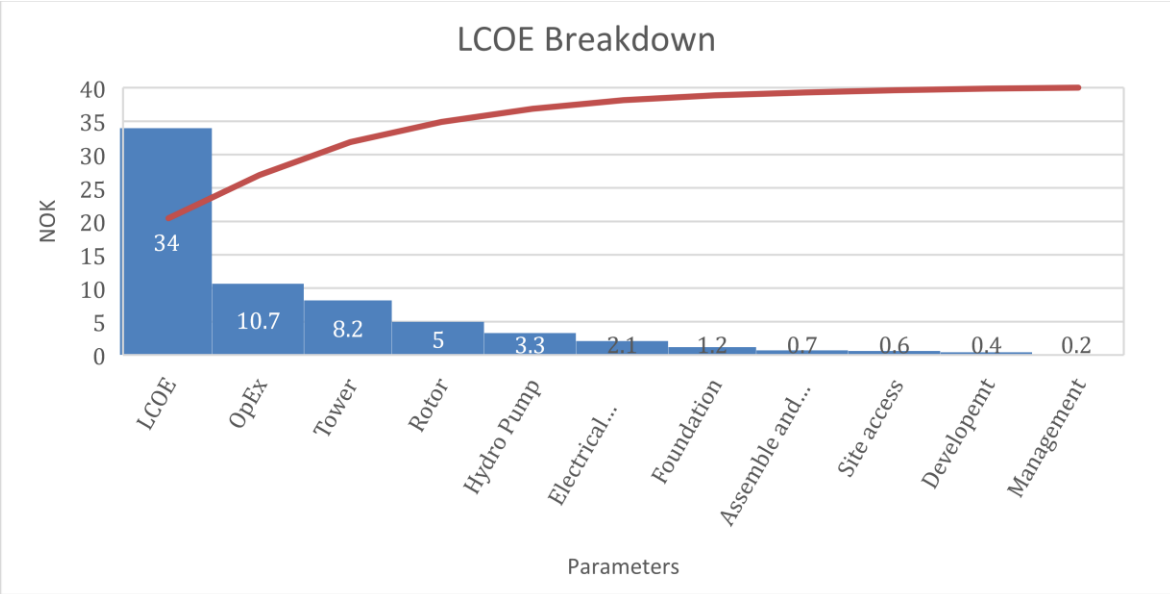

Figure 18: Breakdown of cost development

7 Challenges

The main purpose of the study is to analyze every possible way to optimize the industrial power grid with a certain amount of data. Generally, the idea was to simulate the distribution network and find the best possible solution for the location with the numbers of consumption, production, and distribution. As most of the electrical energy operations in Norway are operated by organizations like Nordkraft, Statnett, Aker Solution the data was expected from those sources which were not completely available. The literature history was found very shortly from some sources of Statnett Network development plan. Also, the most important factor as a challenge was to understand the geographical location of the optimization plan as it was completely unknown.

8 Conclusion and future work

In conclusion, in local communities and industrial sector, optimization holds a lot of significance. For efficient, reliable, and sustainable system implementation it is required to enable advanced technological optimization such as integration of renewable energy.

Engaging industrial plants in Narvik region as well as power grid to supply energy to the industries can effectively improve economic growth and well-being. As a clean energy source, wind turbines and hydroelectric power plants integration is enhancing the green energy solution. The goal to reduce carbon footprint and emissions can be achieved by utilizing renewable energy resources.

Optimization efforts are required to enhance the reliability and resilience of the power grid in Narvik. Adaptation of advanced monitoring and control systems, failures and disruptions can be detected and addressed proactively. The reliable energy storage system can enable energy in case of any outage and demands to ensure stable and continuous power supply.

For the regions sustainable development, the optimization is a transformative endeavor. By engaging in modern technologies, renewable energy integration and collaborating approaches, a robust, efficient, and environmentally friendly power grid for Narvik region can be established.

In future, more detailed study can be done on some aspects of the thesis. Some details study on wind turbines with more analysis has some scopes to establish. The development of Industrial grid also requires optimization on few other industries like Sponge iron production, battery production. Some detailed analysis about the transmission and distribution network, infrastructures, site allocation, efficient power generation, grid expansion can be evaluated. On of the most important future work on this topic can be phase by phase development of the optimization till 2030 and pursuing expansion of development stages can be expected. Advanced technology like cybersecurity, demand response program, grid resilience and collaboration with AI with the system has further scopes. It can be said that optimization has endless chances to expand in power grid development to encourage social and economic development of Narvik region.

References

[1] Statnett Network Development plan 2021 by Hilde Tonne

[2] Temporary Load Shedding - Optimization of power distribution system using load shedding Techniques by Basit, Abdul

[3] Hydrogen: A new market on its way by Bjørn Holsen

[4] https://www.fortum.com/about-us/our-company/our-energy-production/wind-power/wind-farms/nygardsfjellet-wind-farm

[5] https://temakart.nve.no/tema/nettanlegg

[6] http://dhakalabs.bcsir.gov.bd/

[7] The Norwegian power system. Grid connection and licensing by Statnett and NVE

[8] Comparative Analysis of a Current-Source and a Voltage-Source Converter for Three-Phase Grid-Connected Battery Energy Storage System by Saeed Akram, Muhammad

[9] Anleggskonsesjon by Nordkraft

[10] Abdelhalim H, Farid A M, Adegbege A A, Roueo L and Youeef-Toumi K 2013 Small-signal stability effects of turbine governors on power systems with high penetrations of integrated wind power 2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT) (Washington, DC, USA: IEEE) pp 1–6

[11] Parker B, Blevins S, Facemire M and Hatipoglu K 2017 The effect of variable speed wind turbines on a 21 bus power system SoutheastCon 2017 (Concord, NC, USA: IEEE) pp 1–8

[12] Tareka E and Chowdhury S 2020 Transient stability analysis of a grid-integrated wind farm under fault condition at the point of common coupling 2020 International SAUPEC/RobMech/PRASA Conference (Cape Town, South Africa: IEEE) pp 1–6

[13] P. Jain, Wind Energy Engineering, McGraw-Hill Professional, 2010.

[13] The transmission grid by Eberle, Annika, Owen Roberts, Alicia Key, ParangatBhaskar, and Katherine Dykes. 2019. NREL's Balance-of-System Cost Model for Land-Based Wind. Golden,

[14] 2021 Cost of Wind Energy Review by Tyler Stehly and Patrick Duffy National Renewable Energy Laboratory December 2022

[13] Regulations relating to the marking and establishment of safety zones in connection with offshore renewable energy installations.

[14] 1. J. F. Manwell, J.G. McGowan, A.L. Rogers, Wind Energy Explained: Theory, Design and Application, 2nd and previous edition, Wiley.

[15] Research on Energy Storage Technologies to Build Sustainable Energy Systems in the APEC Region

Appendix

MATLAB Codes for Transient stability

```
% Define model parameters
blade_length = 30; % length of each blade (in meters)
air_density = 1.225; % air density (in kg/m^3)
wind_speed = 10; % wind speed (in m/s)
turbine_efficiency = 0.40; % efficiency of the turbine
generator_efficiency = 0.95; % efficiency of the generator
inertia = 10; % moment of inertia of the generator (in kg*m^2)

% Create Simulink model
mdl = 'wind_power_plant_model';
open_system(mdl);
add_block('simulink/Sources/Sine Wave', [mdl '/Wind Speed']);
add_block('simulink/Continuous/Transfer Fcn', [mdl '/Turbine']);
add_block('simulink/Continuous/Transfer Fcn', [mdl '/Generator']);
add_block('simulink/Commonly Used Blocks/Sum', [mdl '/Sum']);
add_block('simulink/Commonly Used Blocks/Gain', [mdl '/Turbine Efficiency']);
add_block('simulink/Commonly Used Blocks/Gain', [mdl '/Generator Efficiency']);
add_block('simulink/Commonly Used Blocks/Gain', [mdl '/Inertia']);

% Connect blocks
add_line(mdl, 'Wind Speed/1', 'Turbine/1');
add_line(mdl, 'Turbine/1', 'Sum/1');
add_line(mdl, 'Sum/1', 'Turbine Efficiency/1');
add_line(mdl, 'Turbine Efficiency/1', 'Generator/1');
add_line(mdl, 'Generator/1', 'Generator Efficiency/1');
add_line(mdl, 'Generator Efficiency/1', 'Sum/2');
add_line(mdl, 'Turbine/1', 'Inertia/1');
add_line(mdl, 'Inertia/1', 'Sum/3');

% Set block parameters
set_param([mdl '/Wind Speed'], 'Amplitude', num2str(wind_speed));
set_param([mdl '/Wind Speed'], 'Frequency', '0.05');
set_param([mdl '/Turbine'], 'Numerator', num2str(turbine_efficiency * 0.5 *
air_density * pi * blade_length^2 * wind_speed^3));
set_param([mdl '/Turbine'], 'Denominator', '[1 0]');
set_param([mdl '/Generator'], 'Numerator', num2str(generator_efficiency));
set_param([mdl '/Generator'], 'Denominator', '[inertia 1]');
set_param([mdl '/Turbine Efficiency'], 'Gain', num2str(turbine_efficiency));
set_param([mdl '/Generator Efficiency'], 'Gain', num2str(generator_efficiency));
set_param([mdl '/Inertia'], 'Gain', num2str(inertia));

% Set simulation parameters
sim_time = 10; % simulation time (in seconds)
sim_step = 0.01; % simulation step size (in seconds)

% Run simulation
sim(mdl, sim_time);

% Plot results
t = ans.wind_power_plant_model.Time;
w = ans.wind_power_plant_model.Wind_Speed;
```

```
p = ans.wind_power_plant_model.Generator;
figure;
subplot(2,1,1);
plot(t, w);
ylabel('Wind speed (m/s)');
subplot(2,1,2);
plot(t, p);
ylabel('Power output (W)');
xlabel('Time (s)');
```

MATLAB Codes for Load flow analysis

```
% IEEE 9-bus 3-machine system data (bus data, generator data, line data, load
data)
% Replace with the actual data values for your specific system

% Bus data
busData = [
    1 138 1.04 0 0 0 0;
    2 138 1.02 0 0 0 0;
    3 138 1.05 0 0 0 0;
    4 138 1.01 0 0 0 0;
    5 138 1.01 0 0 0 0;
    6 138 1.07 0 0 0 0;
    7 138 1.06 0 0 0 0;
    8 138 1.09 0 0 0 0;
    9 138 1.02 0 0 0 0;
];

% Generator data
generatorData = [
    1 2 100 20 0.05 0;
    2 2 100 20 0.05 0;
    3 2 100 20 0.05 0;
];

% Line data
lineData = [
    1 4 0.02 0.06 0.05;
    2 4 0.08 0.24 0.02;
    3 6 0.06 0.18 0.03;
    4 6 0.06 0.18 0.03;
     % Add the remaining line data for the system
];

% Load data
loadData = [
    1 0 0;
    2 0 0;
    3 0 0;
    4 0 0;
    5 80 40;
    6 200 100;
    7 0 0;
    8 200 100;
    9 200 100;
];
```

```
% Convert data to per unit values
baseMVA = 100; % Base MVA
busData(:, 3:end) = busData(:, 3:end) / baseMVA;
generatorData(:, 3:end) = generatorData(:, 3:end) / baseMVA;
lineData(:, 3:end) = lineData(:, 3:end) / baseMVA;
loadData(:, 2:end) = loadData(:, 2:end) / baseMVA;

% Initialize variables
numBuses = size(busData, 1);
numGenerators = size(generatorData, 1);
numLines = size(lineData, 1);

P = zeros(numBuses, 1);
Q = zeros(numBuses, 1);
V = busData(:, 3);
theta = zeros(numBuses, 1);
Ybus = zeros(numBuses, numBuses);

% Build the admittance matrix (Ybus)
for k = 1:numLines
    fromBus = lineData(k, 1);
    toBus = lineData(k, 2);
    r = lineData(k, 3);
    x = lineData(k, 4);
    b = lineData(k, 5);
    y = 1 / (r + 1i * x);

    % Off-diagonal elements
    Ybus(fromBus, toBus) = -y;
```