Grid Capacity and Upgrade Costs

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Abstract—The aim of the study is to analyze the possibility of how and where wind farms should be integrated on the electrical grid. The challenges mainly concern grid capacity and transmission losses. Economic factors will be regarded as well. To fulfill the aim, the Skellefteälven river in Sweden is selected as study object. A regional grid along the river is thereafter simulated with regards to five existing hydro power plants, four electrical consumption points, and the national grid. Additionally, four wind farms are placed on probable sites around the grid. Considering the large amount of data to be calculated in this study, a grid model assembled through numerical analysis in MATLAB is henceforth deemed optimal. Through load flow simulation, the voltage variations and power losses are calculated. Hence, the costs of the losses is found. The investment costs for upgrading the grid are also determined. As the results show, an upgrade of the electrical grid certainly requires a relatively large investment sum. Nevertheless, the return of the project will eventually surpass the initial costs. Accordingly, there are economic benefits of investing in upgrading the grid capacity.

I. INTRODUCTION

Environmental changes have arguably become one of the most pressing issues in modern times. The unsettling development is mainly a result of drastically increasing greenhouse gas emissions in the atmosphere, this due to an unsustainable consumption of principally fossil fuels. Subsequently, outcries around the world now call for alternative options of power production [1]. Renewable resources are potential candidates for viable substitutes, motivating countries to invest further in these sectors. Sweden is no exception [2].

The Nordic country is blessed with abundant river systems throughout the landscape, leading to an extensive electricity production through hydro power. For instance, hydro power accounted for about 50% of the Swedish power generation in 2017 [3]. Simultaneously, Sweden has been exploring new ways of raising the total level of renewables in the national energy mix. As wind power is widely regarded as the most promising renewable energy source in terms of economic growth, the Swedish parliament has set a target of 30 TWh/year to be generated in Sweden by the year 2020, compared to 16.6 TWh in 2015 [3] [4].

Wind power in Sweden is heavily dominated by onshore wind farms. They represent over 10% of the total power production and is continuously expanding evenly across the country, except for electricity area SE1 (see figure 1) [5]. This area is characterized by insufficient infrastructure for transferring produced power to consumers, leading to a larger initial investment if doing so.

Furthermore, SE1 tends to have a general production surplus, whereas the consumption is greater in southern regions [5]. As the population is growing, installing more renewable power sources, like wind turbines, in SE1 will eventually become inevitable. Therefore, it entails upgrading the grid capacity to enable the increased load on the system [6].

Despite the wind energy’s renewable and carbon free nature, it does not ensue flawlessness. The wind namely blows at irregular times, making it difficult, if not impossible, to predict its power. Accordingly, a reliable energy reservoir is needed to complement the production dips [5]. Hydro power is a promising alternative, but likewise raises new issues at hand.
the national grid. Additionally, four wind farms, W1-W4, are placed on probable sites around the hypothetical grid. To simulate the transmission lines, the $\pi$-model was used (see III. C. Transmission lines). Thus, the connections between consuming and producing buses on the regional grid establishes 13 supplementary nodes, T1-T13. Figure 2 illustrates the grid's physical design. Moreover, the area surrounding the grid is considered rural, with an open landscape and room for overhead lines [8].

According to the standard voltage characteristics of public distribution systems, the acceptable voltage variations must stay within $\pm 5\%$ [9]. Considering the large amount of data to be calculated for this study, a grid model assembled through numerical analysis in MATLAB is henceforth deemed optimal. By reason of withholding relevance and focus on the questions at issue, assorted factors are disregarded when determining wind farm whereabouts.

These include social circumstances and local conditions, such as the neighboring communities’ attitude to adjacent wind turbines, land ownership, topography, as well as external effects on the surrounding environment. Instead, the attention is aimed at the electrical power engineering perspective: wind data, transmission line lengths, and connection points on the grid.

B. Periods of importance

To simulate a credible model, seven consecutive days are chosen from the four seasons apiece in 2015. The number of days is determined by the accuracy of representing reality that comes with more data, but is limited due to the time it takes for a computer to run all the calculations. The chosen dates consist of March 8th to 14th in spring, June 8th to 14th in
summer, September 19th to 25th in autumn, and December 8th to 14th in winter.

Likewise in the study, winter consists of January, February, and December; spring consists of March, April, and May; summer consists of June, July, and August; Autumn consists of September, October, and November. Conjointly, the hours from each week in respective periods represents the entire season they belong in. To represent a year, each week’s values of the respective seasons is multiplied with a quarter of the season they belong in. To represent a year, each week’s values from each week in respective periods represents the entire of September, October, and November. Conjointly, the hours summer consists of June, July, and August; Autumn consists and December; spring consists of March, April, and May; October, and November. Conjointly, the hours from each week in respective periods represents the entire season they belong in. To represent a year, each week’s values of the respective seasons is multiplied with a quarter of the weeks of a normal year, which would be \( \frac{52}{4} = 13 \) weeks. The retrieved values are, for instance, used to calculate the power losses on the lines. This paragraph is further explained in IV.

C. Load flow simulations

Moreover, the consumption per season is assumed to be dependent on the prevailing temperature of the period. The colder the weather is, the more energy is consumed. Monthly mean temperature data from 2015 are recovered from Skellefteå Flygplats, close to consumption node C4 [10]. The temperatures are presumed to apply for all consumption nodes, displayed in table I, where \( t \) is the highest energy consumption, consecutively during winter (see table II). Furthermore, all retrieved values in the entire study are from 2015 for maintaining consistency.

### TABLE I
SEASONAL MEAN TEMPERATURE AND CONSUMPTION OF \( t \)

<table>
<thead>
<tr>
<th>Season</th>
<th>Mean temperature ( {^{[\circ C]} } )</th>
<th>Consumption of ( t ) ( [%] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>3.390</td>
<td>70.7</td>
</tr>
<tr>
<td>Summer</td>
<td>14.23</td>
<td>50.0</td>
</tr>
<tr>
<td>Autumn</td>
<td>5.63</td>
<td>75.6</td>
</tr>
<tr>
<td>Winter</td>
<td>-3.40</td>
<td>100.0</td>
</tr>
</tbody>
</table>

D. Wind data

The wind farms of the case study are placed on theoretical sites, where wind speed data can be found from weather stations. The stations belong to SMHI (the Swedish Meteorological and Hydrological Institute), showing measured data from years back [10].

Wind data is retrieved from weather stations Mierkenis A, Lillviken-Roparudden V, Bjuröklubb and Pite-Rönnskär A, which are marked as W1 to W4 aside. Since the available data is at ten meters height above ground level, equation (1) is used to calculate the new velocity at 70 m above ground [15].

\[
v_2 = v_1 \times \left( \frac{h_2}{h_1} \right)^\beta
\]

\( v_1 \) is the velocity at ten meters above ground, \( h_1 \), while \( v_2 \) is the scaled velocity at 70 m, \( h_2 \). \( \beta \) is the ground surface friction coefficient. The further away from the coast the grid reaches, the rougher the terrain becomes, as the grid enters the Scandinavian mountain range. The friction coefficient for mountains is 0.40. On the other hand, the terrain is rather smooth by the coast, with friction coefficient 0.1. Since the grid contains both terrain types, with a gradual change along the grid, \( \beta \) is set as the mean value of the previously mentioned coefficients: \( \beta = 0.25 \) [16].

### TABLE II
ENERGY CONSUMPTION DATA OF C1-C4

<table>
<thead>
<tr>
<th>Area</th>
<th>Bus</th>
<th>Season</th>
<th>Consumption [GWh/year]</th>
<th>Cons. [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Spring</td>
<td>199.520</td>
<td>0.031</td>
</tr>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Summer</td>
<td>1,281.047</td>
<td>0.197</td>
</tr>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Autumn</td>
<td>1,349.986</td>
<td>-</td>
</tr>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Winter</td>
<td>1,128.142</td>
<td>0.174</td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Spring</td>
<td>305.670</td>
<td></td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Summer</td>
<td>216.174</td>
<td></td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Autumn</td>
<td>326.855</td>
<td></td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Winter</td>
<td>432.348</td>
<td></td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Spring</td>
<td>337.496</td>
<td></td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Summer</td>
<td>337.496</td>
<td></td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Autumn</td>
<td>337.496</td>
<td></td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Winter</td>
<td>337.496</td>
<td></td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Winter</td>
<td>269.185</td>
<td></td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Winter</td>
<td>190.372</td>
<td></td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Autumn</td>
<td>287.842</td>
<td></td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Winter</td>
<td>380.743</td>
<td></td>
</tr>
</tbody>
</table>

The seasonal consumption for each bus is presented in table III. The consumption is presumed to be constant throughout each week, however the hydro power is presumed to vary depending on the hour of the day, more specified in II. F. Hydro power.

### TABLE III
ENERGY CONSUMPTION DATA

<table>
<thead>
<tr>
<th>Area</th>
<th>Bus</th>
<th>Season</th>
<th>Consumption [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Spring</td>
<td>47.607</td>
</tr>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Summer</td>
<td>33.669</td>
</tr>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Autumn</td>
<td>50.907</td>
</tr>
<tr>
<td>Arvidsjaur C1</td>
<td>C1</td>
<td>Winter</td>
<td>67.337</td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Spring</td>
<td>305.670</td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Summer</td>
<td>216.174</td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Autumn</td>
<td>326.855</td>
</tr>
<tr>
<td>Piteå C2</td>
<td>C2</td>
<td>Winter</td>
<td>432.348</td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Spring</td>
<td>337.496</td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Summer</td>
<td>337.496</td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Autumn</td>
<td>337.496</td>
</tr>
<tr>
<td>Boliden C3</td>
<td>C3</td>
<td>Winter</td>
<td>337.496</td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Spring</td>
<td>269.185</td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Summer</td>
<td>190.372</td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Autumn</td>
<td>287.842</td>
</tr>
<tr>
<td>Skellefteå C4</td>
<td>C4</td>
<td>Winter</td>
<td>380.743</td>
</tr>
</tbody>
</table>
Wind [m/s]

0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Generated power [MW]

0 5 10 15 20 25 30

Fig. 4. The capability of generating power from a single wind turbine in relation to the wind speed. Wind speed levels under 5 and over 25 m/s will result in no generated power at all, while the power reaches its production maximum at 15 m/s.

Furthermore, the wind turbines have been designed with the cut-in and cut-out speed as 5 m/s respectively 25 m/s. In other words, when the wind density is below 5 m/s or over 25 m/s by wind turbine height, the blades will cease rotation and thus stop producing power. These conditions have been set to protect the turbines from high speed damage. At the same time, wind velocities below 5 m/s in the model equivalent to zero produced power. However, at 15 m/s the turbine reaches its peak power. Since the wind velocity in the studied areas do not exceed 25 m/s, no changes were applied to such powers [16]. The produced power per wind density can be observed in figure 4.

E. Wind power

The wind data is in turn used to calculate the power output \( P \) from a wind turbine as following:

\[
P = \frac{1}{2} \rho A C_p v^3 \quad [\text{W}]
\]

The rotating blades of a wind turbine will take up an area \( A \). In sequence, the wind blows at a speed of \( v \).

<table>
<thead>
<tr>
<th>Location</th>
<th>Bus</th>
<th>Mean power generation [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mierkenis A</td>
<td>W1</td>
<td>0.146</td>
</tr>
<tr>
<td>Lillviken-Roparudden V</td>
<td>W2</td>
<td>0.407</td>
</tr>
<tr>
<td>Bjuröklubb</td>
<td>W3</td>
<td>0.608</td>
</tr>
<tr>
<td>Pite-Rönnskär A</td>
<td>W4</td>
<td>0.414</td>
</tr>
</tbody>
</table>

Since the turbines reaches 70 m height, the assumed mean temperature is 15 °C [18]. The air pressure \( \rho \) at this temperature corresponds to 1.225 kg/m³. \( C_p \) is the power coefficient, which in this case equals to the theoretical maximum efficiency 0.59 [19]. The calculated mean power generation is presented in table IV. Figure 5 visualizes the power output for one day.

F. Hydro power

Besides wind power sites, the five uppermost hydro power plants along Skellefteälven are incorporated into the study. These consist of Sädva, Riebnäs, Bergnäs, Slagnäs, and Bastusel, which represent H1 to H5 in corresponding order (see figure 3) [20]. The produced power from each hydro power plant is presented in table V.

The hydro power production is based on the results from the parallel, ongoing project M2. The aim of M2 is to maximize the economical return of the hydro power. By running all plants at maximum during all hours of the year, the production is considered optimal. A prominent advantage with hydro power is their ability to adequately regulate voltage simultaneously [2].

<table>
<thead>
<tr>
<th>Area</th>
<th>Bus</th>
<th>Production [GWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sädva</td>
<td>H1</td>
<td>111.600</td>
</tr>
<tr>
<td>Riebnäs</td>
<td>H2</td>
<td>230.400</td>
</tr>
<tr>
<td>Bergnäs</td>
<td>H3</td>
<td>28.800</td>
</tr>
<tr>
<td>Slagnäs</td>
<td>H4</td>
<td>25.200</td>
</tr>
<tr>
<td>Bastusel</td>
<td>H5</td>
<td>360.000</td>
</tr>
</tbody>
</table>

Since synchronous generators are used, the amount of reactive power sent into the grid is controllable. In other words, the voltage level is left unregulated when the hydro power plants are inactive, which is deemed problematic for the simulated electrical power system. In the simulation, an assumption is made so that the hydro power plants will all go on 80 % during hours 07:00-22:00 every day. During hours 23:00-06:00 every night, the production is assumed to be on
5% instead. This means there is no regulation from the hydro power plants in our case.

G. Transmission line parameters

The values for resistance, inductance, reactance and shunt susceptance in table VI were chosen as ensuing: $r$ is found with equation (7), $l$ is calculated with equation (8), $x$ is identified with equation (10), and $b$ is determined by equation (15).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance $r$</td>
<td>0.027</td>
<td>Ω/km</td>
</tr>
<tr>
<td>Inductance $l$</td>
<td>0.001</td>
<td>H/km</td>
</tr>
<tr>
<td>Reactance $x$</td>
<td>0.368</td>
<td>Ω/km</td>
</tr>
<tr>
<td>Shunt susceptance $b$</td>
<td>3.023</td>
<td>μS</td>
</tr>
</tbody>
</table>

With Google Maps, the length of the transmission lines is found [21]. The regional grid has a length of 300 km, while the total length of all the transmission lines is 546 km. The grid also consists of 26 buses. Next section describes the theoretical background behind this part.

III. THEORETICAL BACKGROUND

A. Power flow buses

The power flow system makes up the model for the grid. It is composed of different types of buses connected to each other. Each type has various characteristics and purposes (see table VII). First there is the slack-bus, which has both constant voltage and phase angle. In this case it will work as a reference for the rest of the grid, and by being connected to the national grid, it will balance out any lack or surplus of power.

PQ-buses have known active and reactive power, while their voltage and phase angle may vary. They are usually buses that represent loads in a circuit. PU-buses usually represent generators in a circuit instead. Their active power and voltage are known, while their reactive power and phase angle need to be found [22] [23].

<table>
<thead>
<tr>
<th>Bus type</th>
<th>Known parameters</th>
<th>Unknown variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slack-bus</td>
<td>$U, \theta$</td>
<td>$P, Q$</td>
</tr>
<tr>
<td>PQ-bus</td>
<td>$P, Q$</td>
<td>$U, \theta$</td>
</tr>
<tr>
<td>PU-bus</td>
<td>$P, U$</td>
<td>$Q, \theta$</td>
</tr>
</tbody>
</table>

B. Transmission lines

Since the electrical grid is placed in a rural area, the availability of large land areas is assumed. For that reason, overhead lines are better suited as transmission lines in this study. This is preferred because of prices for alternative solutions, such as having the lines underground, are higher [8]. There are several parameters in transmission lines to consider, all given per length unit, and thus dependent of the line length [22]:

- Inductance $l$, a result of when alternating current flows through the line.
- Shunt capacitance $c$, because of the electric field between line and ground.
- Resistance $r$, owing to the resistivity of the conductor.
- Shunt conductance $g$, due to leakage currents in the isolation.

1) Short line model: Short lines are typically defined as shorter than 100 km (see figure 6). Moreover, the shunt parameters are neglected.

2) π-model: The π-model is applied on transmission lines between 100 and 300 km long. The name comes from its shape after taking the shunt capacitance into consideration, as seen in figure 7. The line impedance is calculated with equation (3), like before. However, the phase admittance to the ground is described in the subsequent equation:

$$\bar{Y}_{sh-kj} = \frac{j b_c L}{2} = \bar{y}_{sh-kj} \quad [S/km, phase] \quad (4)$$

The connection between voltage and current at nodes $k$ and $j$ are described in equations (5) and (6) by applying Kirchhoff’s current law.

$$\bar{I}_k = \bar{U}_k \bar{Y}_{kj} = \left( \bar{U}_k - \bar{U}_j \right) \left( \frac{1}{\bar{Z}_{kj}} \right) \quad (5)$$

$$\bar{I}_j = \bar{U}_j \bar{Y}_{kj} = \left( \bar{U}_j - \bar{U}_k \right) \left( \frac{1}{\bar{Z}_{kj}} \right) \quad (6)$$

C. Electrical characteristics in overhead lines

1) Resistance: Each material in a conductor has their own amount of resistivity. For transmission lines, aluminum and copper are most frequently used, where aluminum reaches approximately 60% of the latter one’s conductivity [24]. Since
the materials in the study are chosen by economical factor, the preferred choice is aluminum due to its affordability [25]. \( r \) is found with following equation:

\[
r = \frac{\rho}{A} \quad [\Omega/\text{km}]
\]

Where the resistivity of aluminum is \( \rho = 27.0 \, \Omega \text{mm}^2/\text{km} \), and the cross section \( A = 1000 \, \text{mm}^2 \) [8].

2) Inductance: The inductance has a large impact on the transference capability of the transmission line, including voltage drop and indirectly affects the losses [22]. Given that the material is non-magnetic, like aluminum and copper, the inductance is given by following equation:

\[
l = 2 \times 10^{-4} \left( \ln \frac{a}{d/2} + \frac{1}{4n} \right) \quad [\text{H/km,phase}] \quad (8)
\]

In equation (8), \( a \) is the geometrical mean distance, as defined in equation (9). In turn, \( d \) is the meter diameter of the conductor, while \( n \) is the number of conductors per phase [22]. Figure 8 shows how the variables are geometrically related.

\[
a = \sqrt[3]{a_{12}a_{13}a_{23}} \quad [\text{m}] \quad (9)
\]

3) Reactance: By knowing the inductance of a line, the reactance can be calculated as:

\[
x = \omega l = 2\pi fl \quad [\Omega/\text{km,phase}] \quad (10)
\]

In other words, the reactance is dependent of the geometrical properties. The line reactance can alter between \( x = 0.3-0.5 \, \Omega/\text{km,phase} \) at normal frequency \( f = 50-60 \, \text{Hz} \).

4) Shunt parameters: Wires and transmission lines act as capacitances. When studying shorter lines this can be overlooked with shorter lines, but the shunt parameters may be significant with longer lines [22]. Equation (11) calculates the capacitance. Contingent upon the shape and structure of the line, besides ground parameters such as minerals of the soil, the electric field will adapt accordingly.

\[
c = \frac{10^{-6}}{18\ln(\frac{2H}{d} \times \frac{d}{\sqrt{4n}})} \quad [\text{F/km,phase}] \quad (11)
\]

Where \( H \) is the geometrical mean height for the conductors, see equation (12). \( A \) is defined as the geometrical mean distance between the conductors and their image conductors, as shown in equation (13) (see figure 8).

\[
H = \sqrt{H_1H_2H_3} \quad (12)
\]

\[
A = \sqrt{A_1A_2A_3} \quad (13)
\]

The admittance between nodes \( k \) and \( j \), \( Y_{kj} \), is defined as following:

\[
Y_{kj} = -y_{kj} = -\frac{1}{Z_{kj}} = g + bj \quad (14)
\]

If the real part of the admittance \( Y \) is the conductance \( g \), then the imaginary part is the susceptance \( b \), which is described in equation (15) [8].

\[
b = 2\pi fc \quad [\text{S/km,phase}] \quad (15)
\]

D. Power flow equations

Power flow calculations, or load flow calculations, are a way of describing the power flowing in and out of a \( \pi \)-model between node \( k \) and \( j \). The power flow of the active power \( P_{kj} \) and reactive power \( Q_{kj} \) in a transmission line between the nodes can be calculated with following equation (17). By knowing the active and reactive powers in each bus, the voltage and phase differences \( \theta_{kj} \) may be determined.

\[
P_{kj} = \frac{R_{kj}U_k^2}{Z_{kj}^2} - \frac{U_kU_j}{Z_{kj}^2} (R_{kj}\cos(\theta_{kj}) - X_{kj}\sin(\theta_{kj})) \quad (16)
\]

\[
Q_{kj} = \frac{X_{kj}U_k^2}{Z_{kj}^2} - \frac{U_kU_j}{Z_{kj}^2} (R_{kj}\sin(\theta_{kj}) + X_{kj}\cos(\theta_{kj})) \quad (17)
\]

For every bus \( k \), the net active power \( P_{GDK} \) and net reactive power \( Q_{GDK} \) can be summed up and described as:

\[
P_{GDK} = P_G - P_{DK} = \sum_{i=1,i\neq k}^{N} P_{ki} \quad (18)
\]

\[
Q_{GDK} = Q_G - Q_{DK} = \sum_{i=1,i\neq k}^{N} Q_{ki} \quad (19)
\]

Every node requires a balance of active and reactive power. The power generated and consumed in node \( k \) are defined below:

\[
P_k = V_k \sum j = 1^N V_j (G_{kj}\cos(\theta_{kj}) + B_{kj}\sin(\theta_{kj})) \quad (20)
\]

\[
Q_k = V_k \sum j = 1^N V_j (G_{kj}\cos(\theta_{kj}) + B_{kj}\sin(\theta_{kj})) \quad (21)
\]

Where \( P_k \) is the produced power, and \( Q_k \) is the consumed power. \( G_{kj} \) and \( B_{kj} \) are the negative real part respectively imaginary part of \( Y_{kj} \) [22].
E. Line losses

Because of the physical limits of transmission lines, a certain amount of power loss will occur. This depends on several factors, such as transmission line length, conductor characteristics, as well as the amount of current flowing in the line. Using equation (22), the losses can be calculated.

\[ P_f = 3R_{kj}I^2 \quad [W] \] (22)

When using the \( \pi \)-model, the losses are described with equation (23) instead.

\[ P_f = R_{kj}P^2_{kj} + \left( Q_{kj} + b_{sh-kj}U^2_k \right) \quad [W] \] (23)

Here, \( R_{kj} \) is the line resistance. Thus, it is possible to find the loss in a bus of a three-phase system. The amount of generated reactive power by a shunt capacitance at a bus \( k \) is described by \( b_{sh-kj}U^2_k \). Furthermore, the losses of the line can also be expressed without knowing the current, see equation (24).

\[ I^2 = \bar{I}^* = \frac{\bar{S}^*}{\sqrt{3}U^*} = \frac{S^2}{3U^2} = \frac{P^2 + Q^2}{3U^2} \] (24)

In other words, if the voltage is increased by an amount of \( \alpha \), the current will correspondingly decrease by \( \alpha \), as observed in equation (25). Hence, if the voltage is increased by \( \alpha \), the losses will equate to \( \alpha^2 \) when operating with a given amount of power. This can also be deduced with equations (22) and (23) [23].

\[ U = RI \quad [V] \] (25)

IV. Method

A. Grid modeling

The length of every power line is determined by using Google Maps [21]. First, the location of the five hydro power plants, four wind farms, and four areas with energy consumption are found on the map, giving an overview similar to figure 2. Using pixel measurement from a screen-shot of this map, coordinates are determined for each location, making it possible to form a trend line for some of the points. Accordingly, the shortest distance between the points and the curve is calculated. The intersection points between the local grid and the regional grid, shown in figure 9, are points where the local lines are connected to the regional grid. In turn, the transmission lines in the local grid connects the production and consumption buses to the regional grid. In most cases its the closest distance to between them. This makes up for an overview of the grid, along with distances, also presented in figure 9.

B. Numerical analysis

The hypothetical grid is described with the equations in subsection F. Power flow equations. With MATLAB, the equation system \( F(X) \) is then modeled. By using the iterative, numerical function \texttt{fsolve}, the system is solved for \( F(X) = 0 \).

\[ F(X) \] represents a vector with every value in \( F(X) \) being the sum of the power flowing in and out of a node, making it follow Kirchhoff’s current law when equal to zero. \( X \) represents the various voltages \( U \) and phase angles \( \theta \) in the equation system. This is described in equations (26) and (27).

\[ g_z(k) = P_k - P_{GDk} \] (26)

\[ g_z(k + n - 1) = Q_k - Q_{GDk} \] (27)

The number of the buses in the system is denoted by \( n \). \texttt{fsolve} starts with a guess of values made up of a base voltage of either 130 kV or 220 kV and a phase angle of 0 in every node. The solver continues to iterate and change the value of the voltages and phases to make the function \( F(X) \) as close to 0 as possible [26].

The solver itself is run in a loop with the same number of iterations as the number of hours with wind data. This is because the solver only resolves the equation system for the current time, and the grid values are constantly changing depending on dynamic variables, in this case mainly the wind, but also the hydro power production in H1-H5 and consumption in C1, C2 and C4. Looking at the highest variation of the voltage which the grid is designed for contributed to perceive unwanted voltage levels. The voltages in consumption points C1-C4 could then be observed by looking at values of each corresponding node.

C. Load flow simulations

1) Voltage variations: The simulation is run without any regulations of the voltage. While trying to maintain 130 kV, the grid will suffer from more losses over the transmission lines. The voltage will also diverge from the sought value, which increases with the power generation in any nodes. This allows for investigating how many wind turbines are possible to install...
at every wind farm, if any at all, while still maintaining the voltage within the allowed limits of ±5 % [9]. The simulation lasts for 672 hours, of which every quarter represents the power output of the respective season, thus representing a year.

The first 168 hours represent the simulation run with wind data from March, the next 168 hours from June, the next 168 hours from September and the last 168 hours from December. Simulating with no wind power installed at all resulted in voltage levels presented in figure 10. This means the grid will require a base voltage of 220 kV. Further analysis of the grid will follow below.

Transmission lines between 100 to 300 km long, like the regional grid of the study, must consider an added shunt susceptance. From using equations (16) and (17), the difference in the load flow calculations are the reduced reactive power, which comes with the additional term $-b_{sh}U_k^2$ on the regional grid in equation (17). The $\pi$-model results in a higher number of allowed wind turbines per site. The voltage remains within the allowed limits when a maximum of 81 wind turbines per site were installed. This can be seen in figures 11 and 13. The voltage levels remains within the stated limits. As the grid voltage is therefor deemed stable, it is of
interest to inspect the voltage levels in the fellow consumption nodes. With 81 wind turbines per site as above, each turbine generating power according to figure 4, the voltage levels of a day in the consumption buses are shown (see figure 12).

2) Power losses: The higher the losses are, the more is lost in economic terms as well. Therefore, it is worth evaluating how high the loss quantities are per year and how it varies for different cases. Two cases with their respective losses are presented in figure 14 and 15.

![Power loss representation of each season, with 0 wind turbines at all four sites.](image1)

![Power loss representation of each season, with 81 wind turbines at all four sites.](image2)

**Fig. 14. Power loss representation of each season, with 0 wind turbines at all four sites.**

**Fig. 15. Power loss representation of each season, with 81 wind turbines at all four sites.**

**TABLE VIII**

<table>
<thead>
<tr>
<th>Bus</th>
<th>No. of turbines</th>
<th>Losses per year [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>0</td>
<td>23.805</td>
</tr>
<tr>
<td>W1</td>
<td>20</td>
<td>23.846</td>
</tr>
<tr>
<td>W1</td>
<td>40</td>
<td>23.700</td>
</tr>
<tr>
<td>W1</td>
<td>60</td>
<td>23.891</td>
</tr>
<tr>
<td>W1</td>
<td>80</td>
<td>23.817</td>
</tr>
<tr>
<td>W2</td>
<td>1</td>
<td>23.804</td>
</tr>
<tr>
<td>W2</td>
<td>20</td>
<td>23.807</td>
</tr>
<tr>
<td>W2</td>
<td>40</td>
<td>23.809</td>
</tr>
<tr>
<td>W2</td>
<td>60</td>
<td>23.812</td>
</tr>
<tr>
<td>W2</td>
<td>80</td>
<td>23.809</td>
</tr>
<tr>
<td>W3</td>
<td>1</td>
<td>23.804</td>
</tr>
<tr>
<td>W3</td>
<td>20</td>
<td>23.812</td>
</tr>
<tr>
<td>W3</td>
<td>40</td>
<td>23.885</td>
</tr>
<tr>
<td>W3</td>
<td>60</td>
<td>23.972</td>
</tr>
<tr>
<td>W3</td>
<td>80</td>
<td>23.804</td>
</tr>
<tr>
<td>W4</td>
<td>1</td>
<td>23.804</td>
</tr>
<tr>
<td>W4</td>
<td>20</td>
<td>23.810</td>
</tr>
<tr>
<td>W4</td>
<td>40</td>
<td>23.845</td>
</tr>
<tr>
<td>W4</td>
<td>60</td>
<td>23.026</td>
</tr>
<tr>
<td>W4</td>
<td>80</td>
<td>23.374</td>
</tr>
</tbody>
</table>

These are calculated using equation (22) and (24) for the local grid, and equation (23) for the regional grid (see III. E. Line losses). The simulation has variables for two power flows on the same line, but in different directions, making it necessary to account for the resulting value of the two. The mean value of every hour is calculated and then multiplied by the number of hours in a year. Table VIII shows the total line losses in the grid during different scenarios with wind power solely in one bus at a time. This while having no wind power at all in the other buses.

As table VIII also highlights, the losses actually decrease with an addition of production in some buses. This might seem illogical at first, since higher power generation generally means higher line losses. The reason for having lower line losses when generating more power is when the alternative path from generation to consumption is longer. An example would be if the power flow had to travel from H1 to C4 without any wind power. The path would then get shorter if the power could come from W3 (see figure 2).

**V. RESULTS**

A. Investment costs

To receive the costs of power losses, the yearly values from table VIII are multiplied with the mean value of the yearly day-ahead price for 2015, which was 220,419 SEK/GWh [27]. Since 130 kV does not allow for any wind power, the grid is upgraded to 220 kV instead. For this voltage level, overhead lines with two circuits are preferred [15]. Additionally, AC stations need to be installed for each power generation node, as well as transmission towers for the 1000 mm²-aluminum conductors [28] [29].

**TABLE IX**

<table>
<thead>
<tr>
<th>Total investment costs</th>
<th>Item</th>
<th>Total cost [MSEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission line</td>
<td>2,318.320</td>
<td></td>
</tr>
<tr>
<td>AC station</td>
<td>475.160</td>
<td></td>
</tr>
<tr>
<td>Steel tower</td>
<td>1,426.698</td>
<td></td>
</tr>
</tbody>
</table>

The total investment costs are presented in table IX. The calculation process from previous subsection is also applied on table X and table XI in the next subsections as well.
B. Power loss costs

As shown in table VIII, there is an advantage in form of less costs from power losses when placing a higher amount of wind power turbines in bus W3 and W4. This is because of the shortened distance needed for the power flow to get to the consumption buses. The power loss costs are presented in table X.

<table>
<thead>
<tr>
<th>Bus</th>
<th>No. of turbines</th>
<th>Costs due to losses [MSEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>20</td>
<td>5.442</td>
</tr>
<tr>
<td>W1</td>
<td>40</td>
<td>5.665</td>
</tr>
<tr>
<td>W1</td>
<td>60</td>
<td>5.927</td>
</tr>
<tr>
<td>W1</td>
<td>80</td>
<td>6.233</td>
</tr>
<tr>
<td>W2</td>
<td>20</td>
<td>5.799</td>
</tr>
<tr>
<td>W2</td>
<td>40</td>
<td>6.593</td>
</tr>
<tr>
<td>W2</td>
<td>60</td>
<td>7.755</td>
</tr>
<tr>
<td>W2</td>
<td>80</td>
<td>9.154</td>
</tr>
<tr>
<td>W3</td>
<td>20</td>
<td>5.239</td>
</tr>
<tr>
<td>W3</td>
<td>40</td>
<td>5.265</td>
</tr>
<tr>
<td>W3</td>
<td>60</td>
<td>5.350</td>
</tr>
<tr>
<td>W3</td>
<td>80</td>
<td>5.517</td>
</tr>
<tr>
<td>W4</td>
<td>20</td>
<td>5.248</td>
</tr>
<tr>
<td>W4</td>
<td>40</td>
<td>5.256</td>
</tr>
<tr>
<td>W4</td>
<td>60</td>
<td>5.296</td>
</tr>
<tr>
<td>W4</td>
<td>80</td>
<td>5.373</td>
</tr>
</tbody>
</table>

C. Revenue and profit

The comparison between the buses regarding the subject on where to place more wind power, which is presented in tables VIII and X, shows that the losses decrease for W3 and W4 and that investments in W4 results in the lowest amount of losses. Combined with the mean values of the wind speed presented in IV, it makes W3 or W4 the most profitable locations.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Turbines</th>
<th>Total revenue [MSEK/year]</th>
<th>Profit [MSEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>20</td>
<td>223.108</td>
<td>5.340</td>
</tr>
<tr>
<td>W1</td>
<td>40</td>
<td>228.421</td>
<td>10.652</td>
</tr>
<tr>
<td>W1</td>
<td>60</td>
<td>233.693</td>
<td>15.925</td>
</tr>
<tr>
<td>W1</td>
<td>80</td>
<td>238.922</td>
<td>21.154</td>
</tr>
<tr>
<td>W2</td>
<td>20</td>
<td>232.648</td>
<td>14.879</td>
</tr>
<tr>
<td>W2</td>
<td>40</td>
<td>247.284</td>
<td>29.516</td>
</tr>
<tr>
<td>W2</td>
<td>60</td>
<td>261.553</td>
<td>43.784</td>
</tr>
<tr>
<td>W2</td>
<td>80</td>
<td>275.584</td>
<td>57.815</td>
</tr>
<tr>
<td>W3</td>
<td>20</td>
<td>240.827</td>
<td>23.058</td>
</tr>
<tr>
<td>W3</td>
<td>40</td>
<td>263.871</td>
<td>46.102</td>
</tr>
<tr>
<td>W3</td>
<td>60</td>
<td>286.845</td>
<td>69.077</td>
</tr>
<tr>
<td>W3</td>
<td>80</td>
<td>309.738</td>
<td>91.970</td>
</tr>
<tr>
<td>W4</td>
<td>20</td>
<td>235.474</td>
<td>15.706</td>
</tr>
<tr>
<td>W4</td>
<td>40</td>
<td>249.173</td>
<td>31.405</td>
</tr>
<tr>
<td>W4</td>
<td>60</td>
<td>264.841</td>
<td>47.072</td>
</tr>
<tr>
<td>W4</td>
<td>80</td>
<td>280.471</td>
<td>62.702</td>
</tr>
</tbody>
</table>

Looking at how the revenue is impacted by the investment, as seen in table XI, it is clear that W3 is the most profitable. Compared to the case without any wind power, placing 80 wind turbines at W3 would increase revenue by 91.970 MSEK/year. It shows that if there is any other restrictions on placement of wind turbines, placement at W3 should be prioritized. An example would be if there is lack of space or money for investment.

From table IX, the investment costs for an upgrade of the grid makes a total sum of 4,220.178 MSEK. For a case with 81 wind turbines on all four buses, the increased revenue per year would be 238.540 MSEK. Since \( \frac{4,220.178}{238.540} = 17.7 \), it would take 18 years before the investment is earned back.

VI. DISCUSSION

A. Interpretation of results

As seen in the results, wind power integration is possible to put in practice. Although a 130 kV would not suffice, making the investments mandatory if wind power integration is wanted. Based on the simulation with the mentioned criteria, it is possible to integrate wind power into an existing grid. However, it would require an investment to upgrade the grid for 220 kV to maintain stable voltage levels. The investment would be earned back in 18 years with revenue from the contributions from sold wind power production.

In addition, an unforeseen spike is observed in figure 13. It is unknown whether the divergence is due to error in the simulation or just a coincidental occurrence. A scenario would be that similar anomalies have gone unnoticed, which would drastically affect the result. Despite this, the obtained values are reasonable when compared to the existent data in real grids and power systems. This includes the economical results.

Due to mistakes made in the simulation, the value of the yearly consumption in Boliden which was supposed to be 1,000.000 GWh/year, but instead becomes 1,349.986, as seen in table II. Accordingly, the values of the consumption in table III changes as well. This could have an effect on the results, and should be taken into consideration if a similar project is made.

B. Method evaluation

Because the method of the study is rather general, the results can be applicable to other cases as well. The most notable difference to another case would be wind data, grid arrangement, and existing power generation and consumption nodes. This is mostly due to the many assumptions and approximations applied on the project. However, premises, such as consumption depending on the hour of the day, could affect the achieved results as well. There are also other factors not considered, leading to less of an impact on whether the study is applicable in a real case or not. A more realistic case would involve a much larger grid, and would also have to consider different variables in more detail.

Investments when upgrading a grid has many varying costs. Different components could easily be missed due to the limitations of the project, despite being vital for the grid. Since the aim of this project is not to check for which components are needed for an upgrade, it is decided that a general cost estimation will do. Thus, further studies must be done for a more detailed estimation of investment costs. Here, costs related to socio-economical factors could also be included.
Further investigation on this project could also include an analysis of rerouting the grid with more transmission lines; in one way by making parallel connections between some nodes, and another by connecting some nodes to create more paths in case of an overload and for higher stability.

As for now, all the buses with production or consumption has the reactive power set to 0. To regulate the voltage levels, it would be possible to make the hydro power buses into PU-buses. Since part of the purpose of this study was to examine economical terms, a further collaboration with project M2 would produce a more efficient, interesting and applicable result.

VII. CONCLUSIONS

The aim of the study was to upgrade the national grid in SE1 and analyze suitable wind farm locations. In addition, how these would be assimilated into the grid was discerned as well. Subsequently, a regional grid was built in the area around Skellefteälv (see figure 2), where the nearby important consumption nodes and existing hydro power plants were taken into consideration as well. Furthermore, the profitability was also evaluated, where W3 gives the most profit compared to the rest of the chosen wind farm sites.

Environmental issues have indeed become one of the most pressing issues in modern times. However, renewable resources are potential candidates for viable substitutes, motivating countries, like Sweden, to invest further in these sectors. As wind power is widely regarded as the most promising renewable energy source in terms of economic growth, there is incitement to invest in the industry.

As the results show, an upgrade of the electrical grid certainly requires a relatively large investment sum. Nevertheless, the return of the project will eventually surpass the initial costs within 20 years. Accordingly, there are economic benefits of upgrading the grid capacity. Therefore, the project is worth elaborating, while helping to reach a sustainable future.

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