NTNU – Trondheim
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Science and Technology

Testing a GIS-based methodology for optimal location of Pumped Storage power plants in Norway

Catalina Cortines Garcia

Hydropower Development
Submission date: June 2013
Supervisor: Ånund Killingtveit, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

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Co-Supervisor:	Peggy Zinke

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Trondheim, June 2013.

Catalina Cortines.

Abstract

Europe needs to restructure its energy system. The aim to decrease the reliance on fossil fuels to a higher dependence on renewable energy has now been imposed by The European Commission. In order to achieve this goal there is a great interest in Norway to become "The Green Battery of Europe".

In the pursuit of this goal a GIS-tool was created to investigate the pump storage potential in Norway. The tool searches for possible connections between existing reservoirs and dams with the criteria selected by the user.

The aim of this thesis was to test the tool and see if the results suggested were plausible, develop a cost calculation method for the PSH lines, and make suggestions for further development of the tool.

During the process the tool presented many non-feasible pumped storage hydropower (PSH) connections. The area of Telemark was chosen for the more detailed study. The results were discussed and some improvements were suggested for further development of the tool. Also a sensitivity test was done to see which of the parameters set by the user are the most relevant for the PSH connection suggestion.

From a range of the most promising PSH plants suggested by the tool, the one between Songavatn and Totak was chosen for a case study, where there already exists a power plant between both reservoirs. A new Pumped Storage Plant was designed with a power production of 1200 MW.

There are still many topics open to discussion, such as how to deal with environmental restrictions, or how to deal with inflows and outflows of the reservoirs from the existing power plants.

Consequently the GIS-tool can be a very useful tool to establish the best possible connections between existing reservoirs and dams, but it still needs a deep study and the creation of new parameters for the user.

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DEM	:	Digital elevation model
DISTpl	:	Nearest distance between reservoir polygons (km)
dW	:	Water level change rate (in m/hour)
E	:	Energy storage
EIP	:	Environmental influence point
EPP	:	Existing power plant
EWEA	:	European Wind Energy Association
GHG	:	Greenhouse gas emission
GPH	:	Gross pressure height
HRWL	:	Highest regulated water level of the lower reservoir
HRWU	:	Highest regulated water level of the upper reservoir
INON	:	Ingrepsfrie naturområder i Norge
LRWL	:	Lowest regulated water level
NINA	:	Norwegian Institute for Nature Research
NVE	:	Norwegian Water Resources and Energy Directorate
P	:	Power production / Capacity (in MW)
PSH	:	Pump Storage Hydro Power
Q	:	Discharge (m^3/s)
Td	:	Storage duration (in days)
TUL	:	Length of the tunnel.

1. Introduction

We do not inherit the earth from our ancestors;
we borrow it from our children. Chief Seattle [1].

Most of the energy used in the world comes from fossil fuels; this is something that is trying to be replaced by renewable energies which are environmentally friendly. [2]

Even though there is a big concern; it is very difficult to rely fully on renewable energy. The main reasons are the need of an electric grid because the source of the renewable energy is mostly situated far away from the consumer [3] and the need of energy storage because renewable energy is very intermittent. There are moments where more electricity than needed is produced and also moments where more electricity than produced is needed. [4]

Europe is trying to step away from relying on fossil fuels; therefore it has established some targets for the countries to lower their GHG emissions. It was in March 2007 when the European Leaders urged Europe to become highly energy-efficient and low carbon economy. These targets are now known as "20-20-20" and they consist on [5]:

- *A 20% reduction in EU greenhouse gas emissions from 1990 levels;*
- *Raising the share of EU energy consumption produced from renewable resources to 20%;*
- *A 20% improvement in the EU's energy efficiency.*

Even though the goals for 2020 will help Europe to reduce the GHG emissions in the long run, more actions must be taken to become a greener continent. As Europe is looking towards the future there are new plans coming up to improve the renewable energy dependence. [6] There is a new plan for 2050 called *"Energy Roadmap 2050"* where it is said that EU is committed to reduce the GHG emissions by 80% from the ones in 1990. This will enable Europe to achieve its decarbonisation targets and will serve to ensure the energy supply and competitiveness [4].

Europe's renewables are mostly based on solar and wind power. Solar energy is abundant in Southern Europe and wind in the western part of the North Sea, where vast wind farms are planned to be developed offshore. European Wind Energy Association (EWEA) estimates an increase of wind production from 180TWh to 581TWh by 2020. But as said before wind and sun are highly unpredictable so there is a big need of energy storage. Here is where pump storage gains importance. It can really enhance the performance of renewables with its flexibility, the short time needed to respond and its ability to start without any help from the grid. [4]

Here Norway plays a very important role. It is the country with the largest hydropower production in Europe and it occupies the 6th position in the ranking of hydropower production worldwide. Norway has almost 50% of the reservoirs in this continent. Norwegian hydropower plants allow the country to base 99% of its electricity in hydropower. Although a high percentage of the energy used in Norway comes from renewable sources, this Scandinavian country is committed to increase its energy consumption from renewable sources from 58% in 2005 to 67.5% in 2020 [4].

Many different scenarios have been studied on how to increase the use of renewables. Being this type of energy very intermittent, all the scenarios agree on the need of finding the best way to store the energy for later consumption. As a result a concept of Norway as the 'Green battery' of Europe was developed. This concept of the battery for Europe consists on storing energy by using two connected reservoirs with different heights, delivering the balanced power when needed. This is done by transporting the excess of the energy production with renewables to a hydropower station which would pump water to the upper reservoir, and then when the demand is higher than the supply, power will be generated and sent back to the market by letting the water flow into the turbine [7].

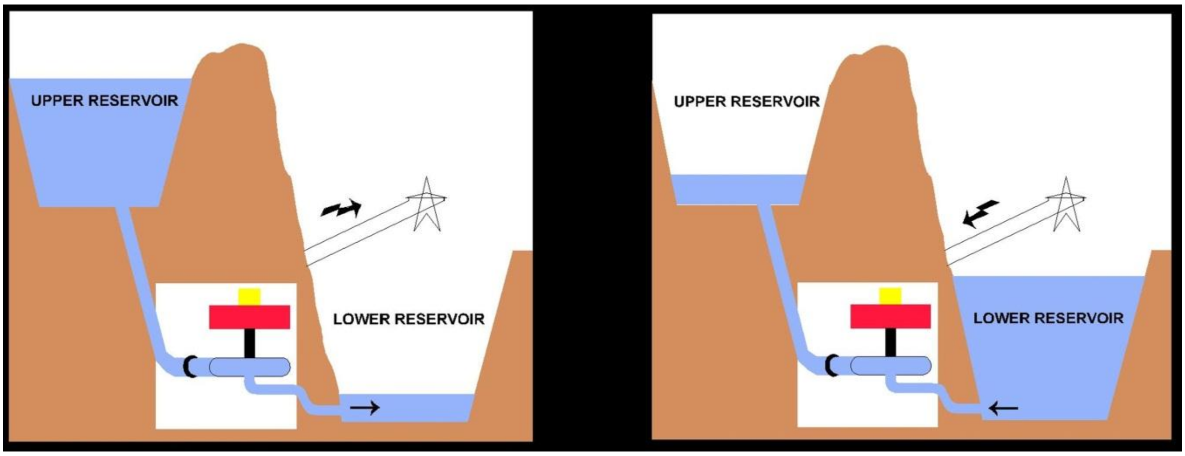


Figure 1: Scheme of how a pump storage hydropower plant works[8]

Actually there exist a few pumped storage plants in Norway, mainly built for seasonable storage. Since 98% of the electricity comes from hydro power [9] there is no need for daily pumped storage. But if we think of Norway as "the Green battery for Europe" this needs to change.

Since Norway has a lot of Hydropower plants and it would be difficult to build new reservoirs, pump storage should be based in existing reservoirs and natural lakes [10]. Hydropower storage development should focus in finding pairs of reservoirs with high head differences and large storage volumes within small distance. Based on this criterion, a GIS-based mapping of the potential pump storage sites in Norway was created by Peggy Zinke and Fredrik Arnesen in 2012[11] to find the most promising pump storage hydropower plant locations within the whole country.

The Master Thesis: 'Testing a GIS-Based methodology for optimal location of pumped storage power plants in Norway' was done with the aim of testing the mentioned ArcGIS Tool [11] to identify the most promising pump storage projects in Norway.

During the process a study was done to investigate and discuss the suggested pumped storage hydropower (PSH) lines and their feasibility within the geographic point of view.

Next, an economic calculation method was developed and a sensitivity test was run to see the importance of the diverse variables on which the suggested connections depend. Furthermore, one of the most promising connections was chosen for a more detailed study, including the optimization of the project size and layout.

2. Test and application of the GIS Tool:

2.1 Description of the Tool.

This application of ARCGIS was designed for the investigation of pumped storage hydropower (PSH) potential in Norway. It is based in a study [12] where 19 specific cases in Southern Norway were selected in order to analyze the potential for increasing the power output of balanced power generation. Due to the environmental and economic constrains that exists nowadays for constructing new reservoirs, this study is based in the potential of existing reservoirs and dams only [10].

Modern hydropower systems in Norway are characterized by tunnels and power stations inside the mountains. Hence, PSH plants will be designed according to these principles to reduce the environmental impacts, being mainly related to the effects of the reservoir regulation and technical infrastructure [10].

The Tool has been designed so that the criteria for the PSH line selection can be chosen in every screening by the user running it. This allows studies of PSH potential with very specific characteristics.

The program has 3 different steps where the different characteristics of the hydropower plant should be inserted, with specific values and boundary conditions.

In this GIS-Tool some assumptions and restrictions are made, which can be read in detail in "GIS-based mapping of potential pump storage sites in Norway" [11].

The most relevant restrictions for the understanding of the Program are: [11]

1. The location adjacent to existing power plants is a criterion that can be freely chosen.
2. The GIS study is restricted to NVE reservoirs. (No inclusion of additional natural lakes)
3. It is possible to set a lower limit for power production to prevent the installation of very small power plants.

4. The screening results can be used to indicate the best lines out of many possible connections from a reservoir, based on parameters such as gross pressure height, production capacity, rate of water level change and tunnel length.
5. Distance to power lines and roads are included as screening parameters.
6. The GIS project provides the main parameters, which are necessary for the cost estimation, as output.

This Tool is based on a calculation model [12] where other important assumptions are made:[11]

- The reservoirs were modeled assuming vertical side surfaces as in an upright cylinder between their upper (HRW) and lower regulation limits (LRW).
- The length of the penstock (PSL) is calculated on the basis of the gross pressure head (GPH) and a 45 degree inclination of the penstock.
- The gross pressure head is calculated for a 2/3 filled reservoir.

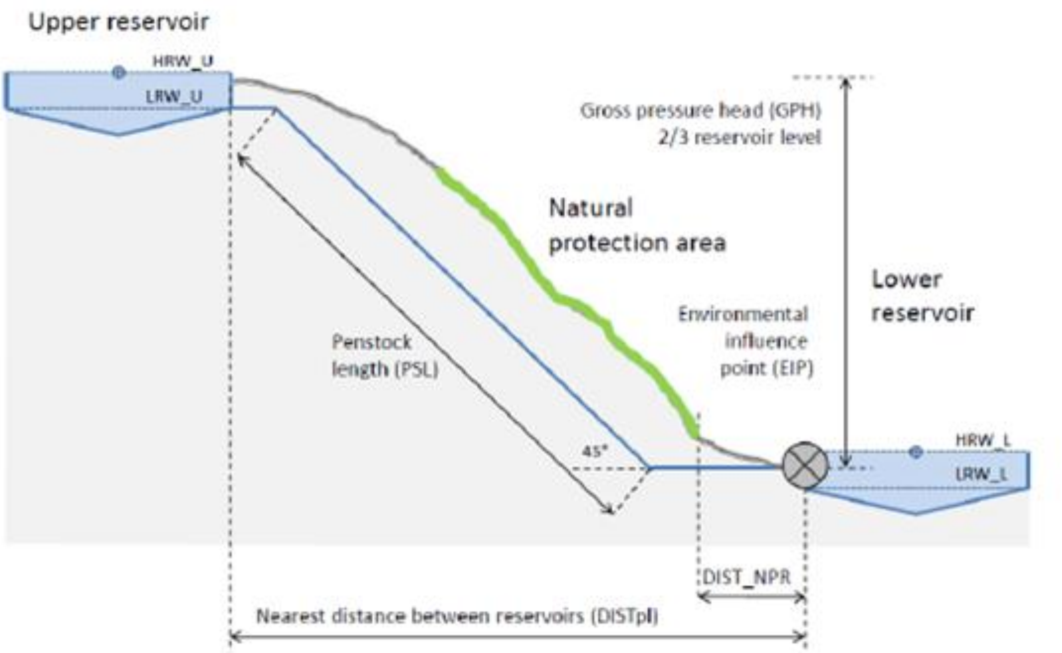


Figure 2: Scheme of the assumptions for the reservoir connection[11]

There are 3 tools to establish the characteristics of the PSH lines that we are looking for:

- The first tool is for the topographical analysis with its three components: distance criterion, terrain criterion and power plant criterion. Here the following decisions can be made:
  1. The maximum distance between potential PHS reservoir pairs.

2. The minimum capacity of the existing power plant (EPP) to be included.
3. The maximum search radius for the distance between lower reservoir and EPP.
Number 2 and 3 are optional.

- The second tool is for the calculation of restriction parameters. It is based on the results of the first tool, and it is limited by the characteristics of the sites where the reservoirs are. Here information is provided about the existing power lines, the roads, environmental restriction areas and the areas protected against hydropower development.
- The last step is the Screening. This step is based in the first and the second tool. The following criteria has to be defined depending on the type of pump storage that we are looking for:
  1. Maximum distance between reservoirs
  2. Minimum GPH
  3. Upper limit of the distance from an environmental influence point (EIP) to the next power line. The EIP is an area of 30-50 ha situated at the intersection between the shoreline of the lower reservoir and the PSH line.
  4. Upper limit for the distance from EIP to the next road
  5. We can choose whether we want to include restrictions for nature or not. If we do we will have to decide the minimum distance to the nearest INON zone, the next wild reindeer area, the nearest cultural protection area, and the minimum distance to a suggested natural protection area. We also have to decide if we want to exclude the reservoirs situated in NVEs protection plan zones and if we want to include reservoir in-and outflows from existing power plants.
  6. Another decision that has to be made is defining the screening mode which can be the storage capacity, the water level change rate or the power generation (explained in the sensitivity analysis, 2.4)

2.2 General test and comments.

In the first runnings of the program, the ArcGIS-tool showed some difficulties at first sight when analyzing the data. The main problem was that it showed plenty of connections that were not geographically possible. In several cases the PSH lines where crossing deep valleys, other reservoirs or big lakes. Also too many connections from one reservoir were sometimes suggested, in reality only one, two or three can be put on the map depending on the reservoir size and the power production. All this is going to be further discussed in chapter 2.4, but down are shown some of the problems faced at the beginning:

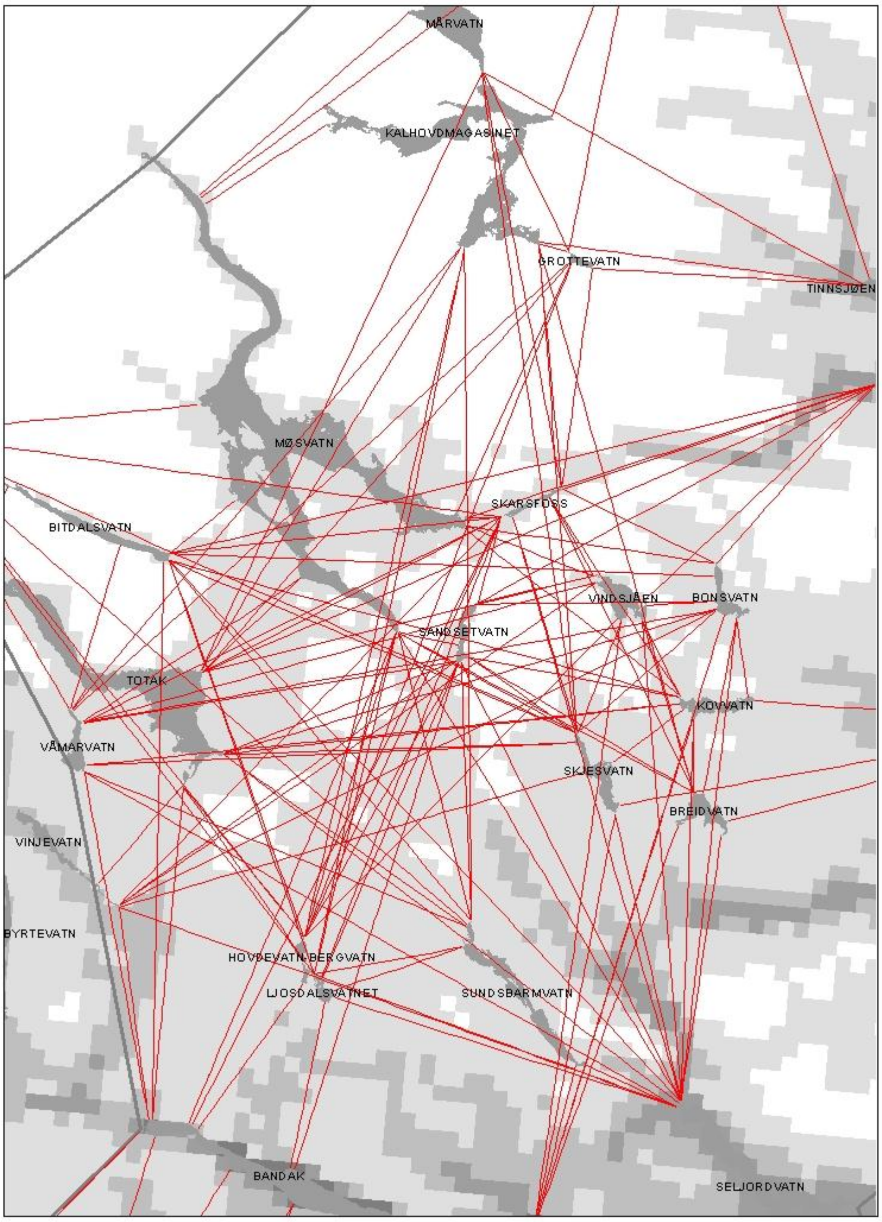


Figure 3: Problem of too many lines suggested by the tool (ArcGIS after tool 2 for the region of Telemark).

Despite the difficulties this tool also provides us with a lot of useful information. Just taking a look at the suggested lines one could have an overview of the PSH potential of Norway. The map below for instance, since the Tool is created for the whole country, shows us all the possible connections within Norway without any restrictions. And we can see that the pump storage potential is higher in the South than in the North part of Norway.

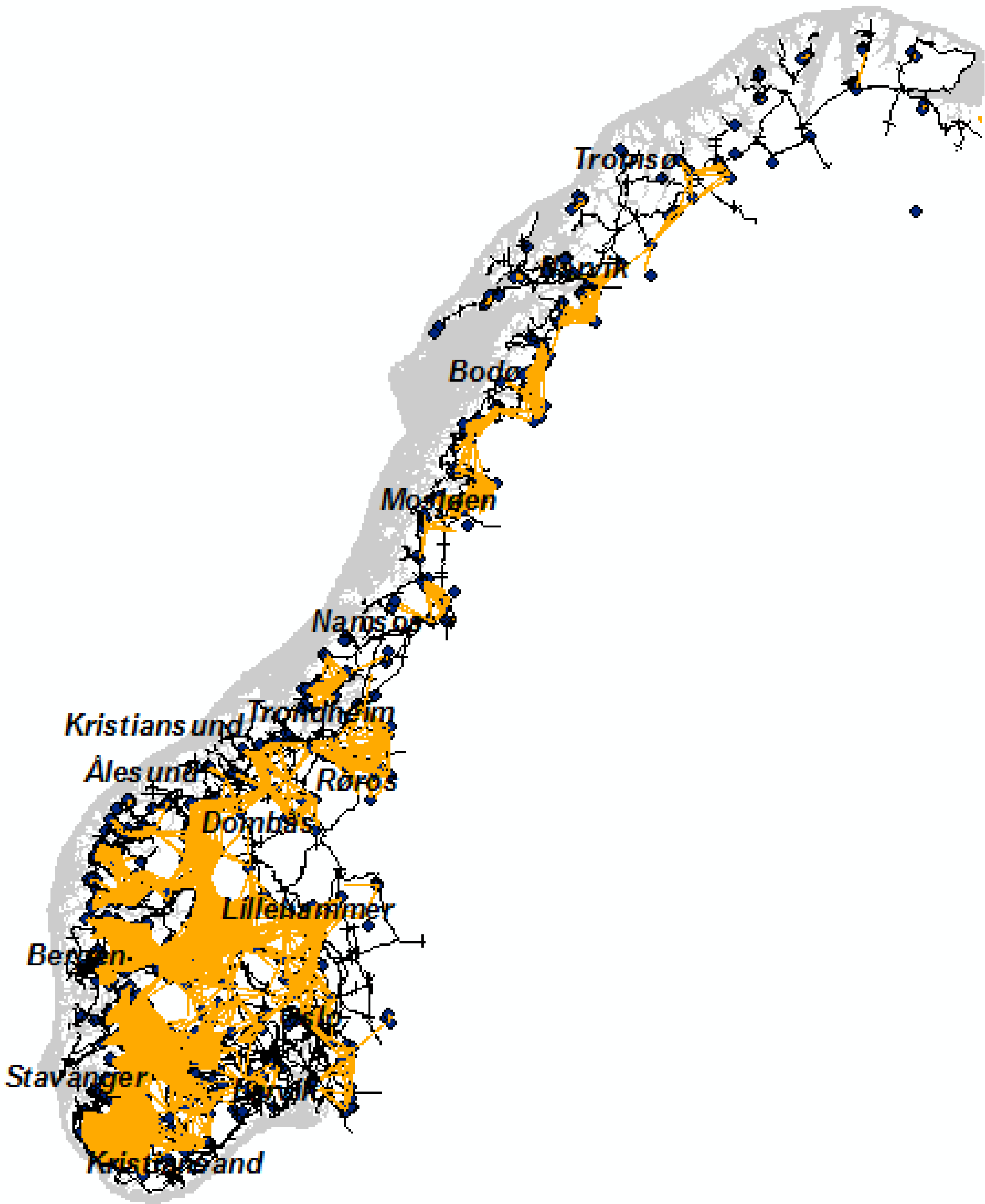


Figure 4: Possible connections for PSH plants in Norway (ArcGISresult from tool 1).

To make a more detailed study of this potential, two regions were chosen: Telemark and Trøndelag.

To compare these two areas, 8 different cases were studied, on the basis that the following values remained unchanged:

- Upper limit for the distance of environmental influence point (EIP) to the next power line was set to 20 km.

- Upper limit for the distance of EIP to the next road was 10km.
- No environmental restrictions included.
- Not excluding reservoirs situated in NVEs protection plans zone.
- No inclusion of reservoir in- and out flows from existing power plants.
- The maximum acceptable rate of change from the reservoir water level was 0.13m/h.

In the different scenarios the distance between reservoir polygons, the GPH and the power generation were set as changing variables. The distance between reservoirs will be bounded for 20 and 50Km its maximum value. The minimum value for the GPH will be 50 and 100m, and the power production will vary between 25 and 100 MW. With these data although there are a lot of non-feasible PSH connections, we get the following results:

Telemark	Trøndelag
• 20km_25MW_50m: 140possibilities • 20Km_25MW_100m: 117 possibilities • 50Km_100MW_50m:274 possibilities • 50Km_100MW_100m:265possibilities	• 20Km_25MW_50m: 21 possibilities • 20Km_25MW_100m: 16 possibilities • 50Km_100MW_50m: 23 possibilities • 50KM_100MW_100m:1 possibility

Table 1: Possible connections for the different scenarios in Telemark and Trøndelag.

In Table 1 the first number represents the distance between reservoirs, the second the power production and the third the GPH. The number of possibilities represent the number of connections suggested by the Tool. Although it is a rough estimation we can assert that the southern region has a higher pump storage potential compared to the central one just by comparing the number of connections proposed. Therefore Telemark was chosen for a more detailed study of the Tool.

When comparing the results by changing the boundary conditions the number of connections varies between very wide ranges. To know which are the most important parameters that affects the results a sensitivity test was decided to be done as a further step when testing the Tool. But before running the sensitivity test, a cost estimation of the PSH lines was needed, to be able to introduce this parameter in the study.

2.3 Cost Calculation

Costs are a very important figure when planning PSH structures in order to study their feasibility. As seen in figure 3, for many reservoirs, the Tool suggests multiple PSH connections. It is necessary to define selection criteria for the most promising projects. Therefore, a cost calculation had to be done to be implemented in the Tool as a new parameter for the PSH lines selection criterion.

This cost calculation consists on a rough estimation, were only the most important parameters that affect the costs in the PSH plants will be taken into account. In the figure bellow the most important parts of a pumped storage plant are shown and these are the ones we are going to focus our cost estimation on:

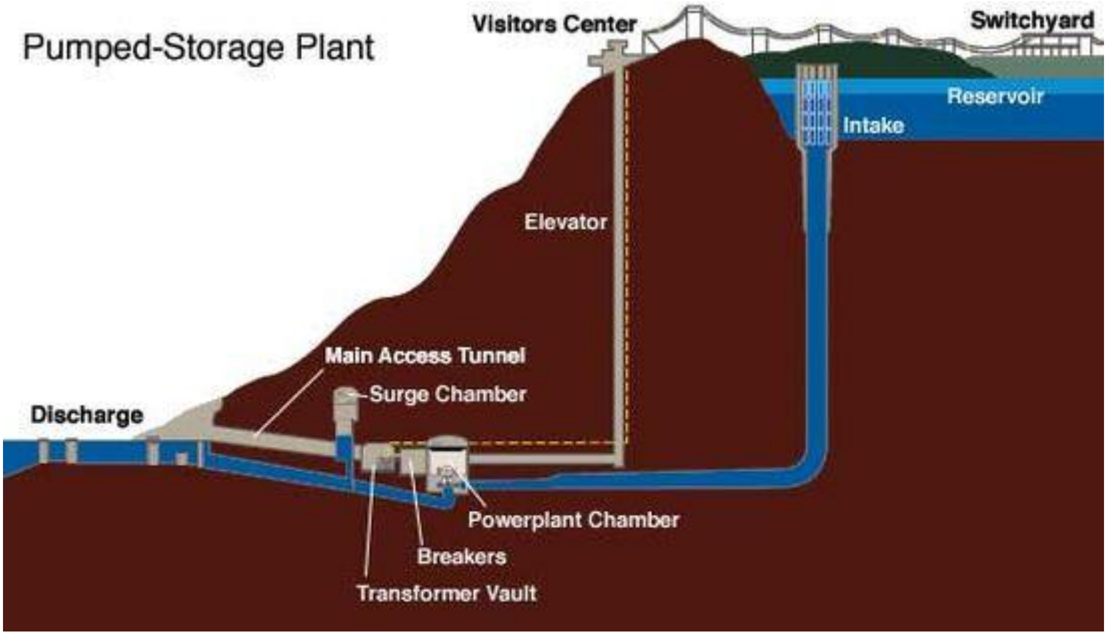


Figure 5: Main components of a PSH plant [13]

For the calculation of the costs we have used data from ArcGIS Tool results. During the screenings some parameters have been directly imposed by the user, some restricted their minimum or maximum values, and some directly calculated by the Tool [11]:

- The total length of the tunnel is considered as :

  $TUL = DISTpl - (PSL * \cos 45)$

  -DISTpl represents the nearest distance between reservoir polygons. Its maximum value is bounded by the user, and is calculated by the Tool as the nearest horizontal distance between the two reservoir polygons.

  -The penstock length is: $PSL = \frac{(LRW_U - LWR_L)}{\sin 45}$

- The tunnel cross section is calculated as:

  $A = \frac{Q}{V}$, with an assumption of a flow velocity of 2 m/s. [12]

- The Gross Pressure Height (GPH) is a value that is also bounded its minimum value in the Tool. It is calculated as follows :

$$GPH = \left[\frac{2}{3} * (HRW_U - LRW_U) + LRW\_U\right] - \left[\frac{2}{3} * (HRW_L - LRW_L) + LRW_L\right]$$

- The maximum absorption capacity is calculated as the minimum value of the discharge calculated for the upper and the lower reservoir based on the storage duration or water level change rate.

- The Power Production is a value that can be imposed or can be calculated. If it has to be calculated, first the Tool calculates the absorption capacity Q with respect to the lower and upper reservoir and chooses the minimum value. Then P result is based on this Q_{min} as:

$$P = \rho * Q * g * GPH * \eta$$

Where:
P= Power Production (MW)
Q=Q_{min}
ρ= density of water (1000Kg/m^3)
g= gravity acceleration (9.81 m/s)
GPH= gross pressure height mentioned above
η = total efficiency (which is set to 0.86) [12]

- The nearest distance from an environmental influence point to a road or a power line of the existing grid is calculated by using an application from ARCGIS that is able to determine the minimum distance between both points. ARCGIS is able to calculate it in different ways, but the one used is the one shown below where the input feature is the EIP and the near feature is the road or power line.

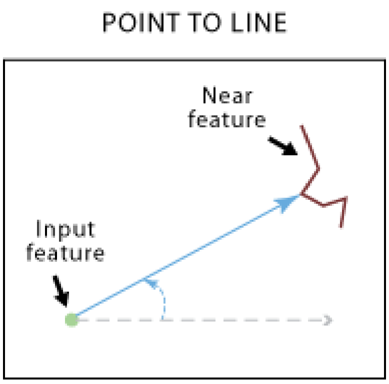


Figure 6: Explanation of how ArcGIS calculates the minimum distance between EIP and roads and power lines [14].

The economic study will be based on ‘Cost Based for Hydropower Plants’. [15]

The costs are divided in three groups:

1. Civil Work
2. Mechanical Equipment
3. Electro technical work

Civil Work represents a high percentage of the total costs, due to the aim of using existing reservoirs for the new PSH plants. As a result, the distance between reservoirs may be long and so the tunnels. Large volumes of rock excavation and deposition will make the costs of the tunnels and rock caverns dominate the cost of the project, with percentage over 50**%**[10].
These costs are calculated on standard constructor costs with a 50% risk of the prices being higher or lower.

In this report we are studying the construction of PSH connections based on already existing dams so these costs will not be included in the cost calculation.

To begin with I have calculated the basic price for the tunnel construction. I will assume the tunnels to be constructed as drilled and blasted tunnels. The construction of the tunnel with tunnel boring machine has not been considered in this rough estimation, but will be taken into account for further and more detailed cost calculation study. The main advantages of the chosen technique are its flexibility with the design, its adaptability to the different geologies and the easy transportation of the machines.

To calculate the blasted tunnels constructor costs a graph (Fig.B.4.1 in [15]), will be used. Normal and favorable conditions as rock of medium quality and blastability are assumed. The curve used is the one of the basic price, with securing and the driving supposed to be driven at upward gradient so there is no need for length correction.

The miscellaneous on blasted tunnels costs are cutting, adit tunnel, plug and air cushion chamber and they have calculated as follows:

- The costs of cutting and wall with gate costs have been calculated based on the graph (B.5.1 in [15]) where the total costs are calculated assuming rock of medium drillability and blastability, the curve comprises cutting a wall with two bladed-gate 2.5x2.5 m and the door ready installed. In addition to this, the contractor rigging and operating costs have been included as 30%.

- The costs of the adit tunnel depend on the tunnel cross section. If the cross section is smaller than 25m^2 the costs are included in the tunnel length so no calculations are needed. But if the cross section is bigger than 25m^2 the price per consecutive meter is set as 20000 NOK/lm where support, unforeseen and rigging and operation are included. The length used is 600m. In addition, 210000NOK have been included for collaring.

- The calculation of the plug is based on the graph (B.5.2 in [15]) where the curve includes all constructor costs for building related work. Between 38000 and 53000 NOK of injection costs have been included for small cross sections and between 53000 and 78000NOK for large cross sections. There are also additional costs for the gate with steel lining which has been calculated with graph (M.3.E in [15]).The area presumed for the gate is $5m^2$.

- For the surge chamber, the assumption of using an air cushion chamber instead of a shaft reservoir was done. This alternative represents the most recent development in surge chambers [16]. To estimate the price, I first calculated $V_{air}=1.2*17.2*f^{5/3}$ where f represents the tunnel cross section. Once I had the volume of air, I could calculate the volume of the rock can be calculated as $V_{rock}=1.35* V_{air}$. The price was then obtained as 360 NOK/m^3 of rock.

For the costs of underground power station, I summed up the costs for the power station itself and for the access tunnel.

The cost calculations are based on the following assumptions and prices:

- Blasting average unit price : 230 NOK/m^3

  The blasting volume is calculated with the following equation:
  $V=78*H^{0.5}*Q^{0.7}*n^{0.1}$, where:
  H=GPH, m.
  Q= total maximum rate of flow, m^3/s
  N=number of power units.
  H and Q are given as a result of the ARCGIS Tool and an assumption of one power unit is made.

- The concrete volume was calculated as the 20% of the blasting volume. The price per cubic meter of concrete used was 2500 NOk.

- The reinforcement was calculated as $60Kg/m^3$ of concrete and the price is calculated as 16000 NOK/tonne.

- The formwork is considered $2.1m^2/m^3$ of concrete and the price is 1000 NOK/m^2.

- The supporting work is calculated as the 15% of the blasting costs.

- The masonry and the plastering work are presumed to be 5% of the blasting and concreting costs.

- The interior work (flooring, painting, steel, glass…) is calculated as the 15% of the blasting and concreting costs.
- The unforeseen costs are considered the 10% of the costs above mentioned.
- The rigging and operation of the construction site is 25% of the above costs.
- The ventilation, water supply and sewer (HVAC) are presumed to be 2.6 million NOK for a medium sized plant.
- The electrical installations, lighting, heating, etc are estimated to be 2 million NOK for a medium sized plant.

The access tunnel is an important part of the construction; it permits the mechanical and electrical equipment to be transported to the power house and also the rock to be carried out. The access tunnel costs includes not only the tunnel itself but also a continuous secured hanging wall, drivable cover, drainage, lighting, cable trench and any other building installations, as for instance, ventilation. For the calculations I assumed a cross section area of 50 m^2 and a length of 600m, and the costs are calculated with a graph (B.10.4 in [15]) where it is presupposed to be driven at upward gradient. Some assumptions are made, such as working with a rock of medium drill ability.

Rigging and operation costs are included as 30% of the basic price and securing, protection work is included. Miscellaneous and unforeseen costs are included as 10% of the basic price and securing. The concrete cable channel laid as pavement has been included with 3500 NOK/lm.

Since we have the distance to the nearest road calculated with the Tool the costs of the temporary roads needed for the construction can be calculated too. Assuming that we are working with a normal terrain and with high standards the costs will be 1500 NOK/m. The annual maintenance will be considered 10% of the building costs and no bridges are included.

The electro technical equipment costs are the average of expected costs for electro technical installations in power and transformer stations. For the total costs supposition is that there is an underground plant with 800m of cable run. There is a transformer for each power unit (one power unit is assumed for all the cases), outgoing lines from the plant, switchgear of a conventional type with a single bus bar and one circuit breaker. For stations above ca.150 MW we have assumed the use of enclosed bus bar and a generator circuit breaker. This cost estimation includes control and auxiliary systems for a medium size underground station.

To be able to calculate the costs with the graphic (E.8.1a in [15]) the rotational speed has to be chosen. Since the connections that the Tool suggests are normally bounded for heads higher than 50 m, I chose a rotational speed of 750 rotations per minutes using 4 pairs of poles on the generator.

The most important mechanical costs are the costs of the turbine. For this an assumption had to be made. There is an important decision between using a twin system and using a reversible turbine. Because using a turbine and a pump is usually used for heads bigger than 400-600m, a reversible Francis turbine is chosen [17]. They are installed within 50-800m and can work with power production from less than 10 to more than 500 MW. Due to the fact that it is a reversible Francis the total costs has been increased in 25% [18].

For the costs of the miscellaneous equipment the curve from the graphics (M.4.A, in [15]) include the intake trash racks dimensioned for 10m of differential pressure, 1m/s speed and daylight opening between the bars adapted for the different turbine types. They also include a machine hall crane, cooling water system and drainage system.

All the calculations are based on the price levels of 1 January 2010, therefore the final values will have to be multiplied by the index of the prices.

Based on the report 'KOSTNADSUTVIKLING VANNKRAFTPROSJEKTER INDEKSREGULERING FRA 1997 TIL 2013' [19] and assuming a linear gradient in inflation from 1997 until 2013, the civil work costs calculated for 2010 prices will have to be increased by 6.7%, the electrical work by 2.6% and the mechanical work by 2.7%

2.4 Sensitivity Test of Telemark Area

By definition a Sensitivity Analysis is: *"the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs"* [20].

Given that in our tool the selection of possible PSH line connections is made on the basis of different parameters, what we want to study with a Sensitivity Test is which of the parameters used in the screenings are the most relevant ones to decide which line to choose.

The sensitivity test will start with a combination of parameters that will be screened with the 3 different modes that the Tool offers [11]:

1. *.The P-Mode allows searching for PSH connections that can provide a defined power production P (in MW), hereby not exceeding the given maximum water level change rate for the reservoirs and not going below the given minimum storage duration.*
2. *The Td-Mode allows searching for PSH connections that can guarantee a defined storage duration (in days), hereby not exceeding the given maximum water level change rate for the reservoirs and not going below the given minimum power production. The storage duration equals the emptying time of the upper reservoir or the filling time of the lower reservoir, depending on which of the two values is lower.*

3. *The dW-Mode can be used to select PSH connections with a defined water level change rate (in m/hours), where the storage duration and power production do not fall below the defined minimum values.*

During the run of the test there are some settings that will remain untouched as:

- no environmental issues are included
- no inflow or outflow from existing power plants are considered
- The maximum distance to the road is 10 Km and 20 Km to the power lines.

The parameters: minimum GPH, maximum DISTp, dW, Td and P will have two different values, an upper and a lower one, that will be used in the screening.

These boundary values used have been established after representing the potential of each parameter with histogram charts where the number of possible connections are shown, depending on the values of the parameters in the study. These possible connections are based in the number of lines suggested as result of Tool 2.

The total potential of the Telemark region gives us a total of 222 lines.

The number of possible connections will depend on the mode used. However there are two parameters that are independent: the GPH and the nearest distance between reservoir polygons:

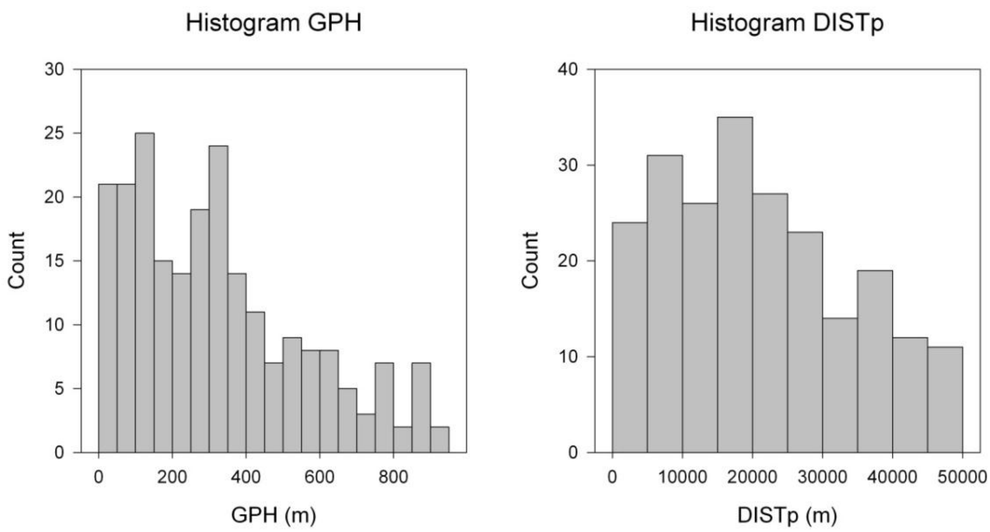


Figure 7: Number of possible connections suggested by the Tool depending on GPH and DISTp.

Looking at the charts (figure 7) the boundary conditions chosen as the minimum value for the GPH are 100 and 400m, and the maximum distance between reservoir polygons 10 and 30 Km. This last decision was based on the characteristics of existing tunnels[21].

The rest of the parameters are dependent on the mode used for the screening what will lead us to PSH connections with disparate characteristics.

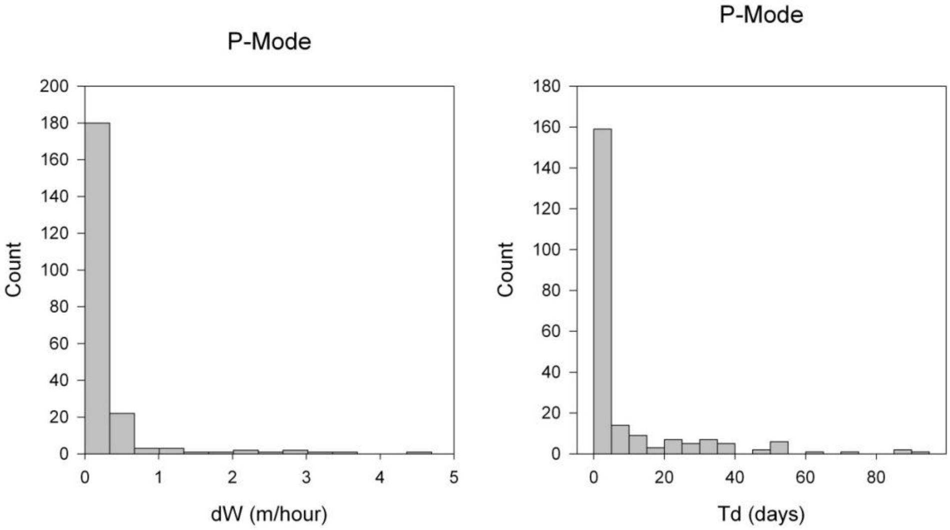


Figure 8: Number of possible connections suggested by the Tool depending on dW and Td run in P-mode

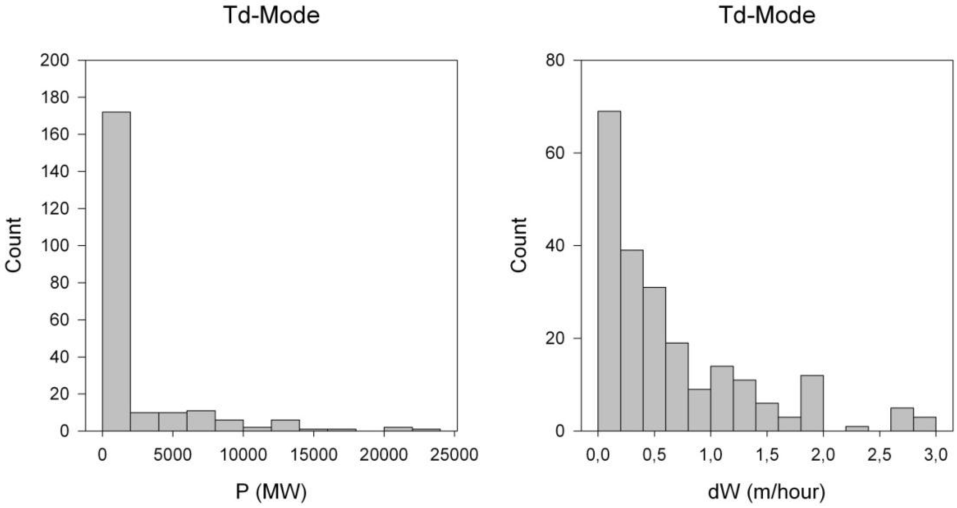


Figure 9: Number of possible connections suggested by the Tool depending on P and dW run in Td-mode

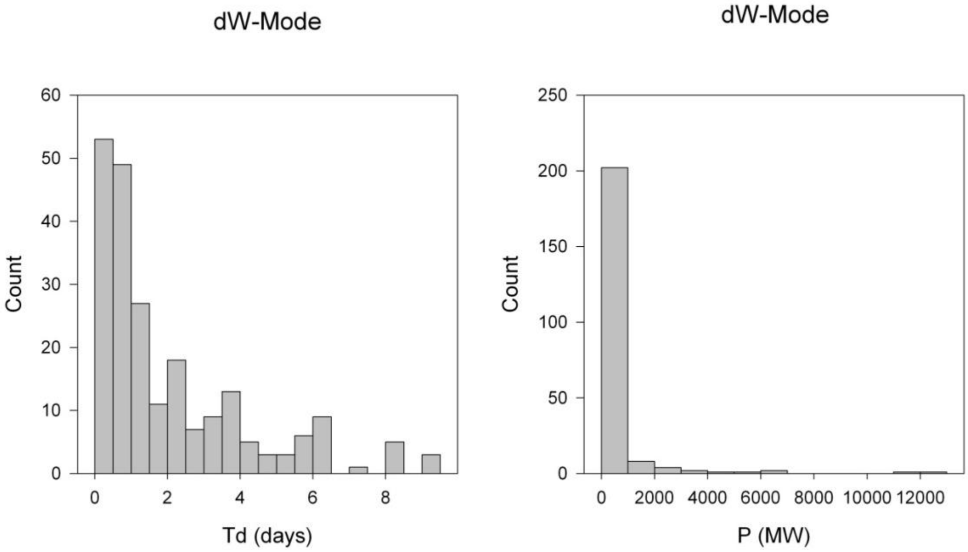


Figure 10: Number of possible connections suggested by the Tool depending on Td and P run in dW-mode

Based on these charts (figures 8, 9 and 10) the following values were chosen for the study:

Variable	Min.Value	Max.Value	Units
P	100	700	MW
Td	0.416	7	Days
dW	0.13	0.4	m/hour
GPH	100	400	m
DISTpl	10	30	Km

Table 2: Boundary values for the parameters used in the Sensitivity test.

With each mode 32 different cases are studied combining all the maximum and minimum values established for each parameter (See Appendix B). In table 3 it is shown the 32 cases for the P-mode:

		GPH	**GPH**	**DISTp**	**DISTp**	**dW**	**dW**	**Td**	**Td**	**P**	**P**	**No.PSH**
Mode	**Scenario Nr**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**L**	
P	1	100		10		0,13		0,416		100		16
P	2	100			30	0,13		0,416		100		81
P	3		400	10		0,13		0,416		100		1
P	4		400		30	0,13		0,416		100		21
P	5	100		10			0,4	0,416		100		25
P	6	100			30		0,4	0,416		100		98
P	7		400	10			0,4	0,416		100		2
P	8		400		30		0,4	0,416		100		40
P	9	100		10		0,13			7	100		6
P	10	100			30	0,13			7	100		8
P	11		400	10		0,13			7	100		0
P	12		400		30	0,13			7	100		0
P	13	100		10			0,4		7	100		6
P	14	100			30		0,4		7	100		32
P	15		400	10			0,4		7	100		0
P	16		400		30		0,4		7	100		20
P	17	100		10		0,13		0,416			700	3
P	18	100			30	0,13		0,416			700	13
P	19		400	10		0,13		0,416			700	0
P	20		400		30	0,13		0,416			700	9
P	21	100		10			0,4	0,416			700	6
P	22	100			30		0,4	0,416			700	36
P	23		400	10			0,4	0,416			700	0
P	24		400		30		0,4	0,416			700	23
P	25	100		10		0,13			7		700	0

P	26	100			30	0,13			7		700	4
P	27		400	10		0,13			7		700	0
P	28		400		30	0,13			7		700	4
P	29	10		10			0,4		7		700	0
P	30	100			30		0,4		7		700	4
P	31		400	10			0,4		7		700	0
P	32		400		30		0,4		7		700	4

Table 3: 32 case scenarios run in P-mode for the Sensitivity test

To make a mathematical study of how the different variables affect the running of the Tool some parameters were chosen:

- The total Energy Potential
- NPSH potential (NO.PSH in the tale above)
- The total Costs of the installation of the power line
- The ratio between the costs and the energy potential: NOK/GWh.

The total potential energy storage is calculated as the sum of the E of each of the power lines. The E by definition is:
$E = \rho * g * \mathrm{GPH} * V * \eta; Q = V/time$ --> $E = P * time$.

The total costs are calculated as the sum of all the costs of each of the power plant suggested by the Tool for each case.

And the NOK/GWh is calculated as: $NOK/GWh = totCOST/totE$.

These 4 parameters are used for the classification of the different variables. The results of the Tool are represented in charts. The Histograms of the results, for example, for the E potential using the three available modes of the Tool are the following:

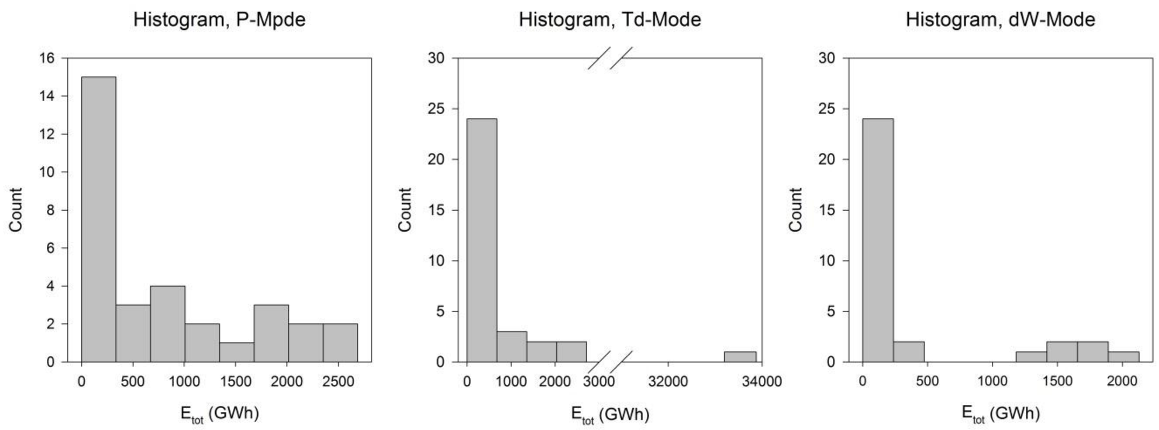


Figure 11: totE potential run in the three modes

As shown there the results present a Poisson distribution, but for a better simpler understanding of the results, a Multiple Linear Regression analysis has been applied, despite it been normally used for Gaussian distributions.

The results are studied with two regression modes, Multiple Linear Regression and Best Subsets Regression.

With the regression mode we are trying to set up an equation of a dependent variable as a function of one or more independent variables. To be able to see the importance of each variable in the different cases of study, the first values we have to look at from the statistic studies are the P values. The P value tells us how confident we can be that each individual variable has some correlation with the dependent one. A P value of 5% shows a 95% probability of being correct asserting that the variable is having some effect on the dependent variable. The R-squared of the regression is the fraction of the variation in your dependent variable that is accounted for independent variables. The R-squared is important when your main concern is using the regression equation to make accurate predictions, and to be considered a good value it should be bigger than 0.6. [22]

If we take a look to the results and analyze, for instance, the result for totE in the P-Mode we obtain the following outcomes displayed in table 4 and 5.

Table 4 shows us that the Rsqr is 0,692. Since it is bigger than 0, 6 we can affirm that is a good value. When looking at the P value we can see that only DISTp_max presents a smaller value than 0.05, so the prediction of totE is mostly based on the distance between reservoir polygons. It can be said that the multiple linear model may be underspecified on the other independent values.

When looking at the results of the Best Subset Regression (table 5), we can say that the best models to explain it are Model 1 and Model 3. Both show a relatively good Rsqr value and also some relatively low P in both cases showing the same result as for the Multiple Linear Regression where the most important parameter is the maximum distance between reservoir pairs.

Multiple Linear Regression torsdag, mai 02, 2013, 10:19:26

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 9 = -204,674 - (0,395 * Col 4) - (1,182 * Col 5) + (64,798 * Col 6) - (41,531 * Col 7) + (1047,338 * Col 8)

N = 32 Missing Observations = 2

R = 0,832 Rsqr = 0,692 Adj Rsqr = 0,633

Standard Error of Estimate = 523,421

	Coefficient	Std. Error	t	P	VIF
Constant	-204,674	354,016	-0,578	0,568	
Col 4	-0,395	0,308	-1,280	0,212	1,000
Col 5	-1,182	0,603	-1,960	0,061	1,001
Col 6	64,798	9,254	7,002	<0,001	1,000
Col 7	-41,531	28,112	-1,477	0,152	1,000
Col 8	1047,338	685,512	1,528	0,139	1,000

Analysis of Variance:

	DF	SS	MS	F	P
Regression	5	16015614,582	3203122,916	11,692	<0,001
Residual	26	7123199,725	273969,220		
Total	31	23138814,308	746413,365		

Column	SSIncr	SSMarg
Col 4	424289,795	448988,643
Col 5	921603,437	1052956,152
Col 6	13431831,879	13431763,896
Col 7	598381,765	597966,476
Col 8	639507,706	639507,706

The dependent variable Col 9 can be predicted from a linear combination of the independent variables:

	P
Col 4	0,212
Col 5	0,061
Col 6	<0,001
Col 7	0,152
Col 8	0,139

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict Col 9 (P < 0.05): Col 6

Normality Test (Shapiro-Wilk) Passed (P = 0,367)

Constant Variance Test: Failed (P = <0,001)

Power of performed test with alpha = 0,050: 1,000

Table 4: Multiple Linear regression study for totE run in P-mode

Best Subsets Regression torsdag, mai 02, 2013, 10:20:54

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	**Symbol**
Col 4	A
Col 5	B
Col 6	C
Col 7	D
Col 8	E

Model #	**Variable**	**Cp**	**Rsqr**	**Adj Rsqr**	**MSerr**	**A**	**B**	**C**	**D**	**E**
1	1	7,917	0,575	0,561	328001,195			*		
2	2	6,157	0,619	0,593	303796,201		*	*		
3	3	5,820	0,647	0,609	291778,825		*	*		*
4	4	5,639	0,673	0,624	280451,421		*	*	*	*
5	5	6,000	0,692	0,633	273969,220	*	*	*	*	*

Model # 1 R squared = 0,575

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-524,584	226,385	-2,317	0,028	0,000
Col 6	64,466	10,124	6,367	<0,001	1,000

Model # 2 R squared = 0,619

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-242,369	266,384	-0,910	0,370	0,000
Col 5	-1,168	0,635	-1,841	0,076	1,000
Col 6	64,795	9,745	6,649	<0,001	1,000

Model # 3 R squared = 0,647

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-524,158	323,015	-1,623	0,116	0,000
Col 5	-1,151	0,622	-1,851	0,075	1,001
Col 6	64,790	9,550	6,784	<0,001	1,000
Col 8	1047,973	707,442	1,481	0,150	1,000

Model # 4 R squared = 0,673

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-366,175	334,665	-1,094	0,284	0,000
Col 5	-1,168	0,610	-1,915	0,066	1,001
Col 6	64,794	9,363	6,920	<0,001	1,000
Col 7	-41,519	28,442	-1,460	0,156	1,000
Col 8	1047,633	693,574	1,510	0,143	1,000

Model # 5 R squared = 0,692

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-204,674	354,016	-0,578	0,568	0,000
Col 4	-0,395	0,308	-1,280	0,212	1,000
Col 5	-1,182	0,603	-1,960	0,061	1,001
Col 6	64,798	9,254	7,002	<0,001	1,000
Col 7	-41,531	28,112	-1,477	0,152	1,000
Col 8	1047,338	685,512	1,528	0,139	1,000

Table 5: Best Subset Regression study for totE run in P-mode

If we kept on analyzing all the results from the different studies (Appendix C), it would lead us to assert that the most sensible parameter is the maximum distance between reservoirs and in a lesser extent to the minimum Td. This is a plausible result due to the important role that DISTp_max parameter plays. The longer the distance the more possibilities of connection between reservoirs you can get. The bigger the distances allowed the more chances of having good GPH and so better Power production. The relation between totE, DISTp_max and Td_min can be represented as in figure 12:

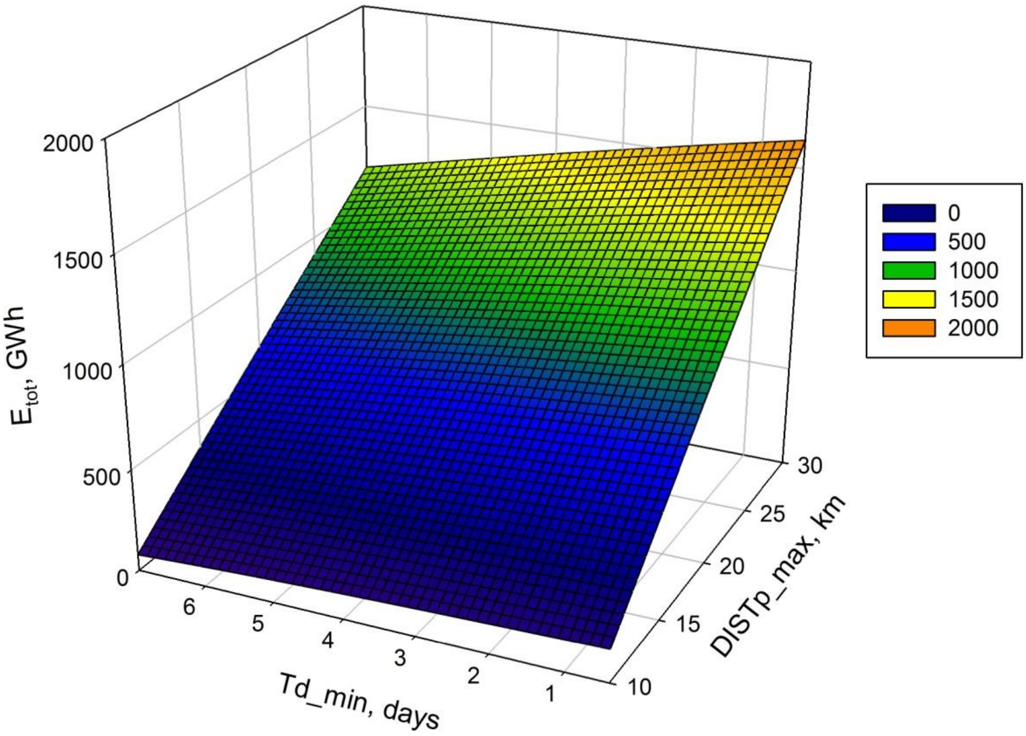


Figure 12: Relation between totE, DISTp_max, and Td_min as a result of the Sensitivity test

Here it is shown how sensitive the totE parameter is. When increasing the maximum distance between reservoir polygons. It shows high differences. And when depending on the minimum storage potential, totE shows lower differences. This graphic is made with only a few points, so, for a better representation of reality more points should be included. Nevertheless it gives us a rough idea of the sensitivity of the total energy storage parameter.

Looking at these results, an additional comment can be done: That the dW-mode, with the combinations of the parameters used, shows a high sensibility. We wanted to see how restrictive is the parameter of 0.13 m/hour- the value normally used for rivers [16]. This I did by increasing the value to 0.4. The results show that in most of the cases, the reservoirs cannot use such water variations, because the rest of the parameters calculated, based on this, present non-feasible outcomes. That is why in several cases no PSH connections where suggested by the Tool.

2.5 Results and suggestion for improvements

2.5.1 Results

From the 220 possible PSH lines suggested for the region of Telemark one will be selected for a more detailed study.

In order to make the best selection 4 different scenarios will be studied, runned with the three different modes. The selected ones are:

- P-6, P-14, P-21 and P-26 for the power production mode.

- Td-6, Td-14, Td-21 and Td-26 for the storage duration mode.

- And dW-6, dW-14, dW-21 and dW-26 for the water level change rate mode (See appendix B).

In all cases we studied their storage potential, the costs, and the cost per GWh, in order to have a broad overview of the most promising PSH line connections. They were classified depending on their values as the most promising ones (colored in green) to the least (colored in red). There other colors in between help us to see the transition. (Appendix D).

Once the results were shown in the maps, with the data used for our screening, we got to the conclusion that the connections from Tinnsjø reservoir and the municipality of Vinje have the biggest storage potential of Telemark.

Then, between these possible connections, we had to select one for the detailed study. The northern area presented four main connections that could be selected as good choices for the case study. However, as the most promising ones in that area had already been analyzed [12] we decided to focus our attention on Vinje municipality.

In this western area of Telemark there are two main lines. If we take a look at the maps created for P-14, we can see that the connection between Songavatn and Totak presents the best Energy storage in Vinje, but with higher costs for the construction of the power plant. Nonetheless, the NOK/GWh parameter shows us that it is a profitable connection.

We can also say that the Songavatn-Totak option is a better choice than the Bitdalsvatn-Totak option, based on the bigger capacity of this reservoir, allowing bigger water transfers. The tunnel will have to be longer but it proves to be cost efficient.

Figure 13:PSH connections suggested by the tool for P-14 classified by the E(GWh)

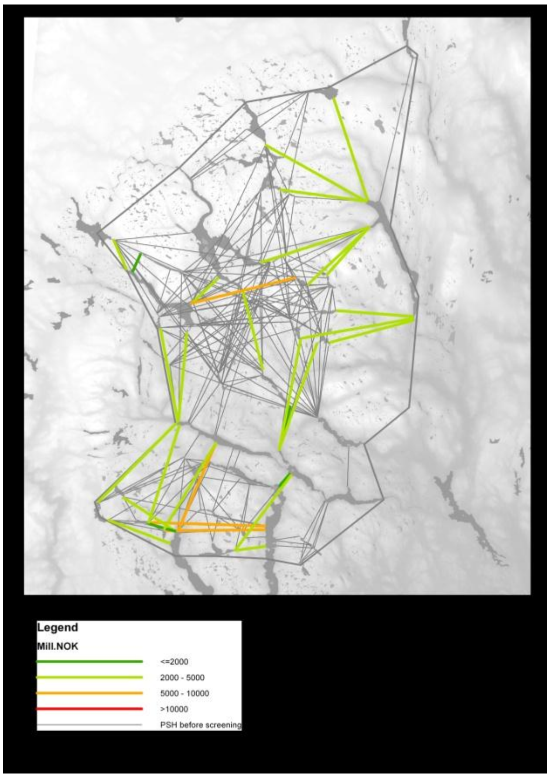


Figure 14: PSH connections suggested by the tool for P-14 classified by the costs

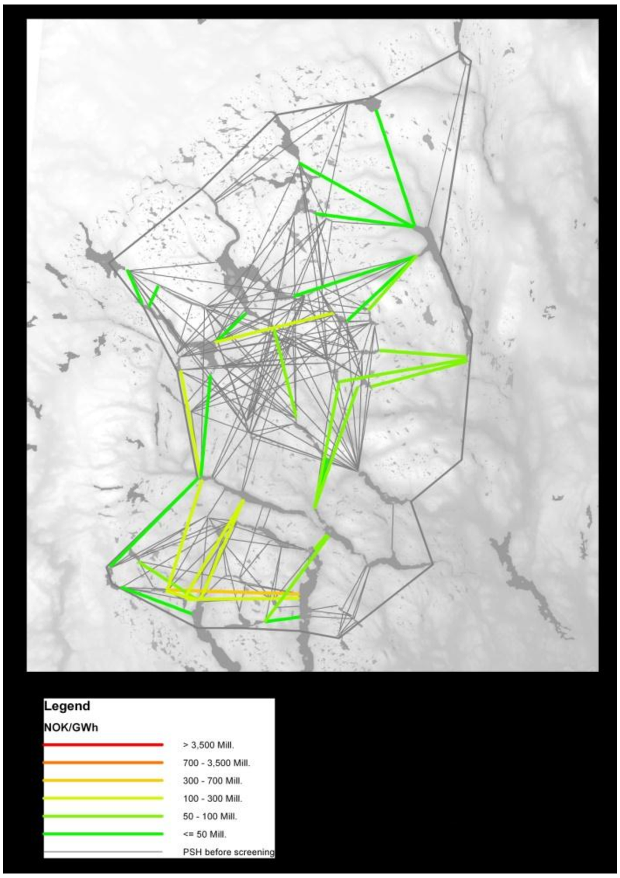


Figure 15: Figure 14: PSH connections suggested by the tool for P-14 classified by the NOK/GWh

2.5.2 Suggestions for improvement

Some problems appeared when working with ARCGIS tool, so some changes are recommended.

Here below are listed some improvements already implemented in the tool and some suggestion for further implementation:

1. In the beginning the digital elevation model (DEM) used in the tool was not very detailed, so a new DEM was needed to allow greater accuracy in the study. NTNU catalogue provided the data needed and then it was transformed to be used in ArcGIS Tool. Thanks to this DEM of 25 meters a better topographical analysis of the power plant potential is possible. It enables the tool to clip out some of the connections suggested initially that were geographically not feasible such as PSH lines crossing deep valleys.
   This improvement of the DEM resolution was a step forward for the PSH lines suggestion, but there are still some problems that are not solved since the tool continues suggesting power plants that cross lakes and other reservoirs.
   The fjord cross elimination criterion is done by the tool directly by *"Select all lines outside of fjords"*. But for the valleys the exclusion criterion followed is that if the

minimum DEM between the connections of the two reservoirs is lower than the LRW of the lower reservoir, then the valley is clipped out. The graphical explanation for this is shown in figure 16:

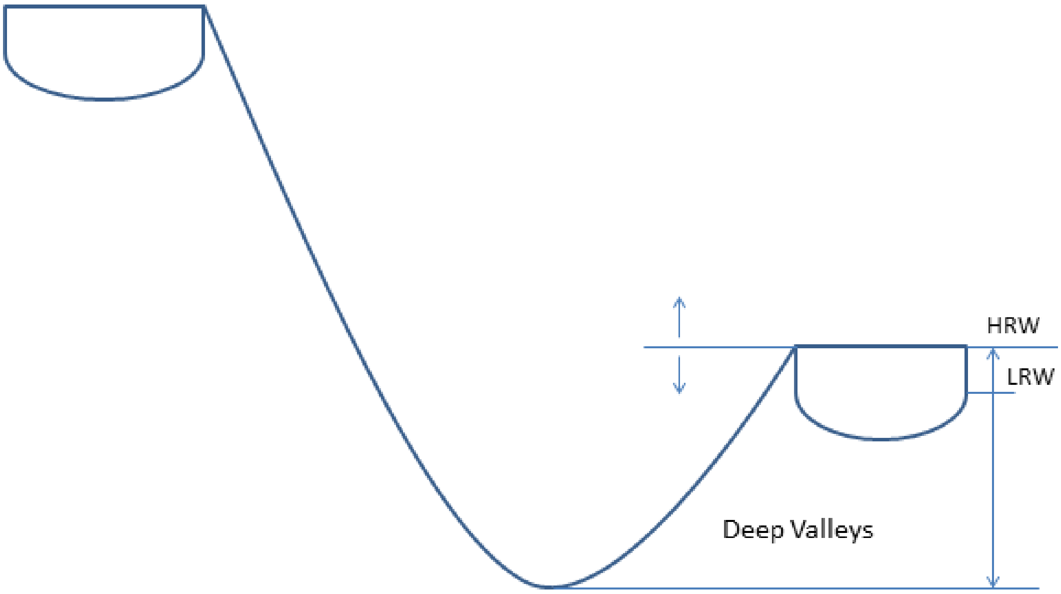


Figure 16: Scheme of valleys clipped out by the tool.

Nonetheless, if instead of the situation above we have the following (See figure 17), the PSH line is suggested by the tool, even though it is not geographically possible because it crosses a deep valley. If the terrain is not lower than LRW then it is not considered a deep valley by the tool.

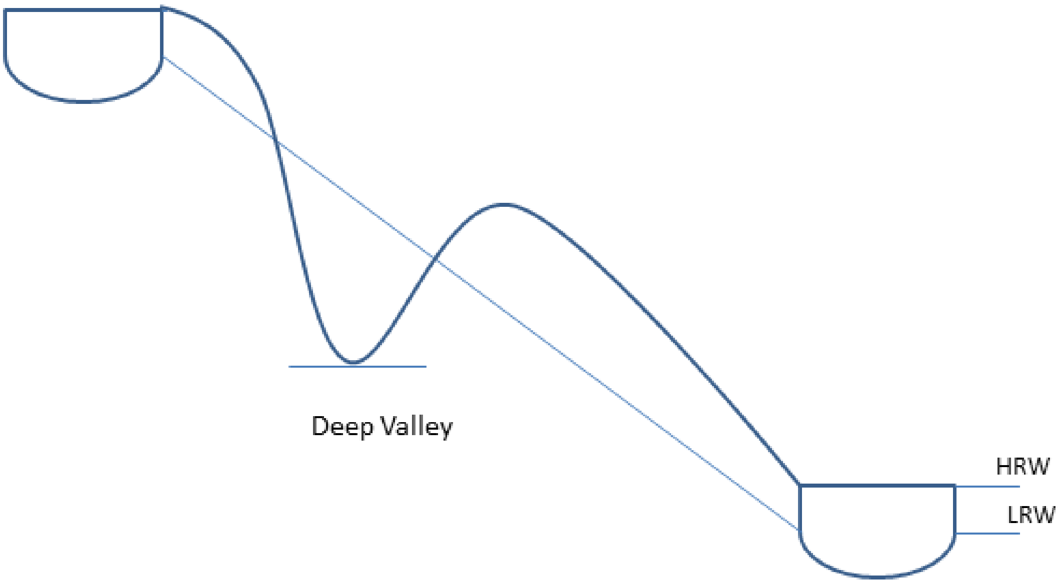


Figure 17: Scheme of valleys not clipped out by the tool

A suggestion to upgrade the tool to clip out these connections of lines could be the following:

- First the tool has to calculate the slope of the connection so we are able to know its height in every point.
- Then in several points -for example every 200m- the height of the suggested power plant connection will be compared to the terrains one. If in any case the terrains height is bigger than the connections, it would mean that we are facing the problem mentioned above so the connection should be clipped-out.

2. The same problem as for the valleys is presented for the existing lakes between reservoirs. But in this case we have an additional problem. The existing data in the tool offers information about the surface of the lakes but not its depth. It would be necessary to implement the depth of the existing lakes in ARCGIS, to be able to use the same routine as for the valleys. But this information is not available for all the lakes of Norway. Nevertheless the information should be implemented in the tool whenever available, because it allows a more realistic study since the lakes would be treated the same as the valleys.

3. The ArcGIS tool was adjusted to export data in CSV-tables, so it could be used in cost calculation, for instance. This still needs some improvement. The main reason is that, when the characteristics of the PSH lines are chosen in the screening mode, some of that information is not included in the tables. For example, if we do the screening with the P-mode, the power production will not appear in the tables as an outcome of the tool. I suggest that all the parameters should be exported in these CSV-tables, regardless if they had been calculated or decided by the user. In these CSV-tables the different parameters should follow the same order, regardless of the screening mode used. This would make the cost calculation easier because, so far, due to the different order of the variables, 3 different excel sheets have been needed, one for each mode.

   I suggest that it could be helpful to the user to have a log-file where the characteristics chosen for the power line are listed. It would help not to forget the features compelled in the search for power lines. Because, so far, once you have run the tool, there is no way of knowing the values used beforehand.

4. The ARCGIS tool has a place reserved in the screening for environmental issues. This is a very important aspect regarding pumped storage development. Therefore some restrictions on where to place the PSH lines are needed. After a meeting with NINA I realized that is a very difficult topic to deal with. Norway has abundant wildlife and it is very difficult to protect the whole of it without causing some damage. Depending on the point of view you focus on, the parameters may change. For example, there is a lot of disagreement regarding the wild reindeer restrictions. There are some

parameters in the tool that can be used as a rough guidance, but during my study of the tool I thought it was better to ignore all restrictions, not including them in the screening. Being such an important topic I think it should be studied in high detail for each individual case. It is one of the topics discussed in the Songa case study in chapter 3.

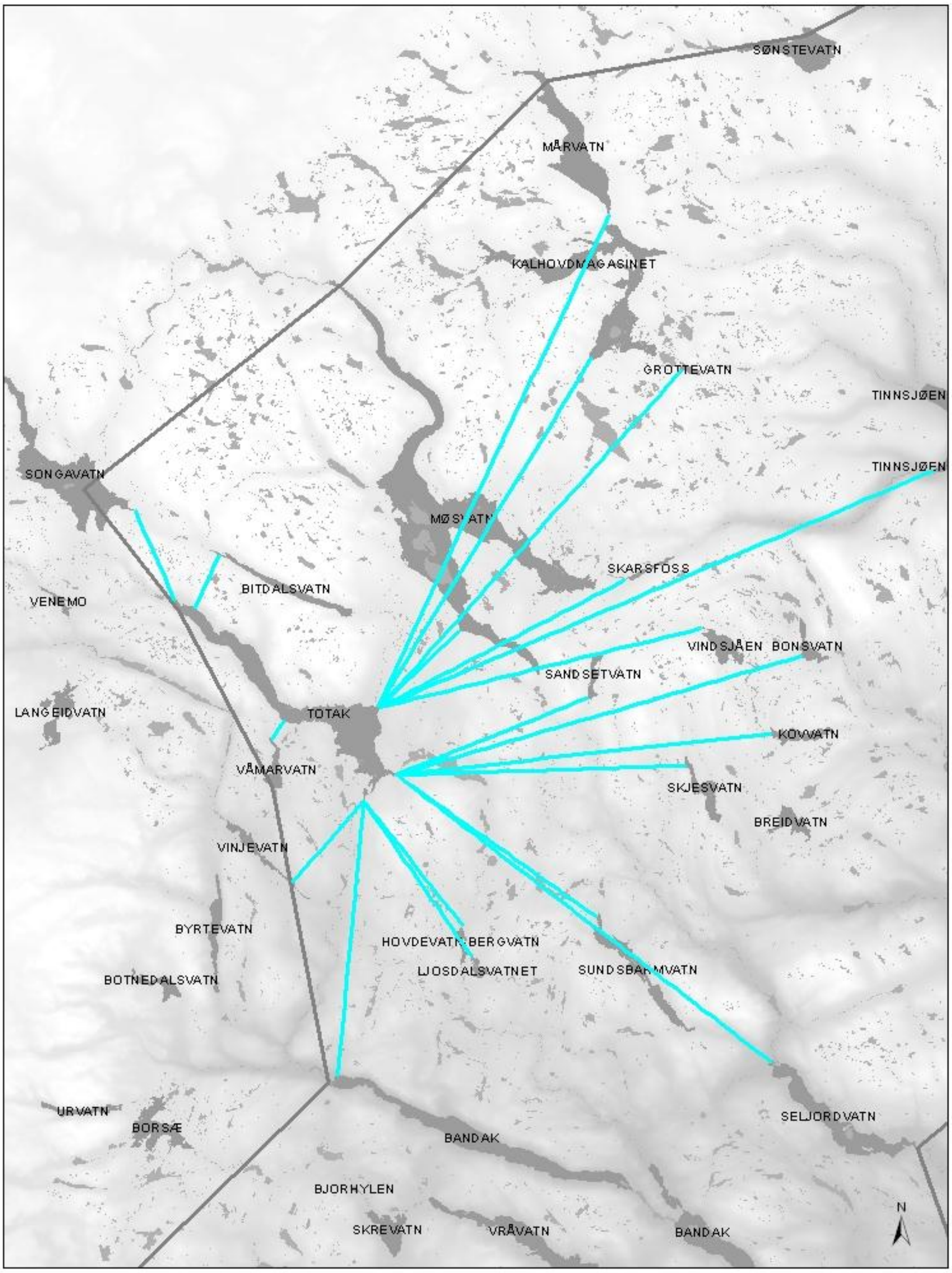
The values used now as guidance to avoid these environmental restrictions by the tool should be further investigated if the user wants to include them in the screening.

5. Since a rough economic study has been done for the PSH connections, this should be implemented in the tool and it should appear in the information given in the CSV tables. Also the tool should implement the calculation of the potential energy storage and the NOK/GWh, since we have seen that they are very important as classification parameters.

   After the layout of the case study, a review of the cost excel sheet was done. Most of the assumptions seemed reasonable comparing them with the Songa case study, but some improvements could be made. For example, the number of power units used in the power plant has been an assumption of only one. Comparing it with the detailed case study, we are using 6 units. The number of units can be roughly calculated based on the power production of the pumped storage hydropower plant. In this way, although the units have to be discussed depending on several variables, the costs deduced would be more realistic than the ones offered at the moment.

   It also presents another problem; the costs are calculated as cost estimation for hydropower plants based on the characteristics of the power plants more recently constructed in Norway [15]. Some of the PSH plants that are suggested by the tool present very big tunnel cross sections and length, so the calculation is done assuming a linear increase of the costs because this dimensions are not included in the graphs. Further investigation on how the prices may change should be done for a better cost estimation.

6. One of the big problems ARCGIS tool presents is that it suggests too many PSH line connections from one reservoir to different ones, as it is shown in the map bellow:



Possible PSH connections for Totak.

Figure 18: Too many PSH lines suggested by the tool for one reservoir

This is in fact is not altogether possible. Each reservoir, depending on its capacity, will normally have one, or a few, PSH line connections with other reservoirs, but not plenty of them as shown above. As a simplification, for the time being, we are going to assume that only one connection is feasible for each reservoir.

We will also assume that all the connections showed in the map above that are geographically possible, having been erased the non-feasible ones with the 1st or 2nd tool, as explained in the first topic discussed in the suggestions (2.5.2.1).

In this upgrade suggestion what we want to do is establish an algorithm so the tool can pick up the best solution for each reservoir.

Sometimes when analyzing the results given by the tool, and comparing the data of the different connections suggested for one of the reservoirs, one of the lines shows:

- Biggest GPH
- Nearest distance
- Biggest volume

When this happens this line should be the one and only line suggested by the tool.

It can also happen that there is not one obvious best solution rooting from the different connections suggested. Nevertheless, comparing some parameters the tool should be able to choose the best option. These parameters would be the ones contemplated in the energy production (GPH and Volume) and the in the costs (mainly affected by the tunnel length). Therefore, in order to clip out, the steps that should be followed are:

1. In tool 3, a cell should be implemented for the user to set the minimum energy storage (E) of the power plant. As a result plenty of the suggested lines would be automatically clipped out. The reason is that since there are no boundary conditions for the E, plenty of lines with very low energy storage are suggested as outcomes.
2. After this step, the number of possible connections that do not meet the requirements we are looking for, should be greatly reduced. The next step for the location of the best connection would then be the selection of the line that presents the minimum NOK/GWh.

Following this steps we make sure that ArcGIS is picking up the most promising PSH lines to be constructed and that it meets the requirements imposed by the user.

These steps are important because, if instead of following them we base our decisions only in the E or only in the NOK/GWh, the tool can make the wrong selection. Basing our decision only in E, the selected line can provide very good E but could also be economically not feasible. In the same way, if we only base the selection in the NOK/GWh, a good cheap line it can be suggested, but with a very small E, so we would not be interested in it.

The clipping out should not only be based on the costs. Investment costs can be high or low depending on the E of the power line. It should then be focused in the long run. That is why we need to base the tool in NOK/GWh and not only in the costs.

Suggestions for further investigation could be that: Where more than one pumped storage can be derived from one reservoir, these three different scenarios should be studied:

- L --> 2 U:

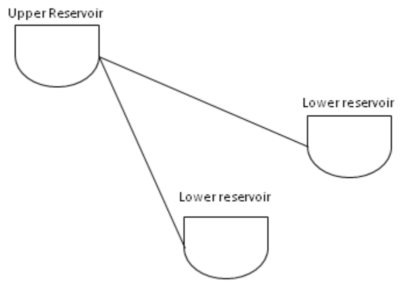


Figure 19: Upper reservoir in connection with two lower.

- U --> 2 L

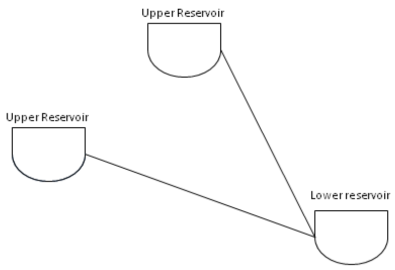


Figure 20: Lower reservoir in connection with two upper

- U --> L --> U:

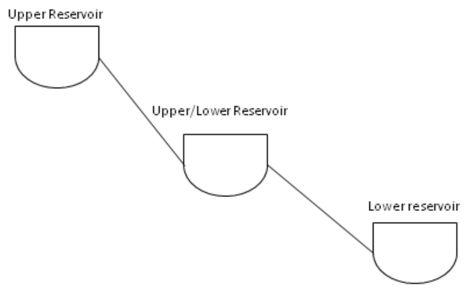


Figure 21: Reservoir as upper and lower at the same time

Following the steps mentioned above for clipping out lines, the real PSH potential of Telemark for P-14 case scenario will be studied. The main parameters used are:

GPH(min)	DISTp(max)	dW(max)	Td(min)	P	No.PSH
100	30	0,4	7	100	32

Table 6: Values of the variables to run case P-14

From the 222 possibilities Telemark shows (See appendix E.1), only 32 connections meet the requirements (See Figure 22).

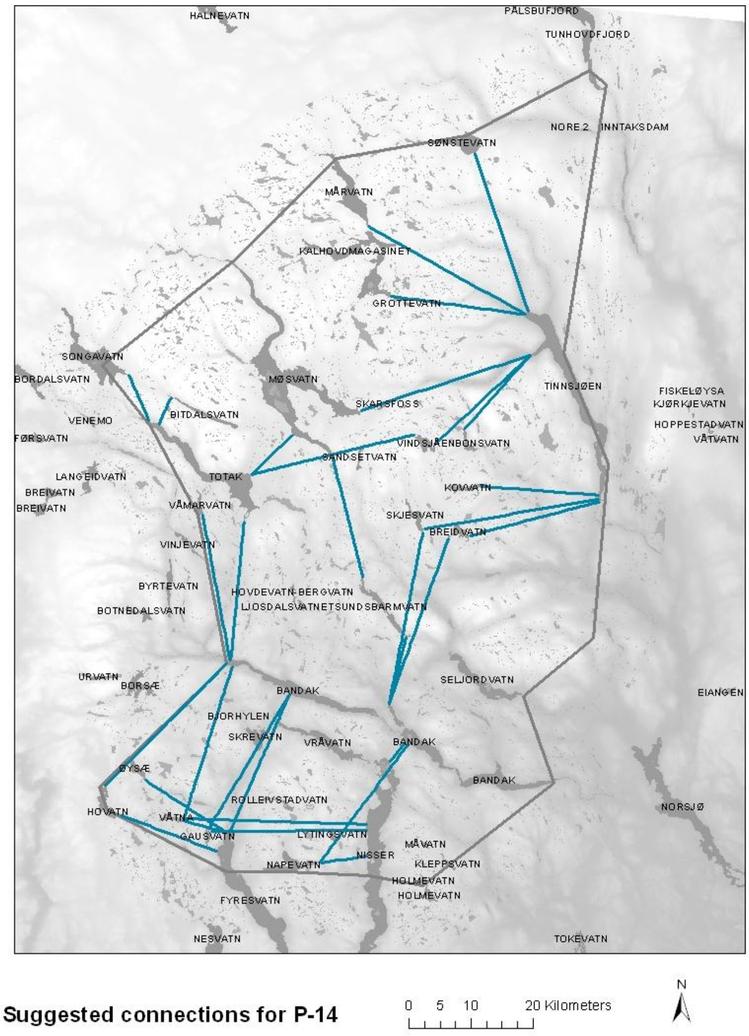


Figure 22: All the connections initially suggested by the Tool for P-14.

From all the PSH lines suggested, the ones that are not geographically possible have been clipped out, so only 20 connections are available now (Appendix E.2).

With these suggested lines it was imposed that E should be higher than 30GWh. Then only 15 lines were available.

Plenty of these 15 connections were suggested for the same reservoir as seen in (See Appendix E.3). After using the higher NOK/GWh value as a selection criterion, only 5 connections were obtained as a final result from the tool as seen in figure 23.

The highlighted connection in blue represents the lowest NOK/GWh in the area for these selected criteria. Since Tinnsjøen reservoir had been investigated earlier in previous studies [12], we chose the next best connection: Songa-Totak, for our case study.

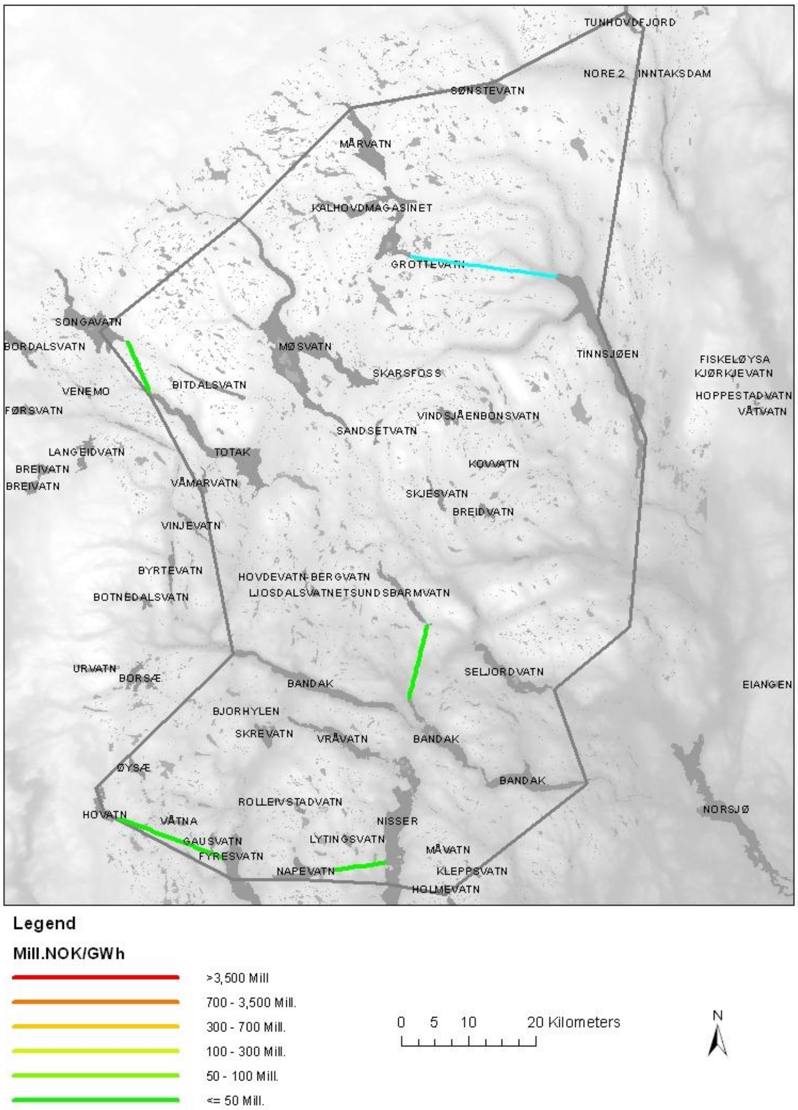


Figure 23: Number of PSH connections the Tool should suggest

3 Case study: Songa pump storage hydropower plant

3.1 Characteristics of the study site

3.1.1 Landscape and Geology

The area between Songa and Totak presents a mountainous terrain and several small lakes. There are some small urban areas. It is illustrated in figure 24:

Figure 24: 3D map of the area between Songa and Totak in Vinje (Telemark)[23]

The construction of power stations and large water tunnels need good geological conditions. Poor rock quality requires expensive and extensive safeguards that can make the project unprofitable. Therefore several geological surveys must be performed beforehand to determine the rock quality. [16]

Nevertheless, it is possible to study the local geological conditions by studying the topographical and bedrock maps (Appendix F and G).The main goal is to identify potential zones of weakness in the rock because such zones are problematic to operate underground.
The bedrock of the area in our case of study shows a good and uniform geology with granite, a hard and tough rock.

3.1.2 The existing power plant and reservoir regulation scheme

There is an existing hydropower plant between Songa and Totak reservoirs. This is a very important aspect to consider in regards to the new pump storage layout.

Songa power station, located in Vinje in Telemark, is a power plant that exists since 1964, owned by Statkraft. It is part of a broad very complex system where all the power stations are connected as shown below [24]:

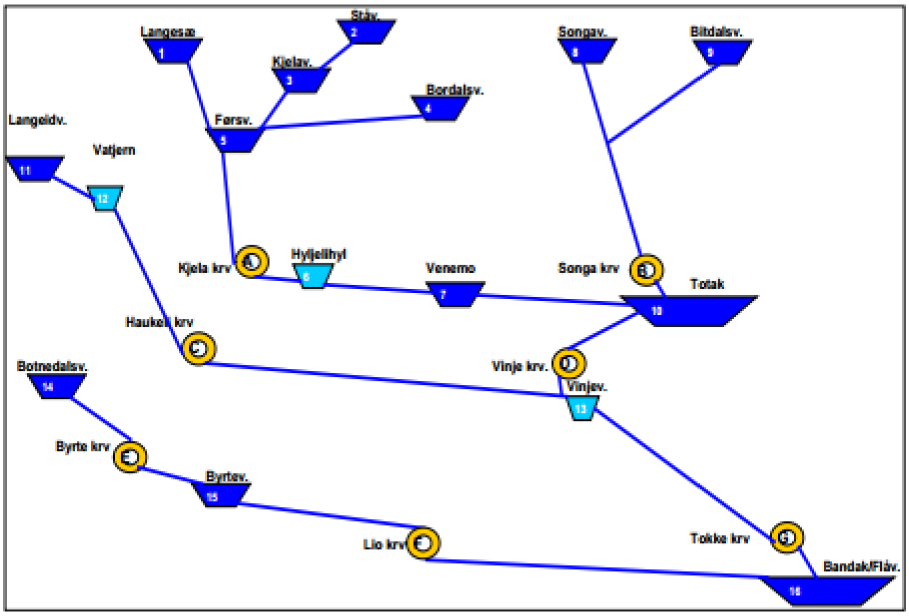


Figure 25: Scheme of the existing hydropower plant system[24].

As a simplification for this case study we are only going to work with Songa, Bitdalsvatn and Totak reservoirs. Songa power plant is supplied by Songavatn and Bitdalsvatn reservoirs and it discharges in Totak. There is a tunnel between Bitdalsvatn and Songavatn so when the water level changes in Songa it also does in Bitdalsvatn. This connection allows us bigger water volume changes because, as a simplification, we are considering Bitdalsvatn as surface of Songa.

SONGA POWER PLANT	
Energy Generation	
Catchment area	591Km2
Volume Songa	639Mm3
Volume Totak	258Mm3
Annual power production	575GWh/year
Capacity	120MW
Absorption capacity	48m^3/s
Average flow	27.2m^3/s
Inflow	857Mm^3/year

Average diluted runoff	46l/s*Km^2
Turbine	
Turbine	1 Francis
Tunnel	
Cross section	$39m^2$
Lenght	8.6Km
Auxiliary intake	$18m^2$ 1.7 Km
Connection Bitdalsvatn-Songa	$7m^2$ 11Km

Table 7: Main characteristics of Songa hydropower plant[21][24].

The following graphics show the reservoir development for Songa(Figure 26) and for Totak(Figure 27) between 1985 and 2009. The orange thick line represents the average water lever through all these years, and it can be compared to the HRW and the LRW. Here we can see the variation the reservoir experiences during the year. First it is shows how the reservoir lowers it level during winter time, then how it rises up with the spring floods until it becomes stabilized, to start decreasing again after that. The idea of using both reservoirs for pump storage would enable them to register similar variations, but, instead of seasonal, in very short periods of time. [24]

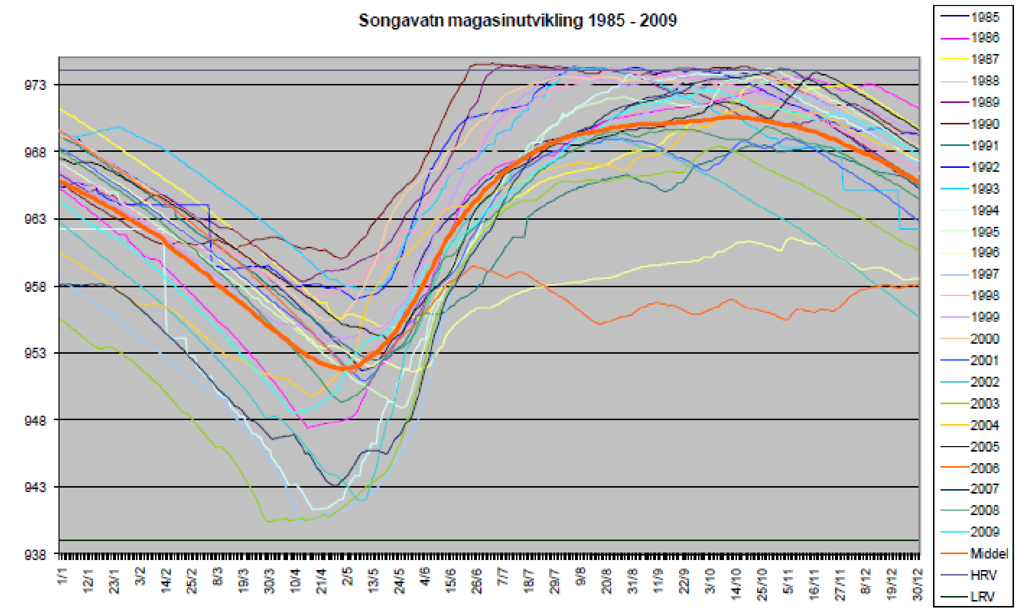


Figure 26: Reservoir water level for Songa between 1985-2009 [24]

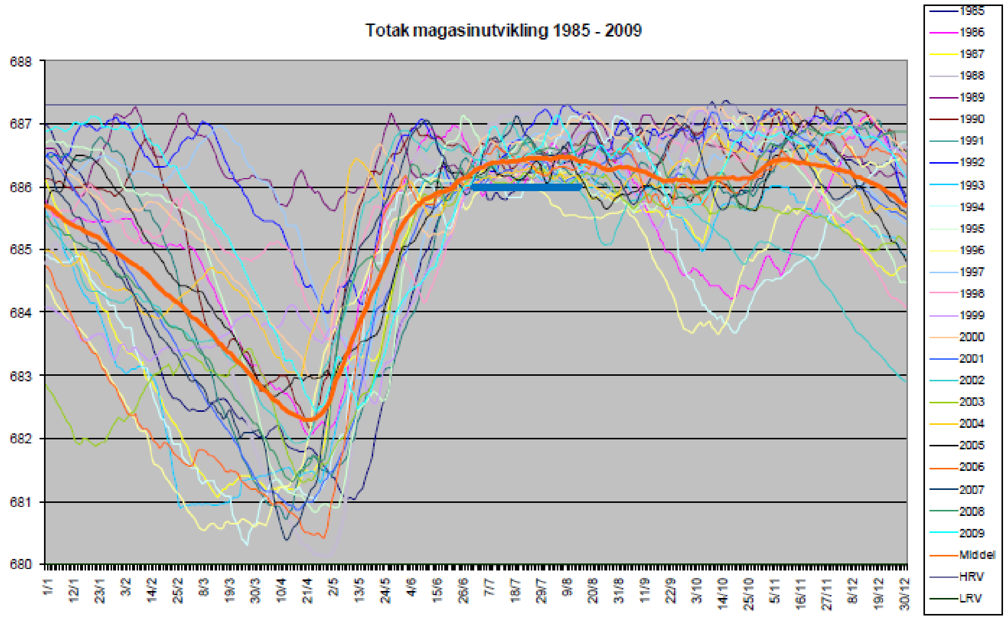


Figure 27: Reservoir water level for Totak between 1985-2009[24]

For the design of the pump storage hydropower plant, the following data is going to be used:

Reservoir	Songavatn & Bitdalsvatn	Totak	
Volume	749	258	million m3
HRWL	974	687,3	m
LRWL	939	680	m
HRWL-LRWL	35	7,3	m
start level	75	50	%
other inflow	0	48	m3/s
other discharge	48	165	m3/s

power generation with max power	24	hours/day
pumping with max power	0	hours/day
gross pressure head	270	m
efficiency	86,0	%

Table 8: Data for calculation of pump storage plant characteristics [12] [21] [24]

The first decision that had to be made for Songa-Totak PSH line is the power production for which it would be designed.

In order to be able to choose a value for the power production, the first step was to establish boundary conditions concerning the maximum water level change rate for the upper and lower reservoir. A maximum value of the power production potential was calculated. With a water level change rate of 0.15 the maximum P was calculated with a result of 2,131 MW and with a minimum time for emptying/filling the reservoirs of 1 day (Formulas from [11]).

With these values, we had the maximum and minimum rates that should not be exceeded. Then several different values were studied and finally it was decided to plan the PSH line for 1200 MW. With this value the Q, WRh and Td for the upper and lower reservoir were calculated as follows:

$$P = 1200MW = 8.4 * Q * H \rightarrow Q = \frac{1200 * 1000}{8.4 * 270} = 529.1\ m3/s$$

$$WRh_U = \frac{3.6\ (HRW_U - LRW_U) * (Q - dQG_U)}{RV_U * 1000} = \frac{3.6 * 35 * (529.1 - 48)}{749 * 1000} = 0.08\ m/hour$$

$$WRh_l = \frac{3.6\ (HRW_l - LRW_l) * (Q - dQG_l)}{RV_l * 1000} = \frac{3.6 * 7.3 * (529.1 - (165 - 48))}{258 * 1000} = 0.042\ m/hour$$

$$Td_u = \frac{SL_u * (HRW_U - LRW_U)}{WRh_u * (GM_u - 0.8 * PM_u)} = \frac{0.75 * 35}{0.08 * 24} = 13.67\ Days.$$

$$Td_l = \frac{SL_l * (HRW_l - LRW_l)}{WRh_l * (GM_l - 0.8 * PM_l)} = \frac{0.5 * 7.3}{0.04 * 24} = 3.80\ days.$$

So the maximum water level change rate in this case is 0.08 m/hour and the minimum storage capacity is almost 4 days.

3.2 Suggested layout for the new pump storage plant

3.2.1 Location of the tunnel and power plant

Where and how to place the tunnel opens a big discussion. The following are some of the alternatives during the planning:

- Upgrade the existing tunnel by increasing its cross section. This would reduce the costs but would mean that the existing power plant should close during the whole construction period. Therefore this alternative was rejected.
- Build a parallel tunnel connecting with the existing one to reduce the area of the new tunnel. The main downside of this alternative is that as they are connected the surge shaft of the existing power plant may not be able to work in connection with the new one so it would have to be concrete clogged. The design would be two parallel

tunnels that connect at the end with the pressure shaft and the power house shared and new. This alternative meant that the existing power station would also need to be closed, so it was also rejected.

- Build a new tunnel ignoring the existing one. This was the chosen alternative. It enables Songa hydropower plant to operate normally while the new tunnel is being built. The low percentage of flow that the old tunnel represents compared to the new one was another of the reasons; we need a tunnel to convey $529m^3/s$ of water while the existing one only transports $48m^3/s$.

Although our decision was based in not closing the existing power plant and planning it as a whole new structure, maybe it is not the cheapest option. This can be discussed in further studies.

To place the tunnel, the existing one had to been taken into consideration. There has to be a minimum distance between both tunnels to avoid interference during the excavation [18]. The final positioning of the tunnel is as shown in figure 28:

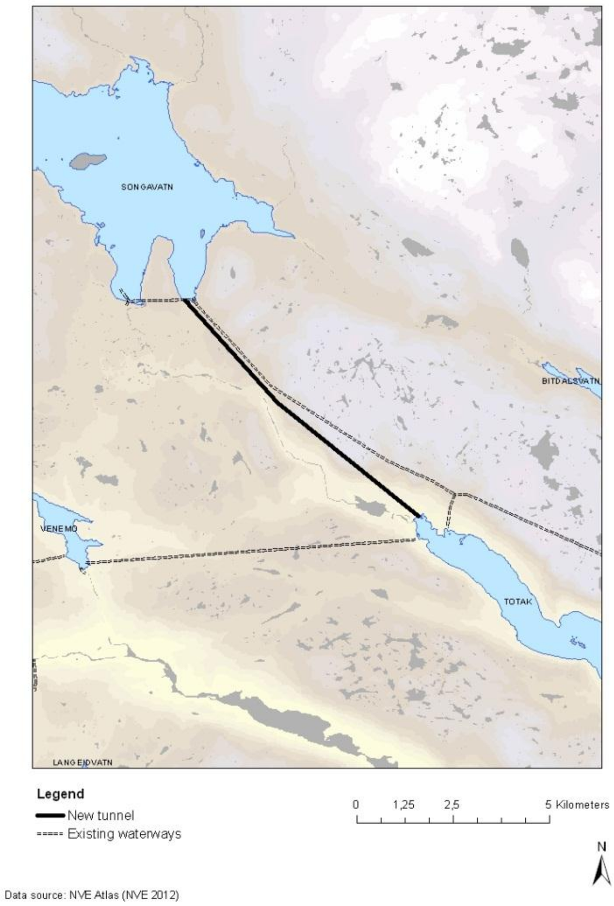


Figure 28: Map showing the positioning of the new and the existing tunnel [18]

When we have situated where the tunnel is going to be and we have the terrain profile,the design of the longitudinal profile of the tunnel can be done. The two main typical designs for this type of structures can be as shown in appendix I. In this case the type of construction chosen is the one with the air surge tank because it appears to be a cheaper option -as discussed in 3.2.3- and the good terrain profile proves to admit it.

3.2.2 Tunnel construction

The two main technics used for digging tunnels in Norway are drill and blast, and tunnel boring machine. One of these two methods has to be chosen, depending on the characteristics of the tunnel and the geology [16].

The construction of this tunnel is going to be planned with drill and blast tunneling. The main advantages of this method are: Flexibility in the design, its ability to adapt to different geologies, and lesser difficulty in the transportation of the machinery [16]. The roads that already exist in the area make it easier when it comes to the transportation of the machinery (See appendix H).

The optimal hydraulic cross sectional profile by drilling and blasting is:

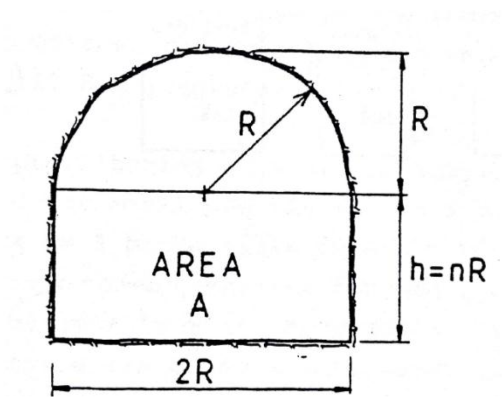


Figure 29: Hydraulic optimally designed tunnel profile for drill and blast[18].

The digging can be done in one or several phases [18]. With a tunnel cross section of more than two hundred square meters, -as it is our case-,operating in at least two phases is a reasonable choice.

In order to design a tunnel of these characteristics we should take as a model the tunnel cross section of Stornorrfors hydropower plant, located in Sweden. This tunnel has a cross section of about 380m^2. For the excavation of the whole section, first the curved top was dug out, and then the bottom part was done in two phases as shown in the figure bellow [18]:

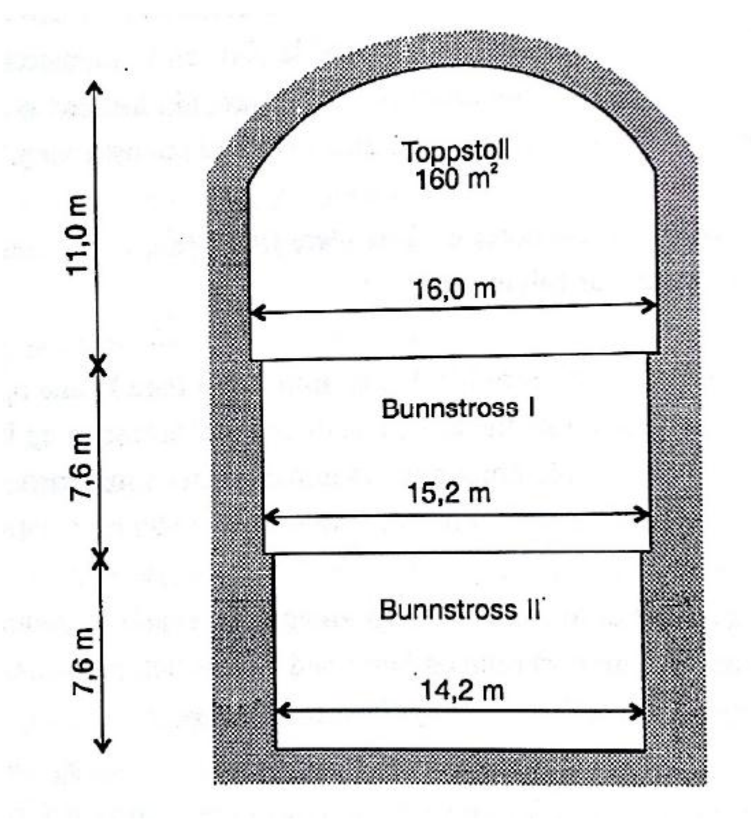


Figure 30: Stornorrfors tunnel Cross-section [18].

Based on this tunnel cross section which has a H/B= 1,7 , we want a similar cross section but with 265 m^2 (Q= V*A, v= 2m/s [12]). The mountain where this tunnel was excavated presented a good geology, of homogeneous granite. Our case study presents the same type of rock so it is a good role model to follow. Therefore, assuming the same H/B relation, our tunnel would present a diameter of 14.6 meters and an nR= 12.4 (shown in figure 31).

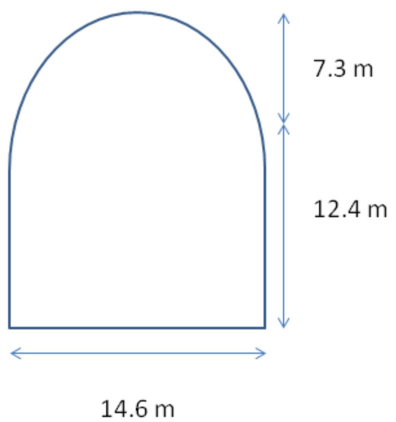


Figure 31: Design of the tunnel cross-section of Songa pump storage hydropower plant.

The costs of the tunnel have been calculated assuming linear increase of the costs with the increase of the area of the tunnel. The total cost of the tunnel is as calculated in appendix J are 477.713.404 NOK.

3.2.3 Surge tank / air cushion chamber

The design of a pump storage hydropower plant normally includes a surge tank or air cushion chamber near to the power house to decrease the water hammer due to changes in the discharge and fluctuations in the tunnel. This is quite usual because sometimes power plants have to start-stop the discharge many times a day damaging the structure. [16]

Normally, in a hydropower plant no surge chamber or air cushion chamber is needed if Ta/Tw >6 [25].

T_a represents the length of time it takes to accelerate the generator from zero to normal speed with full load. As a rule of thumbs it has values varying from 5 to 8 seconds [25].

T_w is the time it takes to accelerate from zero to design discharge of the water in the tunnel and the draft tube. It is calculated as follows:

$$T_w = \frac{Q_0}{g*H_0} * \sum \frac{L}{A} \rightarrow T_w = \frac{529{,}1}{9{,}81*270} * \frac{8170}{265} = 6,16 \text{ s.}$$

In our case: Ta/Tw <<<<6 so the surge chamber or air cushion chamber will be needed. This is normal because it is a PSH plant where the direction of the flowing water is inverted. [16]

Both alternatives are going to be discussed, and the cheapest option chosen. Nevertheless there are plenty of other reasons to base our decision, on the topography for instance, or geology… Normally the air cushion chamber option is chosen when the distance from the power house to the surface is very large, since the prices and the time invested in constructing a surge tank would be too high. Moreover, an air cushion chamber needs a great deal of geology layout to be constructed that is why rock stress measurement and hydraulic jacking tests are also standard procedures to decide amongst both possibilities.[16]

Making cost estimation for the two alternatives [15]:

- Surge tank:

  The shaft cross-section will be calculated as: $F = 1.3x12.3xf^{5/3}/H$=647.4 m^2

  The price is 360 NOK/m^3, so 233093, 6 NOK.

- Air cushion chamber:

The price is also 360 NOK/m^3. And the volume of rock excavated is:

$$Vair = 1.2x17.2xf^{\frac{5}{3}} \rightarrow Vrock = 1.35xVair = 304639.8m^3$$

So, the costs would be 109670313.6NOK.

Comparing both prices, 109,6mill.NOK >>>>23,3Mill.NOK, the surge tank option proves to be, by large, the cheapest alternative for the layout of the hydropower plant. And since the terrain also shows an optimum profile for it, the surge tank will be chosen option for designing the Songa PSH plant. (Illustrated in appendix I)

3.2.4 Turbine

In pumped storage hydropower plants reversible turbines or twin systems are mainly used for pumping and turbine operation [17].

Both turbines have pros and cons if we compare them:

Concept	*Twin System*	*Reversible Pump Turbine*
Investment	-	+
Size	-	+
Efficiency	+	-
Installation depth	+	-
Pressure head	+	-
Transition time P->T/T->P	+	-
Operation cost	-	+
Maintenance	-	+
Technical risk	-	+

Figure 32: Comparison between reversible turbines and twin systems[17].

Due to the GPH=270 the chosen option was a reversible turbine. This type of turbine works well with GPH between 50-800m, whilst twin systems are more appropriate for heads varying between 600-800 m [17]. In addition the reversible turbine represents a cheaper option for both the investment and maintenance and operation. Voith, Almston and Rainpower are the main companies dealing with this type of turbines in Norway. [16]

To decide the number of units that are needed for our power station, first it should be mentioned that at least two units are necessary. This ensures that it can be working although one of them needs to be repaired. [16]

In our case 6 reversible Francis turbines are going to be needed. Four of them with an average pump power input of 250 MW and the other 2 with 100 MW. This decision was made based on the power production and on the choice of the electrical machines; they present some restrictions on the design as it will be explained in 3.2.5.

Assuming the Q that goes to each turbine is proportional to the P, since our power plant is designed for 1200 MW and discharges 529 m^3/s the calculation for the turbine design will use the following data:

4 Francis X 250 MW --> Q = 110 m^3/s.

2 Francis X 100 MW --> Q=44 m^3/s.

The design of the turbines will be laid out according to TVM5125 Hydraulic Design (Autumn 2012) [16] [25]. The given values will correspond to the design of a Francis turbine, but one has to take into consideration that, for a pump system, the number of blades is reduced and the diameter, D_1, is a bit larger.

Therefore the characteristics of the pump turbine will be calculated as follows:

dimension	Q=110m^3/s	Q=44m^3/s	unit
U_2	40	40	m/s
B_2	22	22	deg
Cm_2	16.16	16.16	m/s
D_2	2.94	1.86	m
ω	27.21	42.97	rad/s
Number of poles	11.54	7.31	
Zp	12	7	
New RPM	26.18	44.87	
D_{2k}	3.1	1.78	m
U_1	51.67	51.67	m/s
$\underline{U_1}$	0.71	0.71	
$\underline{Cu_1}$	0.68	0.68	
D_1	3.95	2.3	m
B_1	0.61	0.42	
B_0	0.61	0.42	

Cm_1	14.7	14.7	m
<u>Cm_1</u>	0.20	0.20	
$Tan\beta_1$	6.3	6.3	
B_1	80.98	80.98	deg

Table 9: Calculation of the dimensions of the turbines[25]

Cavitation is a hydraulic effect that should be averted when designing the turbine. In order to accomplish it the depth of the turbine should be calculated as [16][25]:

$$NPSHr = a.\frac{Cm^2}{2.g} + b.\frac{u_2^2}{2.g}$$

The values for:

	turbines	Pumps
a	1.05<a<1.15	1.6<a<2.0
b	0.05<b<0.15	0.2<b<0.25

So,

$$NPSHr = 31.8\ for\ turbine$$

$$NPSHr = 54.3 for\ pump$$

The turbine, therefore, should be situated 54.3m deeper than the LRWL of Totak in order to avoid cavitation.

For the design of the diameter of the spiral case it should be [16] [25]:

$$12.6m < Dspiralcase < 14.4m$$

The costs for the turbines will be: 109375000 NOK for the bigger unit and 43750000 NOK for the smaller. A total investment of 539,2Mill.NOK is needed for the 6 turbines of the design (final price already been index regulated) [15] [19].

3.2.5 Electrical components

Depending on the generator and converter technology, the power systems can be divided into three different groups as shown in the figure bellow [17]:

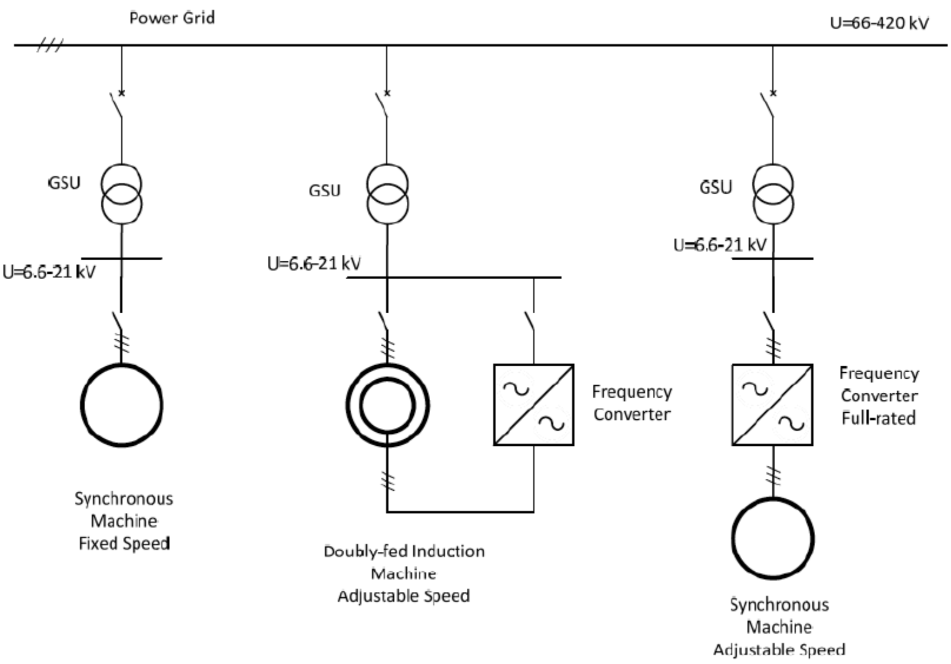


Figure 33: Three basic electric systems for pumped storage[17].

For our case we have chosen 4 fixed speed systems and 2 full frequency converter systems.

The fixed speed systems are synchronous machines connected directly to the power system. These electrical machines are the most commonly used nowadays and present various advantages such as conventional and reliable technology and low cost. But this type of machinery grants no power control. Therefore we have also had to introduce in our design, two full rated frequency converter systems, connected to the stator of the synchronous generator. These converters allow a good flexible operating area in turbine and pump operation. The adjustable speed systems offer quite a range of advantages [17], such as:

- increases the efficiency
- it allows optimal speed and load/frequency control during both turbine and pump operation
- less noise and vibrations
- It allows lowering the minimum generation limits for the turbines.

These types of systems have been introduced in Europe in recent times but they present some drawbacks. One of them is its high costs and, another, the power generation limit of 100 MW. Therefore, for a power production of 1200 MW, it was not an option to install 12 units of adjustable speed. However with the combination of both we can reach a better efficiency of the power plant by ways of increasing -but not too much- the investment on the electrical machines [26].

A vertical design has been chosen for the generator, as in most generators above 10 MW [6]. The cost of the generator connected to the bigger turbines will be around 104mill.NOK/each unit. And to the smaller ones: 58mill.NOK, adding up to a total of 532mill.NOK.

They will all have a voltage between 10-20 KV that will need a transformer to raise the voltage up to 420KV. The decision of the transmission capacity of power lines with alternating current is based on the following table:

Voltage level	Transmission capacity (MVA)
22 kV	approx. 1-10
45 kV	approx. 10-60
66 kV	approx. 20-100
132 kV	approx. 50-400
300 kV	approx. 200-1000
420 kV	approx. 500-2000

Table 10: Transmition capacity of powerlines with alternation current[12]

As the P is 1200 MW, for our case study we have chosen 420KV.

The costs of the transformer will be: Two units of 12 mill.NOK/each, and four of 25 mill.NOK. A total sum of 124 mill.NOK, therefore, invested in transformers.

The variable speed system will also need a converter. A sketch of the final design would be in parallel as shown in the figure bellow:

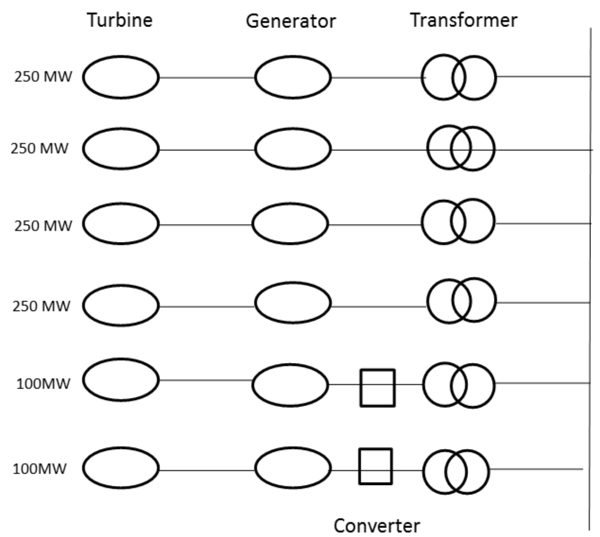


Figure 34: Sketch of the electrical design of Songa PSH plant.

A switchgear will be needed to connect the transformers with the transmission lines.

The total cost for the electro technical equipment -including everything needed for the whole design- is 841,3mill.NOK (see appendix J).

3.2.6 Power house

In the design of hydropower plants, the power house can be above or underground. But in the case of pump storage plants it has to be underground and it has to be placed underneath the LRWL, to avoid cavitation. In this case the turbines have to be 54.3m underneath the LRWL of Totak, as calculated in the turbine design (3.2.4).

The size of the cavern depends on: gross pressure head, flow, electric capacity, and number of units. The main parameters of the power house are:

Blasting Volume	123614 m^3 28427484 NOK
Concrete volume	24723 m^3 61798877 NOK
Reinforcement	1483 Kg 23730769 NOK
Formwork	51918 m^2 51911057 NOK
Supporting work	4264123 NOK
Masonry & plastering work	4511318 NOK
Interior work	13533954 NOK
Unforeseen	18817758 NOK
Rigging	47044495 NOK
HVAC	2600000 NOK
Electrical installations	2000000 NOK
Access tunnels	32106000 NOK
TOTAL (index regulated)	310,02 Mill.NOK

Table 11: Cost calculation for the underground power house

Access to the power house is very important. It is the means of transport of the equipment inside it, and also to transport the rock excavated outside. After the construction it is used as an access for the maintenance of the power house. Waterways are also going to be needed - up and downstream of the water house- with a steel lining design. To split the flow in order to supply the 6 units of our design [16] we have added branches.

The construction of Songa pump storage hydropower plant presents costs of around 2.200 Mill.NOK.(appendix J)

3.2.7 Grid connection

Since this study is trying to explore how Norway can become the 'Green Battery of Europe', the grid connection will focus on how to supply energy to Europe.
If we take a look at the map bellow we can see the possible international links for our pump storage hydropower plant:

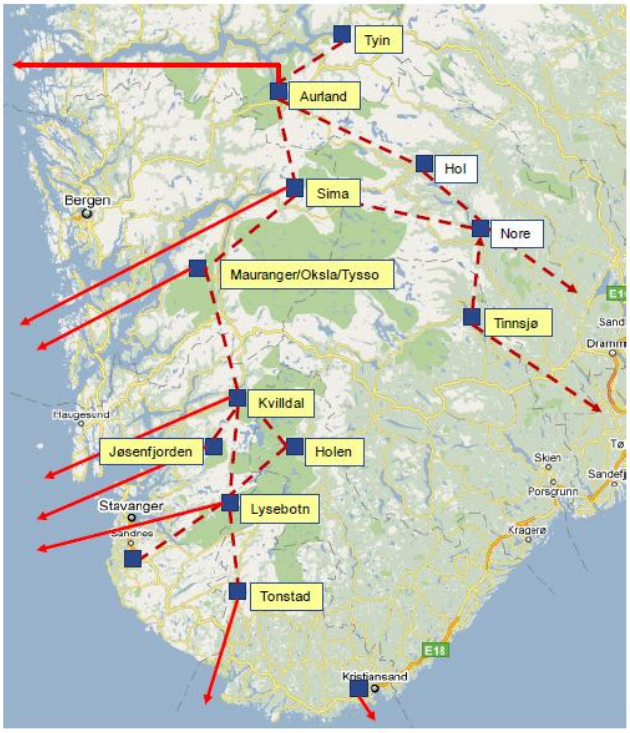


Figure 35: Grid connections from Norway to the United Kingdom, the Netherlands, Germany and Denmark[12].

The closest conncetion to our PSH plant would be Tinnsjø. But even though it is the nearest international link, it is not the best option. If our goal is to supply electricity to Europe using this grid connection, the cables would have to pass through Sweden and then reach the sea, before finally conveying the electricity to Europe. But if we steered the cables to the Western coast instead, this would mean a great advantage since they would be nearer to a fjord or the sea. In the western points the HVDC cables needed for the transmission could be directly connected to international grids. A good option for our case could be to direct our cables to Kvilldal or to Kristiansand, depending to which country we are transporting the electricity to [12].

3.3 Environmental and political constraints

3.3.1 Environmental aspects

If we take a look to the map bellow we can see that this connection has no environmental restrictions beyond the problems of the water level change.

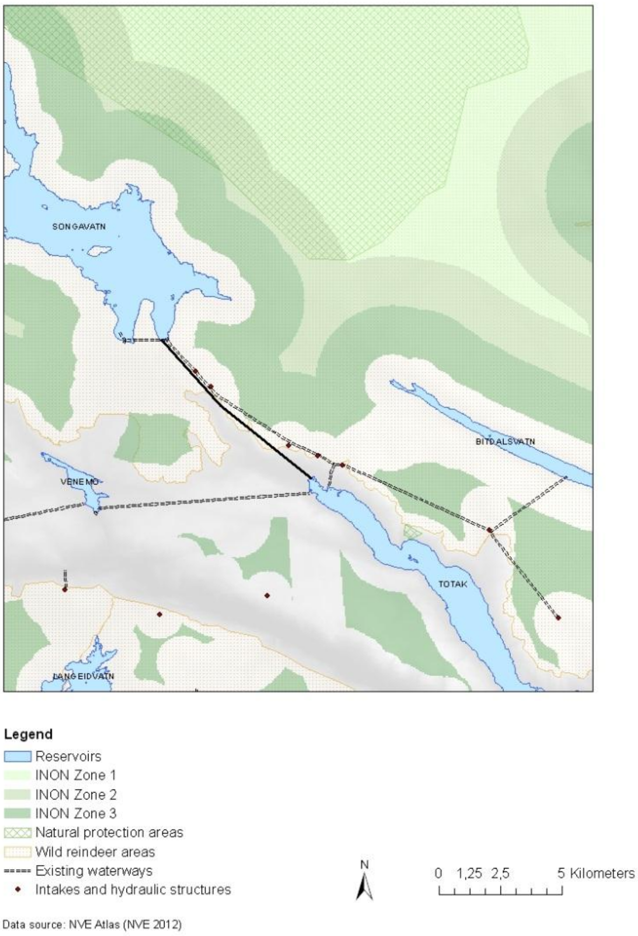


Figure 36: Environmental restrictions.

As shown above, with the tunnel we propose the connection is not affected by natural protection areas or INON zones. Only partly by wild reindeer areas but, since it is an underground construction, it is not considered as a restraint in our planning.

Nonetheless, there is a big concern on how hydropower plants are affecting the environment due to water level change.
All the following technical information is based on a report from Statkraft of Vinje municipality [24]. Telemark is a region with a lot of hydropower plants. From 1995 to 2007 Telemark County, Statkraft and other regulators in Telemark carried out a project to find the best possible scientific basis to implement measures on regulated rivers and evaluate the ones taken on the drawdown of fish.

Also several other studies were carried out by Statkraft and NINA (Tranmæl and Midttun, 2005; Heggenes et al, 2009; Kråbøl, 2010; Johnsen et al, 2012; Gustavsen and Tormodsgard, 2011; Rustadbakken and Schneider, 2011; Liljebrunn and Brabrand, 2011). These studies were mainly focused on the increasing knowledge of the environmental effects of power control, and on the aim to develop measures to reduce or eliminate hostile effects on the environment.

The main conflicts regarding water level change are: local climate, erosion control and biology. All this studies -and more others- provide information that is essential for continued operation and management regulation of the plants in Telemark. And also to optimize the ecological status and production of fish in regulated lakes in the mountains without significant loss in energy production.

Statkraft believes filling restriction should not be introduced in Songa, as it is one of the largest reservoirs in Southern Norway. It is important to preserve flexibility in the operation of this reservoir so that the community can have access to renewable energy when needed. A restriction would cause mayor social and economic damage in dry years. If the Government decides to impose restriction filling in Songa it should be formulated in such terms that it doesn’t build unnecessary barriers on energy production.

Fish Biological surveys in Songavatn show that high water levels of the reservoirs in the fall, can have a positive impact on retrieving trout to the water. But it is still uncertain what effect any filling restriction would have on fish biological conditions. The potential of contour migration barriers have not yet been surveyed.

On the other hand, Totak reservoir has some “self-imposed restrictions”. The water level, from 01.07 to 15.08, should be kept at 686, 0 and from 15.08 to 01.11, at 685.50. By keeping the level in Totak as high as possible, the head loss in the power plants is reduced. Therefore self-imposed restrictions in Totak help to improve fish spawning and recovery.

Totak has had extensive erosion control in the following locations: Myllarheimen, Øygarden, Romtveit, Nordjordet, Sandviki, ou, Sandbekken, Island in Bituosen, Bituåosen and Sporanes.

In Sporanes, for instance, there are ancient stone carvings with fishing, hunting and agriculture motives. This field of art is unique, but part of the gravings suffer inundation and ice cover every year, what can lead to erosion at the field.

Another problem present at Totak is that it holds several boat landing places, both for public and for private use, that are facing problems with the water regulation.

For the construction of a pumped storage hydropower plant between Songa and Totak all these problems would have to be studied in high detailed to see how the new water level regulations would affect the environment, and how feasible troubles could be mitigated.

3.3.2 Licensing

There is no established practice for licensing of large-scale pump storage hydropower plants. In November 2007, The Sira-Kvina Power Company applied for a license for the installation of additional plant capacities of 1000 MW with pumping opportunity, but NVE has not established how the license application will be treated [18].

4 Conclusion and recommendations

Europe is in need of an energy restructuration due to its imposed goals to become a greener continent. One of the proposals to achieve it is by making Norway the battery of Europe. This would mean adapting Norway´s sources to be able to storage the energy.

The GIS-Tool was created to study the PSH potential of Norway. This Tool bases its work in existing dams and reservoirs only. It makes a topographical analysis and a screening where the user has to define a wide range of values such as: power production, water level change rate, storage duration, distance between reservoirs, gross pressure head and distance to roads, power lines and environmental restriction zones.

The aim of this Thesis was to test the Tool, and see if it was able to reflect the reality of Norway, besides making suggestions for further development. Many problems arose while running it, some of them were easy to identify and others quite more difficult.

Just taking a look at the results offered by the Tool, it was clear that it suggested plenty of geographical non-feasible connections. The suggested lines sometimes crossed deep valleys, big lakes and even other reservoirs on the way. Also, the connections suggested from one reservoir to another were much too many.

Further problems appeared when analyzing and using the data. The outcome of the Tool needs to be improved to provide a better understanding to the user, as now commented bellow.

During the testing process some improvements were added to the Tool, such as the implementation of a digital elevation model of 25 meters, which allows the Tool a better geographical study. Also the creation of a rough economic calculation of the PSH lines was created to be included in the Tool.

The cost estimation has been a critical parameter for a broader study of the different cases suggested. It allowed a more detailed study and has been very useful for important classifications of the lines. Various algorithms were suggested for further implementation in the program. For example how to clip out all connections crossing deep valleys, since at this state of art, the Tool still suggests some of these connections. Also an algorithm was suggested to enable the Tool to pick only one connection from each reservoir. With these two clips out criteria, a manual example was carried out to show how the number of lines would be reduced.

For a power production of 100MW, a minimum storage capacity of 7 days, maximum water level change rate of 0.4 m/hour, a maximum distance between reservoirs of 30 Km and a minimum GPH of 100m, from 32 lines initially suggested only 5 of them were possible when using, in addition, the new algorithms for selection.

Also in the estimations of the different parameters of the PSH lines, some parameters such as the energy storage are suggested to be implemented as an outcome. This parameter together with the costs can be very useful to make a detailed study of the feasibility of the power plants suggested by the Tool.

Furthermore a sensitivity analysis was carried out for a better understanding of the Tool. The results showed that the most important parameter for the number of reservoir connections suggested is the distance between reservoirs.

After a study of the best PSH lines suggested from the Tool, in the second part of the thesis, a case study was chosen: The project size and layout of the connection between Songa and Totak reservoirs. This was a way to find out if the Tool is able to suggest good and feasible connections. A rough cost calculation of the main components of the hydropower plant was done, with a result of 2.200 Mill. NOK, as the investment needed for the construction of this connection. Main decisions of the layout were done, such as the size, position and digging technique for the tunnel, the type and dimensions of the turbine used, the electrical machines, the power house size etc.

Pumped storage bears huge environmental constrains. Because due to pump storage the reservoirs suffer quicker and more frequent water level change rates, the landscape varies due to erosion, and the temperature and ice cover of the reservoirs experience changes. Normal life cycle of fish is being threatened by pump storage, with high risk of diminishing the number species, fish size and swimming capabilities.

The Tool is created so that you can take into account, or not, the environmental restrictions. Due to the early stage of the Tool, I have not included any of these restrictions in my study. The actual parameters used in the Tool need to be further investigated. During the test of the Tool a discussion with NINA about the environmental restrains took place. The meeting opened up a big discussion over the difficulties to establish the environmental restrictions, due to the wide range it encompasses. The Tool needs a deep study to establish new parameters for the user. This is a very challenging topic. Every case needs to be studied in high detail but some new and updated parameters for a rough estimation of the environmental constrains should be studied and implemented in the Tool.

Suggestions for further work:

- Creation of a new algorithm to deal with several connections from one reservoir to others, depending on the size of the reservoir, the characteristics of the PSH lines, etc.
- Upgrade of the cost calculation to be as accurate as possible in the cost estimation.
- Deep study of the environmental constrains.
- How to deal with the inflows and outflows of the reservoirs from the existing power plants.

Consequently the GIS-tool can be a very useful tool to establish the best possible connections between existing reservoirs and dams, but it still needs a deep study and the creation of new parameters for the user.

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Appendix

Appendix A

TOTAL COST OF EACH POWERLINE(NOK)	totCost (NOK of all powerlines)	E	E(GWh)	totE	totE(GWh)	NOK/GWh
3587906920,03	106480042846,65	7199,21	172,78104	95609,708	2294,63299	20765628,7
3903863999,88		2040,29	48,96696			79724450,9
3227060004,38		9210,62	221,05488			14598456,3
2554129759,42		1952,05	46,8492			54518108,3
2596126596,79		3296,7	79,1208			32812188,4
2410062667,20		1220,97	29,30328			82245491,5
3202251317,81		2475,95	59,4228			53889270,1
2520841248,35		8897,26	213,53424			11805325,7
3105346644,03		8567,37	205,61688			15102586,1
2624656932,59		2865,25	68,766			38167945,4
2004576515,42		3495,06	83,88144			23897736,1
1287199434,05		2235,21	53,64504			23994752,1
6156903819,93		1194,14	28,65936			214830471
4271946980,94		3245,26	77,88624			54848545,5
1992285484,46		2806,86	67,36464			29574647,5
5090915283,94		747,586	17,942064			283741897
5896400808,91		793,971	19,055304			309436197
2875851594,80		1841,41	44,19384			65073584,8
2942767992,17		3258,45	78,2028			37629956,9
1693039298,21		717,591	17,222184			98305725,8
1504000933,17		1065,6	25,5744			58808845,3
6964305049,62		1263,27	30,31848			229704954
4027070155,70		2640,36	63,36864			63549890,9
3906675686,06		1142,71	27,42504			142449225
3946053139,89		1205,72	28,93728			136365724
1806138013,67		3224,63	77,39112			23337794
3024361417,64		2804,03	67,29672			44940695,7
3282687664,52		1175,64	28,21536			116343994
3108471362,14		3745,41	89,88984			34580897,7
3733637826,27		3834,65	92,0316			40569085,3
3715770863,91		3009,75	72,234			51440746,2
3516737430,73		2436,73	58,48152			60134166

Table 12 Results from the cost Excel sheet for P14

Appendix B.1

		GPH	GPH	DISTp	DISTp	dW	dW	Td	Td	P	P	No.PSH
Mode	**Scenario Nr**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	
P	1	100		10		0,13		0,416		100		16
P	2	100			30	0,13		0,416		100		81
P	3		400	10		0,13		0,416		100		1
P	4		400		30	0,13		0,416		100		21
P	5	100		10			0,4	0,416		100		25
P	6	100			30		0,4	0,416		100		98
P	7		400	10			0,4	0,416		100		2
P	8		400		30		0,4	0,416		100		40
P	9	100		10		0,13			7	100		6
P	10	100			30	0,13			7	100		8
P	11		400	10		0,13			7	100		0
P	12		400		30	0,13			7	100		0
P	13	100		10			0,4		7	100		6
P	14	100			30		0,4		7	100		32
P	15		400	10			0,4		7	100		0
P	16		400		30		0,4		7	100		20
P	17	100		10		0,13		0,416			700	3
P	18	100			30	0,13		0,416			700	13
P	19		400	10		0,13		0,416			700	0
P	20		400		30	0,13		0,416			700	9
P	21	100		10			0,4	0,416			700	6
P	22	100			30		0,4	0,416			700	36
P	23		400	10			0,4	0,416			700	0
P	24		400		30		0,4	0,416			700	23
P	25	100		10		0,13			7		700	0
P	26	100			30	0,13			7		700	4
P	27		400	10		0,13			7		700	0
P	28		400		30	0,13			7		700	4
P	29	10		10			0,4		7		700	0
P	30	100			30		0,4		7		700	4
P	31		400	10			0,4		7		700	0
P	32		400		30		0,4		7		700	4

Table 13:Sensitivity test, 32 cases run in the P-mode.

Appendix B.2

		GPH	GPH	DISTp	DISTp	dW	dW	Td	Td	P	P	**No.PSH**
Mode	Scenario Nr	L	H	L	H	L	H	L	H	L	H	
Td	1	100		10		0,13		0,416		100		3
Td	2	100			30	0,13		0,416		100		222
Td	3		400	10		0,13		0,416		100		1
Td	4		400		30	0,13		0,416		100		2
Td	5	100		10			0,4	0,416		100		11
Td	6	100			30		0,4	0,416		100		39
Td	7		400	10			0,4	0,416		100		1
Td	8		400		30		0,4	0,416		100		17
Td	9	100		10		0,13			7	100		5
Td	10	100			30	0,13			7	100		29
Td	11		400	10		0,13			7	100		0
Td	12		400		30	0,13			7	100		19
Td	13	100		10			0,4		7	100		6
Td	14	100			30		0,4		7	100		32
Td	15		400	10			0,4		7	100		26
Td	16		400		30		0,4		7	100		20
Td	17	100		10		0,13		0,416			700	1
Td	18	100			30	0,13		0,416			700	2
Td	19		400	10		0,13		0,416			700	0
Td	20		400		30	0,13		0,416			700	0
Td	21	100		10			0,4	0,416			700	3
Td	22	100			30		0,4	0,416			700	13
Td	23		400	10			0,4	0,416			700	0
Td	24		400		30		0,4	0,416			700	6
Td	25	100		10		0,13			7		700	0
Td	26	100			30	0,13			7		700	4
Td	27		400	10		0,13			7		700	0
Td	28		400		30	0,13			7		700	4
Td	29	10		10			0,4		7		700	0
Td	30	100			30		0,4		7		700	4
Td	31		400	10			0,4		7		700	0
Td	32		400		30		0,4		7		700	4

Table 14: Sensitivity test 32 cases run in the Td-mode.

Appendix B.3

		GPH	GPH	DISTp	DISTp	dW	dW	Td	Td	P	P	No.PSH
Mode	Scenario Nr	L	H	L	H	L	H	L	H	L	H	
dW	1	100		10		0,13		0,416		100		13
dW	2	100			30	0,13		0,416		100		75
dW	3		400	10		0,13		0,416		100		0
dW	4		400		30	0,13		0,416		100		36
dW	5	100		10			0,4	0,416		100		14
dW	6	100			30		0,4	0,416		100		59
dW	7		400	10			0,4	0,416		100		1
dW	8		400		30		0,4	0,416		100		23
dW	9	100		10		0,13			7	100		1
dW	10	100			30	0,13			7	100		2
dW	11		400	10		0,13			7	100		0
dW	12		400		30	0,13			7	100		1
dW	13	100		10			0,4		7	100		0
dW	14	100			30		0,4		7	100		0
dW	15		400	10			0,4		7	100		0
dW	16		400		30		0,4		7	100		0
dW	17	100		10		0,13		0,416			700	2
dW	18	100			30	0,13		0,416			700	11
dW	19		400	10		0,13		0,416			700	0
dW	20		400		30	0,13		0,416			700	0
dW	21	100		10			0,4	0,416			700	3
dW	22	100			30		0,4	0,416			700	23
dW	23		400	10			0,4	0,416			700	0
dW	24		400		30		0,4	0,416			700	17
dW	25	100		10		0,13			7		700	0
dW	26	100			30	0,13			7		700	0
dW	27		400	10		0,13			7		700	0
dW	28		400		30	0,13			7		700	0
dW	29	10		10			0,4		7		700	0
dW	30	100			30		0,4		7		700	0
dW	31		400	10			0,4		7		700	0
dW	32		400		30		0,4		7		700	0

Table 15:Sensitivity test, 32 cases runned in the dW-mode.

Appendix C.1

Multiple Linear Regression tirsdag, april 30, 2013, 14:26:09

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 22 = -4505,034 + (2,825 * Col 17) - (6,610 * Col 18) + (143,759 * Col 19) + (398,414 * Col 20) + (7996,356 * Col 21)

N = 32 Missing Observations = 2

R = 0,444 Rsqr = 0,197 Adj Rsqr = 0,0429

Standard Error of Estimate = 5822,722

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	-4505,034	3938,202	-1,144	0,263	
Col 17	2,825	3,432	0,823	0,418	1,000
Col 18	-6,610	6,706	-0,986	0,333	1,001
Col 19	143,759	102,949	1,396	0,174	1,000
Col 20	398,414	312,726	1,274	0,214	1,000
Col 21	7996,356	7625,884	1,049	0,304	1,000

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	216583313,637	43316662,727	1,278	0,303
Residual	26	881506279,121	33904087,659		
Total	31	1098089592,758	35422244,928		

Column	**SSIncr**	**SSMarg**
Col 17	24001861,646	22974695,226
Col 18	34118966,019	32941472,570
Col 19	66185312,075	66111480,429
Col 20	54998888,533	55029284,759
Col 21	37278285,363	37278285,363

The dependent variable Col 22 can be predicted from a linear combination of the independent variables:

	P
Col 17	0,418
Col 18	0,333
Col 19	0,174
Col 20	0,214
Col 21	0,304

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict Col 22 (P < 0.05): [None]

Normality Test (Shapiro-Wilk) Failed (P = <0,001)

Constant Variance Test: Failed (P = <0,001)

Power of performed test with alpha = 0,050: 0,729

The power of the performed test (0,729) is below the desired power of 0,800.
Less than desired power indicates you are less likely to detect a difference when one actually exists.
Negative results should be interpreted cautiously.

Table 16: Td-mode, totE (Multiple Linear Regression)

Appendix C.2

Best Subsets Regression tirsdag, april 30, 2013, 14:28:09

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	**Symbol**
Col 18	A
Col 19	B
Col 20	C
Col 21	D

Model #	**Variable**	**Cp**	**Rsqr**	**Adj Rsqr**	**MSerr**	**A**	**B**	**C**	**D**
1	1	2,856	0,059	0,027	34455180,936		*		
2	2	3,166	0,110	0,049	33690895,546		*	*	
3	3	4,014	0,145	0,054	33516057,619		*	*	*
4	4	5,000	0,176	0,054	33499295,346	*	*	*	*

Model # 1 R squared = 0,059

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-1375,569	2320,263	-0,593	0,558	0,000
Col 19	141,900	103,765	1,368	0,182	1,000

Model # 2 R squared = 0,110

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-2873,831	2569,036	-1,119	0,272	0,000
Col 19	141,900	102,608	1,383	0,177	1,000
Col 20	404,062	311,689	1,296	0,205	1,000

Model # 3 R squared = 0,145

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-5029,361	3255,990	-1,545	0,134	0,000
Col 19	141,900	102,341	1,387	0,177	1,000
Col 20	404,062	310,879	1,300	0,204	1,000
Col 21	8134,074	7580,847	1,073	0,292	1,000

Model # 4 R squared = 0,176

Variable	**Coef.**	**Std. Error**	**t**	**P**	**VIF**
Constant	-3349,766	3657,626	-0,916	0,368	0,000
Col 18	-6,712	6,665	-1,007	0,323	1,001
Col 19	143,788	102,333	1,405	0,171	1,000
Col 20	398,328	310,854	1,281	0,211	1,000
Col 21	7994,249	7580,223	1,055	0,301	1,000

Table 17: Td-mode, totE (Best Subset Regression)

Appendix C.3

Multiple Linear Regression tirsdag, april 30, 2013, 14:29:46

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 32 = 112,835 - (0,160 * Col 27) - (0,366 * Col 28) + (29,490 * Col 29) - (106,101 * Col 30) + (768,060 * Col 31)

N = 32 Missing Observations = 2

R = 0,721 Rsqr = 0,519 Adj Rsqr = 0,427

Standard Error of Estimate = 505,071

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	112,835	341,605	0,330	0,744	
Col 27	-0,160	0,298	-0,536	0,596	1,000
Col 28	-0,366	0,582	-0,629	0,535	1,001
Col 29	29,490	8,930	3,302	0,003	1,000
Col 30	-106,101	27,126	-3,911	<0,001	1,000
Col 31	768,060	661,479	1,161	0,256	1,000

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	7166805,980	1433361,196	5,619	0,001
Residual	26	6632508,635	255096,486		
Total	31	13799314,615	445139,181		

Column	**SSIncr**	**SSMarg**
Col 27	70315,830	73414,015
Col 28	68648,761	101027,373
Col 29	2780471,067	2782025,119
Col 30	3903446,329	3902668,073
Col 31	343923,993	343923,993

The dependent variable Col 32 can be predicted from a linear combination of the independent variables:

	P
Col 27	0,596
Col 28	0,535
Col 29	0,003
Col 30	<0,001
Col 31	0,256

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict Col 32 (P < 0.05): Col 29 , Col 30

Normality Test (Shapiro-Wilk) Passed (P = 0,322)

Constant Variance Test: Failed (P = <0,001)

Power of performed test with alpha = 0,050: 0,998

Table 18: dW-mode, totE (MLR)

Appendix C.4

Best Subsets Regression tirsdag, april 30, 2013, 14:31:25

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	Symbol
Col 27	A
Col 28	B
Col 29	C
Col 30	D
Col 31	E

Model #	Variable	Cp	Rsqr	Adj Rsqr	MSerr	A	B	C	D	E
1	1	10,881	0,281	0,257	330610,611				*	
2	2	2,047	0,482	0,446	246715,786			*	*	
3	3	2,672	0,507	0,454	242994,709			*	*	*
4	4	4,288	0,514	0,442	248367,506		*	*	*	*
5	5	6,000	0,519	0,427	255096,486	*	*	*	*	*

Model # 1 R squared = 0,281

Variable	Coef.	Std. Error	t	P	VIF
Constant	750,650	153,099	4,903	<0,001	0,000
Col 30	-105,788	30,876	-3,426	0,002	1,000

Model # 2 R squared = 0,482

Variable	Coef.	Std. Error	t	P	VIF
Constant	162,905	219,843	0,741	0,465	0,000
Col 29	29,387	8,781	3,347	0,002	1,000
Col 30	-105,788	26,672	-3,966	<0,001	1,000

Model # 3 R squared = 0,507

Variable	Coef.	Std. Error	t	P	VIF
Constant	-42,652	277,239	-0,154	0,879	0,000
Col 29	29,387	8,714	3,372	0,002	1,000
Col 30	-105,788	26,471	-3,996	<0,001	1,000
Col 31	775,687	645,490	1,202	0,240	1,000

Model # 4 R squared = 0,514

Variable	Coef.	Std. Error	t	P	VIF
Constant	47,530	314,941	0,151	0,881	0,000
Col 28	-0,360	0,574	-0,628	0,535	1,001
Col 29	29,489	8,811	3,347	0,002	1,000
Col 30	-106,096	26,766	-3,964	<0,001	1,000
Col 31	768,180	652,697	1,177	0,249	1,000

Model # 5 R squared = 0,519

Variable	Coef.	Std. Error	t	P	VIF
Constant	112,835	341,605	0,330	0,744	0,000
Col 27	-0,160	0,298	-0,536	0,596	1,000
Col 28	-0,366	0,582	-0,629	0,535	1,001
Col 29	29,490	8,930	3,302	0,003	1,000
Col 30	-106,101	27,126	-3,911	<0,001	1,000
Col 31	768,060	661,479	1,161	0,256	1,000

Table 19: dW-mode totE (BSR)

Appendix C.5

Multiple Linear Regression torsdag, mai 02, 2013, 10:19:26

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 9 = -204,674 - (0,395 * Col 4) - (1,182 * Col 5) + (64,798 * Col 6) - (41,531 * Col 7) + (1047,338 * Col 8)

N = 32 Missing Observations = 2

R = 0,832 Rsqr = 0,692 Adj Rsqr = 0,633

Standard Error of Estimate = 523,421

	Coefficient	**Std. Error**	**t**	**P**	**VIF**
Constant	-204,674	354,016	-0,578	0,568	
Col 4	-0,395	0,308	-1,280	0,212	1,000
Col 5	-1,182	0,603	-1,960	0,061	1,001
Col 6	64,798	9,254	7,002	<0,001	1,000
Col 7	-41,531	28,112	-1,477	0,152	1,000
Col 8	1047,338	685,512	1,528	0,139	1,000

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	16015614,582	3203122,916	11,692	<0,001
Residual	26	7123199,725	273969,220		
Total	31	23138814,308	746413,365		

Column	**SSIncr**	**SSMarg**
Col 4	424289,795	448988,643
Col 5	921603,437	1052956,152
Col 6	13431831,879	13431763,896
Col 7	598381,765	597966,476
Col 8	639507,706	639507,706

The dependent variable Col 9 can be predicted from a linear combination of the independent variables:

	P
Col 4	0,212
Col 5	0,061
Col 6	<0,001
Col 7	0,152
Col 8	0,139

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict Col 9 (P < 0.05): Col 6

Normality Test (Shapiro-Wilk) Passed (P = 0,367)

Constant Variance Test: Failed (P = <0,001)

Power of performed test with alpha = 0,050: 1,000

Table 20: P-mode totE (MLR)

Appendix C.6

Best Subsets Regression torsdag, mai 02, 2013, 10:20:54

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	Symbol
Col 4	A
Col 5	B
Col 6	C
Col 7	D
Col 8	E

Model #	Variable	Cp	Rsqr	Adj Rsqr	MSerr	A	B	C	D	E
1	1	7,917	0,575	0,561	328001,195			*		
2	2	6,157	0,619	0,593	303796,201		*	*		
3	3	5,820	0,647	0,609	291778,825		*	*		*
4	4	5,639	0,673	0,624	280451,421		*	*	*	*
5	5	6,000	0,692	0,633	273969,220	*	*	*	*	*

Model # 1 R squared = 0,575

Variable	Coef.	Std. Error	t	P	VIF
Constant	-524,584	226,385	-2,317	0,028	0,000
Col 6	64,466	10,124	6,367	<0,001	1,000

Model # 2 R squared = 0,619

Variable	Coef.	Std. Error	t	P	VIF
Constant	-242,369	266,384	-0,910	0,370	0,000
Col 5	-1,168	0,635	-1,841	0,076	1,000
Col 6	64,795	9,745	6,649	<0,001	1,000

Model # 3 R squared = 0,647

Variable	Coef.	Std. Error	t	P	VIF
Constant	-524,158	323,015	-1,623	0,116	0,000
Col 5	-1,151	0,622	-1,851	0,075	1,001
Col 6	64,790	9,550	6,784	<0,001	1,000
Col 8	1047,973	707,442	1,481	0,150	1,000

Model # 4 R squared = 0,673

Variable	Coef.	Std. Error	t	P	VIF
Constant	-366,175	334,665	-1,094	0,284	0,000
Col 5	-1,168	0,610	-1,915	0,066	1,001
Col 6	64,794	9,363	6,920	<0,001	1,000
Col 7	-41,519	28,442	-1,460	0,156	1,000
Col 8	1047,633	693,574	1,510	0,143	1,000

Model # 5 R squared = 0,692

Variable	Coef.	Std. Error	t	P	VIF
Constant	-204,674	354,016	-0,578	0,568	0,000
Col 4	-0,395	0,308	-1,280	0,212	1,000
Col 5	-1,182	0,603	-1,960	0,061	1,001
Col 6	64,798	9,254	7,002	<0,001	1,000
Col 7	-41,531	28,112	-1,477	0,152	1,000
Col 8	1047,338	685,512	1,528	0,139	1,000

Table 21: P-mode totE (BSR)

Appendix C.7

Multiple Linear Regression tirsdag, april 30, 2013, 13:45:49

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 3 = 17,274 - (0,0265 * Col 4) - (0,0436 * Col 5) + (1,050 * Col 6) - (2,752 * Col 7) + (29,184 * Col 8)

N = 32 Missing Observations = 2

R = 0,783 Rsqr = 0,613 Adj Rsqr = 0,539

Standard Error of Estimate = 15,505

	Coefficient	Std. Error	t	P	VIF
Constant	17,274	10,487	1,647	0,112	
Col 4	-0,0265	0,00914	-2,895	0,008	1,000
Col 5	-0,0436	0,0179	-2,442	0,022	1,001
Col 6	1,050	0,274	3,829	<0,001	1,000
Col 7	-2,752	0,833	-3,305	0,003	1,000
Col 8	29,184	20,306	1,437	0,163	1,000

Analysis of Variance:

	DF	SS	MS	F	P
Regression	5	9915,675	1983,135	8,250	<0,001
Residual	26	6250,200	240,392		
Total	31	16165,875	521,480		

Column	SSIncr	SSMarg
Col 4	1953,125	2014,260
Col 5	1315,259	1433,800
Col 6	3524,090	3525,243
Col 7	2626,653	2625,886
Col 8	496,548	496,548

The dependent variable Col 3 can be predicted from a linear combination of the independent variables:

	P
Col 4	0,008
Col 5	0,022
Col 6	<0,001
Col 7	0,003
Col 8	0,163

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict Col 3 (P < 0.05): Col 4 , Col 5 , Col 6 , Col 7

Normality Test (Shapiro-Wilk) Failed (P = <0,001)

Constant Variance Test: Failed (P = 0,043)

Power of performed test with alpha = 0,050: 1,000

Table 22: P-mode NPSH (MLR)

Appendix C.8

Best Subsets Regression tirsdag, april 30, 2013, 13:47:15

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	Symbol
Col 4	A
Col 5	B
Col 6	C
Col 7	D
Col 8	E

Model #	Variable	Cp	Rsqr	Adj Rsqr	MSerr	A	B	C	D	E
1	1	24,919	0,213	0,187	424,046			*		
2	2	16,286	0,371	0,328	350,526			*	*	
3	3	10,161	0,492	0,438	293,290	*		*	*	
4	4	6,066	0,583	0,521	249,880	*	*	*	*	
5	5	6,000	0,613	0,539	240,392	*	*	*	*	*

Model # 1 R squared = 0,213

Variable	Coef.	Std. Error	t	P	VIF
Constant	-6,313	8,140	-0,776	0,444	0,000
Col 6	1,038	0,364	2,850	0,008	1,000

Model # 2 R squared = 0,371

Variable	Coef.	Std. Error	t	P	VIF
Constant	3,754	8,287	0,453	0,654	0,000
Col 6	1,038	0,331	3,135	0,004	1,000
Col 7	-2,715	1,005	-2,700	0,011	1,000

Model # 3 R squared = 0,492

Variable	Coef.	Std. Error	t	P	VIF
Constant	14,171	8,588	1,650	0,110	0,000
Col 4	-0,0260	0,0101	-2,581	0,015	1,000
Col 6	1,038	0,303	3,427	0,002	1,000
Col 7	-2,715	0,920	-2,952	0,006	1,000

Model # 4 R squared = 0,583

Variable	Coef.	Std. Error	t	P	VIF
Constant	25,125	9,126	2,753	0,010	0,000
Col 4	-0,0265	0,00932	-2,840	0,008	1,000
Col 5	-0,0441	0,0182	-2,422	0,022	1,001
Col 6	1,050	0,279	3,757	<0,001	1,000
Col 7	-2,753	0,849	-3,242	0,003	1,000

Model # 5 R squared = 0,613

Variable	Coef.	Std. Error	t	P	VIF
Constant	17,274	10,487	1,647	0,112	0,000
Col 4	-0,0265	0,00914	-2,895	0,008	1,000
Col 5	-0,0436	0,0179	-2,442	0,022	1,001
Col 6	1,050	0,274	3,829	<0,001	1,000
Col 7	-2,752	0,833	-3,305	0,003	1,000
Col 8	29,184	20,306	1,437	0,163	1,000

Table 23: P-mode NPSH (BSR)

Appendix C.9

Multiple Linear Regression torsdag, mai 02, 2013, 10:21:34

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 10 = 4679636221,432 + (26144199,226 * Col 4) - (195768386,108 * Col 5) + (6259682250,683 * Col 6) - (17516865207,022 * Col 7) + (231373914850,697 * Col 8)

N = 30 Missing Observations = 4

R = 0,743 Rsqr = 0,552 Adj Rsqr = 0,459

Standard Error of Estimate = 93735731509,949

	Coefficient	Std. Error	t	P	VIF
Constant	4679636221,432	63820281546,409	0,0733	0,942	
Col 4	26144199,226	57499231,269	0,455	0,653	1,011
Col 5	-195768386,108	111715503,087	-1,752	0,092	1,008
Col 6	6259682250,683	1717523678,110	3,645	0,001	1,007
Col 7	-17516865207,022	5239905644,207	-3,343	0,003	1,011
Col 8	231373914850,697	127776069486,880	1,811	0,083	1,011

Analysis of Variance:

	DF	SS	MS	F	P
Regression	52,603E+0235,206E+022			5,925	0,001
Residual	242,109E+0238,786E+021				
Total	294,712E+0231,625E+022				

Column	SSIncr	SSMarg
Col 46,493E+021	1,817E+021	
Col 51,772E+022	2,698E+022	
Col 61,165E+023	1,167E+023	
Col 79,075E+022	9,819E+022	
Col 82,881E+022	2,881E+022	

The dependent variable Col 10 can be predicted from a linear combination of the independent variables:

	P
Col 4	0,653
Col 5	0,092
Col 6	0,001
Col 7	0,003
Col 8	0,083

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict Col 10 ($P < 0.05$): Col 6 , Col 7

Normality Test (Shapiro-Wilk) Failed (P = 0,007)

Constant Variance Test: Failed (P = <0,001)

Power of performed test with alpha = 0,050: 0,999

Table 24: P-mode totCost (MLR)

Appendix C.10

Best Subsets Regression torsdag, mai 02, 2013, 10:22:21

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	Symbol
Col 4	A
Col 5	B
Col 6	C
Col 7	D
Col 8	E

Model #	Variable	Cp	Rsqr	Adj Rsqr	MSerr	A	B	C	D	E
1	1	15,314	0,230	0,202	129643425654674940000000,000			*		
2	2	6,865	0,424	0,382	100440810145474420000000,000			*	*	
3	3	5,308	0,491	0,432	92283130118613636000000,000			*	*	*
4	4	4,207	0,549	0,476	85075921274631556000000,000		*	*	*	*
5	5	6,000	0,552	0,459	87863873617051811000000,000	*	*	*	*	*

Model # 1 R squared = 0,230

Variable	Coef.	Std. Error	t	P	VIF
Constant	-3,717E+010	4,648E+010	-0,800	0,431	0,000
Col 6	6005183348,743	2078809159,548	2,889	0,007	1,000

Model # 2 R squared = 0,424

Variable	Coef.	Std. Error	t	P	VIF
Constant	2,898E+010	4,640E+010	0,625	0,538	0,000
Col 6	6005183348,743	1829761461,188	3,282	0,003	1,000
Col 7	-1,684E+010	5570599033,877	-3,023	0,005	1,000

Model # 3 R squared = 0,491

Variable	Coef.	Std. Error	t	P	VIF
Constant	-2,976E+010	5,474E+010	-0,544	0,591	0,000
Col 6	6005183348,743	1753882646,384	3,424	0,002	1,000
Col 7	-1,755E+010	5353264282,567	-3,278	0,003	1,005
Col 8	2,402E+011	1,305E+011	1,840	0,077	1,005

Model # 4 R squared = 0,549

Variable	Coef.	Std. Error	t	P	VIF
Constant	1,545E+010	5,832E+010	0,265	0,793	0,000
Col 5	-196693615,530	109910591,919	-1,790	0,086	1,008
Col 6	6260885048,932	1690053198,593	3,705	0,001	1,007
Col 7	-1,770E+010	5140704020,912	-3,443	0,002	1,005
Col 8	2,358E+011	1,254E+011	1,881	0,072	1,006

Model # 5 R squared = 0,552

Variable	Coef.	Std. Error	t	P	VIF
Constant	4679636221,432	6,382E+010	0,0733	0,942	0,000
Col 4	26144199,226	57499231,269	0,455	0,653	1,011
Col 5	-195768386,108	111715503,087	-1,752	0,092	1,008
Col 6	6259682250,683	1717523678,110	3,645	0,001	1,007
Col 7	-1,752E+010	5239905644,207	-3,343	0,003	1,011
Col 8	2,314E+011	1,278E+011	1,811	0,083	1,011

Table 25: P-mode totCost (BSR)

Appendix C.11

Multiple Linear Regression torsdag, mai 02, 2013, 10:23:21

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Col 11 = 4771761887,664 - (9411141,766 * Col 4) - (14192147,637 * Col 5) + (207174383,377 * Col 6) - (819484384,529 * Col 7) + (16089286929,474 * Col 8)

N = 32 Missing Observations = 2

R = 0,466 Rsqr = 0,218 Adj Rsqr = 0,0671

Standard Error of Estimate = 11246477471,911

	Coefficient	Std. Error	t	P	VIF
Constant	4771761887,664	7606563733,003	0,627	0,536	
Col 4	-9411141,766	6628162,937	-1,420	0,168	1,000
Col 5	-14192147,637	12953244,075	-1,096	0,283	1,001
Col 6	207174383,377	198844888,113	1,042	0,307	1,000
Col 7	-819484384,529	604024568,995	-1,357	0,187	1,000
Col 8	16089286929,474	14729250971,355	1,092	0,285	1,000

Analysis of Variance:

	DF	SS	MS	F	P
Regression	59,145E+0201,829E+020			1,446	0,241
Residual	263,289E+0211,265E+020				
Total	314,203E+0211,356E+020				

Column	SSIncr	SSMarg
Col 42,479E+020	2,550E+020	
Col 51,454E+020	1,518E+020	
Col 61,373E+020	1,373E+020	
Col 72,329E+020	2,328E+020	
Col 81,509E+020	1,509E+020	

The dependent variable Col 11 can be predicted from a linear combination of the independent variables:

	P
Col 4	0,168
Col 5	0,283
Col 6	0,307
Col 7	0,187
Col 8	0,285

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified). The following appear to account for the ability to predict Col 11 (P < 0.05): [None]

Normality Test (Shapiro-Wilk) Failed (P = <0,001)

Constant Variance Test: Failed (P = <0,001)

Power of performed test with alpha = 0,050: 0,777

The power of the performed test (0,777) is below the desired power of 0,800.
Less than desired power indicates you are less likely to detect a difference when one actually exists.
Negative results should be interpreted cautiously.

Table 26:P-mode NOK/GWh (MLR)

Appendix C.12

Best Subsets Regression torsdag, mai 02, 2013, 10:24:26

Data source: Data 1 in Statistics_SensitivityRegression.JNB

Using R squared as best criterion.

Variable	Symbol
Col 4	A
Col 5	B
Col 6	C
Col 7	D
Col 8	E

Model #	Variable	Cp	Rsqr	Adj Rsqr	MSerr	A	B	C	D	E
1	1	3,270	0,059	0,028	1318375162982377770000,000	*				
2	2	3,483	0,113	0,052	1285888289302915000000,000	*			*	
3	3	4,245	0,150	0,059	1275895070793108400000,000	*			*	*
4	4	5,086	0,185	0,064	1268839429789237700000,000	*	*		*	*
5	5	6,000	0,218	0,067	1264832555261948400000,000	*	*	*	*	*

Model # 1 R squared = 0,059

Variable	Coef.	Std. Error	t	P	VIF
Constant	6578920446,111	3382931989,463	1,945	0,061	0,000
Col 4	-9278090,382	6765863,979	-1,371	0,180	1,000

Model # 2 R squared = 0,113

Variable	Coef.	Std. Error	t	P	VIF
Constant	9572609139,428	4032416153,189	2,374	0,024	0,000
Col 4	-9278090,382	6681983,159	-1,389	0,176	1,000
Col 7	-807359410,280	608929206,450	-1,326	0,195	1,000

Model # 3 R squared = 0,150

Variable	Coef.	Std. Error	t	P	VIF
Constant	5230595621,373	5612261475,702	0,932	0,359	0,000
Col 4	-9278090,382	6655968,163	-1,394	0,174	1,000
Col 7	-807359410,280	606558459,524	-1,331	0,194	1,000
Col 8	1,638E+010	1,479E+010	1,108	0,277	1,000

Model # 4 R squared = 0,185

Variable	Coef.	Std. Error	t	P	VIF
Constant	8851053933,824	6531852883,643	1,355	0,187	0,000
Col 4	-9408823,688	6638652,970	-1,417	0,168	1,000
Col 5	-13944885,953	12971567,566	-1,075	0,292	1,001
Col 7	-819273138,026	604980525,844	-1,354	0,187	1,000
Col 8	1,609E+010	1,475E+010	1,091	0,285	1,000

Model # 5 R squared = 0,218

Variable	Coef.	Std. Error	t	P	VIF
Constant	4771761887,664	7606563733,003	0,627	0,536	0,000
Col 4	-9411141,766	6628162,937	-1,420	0,168	1,000
Col 5	-14192147,637	12953244,075	-1,096	0,283	1,001
Col 6	207174383,377	198844888,113	1,042	0,307	1,000
Col 7	-819484384,529	604024568,995	-1,357	0,187	1,000
Col 8	1,609E+010	1,473E+010	1,092	0,285	1,000

Table 27: P-mode NOK/GWh (BSR)

Appendix D.1

Figure 37: PSH potential for dW-6 classified by NOK/GWh

Appendix D.2

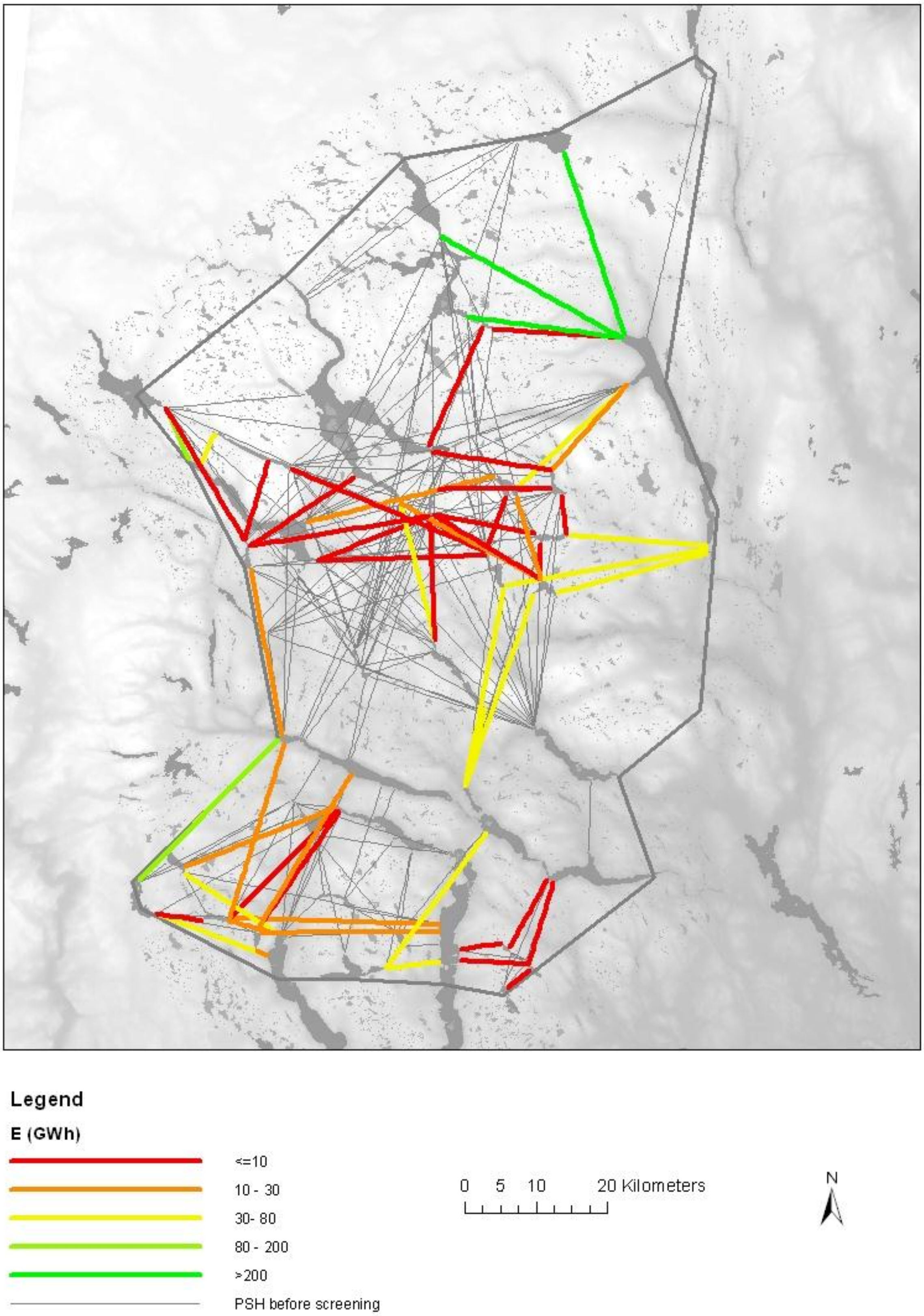


Figure 38: PSH potential dW-6 classified by E

Appendix D.3

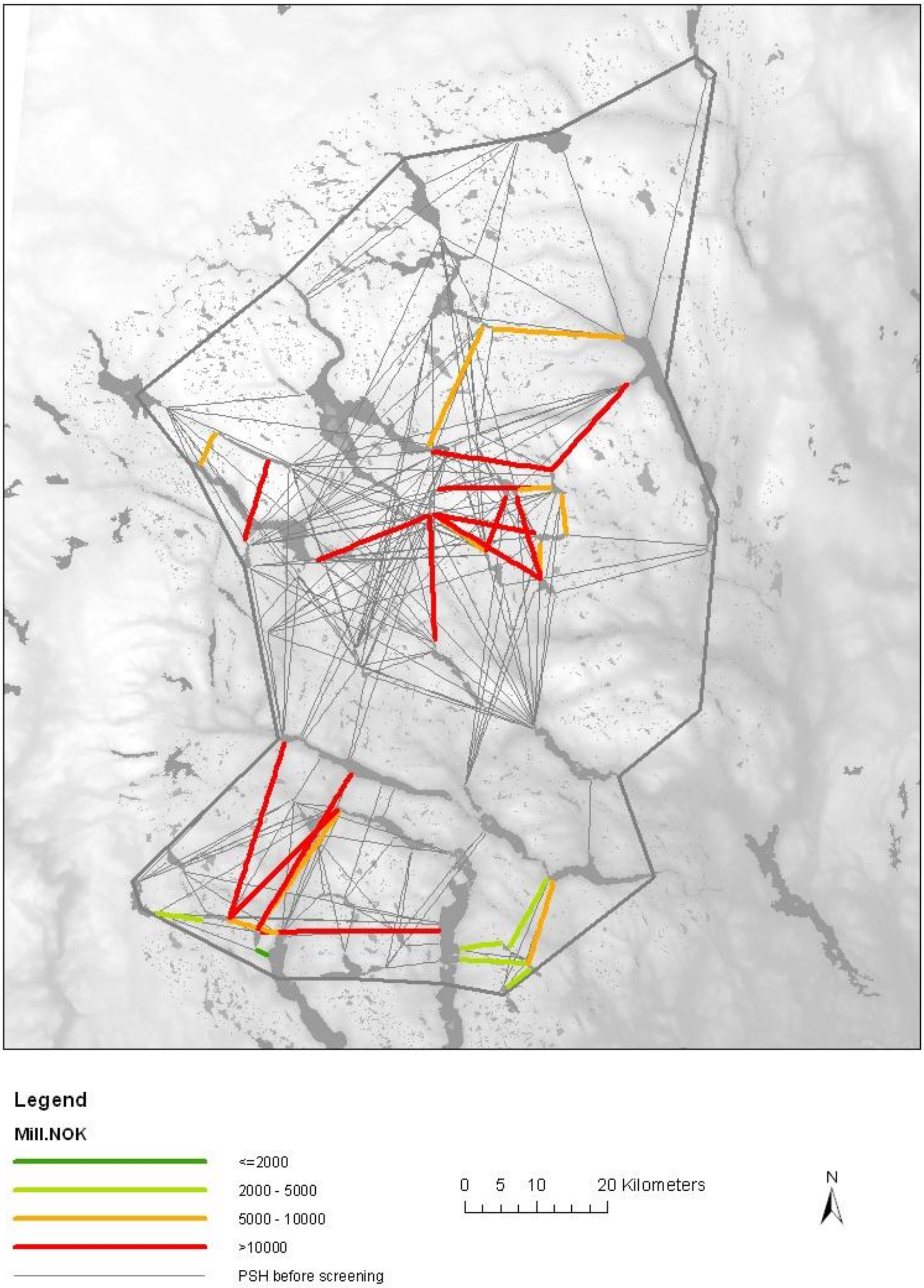


Figure 39: PSH Potential for dW-6 classify by the costs

Appendix D.4

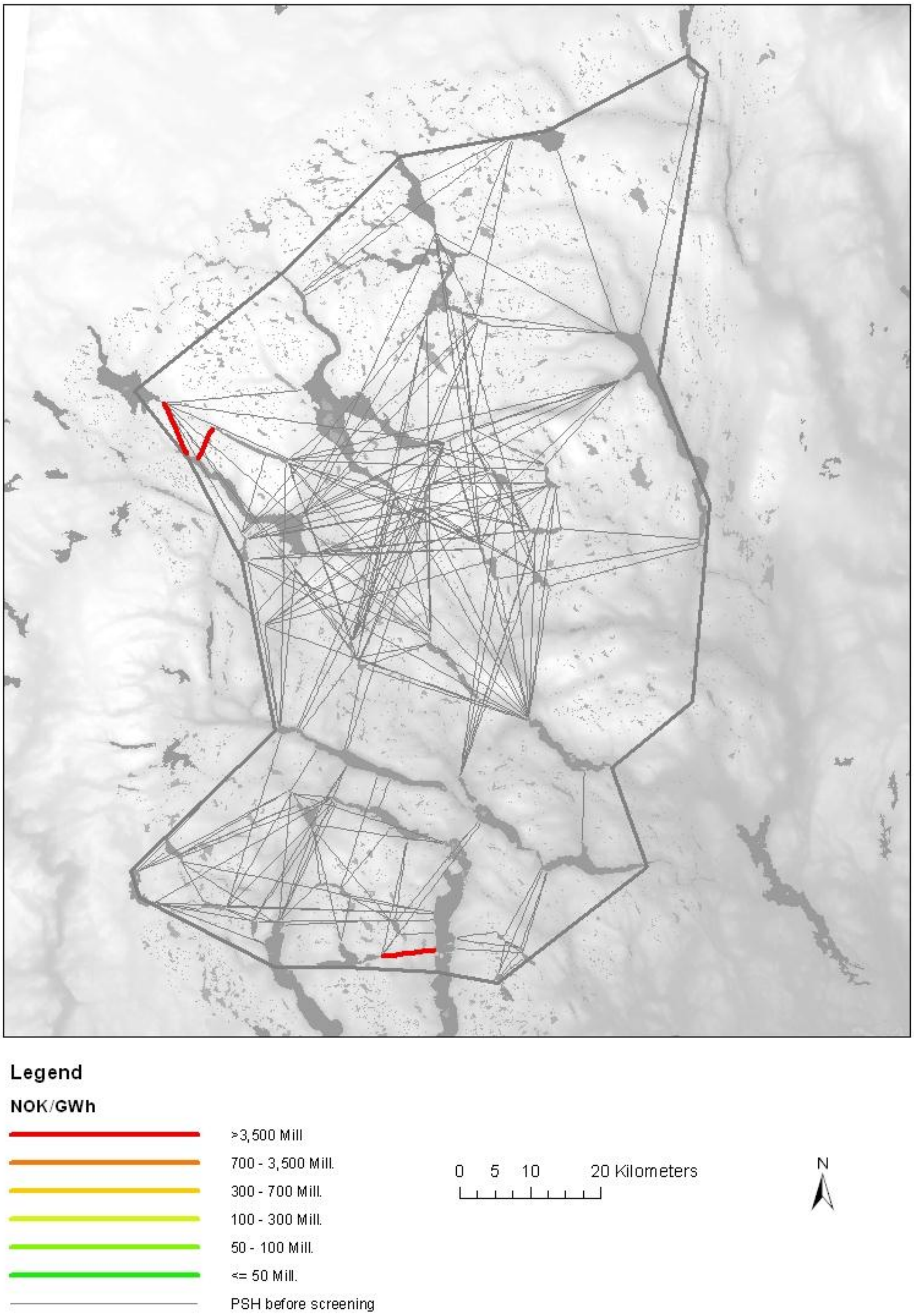


Figure 40: PSH potential for dW-21 classified by NOK/GWh

Appendix D.5

Figure 41: PSH potential for dW-21 classified by E

Appendix D.6

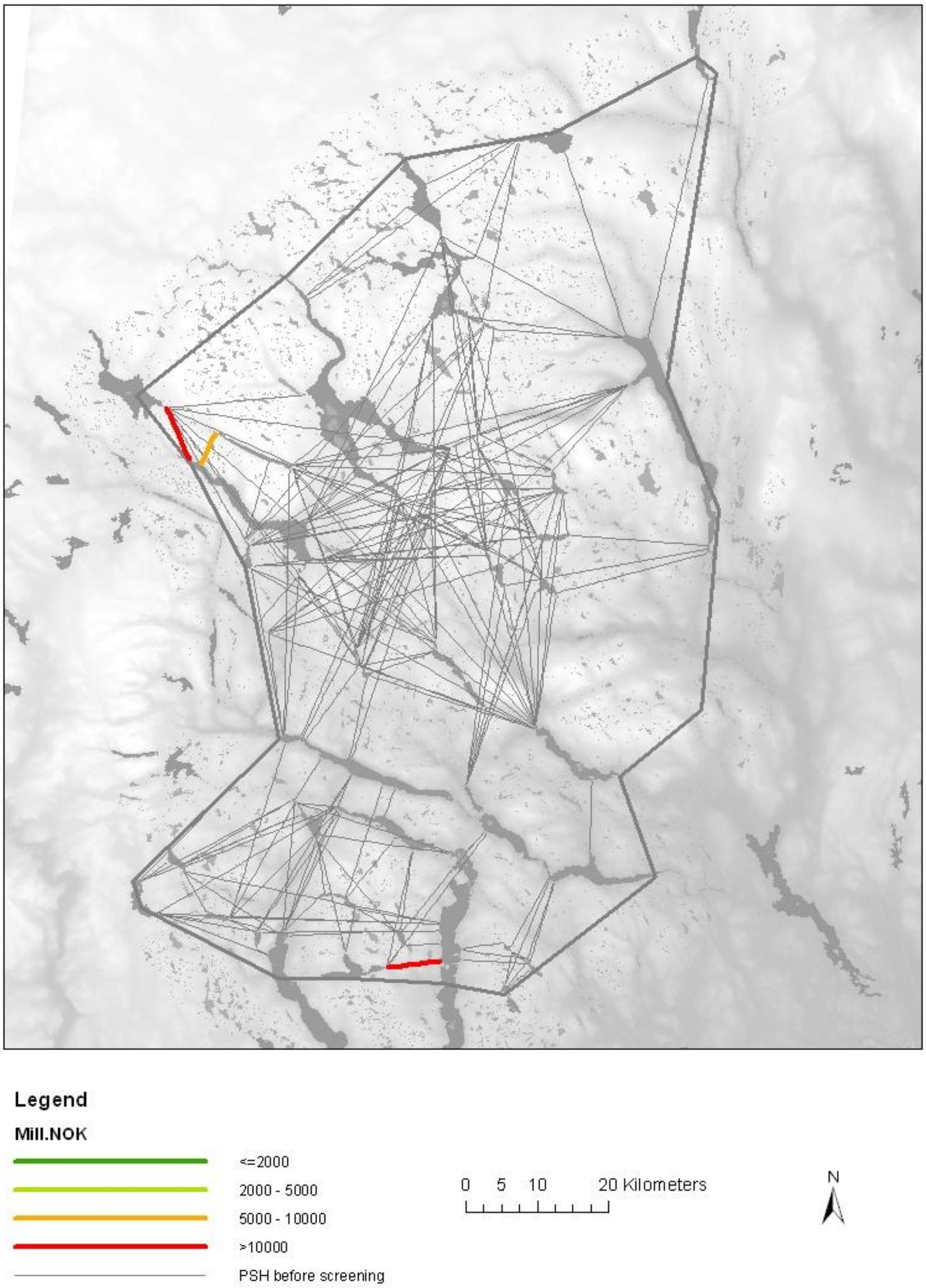


Figure 42: PSH Potential for dW-21 classify by the costs

Appendix D.7

Figure 43: PSH potential for P-6 classified by NOK/GWh

Appendix D.8

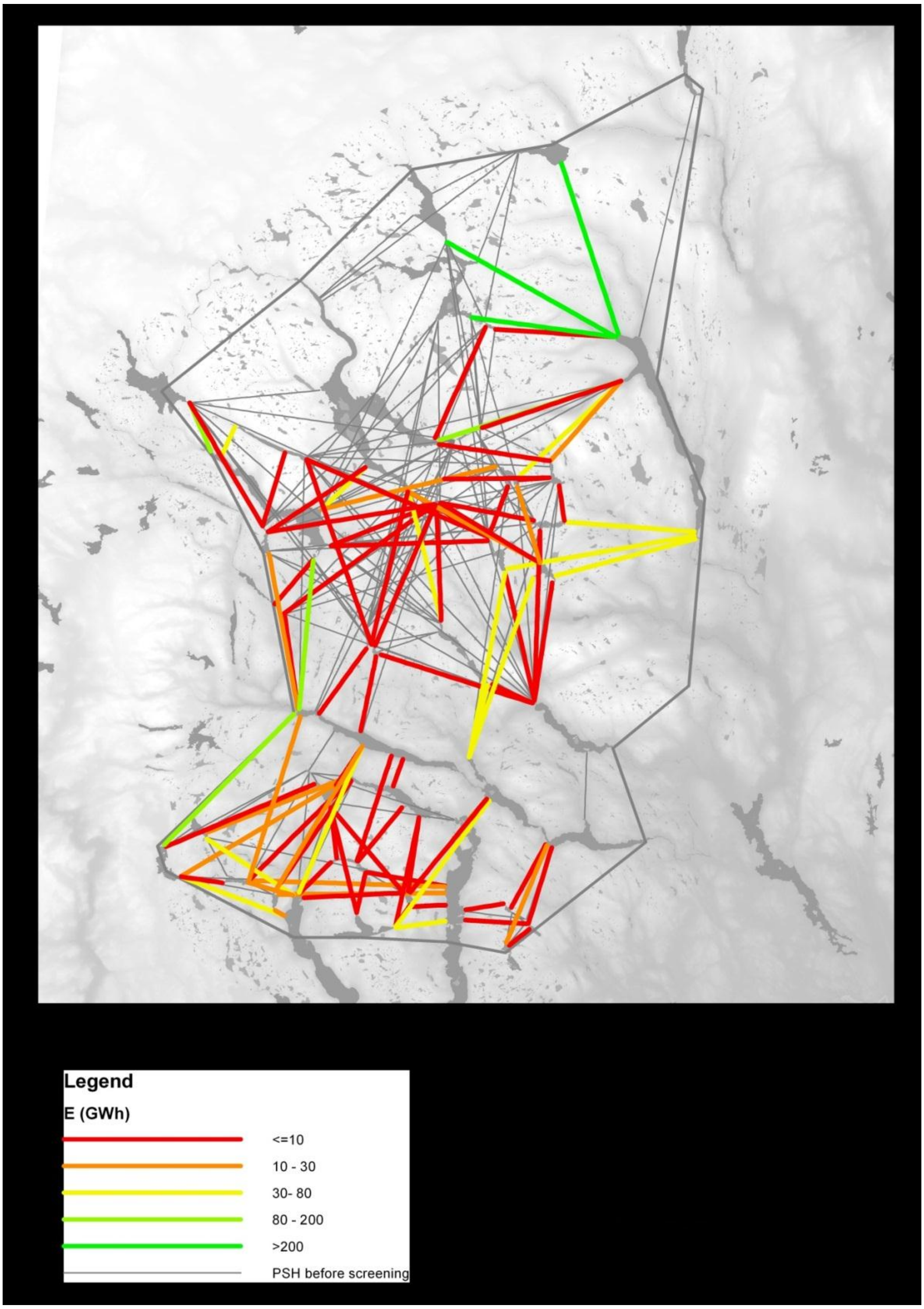


Figure 44:PSH potential P-6 classified by E

Appendix D.9

Figure 45: PSH Potential for P-6 classify by the costs

Appendix D.10

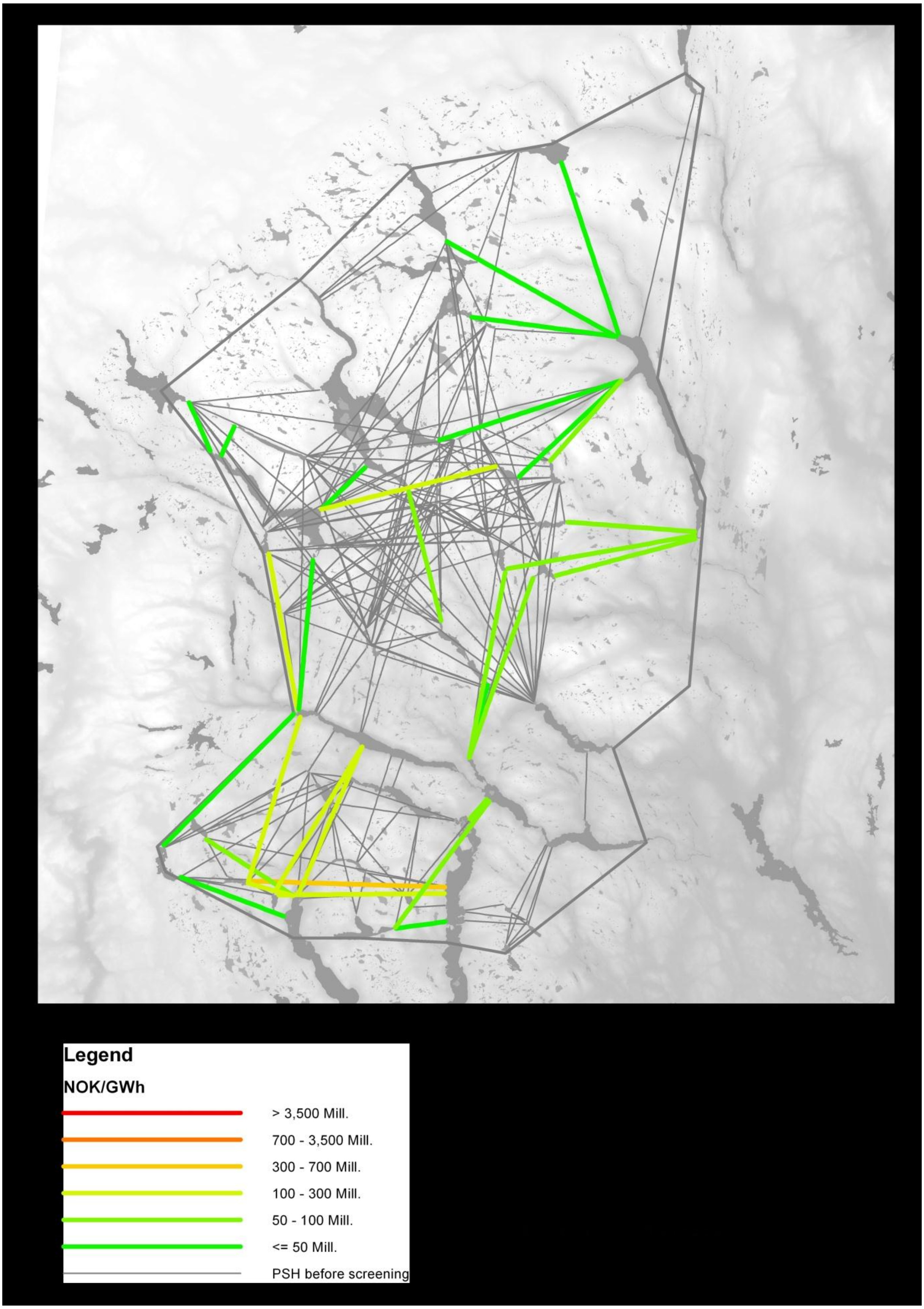


Figure 46: PSH potential for P-14 classified by NOK/GWh

Appendix D.11

Figure 47:PSH potential P-14 classified by E

Appendix D.12

Figure 48: PSH Potential for P-14 classify by the costs

Appendix D.13

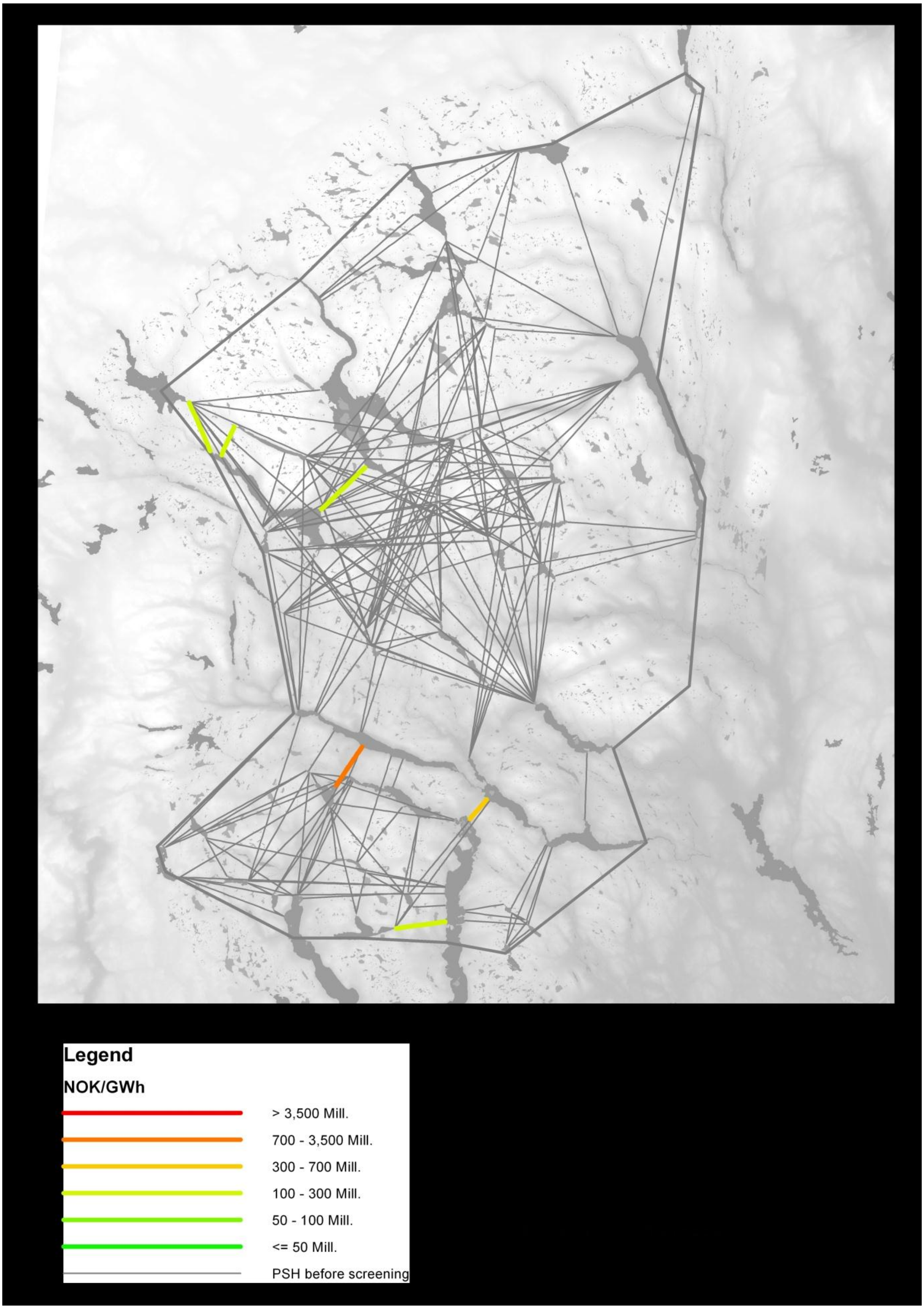


Figure 49: PSH potential for P-21 classified by NOK/GWh

Appendix D.14

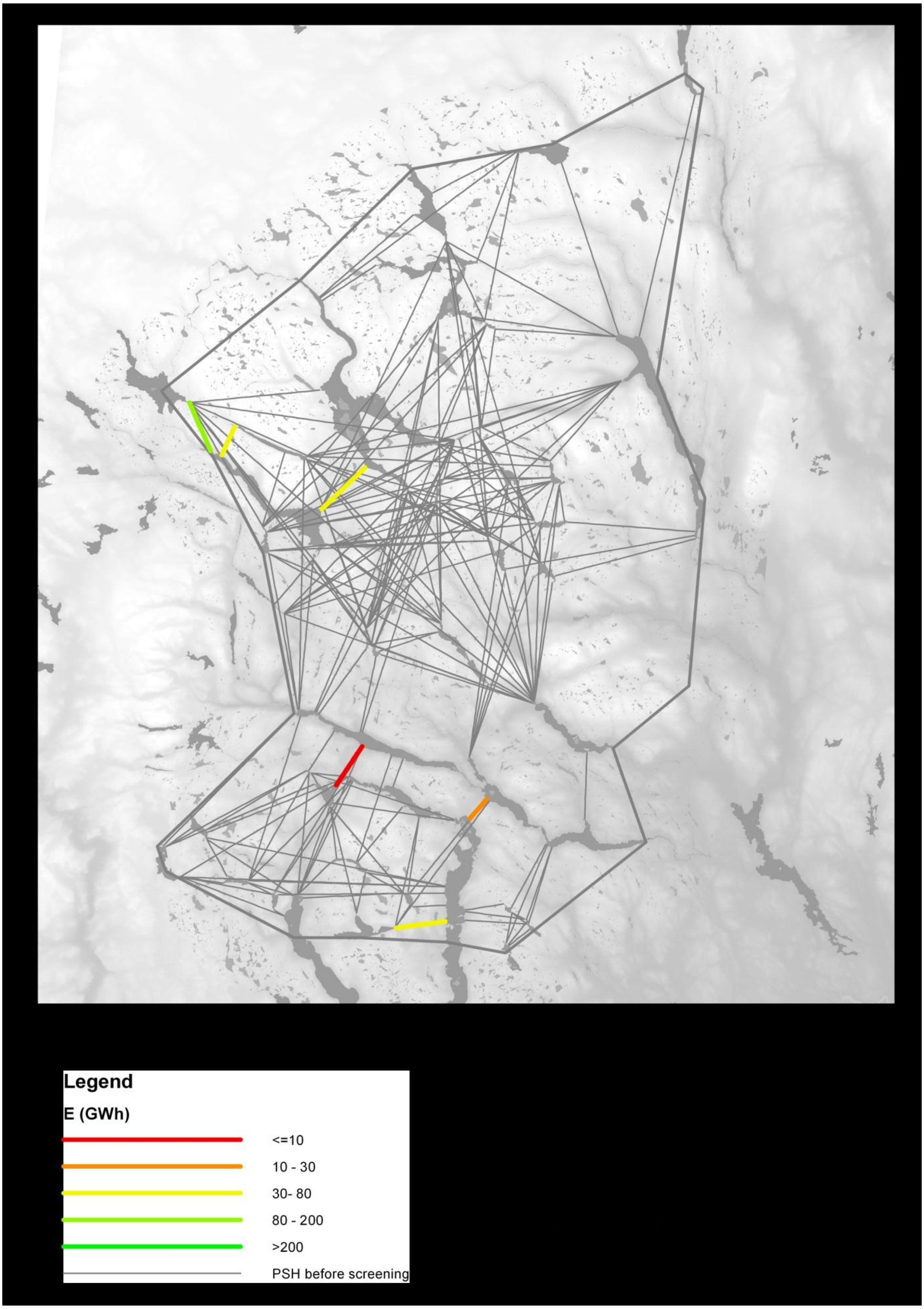


Figure 50: PSH potential P-21 classified by E

Appendix D.15

Figure 51: PSH Potential for P-21 classify by the costs

Appendix D.16

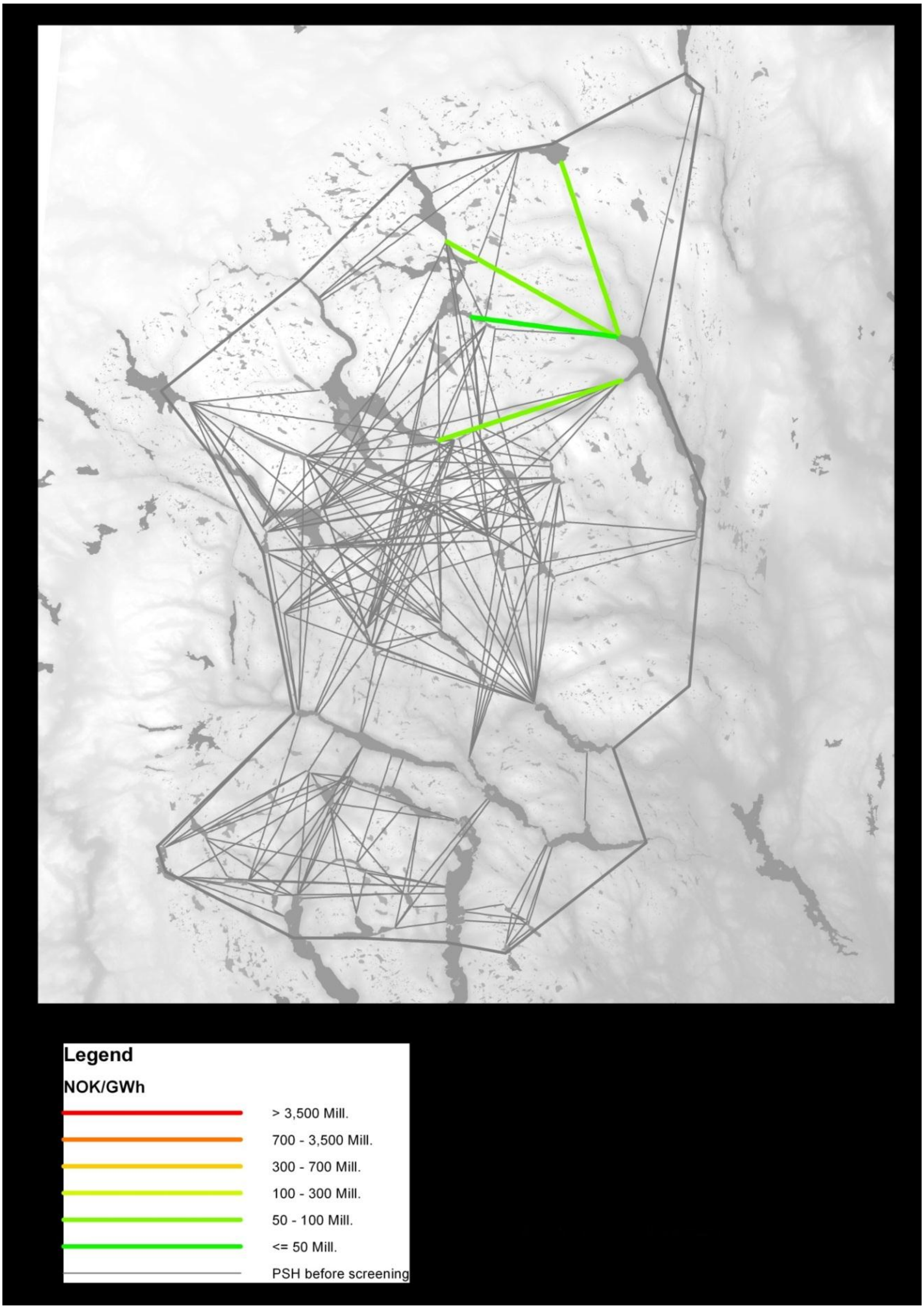


Figure 52: PSH potential for P-26 classified by NOK/GWh

Appendix D.17

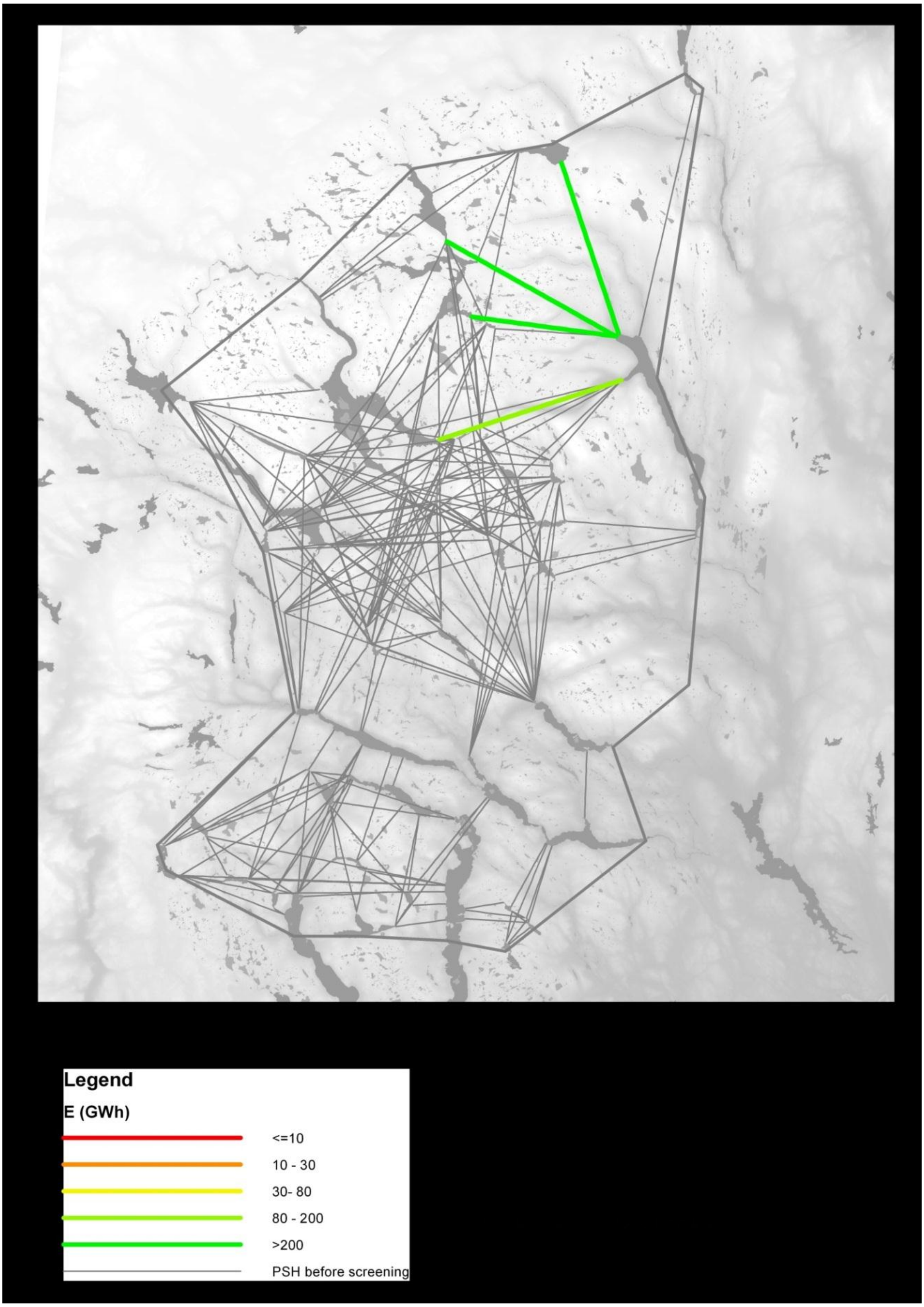


Figure 53: PSH potential P-26 classified by E

Appendix D.18

Figure 54: PSH Potential for P-26 classify by the costs

Appendix D.19

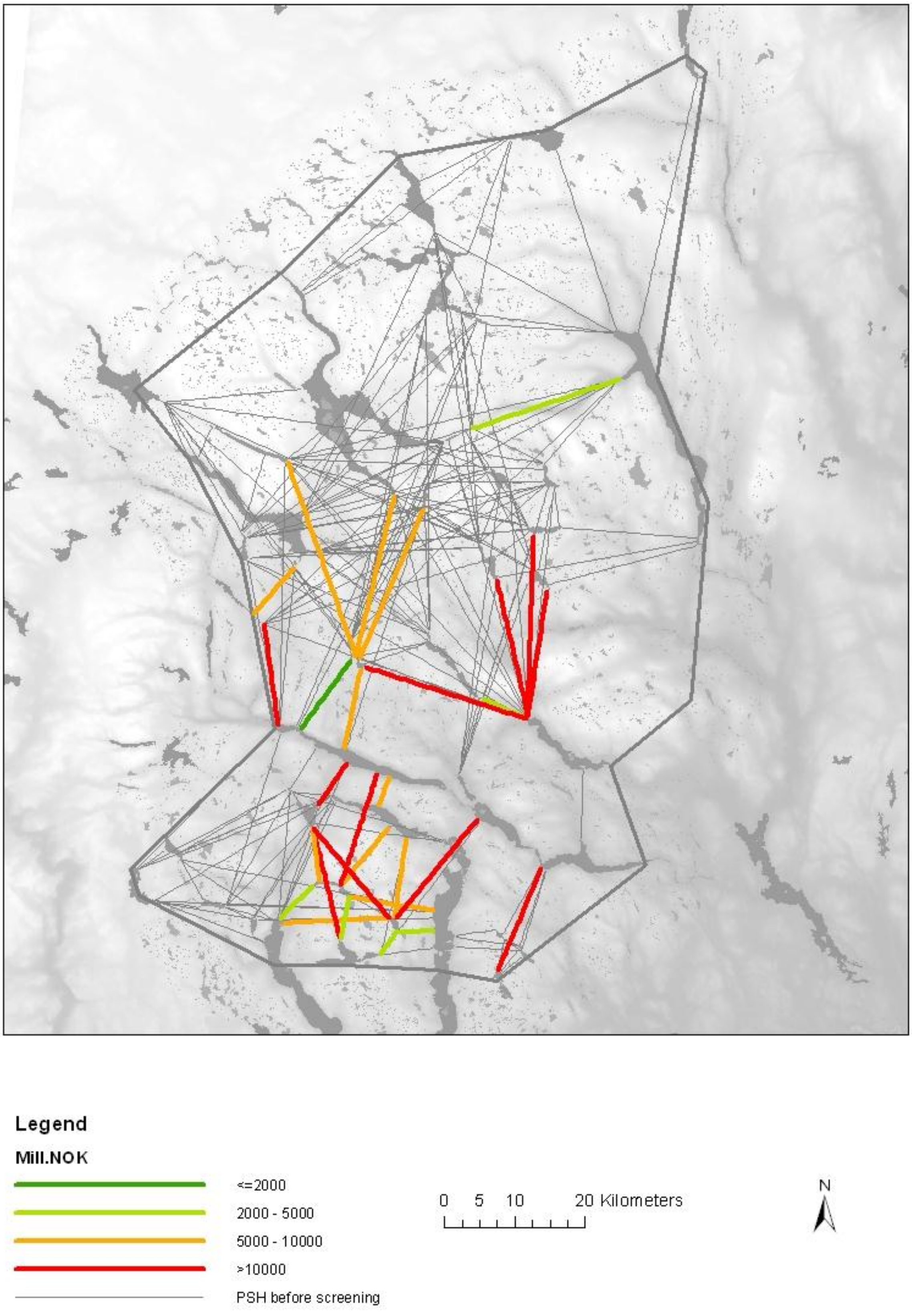


Figure 55: : PSH Potential for Td-6 classify by the costs

Appendix D.20

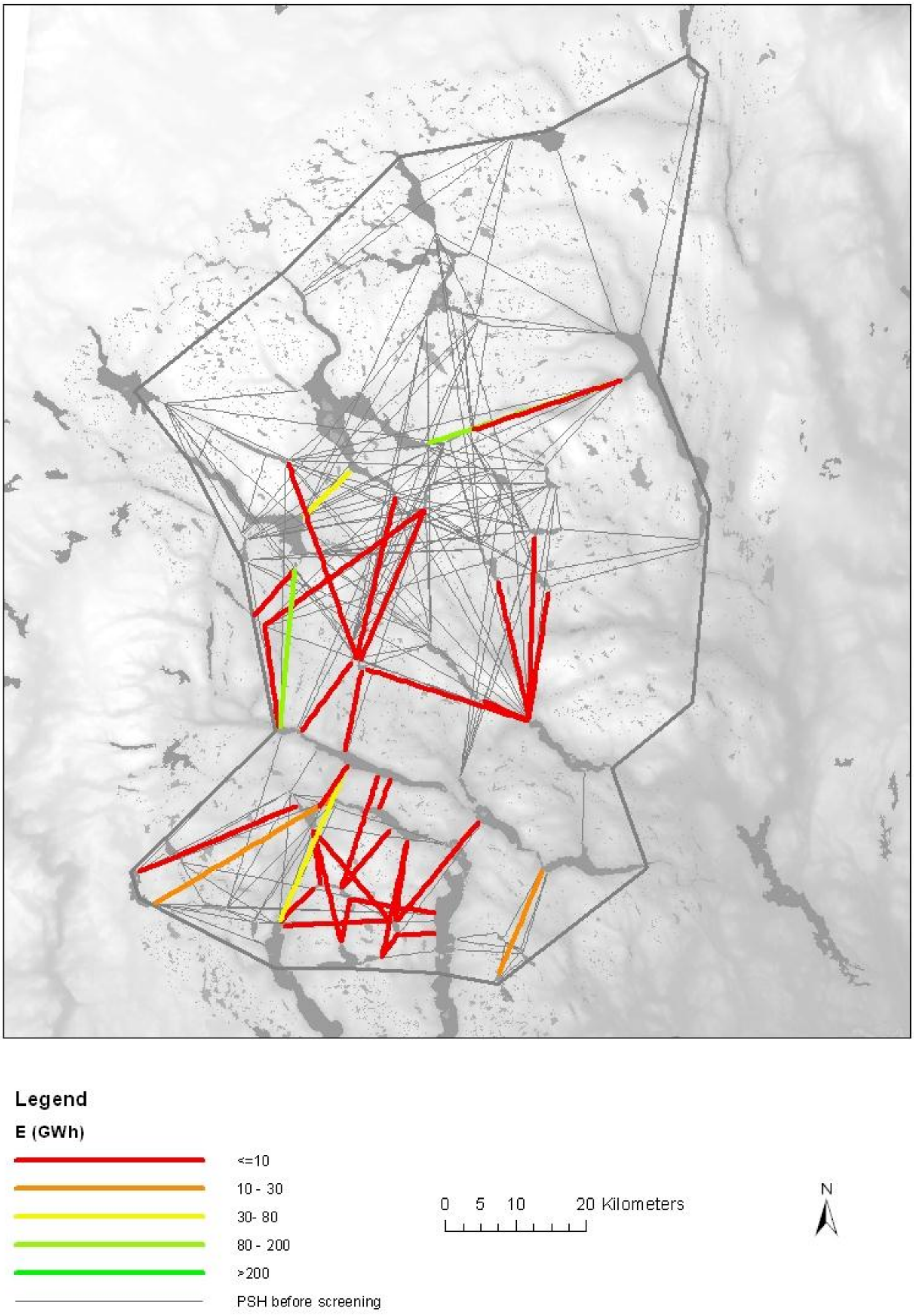


Figure 56:PSH potential Td-6 classified by E

Appendix D.21

Figure 57: PSH Potential for Td-14 classify by the costs

Appendix D.22

Figure 58: PSH potential Td-14 classified by E

Appendix D.23

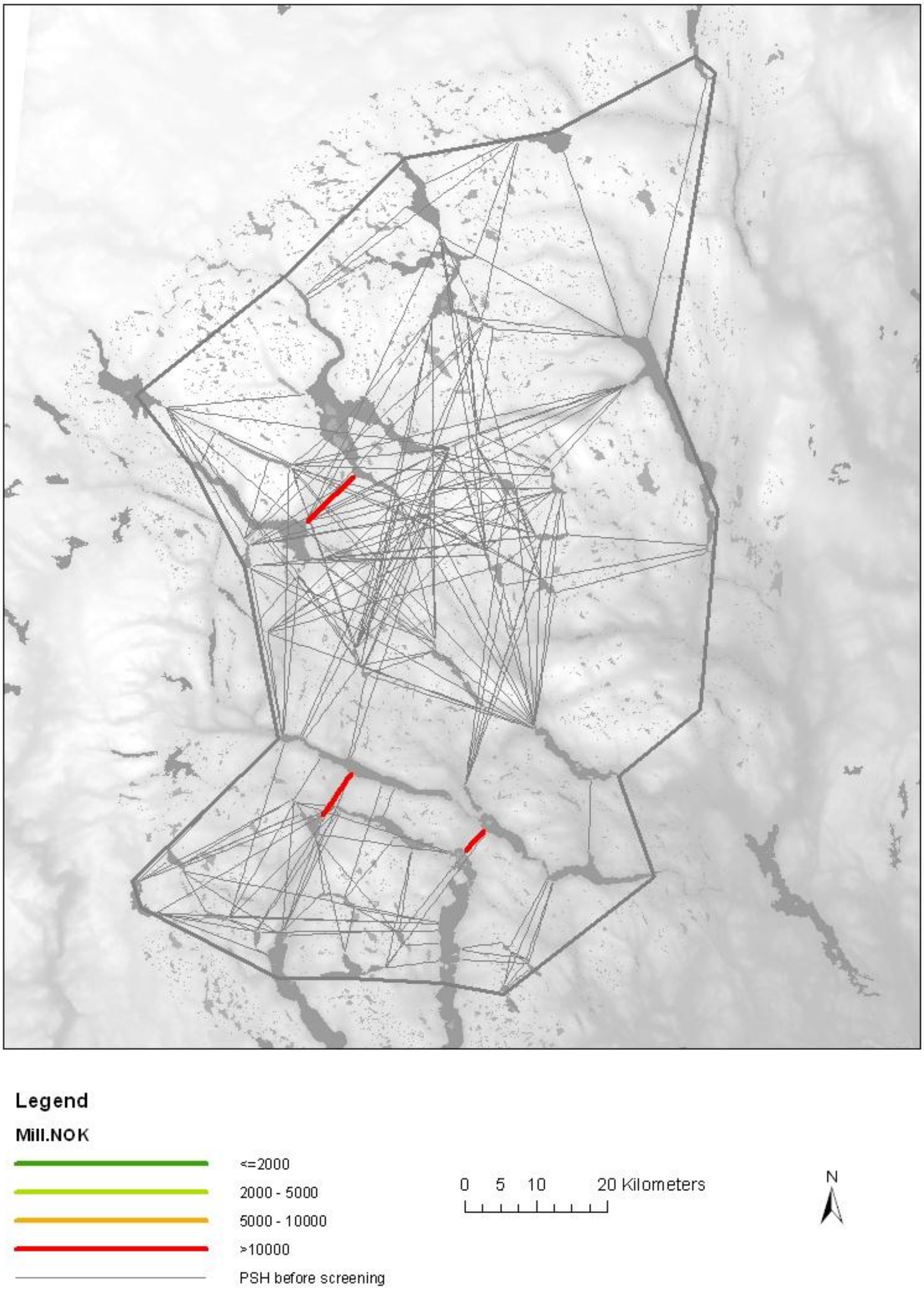


Figure 59: PSH Potential for Td-21 classify by the costs

Appendix D.24

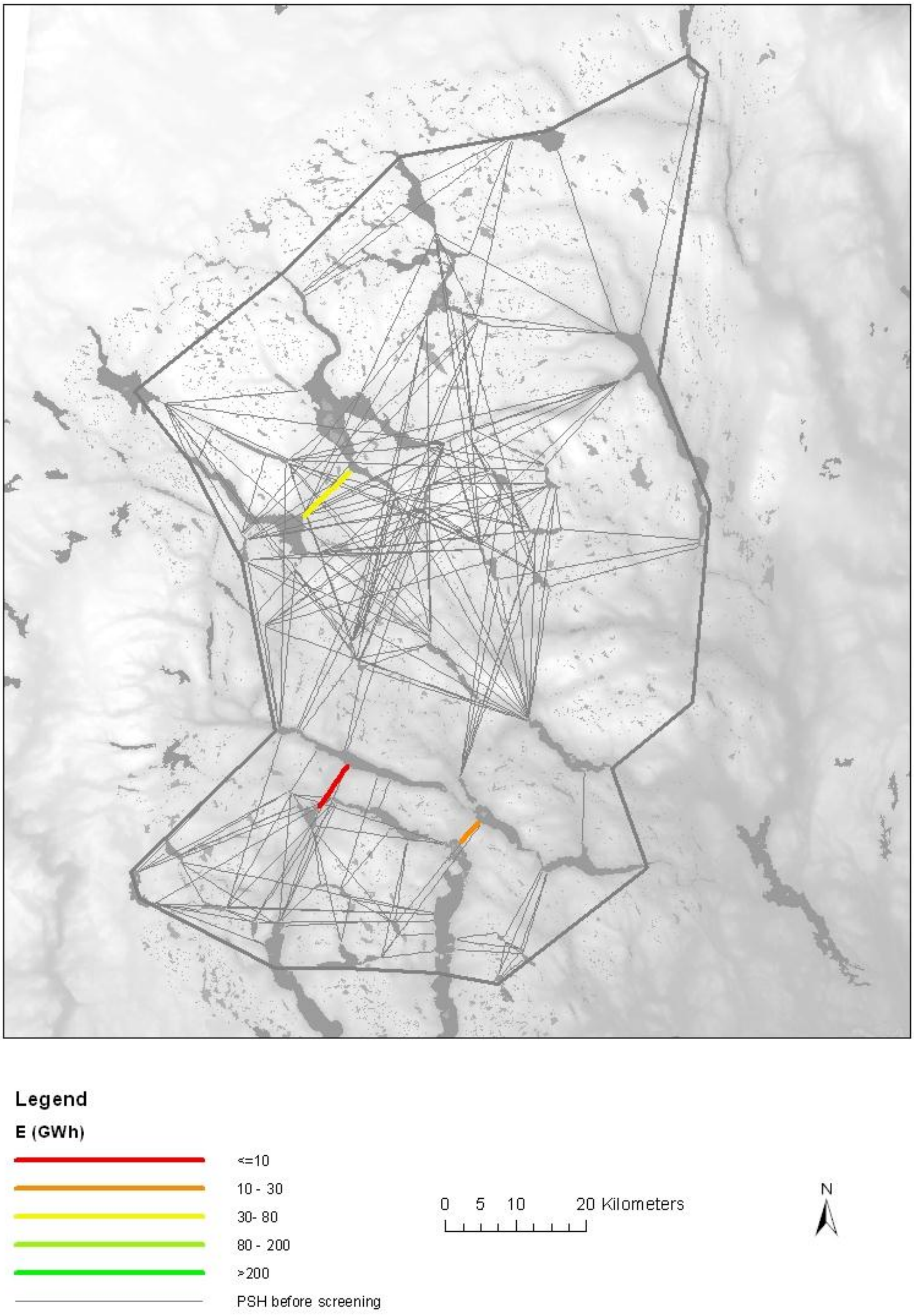


Figure 60:PSH potential Td-21 classified by E

Appendix D.25

Figure 61: PSH Potential for Td-26 classify by the costs

Appendix D.26

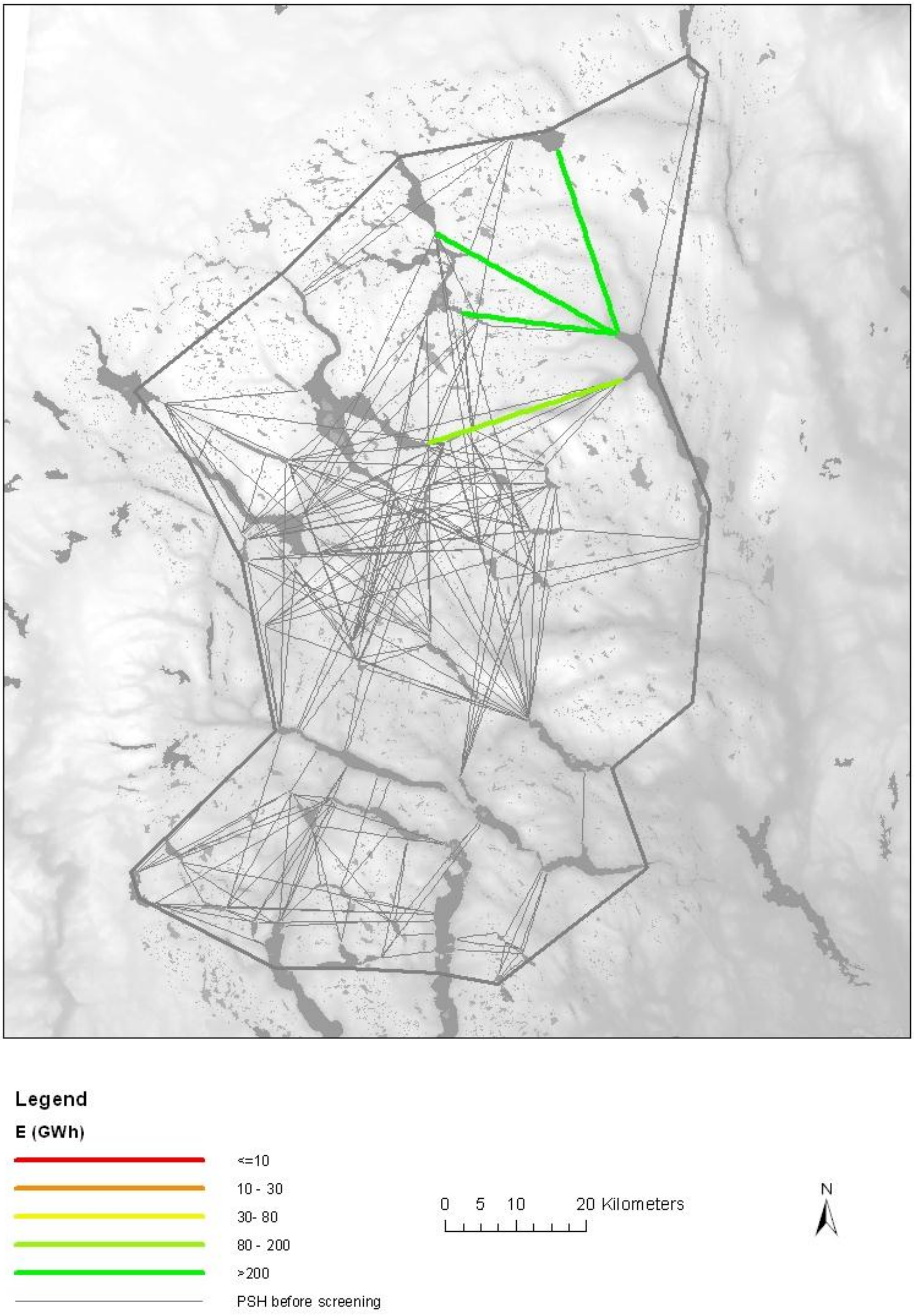


Figure 62:PSH potential Td-26 classified by E

Appendix E.1

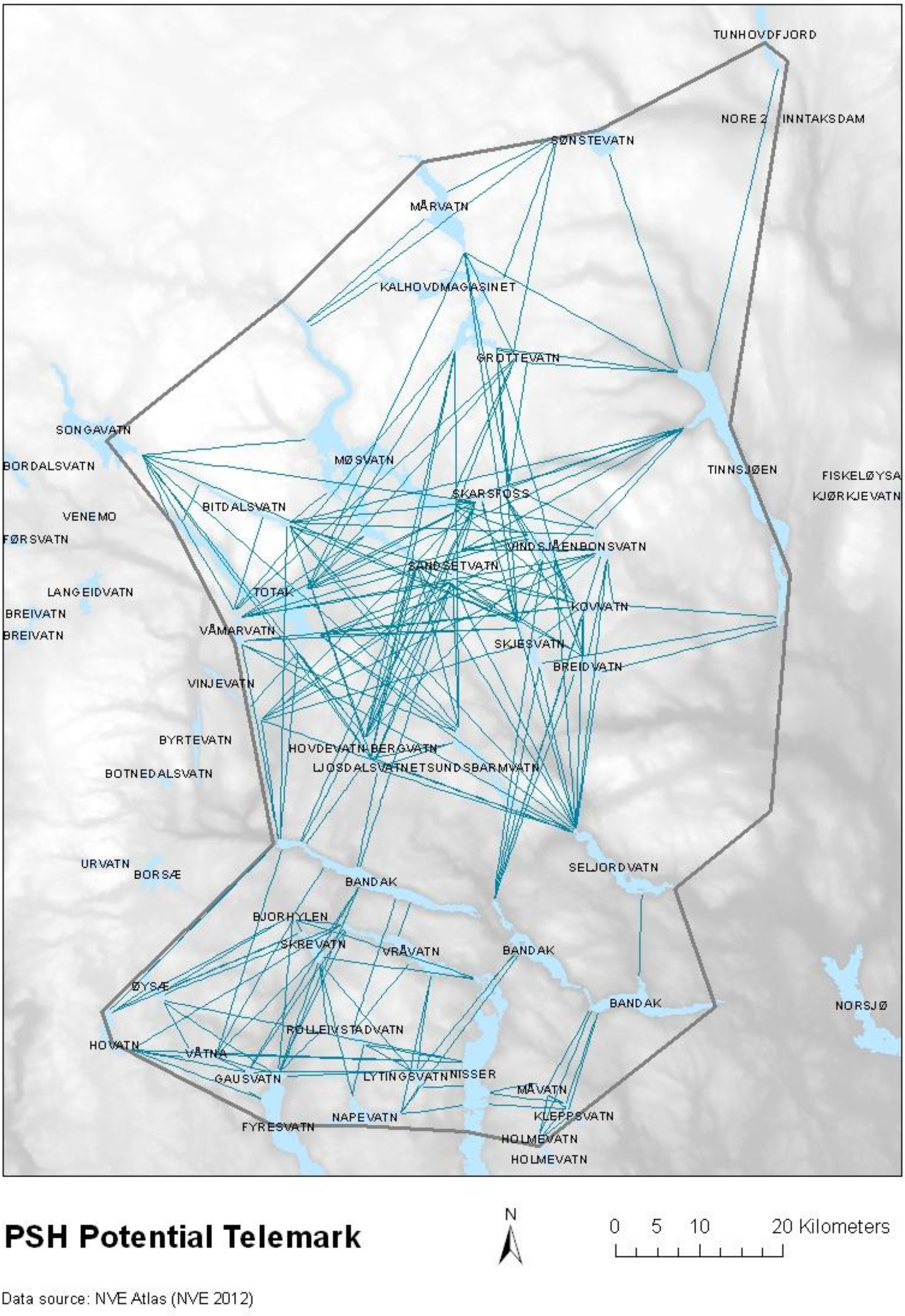


Figure 63: PSH potential of Telemark without any restriction after tool 2.

Appendix E.2

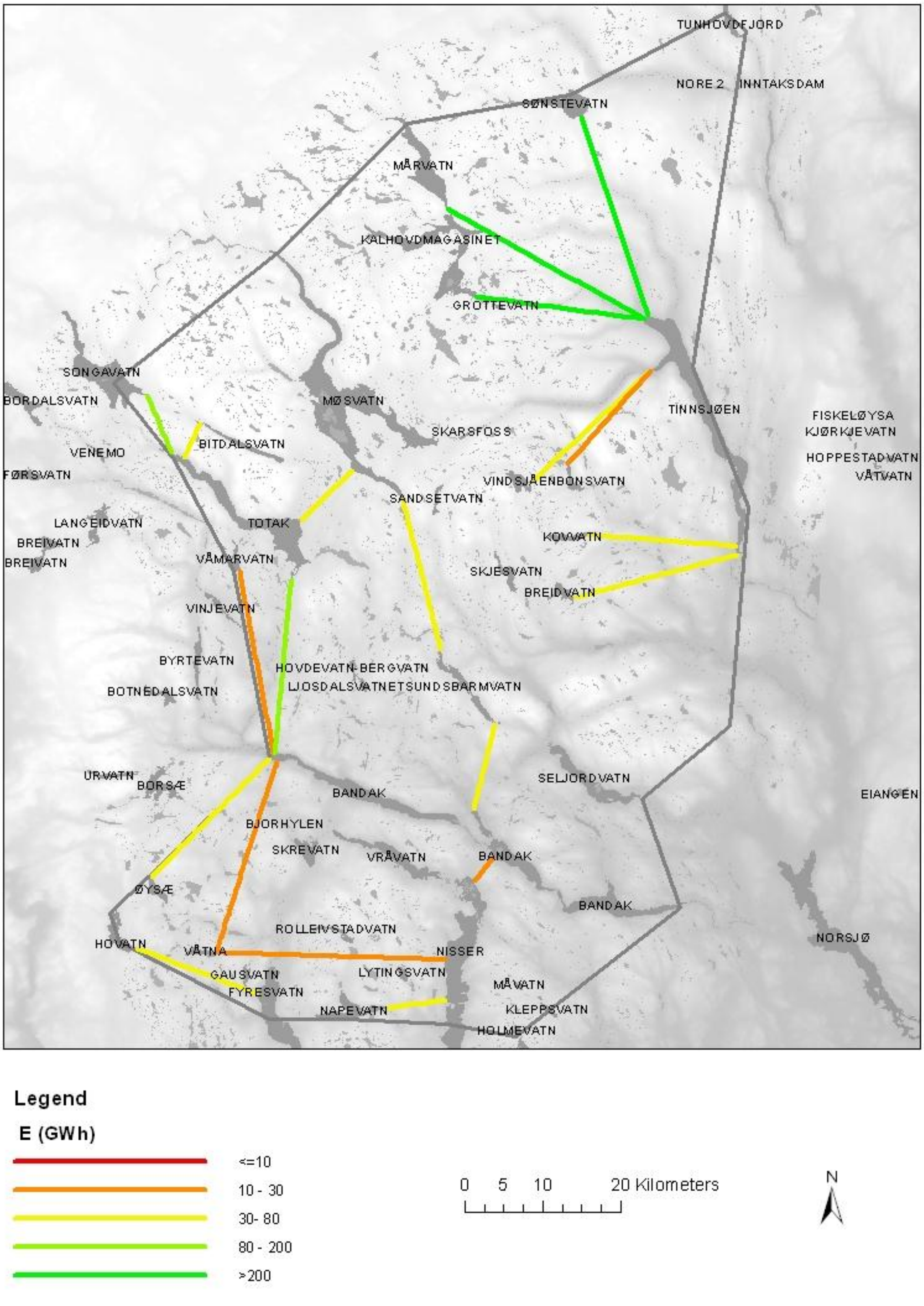


figure 64: PSH potential of telemark run in P-14, clipped out non geographically possible connections. Classified with E.

Appendix E.3

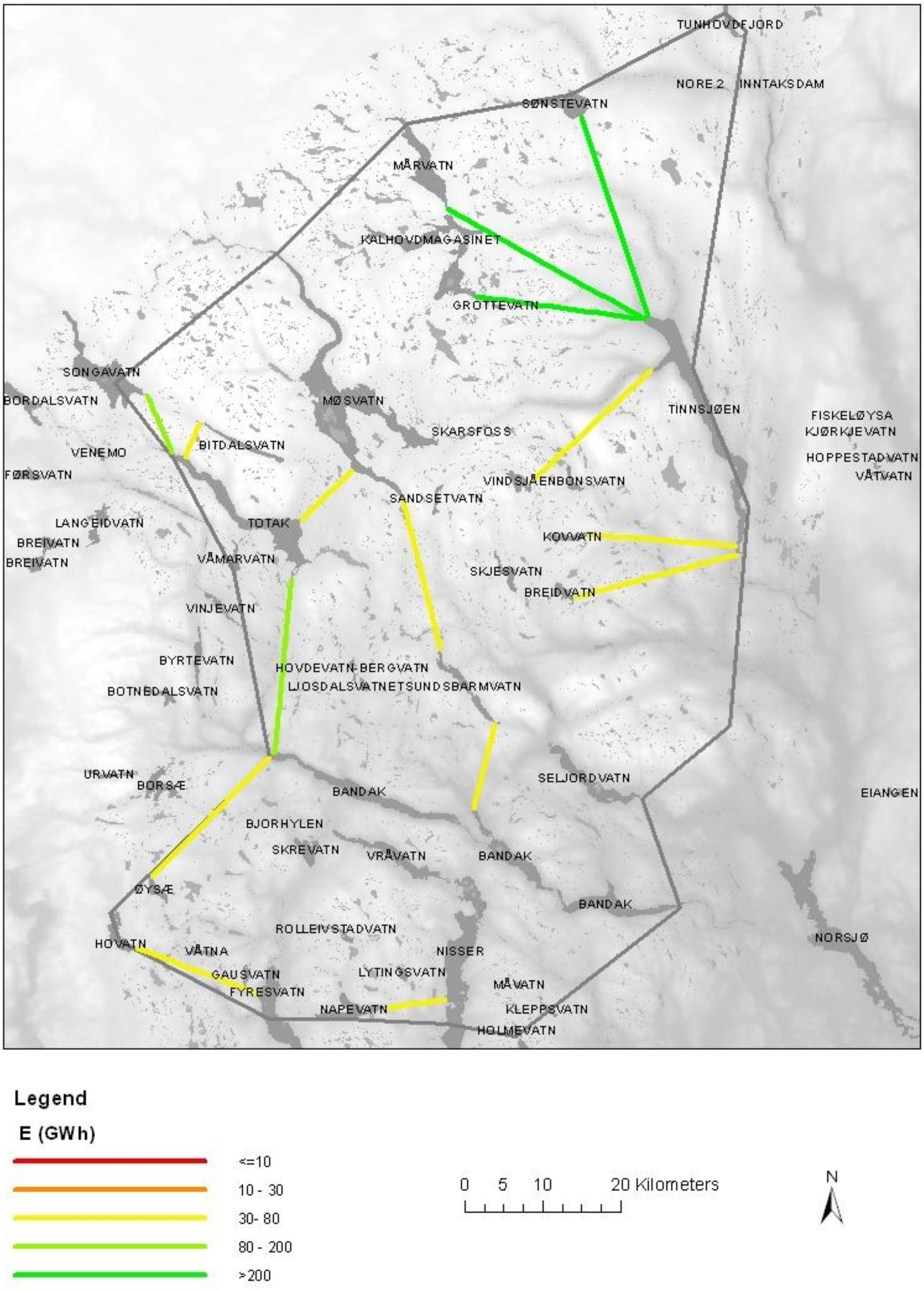
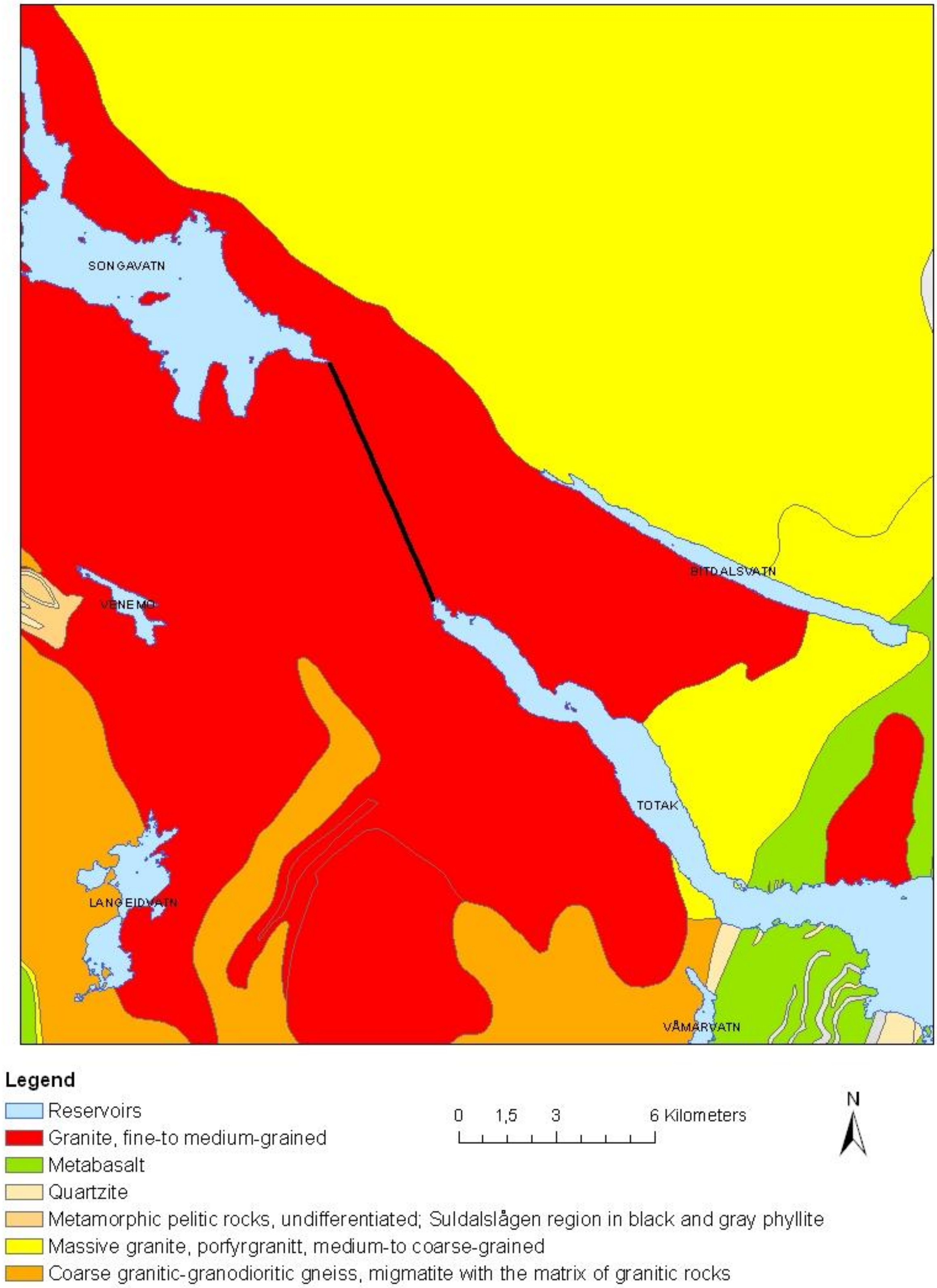


figure 65: PSH potential for P-14 for E> 30GWh

Appendix F



Data source: NGU, ND_Berggrunn250.(NGU 2013)

Figure 66: Geology map with the connection suggested by the tool [19]

Appendix G

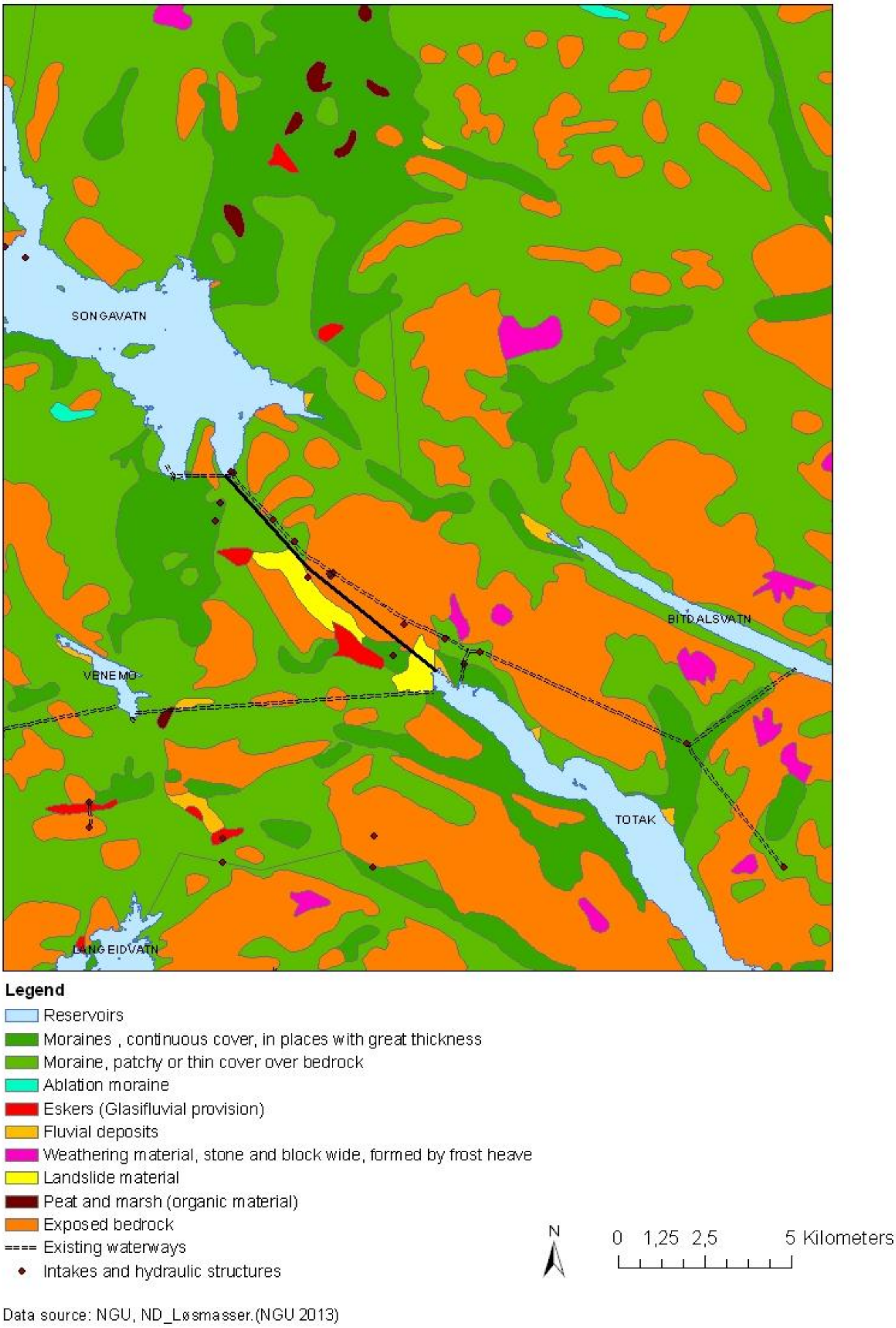


Figure 67: Bedrock map with the connection suggested in the layout. [19]

Appendix H

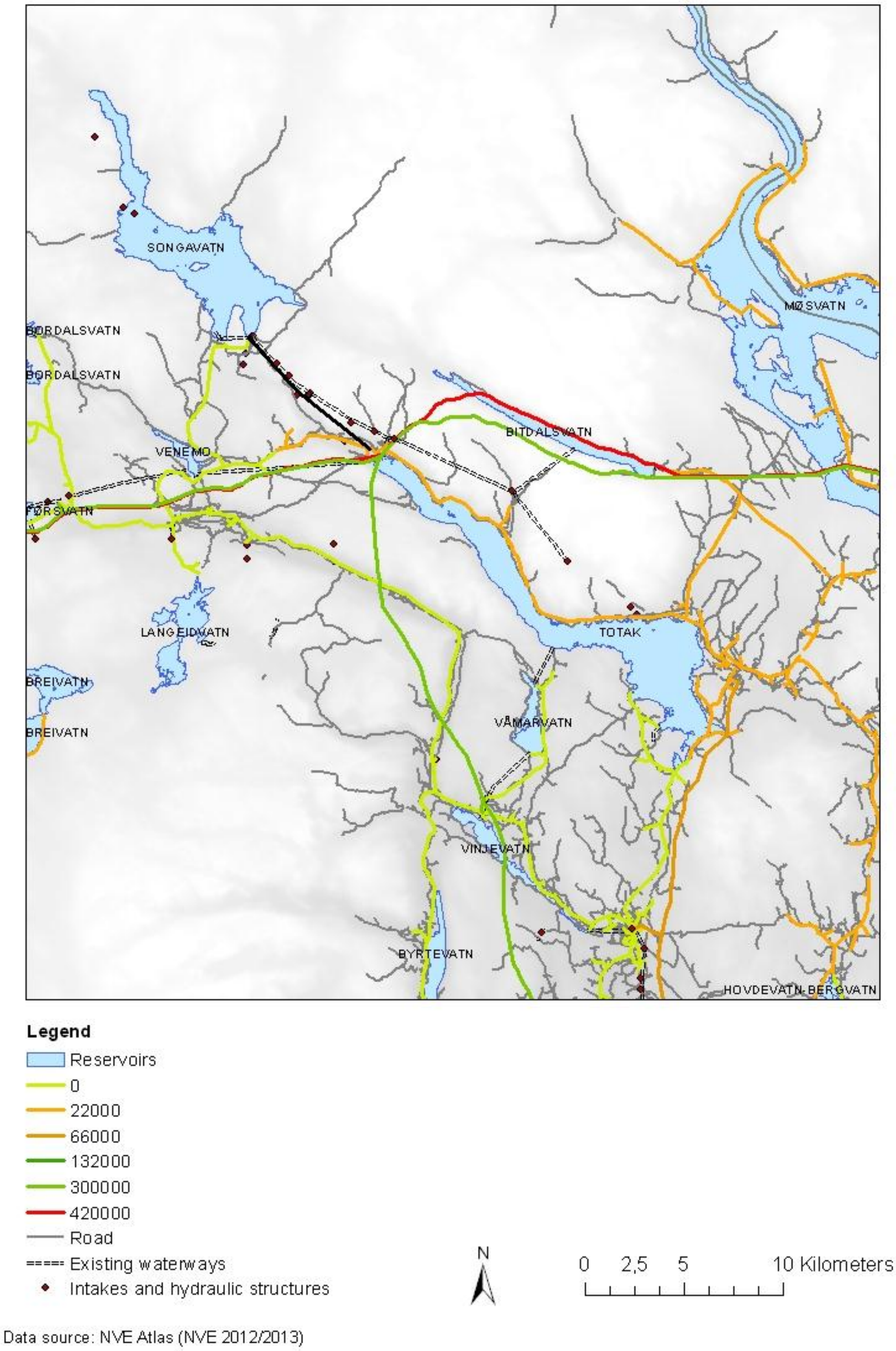


Figure 68: Map showing the roads and grid connection between Songa and Totak reservoirs [18]

Appendix I.1

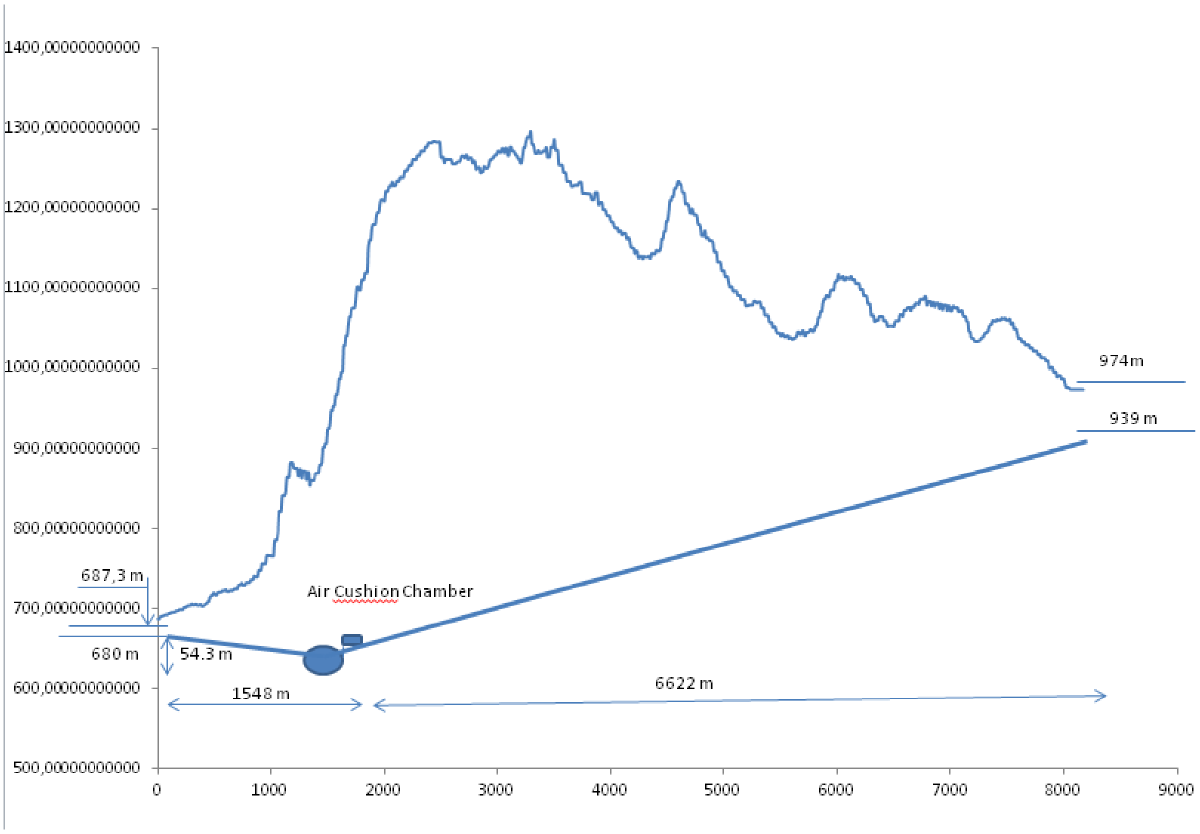


Figure 69:Scheme of the tunnel longitudinal profile with an air cushion chamber

Appendix I.2

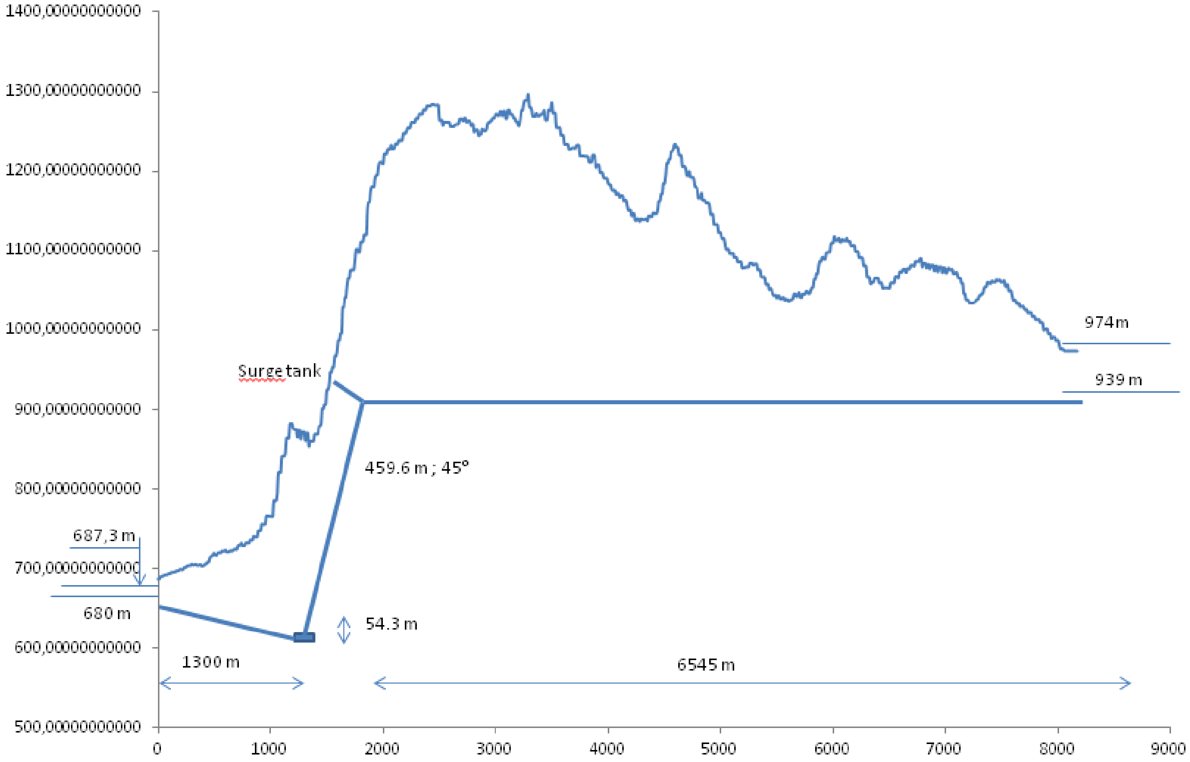


Figure 70: Scheme of the tunnel longitudinal profile with a surge tank

Appendix J

		DATA			
P	Q	GPH	A_TUL	TOTAL LENGTH OF THE TUNNEL	
1200	529	270	265	8171	
CIVIL COSTS					
Basic Price	Tunnel support(30%)	Jnforseen(10%	Rigging(30%)	Total tunnel costs	Surge Chamber
262479892,9	78.743.967,86	34.122.386,07	102.367.158,21	477.713.404,99	233093,5862
Power House					
Blasted volume(m3)	Blasting	Concrete	Reinforcement	Formwork	
123597,7544	28427483,51	61798877,19	23730768,84	51911056,84	
Supporting work	Masonry and plastering	Interior work	Unforseen	Rigging and operation	
4264122,526	4511318,035	13533954,1	18817758	47044395	
HVAC	Electrical installation	Access tunnels			
2600000	2000000	32106000			
TOTAL POWER HOUSE (NOK)					
290745734					
TOTAL CIVIL COSTS INDEX REGULATED(NOK)					
820194612,2					
MECHANICAL EQUIPMENT					
TURBINES	EACH(NOK)	TOTAL(NOK)	INDEX REGULATED(NOK)		
250MW	109375000	525000000	539175000		
100MW	43750000				
ELECTROTECHNICAL EQUIPMENT					
TOTAL COSTS FOR TWO GENERATORS		TOTAL	INDEX REGULATED		
4X250MW	330000000	820000000	841320000		
2X100MW	160000000				
TOTAL COSTS	Considering a 15% of these costs as unpredictable costs				
2.200.689.612,21	2.530.793.054,04				

Table 28:Songa PSH plant cost calculation