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Report

Developing future 20 000 MW hydro electric power in Norway

Possible concepts and need of resources

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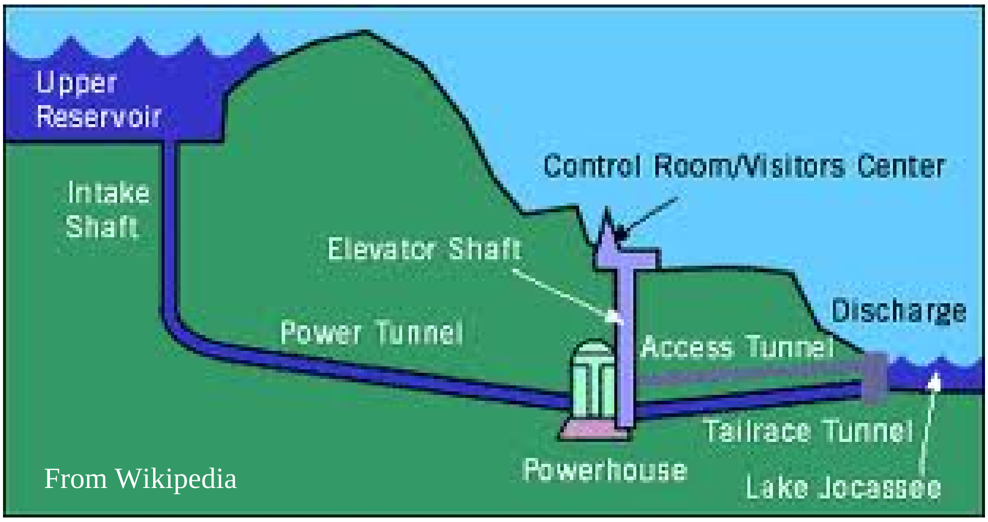

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ABSTRACT

Abstract heading

Through a formal cooperation between two institutes at NTNU and one department of SINTEF, the Gemini centre on Underground Technology has prepared a report on the possibility of developing 20 000 MW of hydro electric power production in Norway during a period of 15 years. This report is a part of the CEDREN project. This power supply is planned to be power to balance the European wind production. The report looks at the possibility of producing this development through pumped storage facilities, which are capable of having production durations of a few days to a couple of weeks. A schedule has been presented with an increment of 1000 to 2000 MW annually during this period of 15 years. This means a peak development of 6000 MW in one given year. Such development will have a significant impact on the consulting business as well as the construction business in Norway. The average production in tunnelling excavation is expected to be in the range of almost 3 million m^3 per year, with a peak reaching more than 10 million m^3. This production rate will come in addition to the yearly ordinary production volume within the tunnelling industry. Consequently, as the situation is today in this industry it is hardly believed that the current parties are able to absorb this amount of work with the current manning and equipment. It would be required to increase the capacity of the industry with significant resources to enable such a development to take place.

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1 Introduction, background and purpose

1.1 Development of Hydro electric power in Norway

A report has been prepared for the CEDREN project (Hydro PEAK) looking at the potential resources that are required to develop an installed capacity of 20 000 MW (or 20 GW) of hydro electric power in Norway during a period of 20 years until 2030. The future potential development of 20 GW constitutes approximately 2/3 of the current total hydro electric power installations in Norway. Commencing shortly after the Second World War, reaching a total of approximately 27 GW took several tens of years with peak activities during the 1960s through the 1980s and crossing the 25 GW mark in installation in the 1990s. Since then only a marginal development of hydro electric power has taken place in Norway.

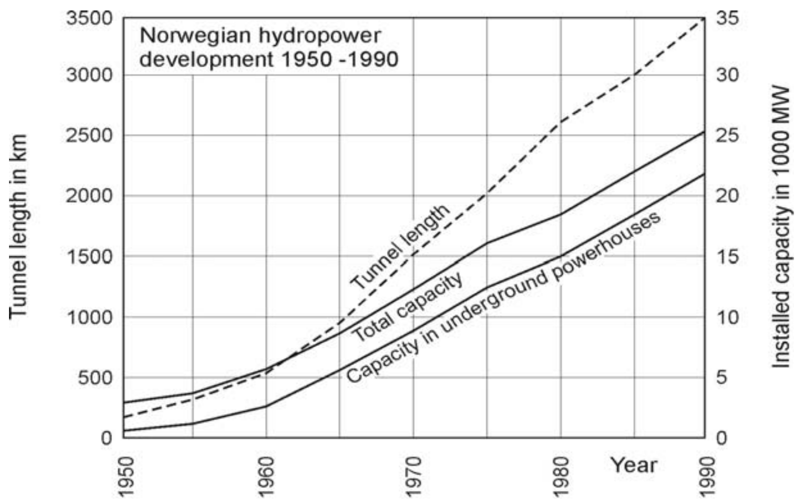

Figure 1. Development of hydro electric power production in Norway (Ref. Broch)

Based on Figure 1 above the capacity in underground power houses increased from about 2.5GW in 1960 to 22.5GW in 1990, that accumulates a growth of 20 000 MW in 30 years, compared to the potential of developing 20 000 MW in 20 years that will be discussed in this report. In practical terms this would likely be reduced to about 15 years of construction as we are well into 2011 already and no such projects will be ready for the construction phase realistically before the year 2015, taking into account some 3 years for planning and design purposes.

Within the three bodies Institutt for Geologi og bergteknikk IGB) and Instrutt for Bygg, anlegg og transport (IBAT) at NTNU together with SINTEF Geologi og bergteknikk a Gemini centre on Underground technology has been in operation for 6 years and through this Gemini centre personnel has been made available to prepare this report. Consequently, this report is a product of the joint tunnelling environment at NTNU and SINTEF together.

The background of this report is the need of producing hydro electric power to balance the power production from wind mills, which could be either off-shore or onshore wind mills, and produce power at peak hours when the ordinary power production is not capable of providing sufficient supplies.

The current hydro electric power production in Norway is based on high head, limited water flow and more or less continuous production. Future production would be related to peak production which means that the concept would move towards a concept development with frequent production on and off, with high output whilst in production mode. This will favour concepts such as pumped storage facilities and similar, which are not well developed concepts in Norway. One challenge would consequently be to arrange a new concept of hydro electric power production in Norway that could fit to the demands on peak production for a short time duration (e.g. 6-8 hours) and load balancing, which may have a duration of several days to some weeks. The latter is expected to be the most promising concept for the prevailing circumstances in Norway.

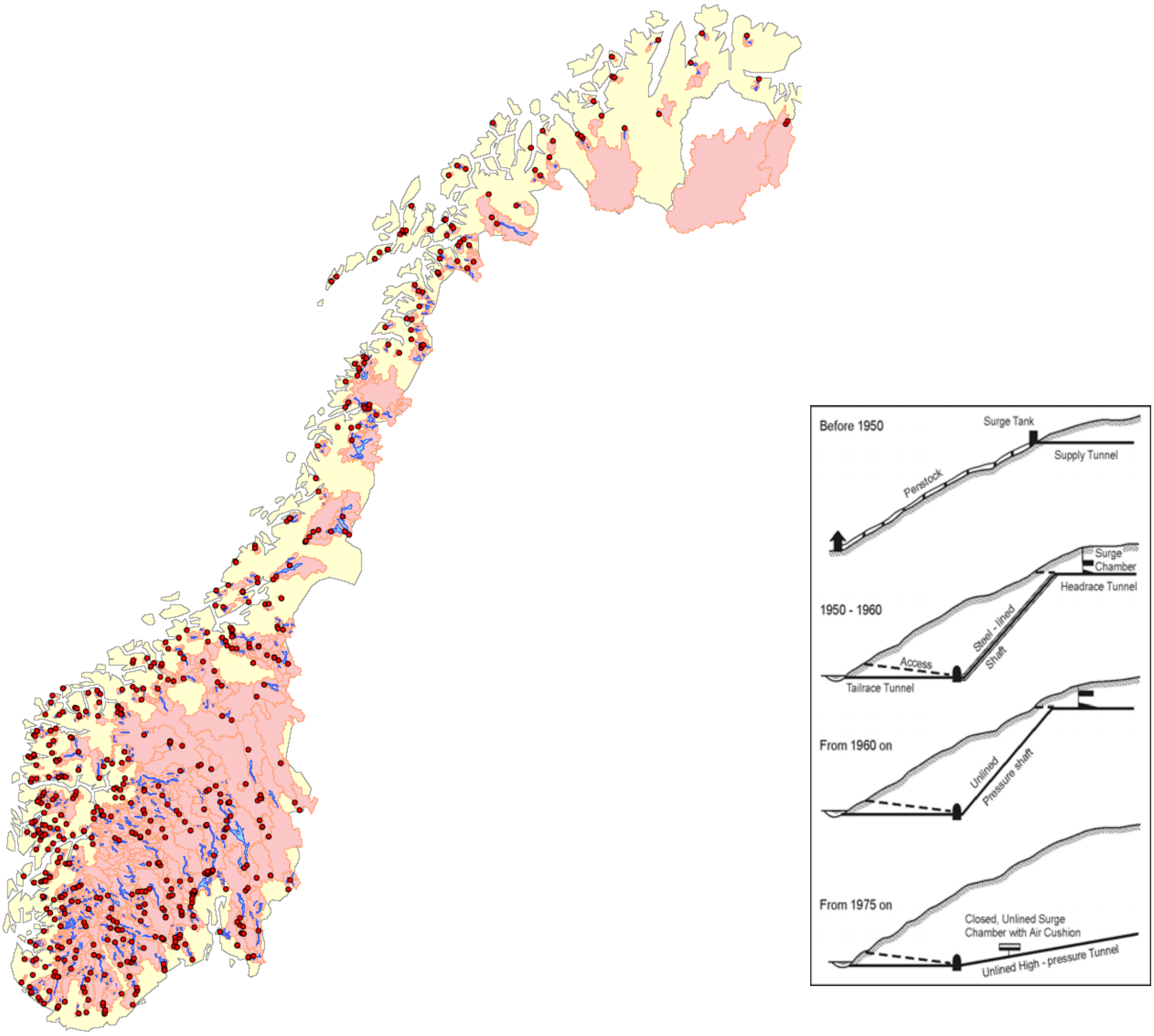

Figure 2. Current hydro electric power schemes (map on left hand side) and development of high head Norwegian hydro electric power concept (figure on right hand side) (Ref. Broch)

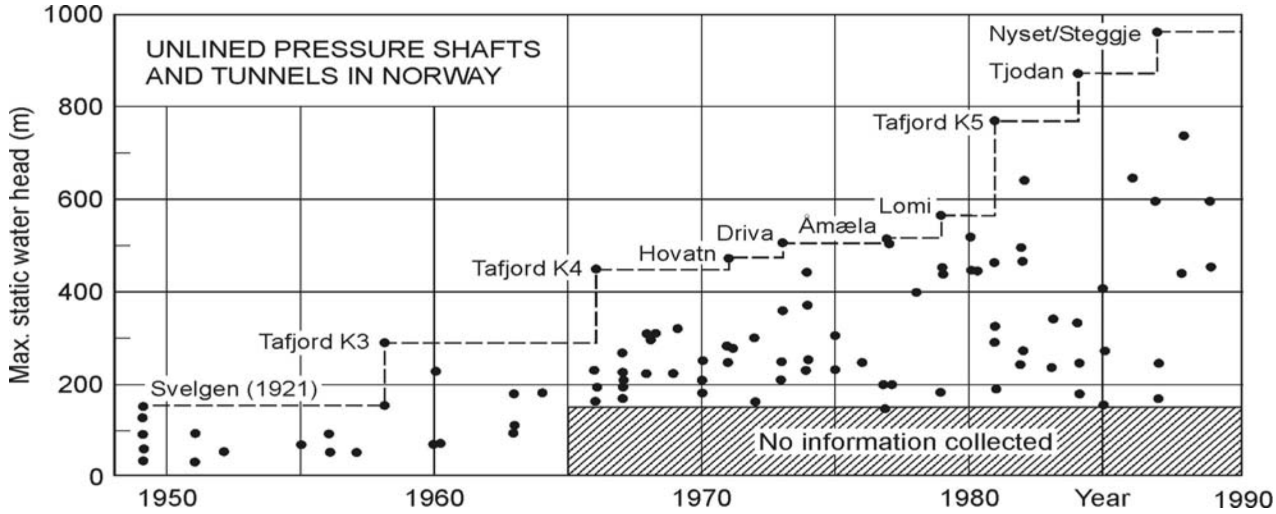

Figure 3. Development of high head Norwegian hydro electric power schemes (Ref. Broch)

1.2 Scope of this report

For this particular evaluation, we have assumed that new concessions for water reservoirs being built as upstream dams will not be granted, and the same applies for the down-stream reservoir. This means in practical terms that the current concessions need to be utilized. This again implies that an improved water management concept will be required as the availability of water resources remain basically as it is today.

The scope of work that has been established for this report is as follows:

- Identify the future needs for resource availability such that a development may require, be it in planning, research, construction (manpower, machinery, construction management, administration). One has to look at the future construction methods and possibly what can be found on capacity improvements in the future (more efficient TBMs for example)
- Identify what capacity Norwegian contractors have as we see it today, and what is needed to meet future needs. Here one needs to identify expected/estimated resources required to build 1 MW of a given type of hydro electric power project.
- It will first be necessary to identify what types of projects that may come (pump power or traditional Norwegian high pressure concepts), here it is conceivable that one must create a "standard" concept as a basis for the other assessments.

It is assumed that the total development of 20 000 MW is split into the following distribution: 5 power plants each with 1000 MW installed capacity, and the remaining capacity will be reached by constructing 60 units of 250 MW plants each. It is further assumed that the construction works will start in 2015 with an increment of 1000 MW for 5 years, and then follows the remaining installation of 15 000 MW within 10 years averaging 1500 MW per year. It is possible that such a large number of potential sites with existing, either man made or natural upper and lower reservoirs may not exist in Norway This is however the basis for our estimates and assessments. To allow for a solution in case the latter situation may prevail, we have included a solution where a lower reservoir is established by excavating dedicated rock caverns, a solution which will produce substantially increased demand on the tunnelling resources.

1.3 Reference to future power generation on a global scale

A recent article in Aftenposten (February 21st 2011) is related to the future energy sources on a global scale covering the period from 2000 to 2050. The estimate or prognosis presented in the article is based on a consumption/production of approximately 250 Exajoule (1 Exajoule = 278 TWh) on an annual basis reaching the same amount in year 2050. See Figure 4 below.

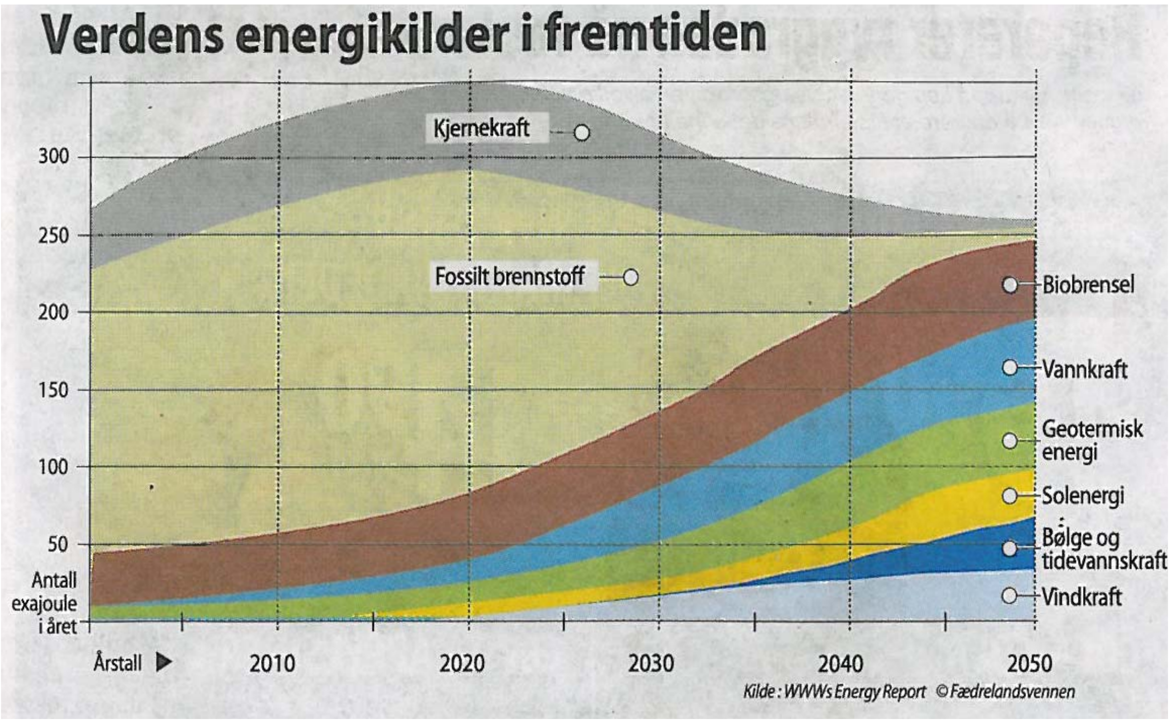

Figure 4. Annual power production and distribution per energy source (Ref. Aftenposten)

Amongst the energy sources being evaluated as far as future development is concerned is also hydro electric power. Today, hydro electric power supply consists of approximately 15 % of the total electricity production on a worldwide basis. This is expected to grow significantly in the future and as it can be seen in the graph above, the contribution from hydro power is expected to be one of the main energy sources, equal in size to bio fuel and geothermal power. In total, it is expected that hydro power would contribute with around 20 % of the total energy sources.

The output from the hydro electric power sector in this graph is about 50 Exajoule annually according to Figure 4 and the article in Aftenposten. Information that we have received suggests that the maximum output from hydro electric power worldwide is 51 Exajoule and that the current output is in the range of 10-12 Exajoule.

To bring this number into perspective, Figure 4 represents a 'dream' scenario, or a very optimistic scenario and may not necessarily be a realistic one as it might as well be needed to maintain some fossil fuel as well as nuclear power in the future and it is not expected that the full output from hydro electric power would be developed.

1.4 Development of pumped storage outside Norway

Looking at the current status for mega-projects where the pumped storage concept has been applied, see Figure 5, it can be seen that 40 projects exist as per today which have installed capacity beyond 1000 MW.

1000 MW and Larger Pumped Hydro Installations Worldwide

Electronic Storage Association

There are 40 pumped hydro facilities with capacities of 1000 MW or greater worldwide, representing 6 continents and 13 countries.

Location	Plant Name	On-Line Date	Hydraulic Head (m)	Max Total Rating (MW)	Hours of Discharge	Plant Cost
Australia	Tumut 3	1973		1690		
China	Tianhuangping	2001	590	1800		$1080 M
	Guangzhu	2000	554	2400		
France	Grand Maison	1987	955	1800		
Germany	Markersbach	1981		1050		
	Goldisthal	2002		1060		$700 M
Iran	Siah Bisheh	1996		1140		
Italy	Piastra Edolo	1982	1260	1020		
	Chiotas	1981	1070	1184		
	Presenzano	1992		1000		
	Lago Delio	1971		1040		
Japan	Imaichi	1991	524	1050	7.2	
	Okuyoshino	1978	505	1240		
	Kazunogowa	2001	714	1600	8.2	$3200 M
	Mananogawa	1999	489	1200		
	Ohkawachi	1995	411	1280	6	
	Okukiyotsu	1982	470	1040		
	Okumino	1995	485	1036		
	Okutataragi	1998	387	1240		
	Shimogo	1991	387	1040		
	Shin Takesagawa	1981	229	1280	7	
	Shin Toyne	1973	203	1150		
	Tamahara	1986	518	1200	13	
Luxembourg	Vianden	1964	287	1096		
Russia	Zagorsk	1994	539	1200		
	Kaishador	1993		1600		
	Dneister	1996		2268		
South Africa	Drakensbergs	1983	473	1200		
Taiwan	Minghu	1985	310	1008		$866 M
	Mingtan	1994	380	1620		$1338 M
U.K./Wales	Dinorwig	1984	545	1890	5	$310 M
U.S.A./CA	Castaic	1978	350	1566	10	
	Helms	1984	520	1212	153	$416 M
USA/MA	Northfield Mt	1973	240	1080	10	$685 M
USA/MI	Ludington	1973	110	1980	9	$327 M
USA/NY	Blenheim-Gilboa	1973	340	1200	12	$212 M
	Lewiston (Niagra)	1961	33	2880	20	
USA/SC	Bad Creek	1991	370	1065	24	$652 M
USA/TN	Racoon Mt	1979	310	1900	21	$288 M
USA/VA	Bath County	1985	380	2700	11	$1650 M

Figure 5. Statistics on Pumped Storage Hydro electric power installations

1.5 Norwegian tunnelling for hydro electric projects

The purpose of this report would be to look at the possibilities that may exist in Norway in developing hydro electric power supply taking new concepts into account to reach the 20 GW installation goal and the consequences in terms of need of resources.

As mentioned above, the peak activity in the hydro electric power development in Norway took place during the 1960s through the 1980s. This is clearly confirmed by the tunnelling statistics that is yearly produced by the Norwegian Tunnelling Society. Figure 6 below, showing yearly statistics of the annual production by the

Norwegian contractors involved in tunneling, published since 1973, clearly suggests that by the beginning of the 1990s, the tunnelling production associated with hydro electric power ceased dramatically and infra structure projects became the dominating users of the underground. As it can be seen, the yearly capacity in the tunnelling sector has been more or less steady on a production rate of approximately 4 million solid cubic metres of rock.

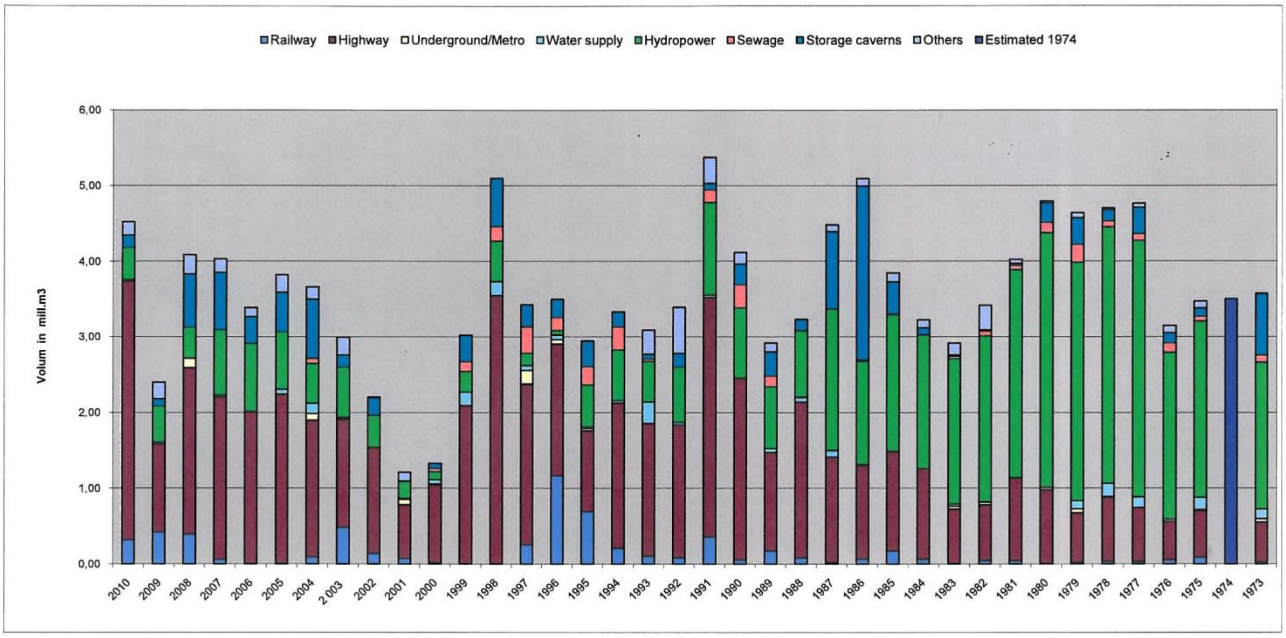

Figure 6. Yearly production reported by Norwegian tunnelling contractors (Ref. NFF)

In Figure 6, hydro power activity is shown with green color in the columns while the dark red parts of the columns are road tunnels. The lower blue part is railway tunnels. Hence, infrastructure in terms of road and railway construction currently dominates the tunnelling industry in Norway, whilst historically it has been a different situation.

From figure 6 above, it can be seen that the Norwegian tunnelling industry had its peak production related to hydro electric power development during the years 1977 through 1981. In this period the production was in the range of 3-3.5 million m^3 per year. Following from 1981, the production rate decreased and reached finally an almost steady production of 0.5 to 1 million m^3 annually for some years. In 2010, the production rate was only 0.25 million m^3, almost the lowest tunnelling activity with respect to hydro power development in 40 years.

If we look at Figure 1, the installed capacity increased from approximately 10 000M W in 1973 to 25 000 MW in 1990. During the same period, output in terms of annual production in tunnelling is around 35 million m^3 of solid rock directly related to hydro electric power development projects according to Figure 6. That produces a ratio of almost 3 500 m^3 per MW installed hydro power capacity. During some 10 of these years, the hydro power sector dominates the tunnelling industry.

Assuming that the average production capacity in the tunnelling sector historically is about 3.5million m^3 per year for the years that we have statistical data, and that a development of 10 000 MW during 17 years yields an average of about 600 MW per year, the annual average output in the tunnelling industry is about 2mill m3 per year related to hydro power development.

These are historical and statistical data that are useful to keep in mind when considering the demands of capacity and resources that will be focused later on in the report.

Today, the development associated with railways and roads are dominating the use of underground in Norway. Whether or not this trend and magnitude of activities are going to continue into the next two decades reaching 2030 is uncertain, but most likely these project types will continue to be the dominating areas of tunnelling. Therefore, in the coming estimates we have to assume that a significant level of activity is maintained and that the required resources for developing 20 000 MW in hydro electric power will be on top of the existing activities of approximately 3-3.5mill m^3 per year.

Based on information that is available at present some 40 drilling jumbos are in operative mode in the Norwegian tunnelling industry. With a utilization of about 80 %, the production per unit is around 125 000 m^3 of solid rock annually. These jumbos are operating in mixed types of projects, road and railway, hydro electric power schemes etc. At present no TBMs are in operation in Norway.

1.6 Current tunnelling technology in short

At present there is a number of possibilities for excavation of tunnels and caverns for future underground hydro power development schemes. In general, the principles of the tunnel technology has not changed significantly over the last 20-30 years, however small steps of improvements in drilling equipment, explosives technology, surveying and so on would enable tunnels to be excavated with a shorter construction time, fewer adits and other auxiliary tunnels that are not a part of the 'production line', smoother tunnel contour and so on. Improvements that enable tunnelling to be an even more competitive solution will most likely materialize for future hydro electrical power developments.

At present, there are basically four excavation methods that would be applicable for future hydro electric power tunnel developments:

1. Conventional drill&blast, which is by far the dominating tunnelling method applied in Norway for excavation of ordinary tunnels ranging from 15 m^2 to more than 100 m^2.
2. Tunnel Boring Machines, which have not been used in Norway since the Meråker Hydro electric Power Project in the early 1990s. The Hard Rock TBM equipment was developed mainly by The Robbins Company to fulfill demands arising from Norwegian projects. Since then, the development of TBMs has taken place without any major Norwegian contribution or participation.
3. Pilot and reaming, a method that is expected to be highly applicable for pumped storage projects to establish shaft connection between the lower and upper reservoir with a minimum of head- and tailrace tunnels. Previously, the Alimak method was extensively applied, but this latter method is no longer a primary choice taking into account current HSE restrictions.
4. Directional drilling applying mini TBMs which are remote controlled. This is a new method that is currently developed for diameters up to 1-1.5 m and with a length of some 500-1000 m in hard rock environment.

The main dilemma for future tunnels for hydro electric power development would be related to the design and layout of the headrace tunnel and shaft solutions. Equipment need to be developed to allow for single face drives which are as long as possible still within the practical limitations and constrictions related to ventilation, transport etc. In the table below some examples of long single heading tunnels are shown.

A table has been developed that indicates the length of such single face tunnels being excavated for some various tunnelling projects. Please observe that this is by conventional drill&blast. Increasing the maximum length of single heading tunnels by conventional drill&blast would of course make it more competitive towards the use of TBM. A TBM would probably require a length of approximately 6 km or so to be competitive in terms of costs per metre of tunnel and construction time. Shorter TBM tunnels are likely not an alternative to drill&blast due to high initial investments and long lead-in time for the purchasing of machine and mobilisation before actual excavation can take place.

It would be logical to expect that the amounts of tunnels expressed in cubic metre of excavated rock per installed MW power production during the period until 2030 is likely to be less than it was in the 1970s and 1980s, however we do not have any figures or numbers to substantiate this postulate except the statistics obtained from NFF in Figure 6 above. Consequently we utilize the numbers that are at hand and in general terms some savings can be obtained when later details are at hand.

Table 1. Long single heading tunnels

Project	**Lingvang tunnel**	**Breidal tunnel**	**Tyin tunnel**	**Svea tunnel**	**Dividalen tunnel**	**Troll tunnel**	**Langevann tunnel, IVAR**
Type of tunnel project	Water transfer tunnel	Water transfer tunnel	Headrace tunnel	Coal transport tunnel	Access to radar site	Subsea pipeline tunnel	Water transfer tunnel
Tunnel length	8.9 km	10 km	11.3 km	5.7 km	9.8 km	7.5 km	7.8 km
Tunnel width	5 m ($25\ m^2$)		5 m ($20\ m^2$)	7 m	3.6 m ($18\ m^2$)	6.6 - 8.6 m	4 m
Overburden	Approxi-mately 600 m		Up to 1000 m rock cover	Up to 600 m (half of tunnel is below a glacier)		180 m below sea level	
Number of exits/entrances	1	2	1 + 1 adit	1	1 (+ 1 adit for air and dump site)	1	1 + 1 adit (?)
Number of working faces	1	2	3	1	1	4	2 (?)
Maximum length of tunnel face	8.9 km	5 km	4.4 km	5.7 km	9.8 km	3.6 km	4 km (?)
Tunnelling method	Drill & blast	Drill & blast	Drill & blast	Drill & blast	Drill & blast	Drill & blast	Drill & blast
Construction time (mobilisation to opening of the tunnels)	2005 – 2008		October 2001 – September 2003	November 2002 – December 2003	September 1990 – September 1993	October 1991 – January 1996	April1997 – November 2002
Notes				Started in permafrost	1400 m height difference or 1 : 7 uphill	Lowest level 240 m below sea level	

Based on some statistics that can be found in the website of Statistics Norway it is possible to estimate the cost escalation that tunnel construction has experienced since 1985. The data available suggests that in 1985 the index for tunnel cost was 53, it reached 100 in the first quarter of 2004 and then again 131 in fourth quarter of 2010. This indicates a price escalation of approximately 3 % per year during this period. This is basically the same development that has been experienced by the Norwegian Consumer Price Index for the same period of 25 years.

2 Standard conceptual design

2.1 Some reference projects on pumped hydro electric development

The standard design is based on the concept that has been presented by Sira-Kvina kraftselskap in their application for concession associated with the development of Tonstad kraftverk. Sira-Kvina kraftselskap submitted their application in November 2007.

Their solution for a pumped storage facility is based on utilising existing lower and upper reservoirs, being Sirdalsvatnet and Homstølvatn respectively. This is shown below in Figure 7 below.

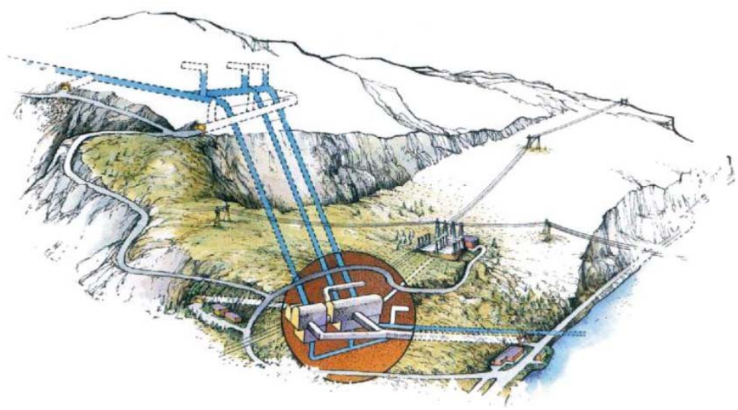

Figure 7. Tonstad hydro power project (Ref. Wikipedia)

The development of the Tonstad hydro power to a pumped storage facility would include the following construction and installations works:

Excavation of a new headrace tunnel, with length 12 000 m and a cross section of 120 m^2. In addition, there will be new access tunnels, tailrace tunnel and distribution basin at the headrace side. A total of some 14 000 m of tunnel is expected to be needed to establish 1000 MW

There will be a need of 2 parallel shafts, with an inclination of 45°, both shall be steel lined. The size of these shafts shall fit to a capacity of 250 m^3 of water per second, length will be approximately 600 m.

An extension of the power station would be needed. It will be sized to accommodate two units of 480 MW each. The Francis turbines planned to be used will each have a capacity of 125 m^3 per second in production modus and 100 m^3 per second in pumping modus.

In the concession application, the cost of the pumped storage facility has been estimated to a total of 2.7 billion NOK in 2007, roughly scaled to 3 billion NOK in 2011. The cost distribution in 2011 value will be approximately 1450 million NOK for civil works (approximately 48 %), 650 million NOK for mechanical installations (approximately 22 %), 500 million NOK for electrical installations (approximately 17 %) and finally 400 mill NOK for all planning, administration and financing (approximately 13 %). This distribution of the costs can be considered as a reference for other cost estimates.

This will produce a cost of approximately 3 million NOK per MW installed capacity.

Another pumped storage power station to be mentioned was built in China during the 1990s and entered operation in 2001, the Tianhuangping Pumped Storage Hydro Plant (THP). This project was financed by the World

Bank and several Norwegian engineers were involved in the project through the Advisory group of Norway (AGN). THP was built with an upper and lower reservoir with two parallel shafts and with a minimum of horizontal tunnels. The head is about 600 m, the shafts are 7 m in diameter and the installed capacity is approximately 1850 MW. The power house hosts 6 parallel Francis turbines each with 306 MW installed capacity. The reservoirs have a capacity of storing about 8 million m^3 of water and the plant operates on a typical daily cycle.

It is interesting to learn that the underground cavern that hosts the power house has a length of as much as 200 m, a width of 21 m and almost 50 m height. The length is governed by the number of turbines.


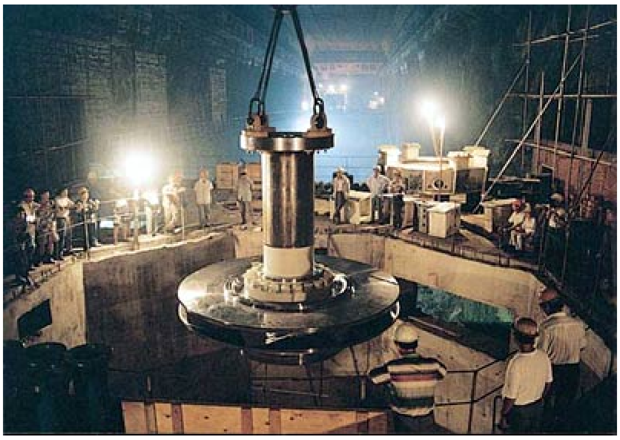

Figure 8. Tian Huang Ping Lower reservoir (left picture) and installation works (right hand side) (Ref. Wikipedia)

The overall cycle efficiency is per design 70 %, whilst the turbine efficiency neglecting the head losses is designed to be 90 %, or even better.

Construction began in March 1994 and the plant came online in 2001. The first generator began operation in October 1998, later than initially planned partly as a result of a major landslide the previous year, whilst the commissioning of the remaining generators was delayed until 2001 for the last one.

The cost of the project was reported to be a total of 1.1 billion USD with a construction cost of 900 million USD. These are 2001 values and assuming a yearly cost escalation of 3 %, the cost in 2011 would be in the range of 1.5billion USD, or equivalent to 9 billion NOK. That will produce a cost of 5 million NOK per MW installed capacity.

In total, China has approximately 15 000 MW installed capacity associated with pumped storage facilities, and the THP-project is the largest project of this kind in China and Asia.

Another relevant case to mention is the Tevla pumped storage power plant in Norway, which was built in 1990-94 as part of the Meråker hydro electric power project. The layout of this project is shown in Figure 9, and the plan of the Tevla power plant with tunnel systems is shown in Figure 10.

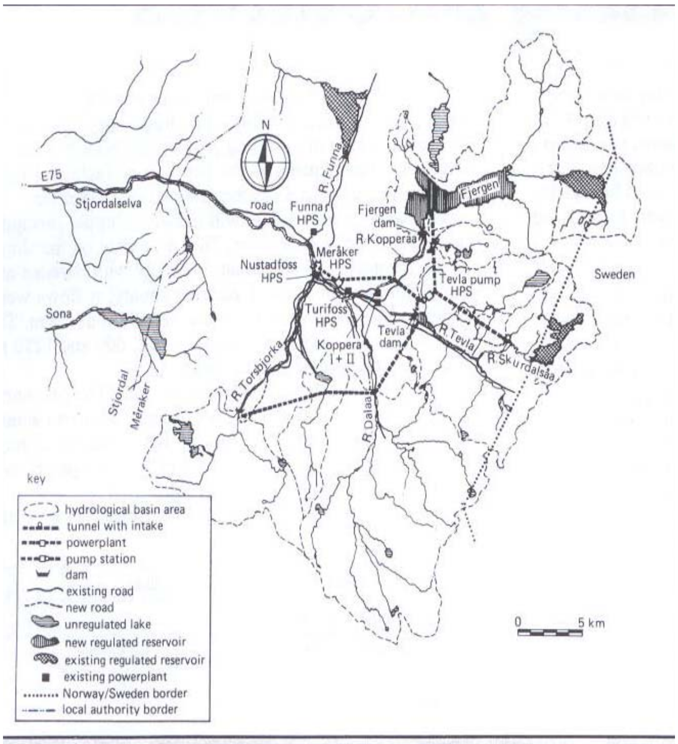

Figure 9. Map of the Meråker project area.

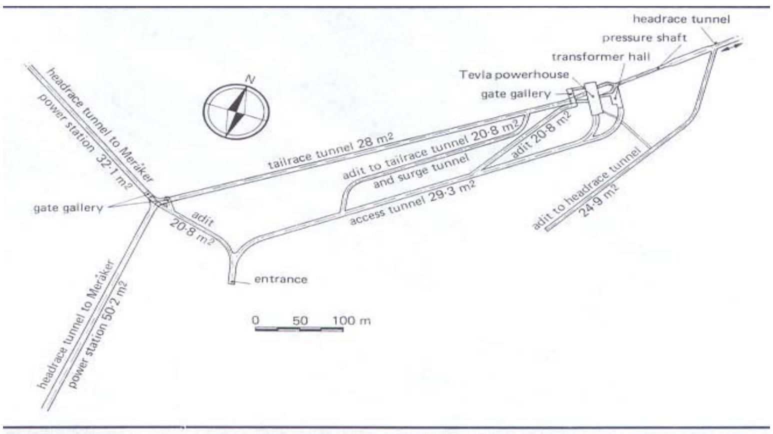

Figure 10. Plan of the Tevla power plant.

The two power plants of the Meråker project have a mean annual production capacity of 534 GWh. Meråker is a conventional power plant with an installed capacity of 87 MW (two Francis turbines), while Tevla has two reversible pump turbines, each with capacity 24.8 MW in the turbine mode and 21.1 MW in the pumping mode.

The Tevla power plant is fed by the enlarged Fjergen reservoir, with lower and upper operating levels of 514 and 498 m respectively, and a volume of 204.2 million m^3. A new reservoir built at the Tevla river (the Tevla reservoir), with a volume of 4.5 million m^3 and max/min levels of 358.5 m and 350 m respectively, makes it possible to pump water back to the Fjergen reservoir.

The Tevla power plant has approx. 17 km of associated tunnels. The 10 km long transfer tunnel from Torsbjørka in SW (see Figure 8) was excavated by TBM, while all other excavation was carried out by conventional drill&blast. The headrace tunnel is inclined at 1:10. The power house cavern is 42 m long, 13 m wide and 25 m high.

Details of capacities and production numbers for Tevla and Meråker power plants are shown in Table 2.

Table 2. Some key numbers for Meråker hydro electric power project

Table II — Meraker hydro power project (data given are average annual production figures)

Hydro plants	Capacity (MW)	Total production (GWh)	Consumption for pumping (GWh)	Net production (GWh)
New hydro stations				
Meråker	60.4 + 26.6	425		425
Tevla	2 × 24.8 (Turbine) 2 × 21.1 (Pump)	137.9	46.7	91.2
Total new plants	135.6	562.9	46.7	516.2
Funna (existing)	8.4			
Replaced stations, total 19.7 MW: Kopperå I (62 GWh); Kopperå II (40 GWh); Turifoss (21 GWh); and Nustadfoss (17 GWh).				

The total construction time for the Meråker project was 3.5 years. The planning process for this project started in 1983 already. Normally, the planning, application and decision process for a project of this type will be at least 3-5 years.

In the following, a standard design is proposed which will serve as the basis for evaluation of the resource requirements.

2.2 Standard design

It is advantageous that the existing head and tail reservoirs are utilized for the development of pumped storage power plants. This will not only reduce the overall construction cost, but also will minimize environmental impacts. Therefore, in this standard design it is assumed that the regulation height of the head reservoir will not be changed from the existing one. It is important that the tail reservoir should be as large as possible. Because, the larger the reservoir, the less will be the regulation height and in the impact on the surrounding environment.

In this respect, two different standard designs are proposed for two different installed capacities; i.e. 1000 MW and 250 MW. The 1000 MW capacity project is based on the Tonstad kraftverk (Figure 11) and the 250 MW capacity project is proposed for the existing 45 MW Bogna kraftverk (Figure 12). The attraction of these two projects is that both have fairly good sized head reservoir with existing regulation capacity. The surface area of Homstølvatn (the head reservoir for Tonstad) exceeds 2 million m^2 and the surface area for Ytter Bangsjø (the head reservoir for Bogna) exceeds 21 million m^2. Similarly, both projects have large sized existing lakes as tail reservoir, which will provides the possibility of controlling the regulation height. The Sirdalsvatn has a surface area exceeding 19 million m^2 and the Snåsavatn has a surface area exceeding 120 million m^2, respectively. Similarly, existing regulation height of Homstølvatn is about 26 m with total regulation volume of 55 million m^3. The existing regulation height of Ytter Bangsjø is 10 m with total regulation capacity of approximately 210 million m^3. For the proposed installed capacities the total regulation time available from existing regulation capacity for these two projects are 53 hours for Tonstad and 547 hours for Bogna, respectively.

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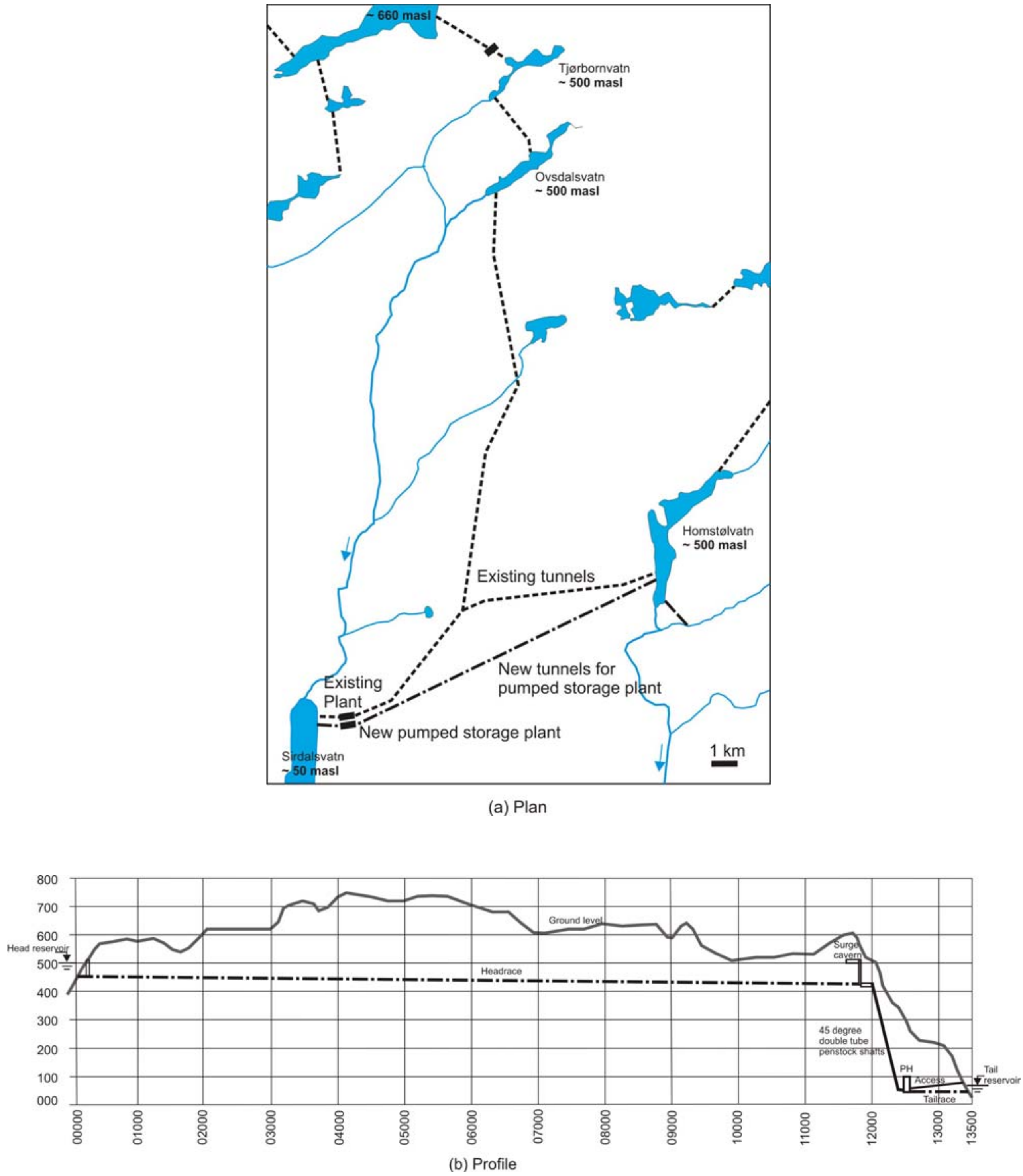

Figure 11. Layout plan (above) and profile (below) for proposed 1000 MW Tonstad pumped storage project

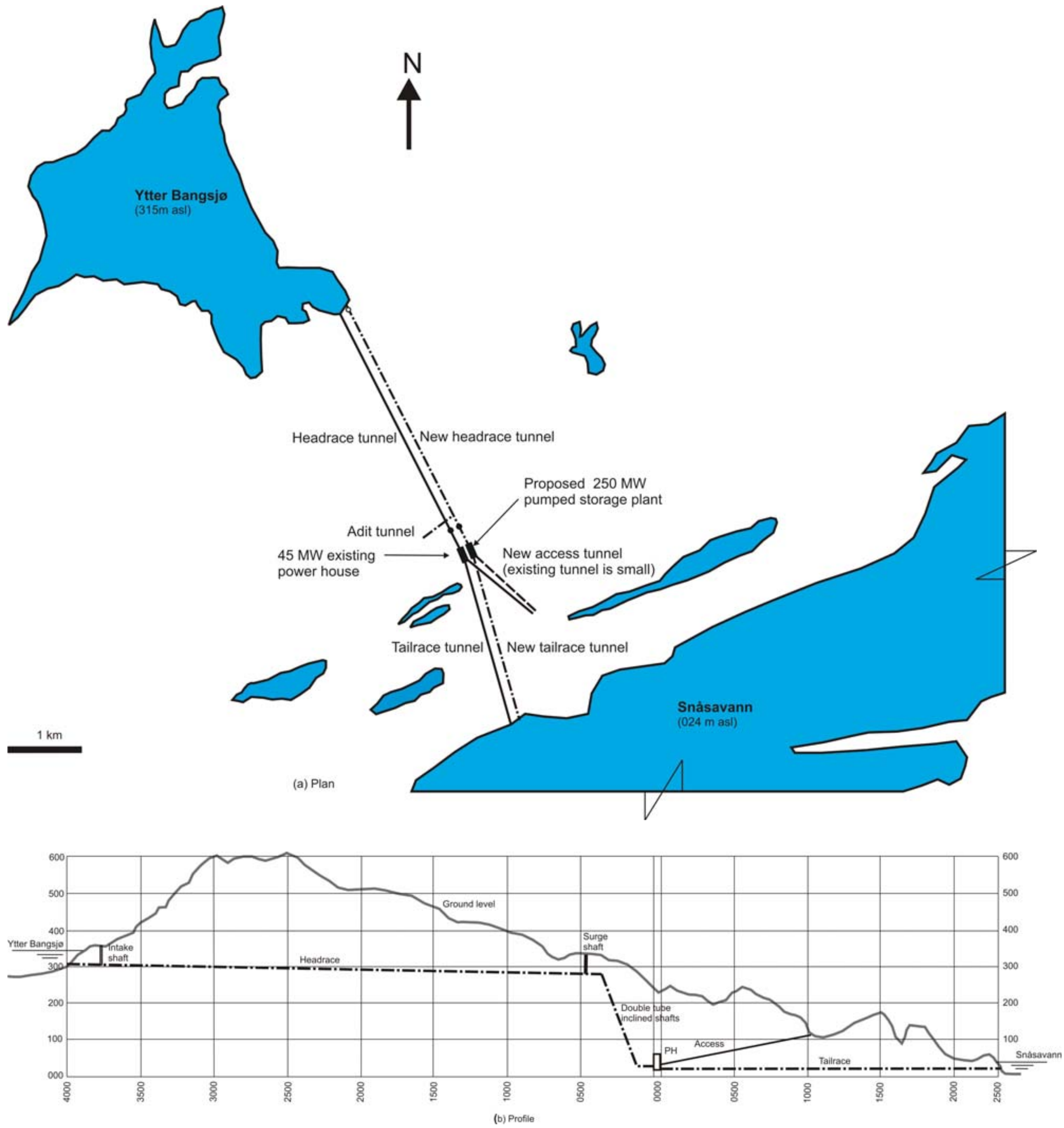

Figure 12. Layout plan (above) and profile (below) for proposed 250 MW Bogna pumped storage project (Drawings provided by Nord-Trøndelag Elektrisitetsverk (NTE))

For the proposed pumped storage plants, the reversible pump-turbine-generator units will be used for both electricity generation and water pumping. As shown in Figure 10 and 11, both projects consist of existing head reservoirs for pumped storage facilities and the tail reservoirs will function as storage facilities for the water discharged from the tailrace system after power generation. The standard design proposed for both schemes is shown in Table 3.

Table 3. Basic calculations for 1000 MW and 250 MW plants, respectively

Power Calculation	Unit	ALT 1	ALT 2
Density of water	kg/m3	1000	1000
accelaration	m/s2	9.8	9.8
Gross water head	m	445	291
Output	MW	1000	250
Effyciency co-eficient		0.8	0.8
Flow rate	m3/s	287	110
Turbine width	m	11.2	9.1
Turbine height	m	12.0	10.0
Power generation capacity of single unit	MW	250	125
No of units		4	2
Regulation requirement			
Estimated discharge time	hours	53	547
Water volume	m3	54,689,291	215,784,768
Headrace and tailrace tunnels			
pi		3.14	3.14
Flow vilocity	m/s	2.3	2.3
Required tunnel cross section	m2	124.6	47.6
Diameter of single inverted D-shaped DBM tunnel	m	11.8	7.3
Diameter of single TBM tunnel	m	12.6	7.8
Diameter of double circular TBM tunnels	m	8.9	5.5
Length of headrace tunne	m	12000	3600
Length of tailrace tunnel	m	1000	2600
Volume of headrace tunnel	m3	1495469	171516
Volume of tailrace tunnel	m3	124622	123873
Surge shaft			
Diameter of surge shafts	m	20	20
Surge shaft (20m diameter)	m	125	50
Volume of surge shaft	m3	39270	15708
High pressure shafts			
Inclination	degree	45	45
Diameter of circular double penstock shafts	m	5.9	4.1
Total length of pressure shaft	m	1409	973
Volume of pressure shafts	m3	38198	12554
Underground powerhouse			
Width	m	20	18
Height	m	40	35
Length	m	157	73
Volume of powerhouse	m3	125440	45864
Access tunnels			
Diameter/height	m	7	7
Access adit to surge shaft	m	450	
Access adit to headrace tunnel	m	300	300
Access adit to tailrace tunnel	m	150	150
Access tunnels	m	250	1000
Access shaft at intake (5 m diameter)	m	50	50
Volume of access tunnels	m3	51285	64408
Total excavation length	**m**	**15890**	**8796**
Total excavation volume	**m3**	**1874285**	**433923**

As shown in Table 3, the installed power generation capacities for two different alternatives are set to 1000 MW and 250 MW. These two alternatives have a gross head of 445 m and 291 m respectively, and an efficiency coefficient of 0.8. The flow velocity in the headrace and tailrace tunnels has in this case been set to 2.3 m/s. The inclined double tube high pressure shafts are considered to have a flow velocity 8 m/s. The 1000 MW capacity plant has 4 power generation units, each having installed capacity of 250 MW. On the other hand, the 250 MW plant has 2 power generation units, each having installed capacity of 125 MW. The longitudinal layout of each plant is similar to traditional hydro electric power plants and consists of long headrace tunnel, surge shaft, 45° inclination high pressure shaft, underground power house, tailrace and access tunnels. Access adits are also provisioned to get access at different levels installation. In total, approximately 16 000 m and 9 000 m of underground excavation is needed for 1000 MW and 250 MW pumped storage plants, respectively.

Table 3 also suggests that our standard design plants produce 1875 m^3 of rock excavation per MW installed capacity (for the 1000 MW plant) and 1735 m^3 of rock excavation per MW installed capacity (for the 250 MW plant).

2.3 Waterways

The calculation indicates that both schemes require surge shafts to dampen the up-surge and down-surge effects during sudden power plant closure and start-up. The calculation indicated that 125 m and 50 m high surge shafts with a diameter of 20 m are required for 1000 MW and 250 MW plants, respectively. It needs to be noted here that for the first case, the height of the surge shaft may be reduced considerably by introducing aair-cushion surge chamber or similar facility.

The headrace, tailrace, access and adit tunnels are either unlined or shotcrete lined. Traditional drill&blast method of excavation is considered for all these tunnels. As can be seen in Table 3, an equivalent TBM diameter (double tube or single tube) for the headrace tunnel is also given, so that possibility for the use of TBM is not fully discarded. The total length of headrace tunnels for 1000 MW and 250 MW plants are 12000 and 3600 m, respectively. The designed headrace and tailrace tunnels cross-section are 125 and 48 m^2, respectively.

The 45° inclined parallel high pressure shafts for each plant will supply 287 and 110 m^3/s discharge to the turbines, respectively. The length of each pressure shaft is 712 m and 500 m for 1000 MW and 250 MW plants, respectively. The excavation diameter of each pressure shaft is designed to be 5.9 and 4.1 m, respectively. Inclined pressure shafts are considered to be either excavated by TBM or raise boring.

2.4 Power house cavern

The dimension of the power house cavern is evaluated as per the requirements of turbines, generator units and electrical appliances. Assuming single unit of 250 MW each, four units are required for designed standard plant capacity of 1000 MW. The estimated dimensions of the power house cavern will be 20 m wide, 40 m high and 157 m long.

Similarly, assuming single unit of 125 MW each, two units are required for designed standard plant capacity of 250 MW. The estimated dimensions of the power house cavern then will be 18 m wide, 35 m high and 73 m long.

2.5 Access tunnels

To fulfil the access requiremenst of the power plant, different access and adit tunnels are purposed. An excavation diameter of 7 m with a shape of inverted D is suggested to be used (Table 3). The same access tunnel may be used for 1000 MW Tonstad pumped storage project. Only a by-pass access is needed to connect the new power house cavern from the existing access tunnel. However, in case of 250 MW Bogna pumped storage project, a new access tunnel needs to be excavated since the existing access tunnel has only 4 m wide section, which is too small for 250 MW plant.

The following main access and adit tunnels are believed to be required for the smooth construction and operation of the proposed pumped storage hydro electric plants;

For 1000 MW Tonstad plant:

- By-pass access to new power house caverns, cross section approximately 50 m^2 (7 x 7 m)
- Gate shaft to the headrace tunnels at intake (5 m diameter)
- Adit access to headrace tunnel cross section approximately 50 m^2 (7 x 7 m)
- Adit access to the top of surge tank cross section approximately 50 m^2 (7 x 7 m)
- Adit by-pass to the bottom of inclined shafts cross section approximately 50 m^2 (7 x 7 m)
- Adit by-pass to the tailrace tunnel cross section approximately 50 m^2 (7 x 7 m)

For 250 MW Bogna plant:

- Access tunnel to new power house caverns cross section approximately 50 m^2 (7 x 7 m)
- Gate shaft to the headrace tunnels at intake (5 m diameter)
- Adit access to the headrace tunnel cross section approximately 50 m^2 (7 x 7 m)
- Adit by-pass to the bottom of inclined shafts cross section approximately 50 m^2 (7 x 7 m)
- Adit by-pass to the tailrace tunnel cross section approximately 50 m^2 (7 x 7 m)

In overall, approximately 1200 m and 1500 m long access tunnel is required for the proposed 1000 MW and 250 MW plants, respectively. This will give an estimated excavation volume of approximately 51 000 and 64 000 m^3 rock excavation. Due to a need for inverted D-shape, drill&blast method of excavation is more appropriate for these tunnels.

3 Construction method, investigations and support

3.1 Construction methods

The headrace tunnels are considered to be excavated by TBM and all other underground excavations are done with the drill&blast method. As described before, there is a huge experience from such work in Norwegian geological conditions.

3.2 Investigations

The requirement for investigation and planning will be considerably higher for building a new pumped storage project than for enlarging/rebuilding an existing conventional plant. Evaluations for the main alternatives are given in the following.

Enlargement/rebuilding of existing hydro electric power project

For this alternative, extension of the power house cavern, building of additional shaft(s), some additional tunnelling and possibly enlargement of the upper and/or lower reservoir will be required. This, however, will be within the area of the existing plant where the geological conditions are mainly known. For tunnels and underground excavations, the required investigations therefore will be of a relatively modest extent. More investigation, including drilling, seismic investigation and soil testing will be needed in the reservoir areas if enlargement of reservoirs is required.

Large caverns may be considered as alternative to the conventional lower reservoir. This may have considerable environmental advantages and make the project more acceptable for the public. Such large caverns may be built and put into operation one by one, without interrupting the power production. Large caverns as lower reservoir will require additional investigations, but not of a very large extent, and less than what will be needed for enlargement of a lower reservoir.

For a project of this category, a total investigation and planning time of less than 1 year is considered realistic if new reservoirs are not needed, and minimum 1-2 years if enlargement of reservoirs is required. Construction time will be considerably less than for a new project. The concession time will depend mainly on political decisions.

Building new pumped storage projects

For a new project, quite extensive investigations will be needed, covering all tunnels, shafts, caverns and dam sites. As described above, the planning, application and decision process for a project like Meråker normally will take at least 3-5 years, and the total construction time for the Meråker project, with a relatively modest pumped storage capacity, was 3.5 years. Based on this, and the limited potential for new developments, it is very difficult to imagine that new pumped storage projects may represent the major share of the goal of 20 000 MW new hydro electric power within 10 years. It is however believed that some contribution may be achieved by this alternative.

For new projects, the cost of geological investigation may be estimated based on Figure 13, where hydro electric power projects are represented by line A and B .

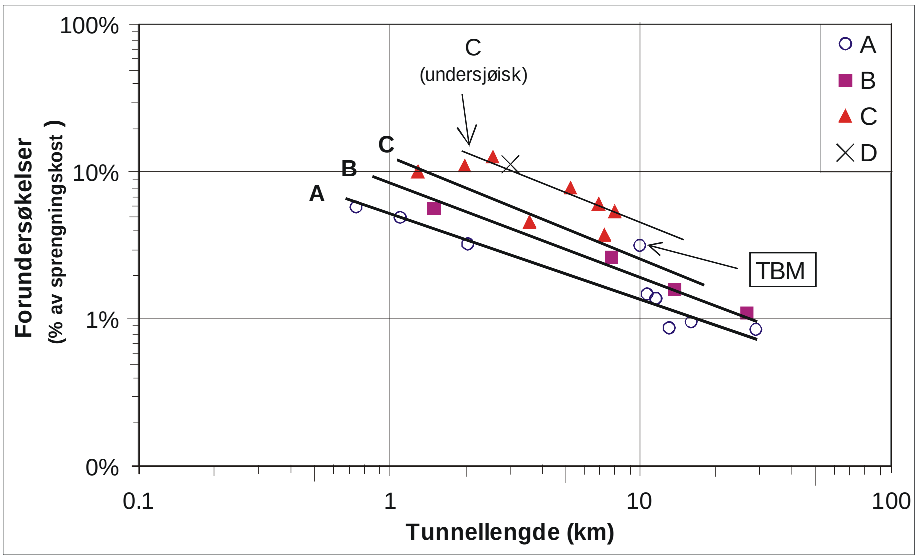

Figure 13. Recommended extent of investigation (investigation cost as % of excavation cost) versus tunnel length for different categories of tunnels. Hydro electric power tunnels are represented by line A and B. From NFR-project "Tunnels for the citizen" (Ref. Palmstrøm at.al. 2003).

Abandoned mines/shaft and caverns

For a concept with an upper reservoir and shaft to an abandoned mine or excavated caverns (i.e. Riverbank concept, Figure 18), the minimum investigation and planning time is estimated to be something between those for the two alternatives discussed above; i.e. approx. 2-3 years. This however will depend to as great extent on the site specific conditions. The greatest share of time most likely will be needed for the planning and investigation for the upper reservoir.

3.3 Rock support requirements

The stability and rock support requirement will to a great extent depend on the site specific conditions. The projects considered most relevant in this connection are however mainly located in Precambrian bedrock (mainly gneiss) on the west coast of Norway. Thus, the rock conditions will be mainly good, although some problems due to high stresses (rock spalling) and weakness zones may be expected. The rock support requirement will depend on the local geological conditions, and although general estimates will always be uncertain, some indications based on experience may be given:

- The roof of caverns generally will require 6-8 cm thick steel fibre reinforced shotcrete. Power house caverns in addition will require systematic bolting (1.5x1.5 m) and in some cases grouting.
- Walls of caverns will require bolting (approximately 2.5x2.5 m) and some shotcreting.
- Tunnels and shafts will normally require only spot bolting (<1 bolt/m), minor shotcreting (<10 % of length) and very little (<3 % of length) of heavy support (concrete lining/shotcrete arches).
- In cases with high stresses causing rock spalling, continuous shotcreting and extensive bolting (1x1 m) will be required in tunnels as well as caverns.

For site specific estimations, experience from existing parts of the project and from nearby projects should be used. Empirical methods such as the Q-system (see Figure 14) may also be useful.

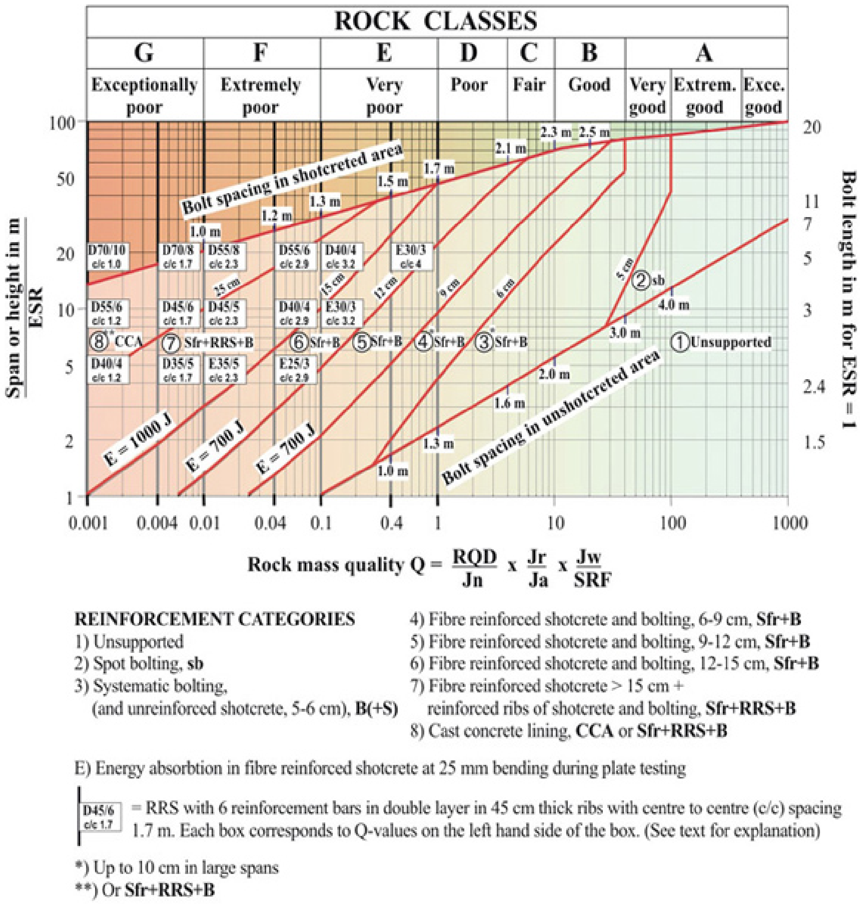

Figure 14. Updated version of the Q-system (from www.ngi.no)

4 Estimate of resource requirements

4.1 Resources related to planning and preparation of the 20 000 MW development

To be able to produce a total installation of 20 000 MW within 2030, significant efforts need to be established for the planning and preparation of the works. The following elements need to be considered in association with planning and preparation:

- Owners' organizations
- Governmental agencies and political system
- Local authorities
- Financing and legal advisory
- Consultants
- Environmental consideration

We assume that the entire process for a 250 MW project will likely take 7 years, whereof 3-4 years are related to the planning and preparation of the project whilst the physical construction is estimated to 3 years. It is assumed that in these calculations the total development of 20 000 MW is split into a total of 5 power plants each with 1000 MW installed capacity and the remaining capacity will be reached by constructing 60 250 MW plants. Assuming further that the construction works will start in 2015 with an increment of 1000 MW for 5 years, then follows the remaining installation of 15 000 MW within 10 years, averaging 1500 MW per year. It is possible that such a large number of potential sites with existing, either man made or natural upper and lower reservoirs may not exist in Norway today, however this is the basis for our estimates and assessments. To allow for a solution in case the latter situation may prevail, we have included in this report also a solution where a lower reservoir is established by excavating rock caverns for the lower reservoir, a solution which will produce substantially increased demand on the tunnelling resources.

Assuming that the construction time will be 3 years for each project, there will be an average of 13 projects under construction at any time during these 15 years. Every year the construction of 1000-2000 MW (or 4 to 8 projects) will commence. This is the scenario that we have used for the calculation of resources. However, if such an amount of installed capacity is going to be constructed, a gradual increase from zero to maximum activity must be considered as well as a fading out in the end of this period of 20 years. It means that the peak demands will be above the average demands that we are calculating. Assuming a gradual escalation to reach a maximum of production, we assess that construction works need to commence at as many as 8 projects yearly for some years when the production is at its peak, meaning that as many as between 24 projects might be under execution simultaneously during some critical years to reach completion by the year 2030. The maximum production rate annually would be up to 6000 MW in one single year as shown in Figure 15 below.

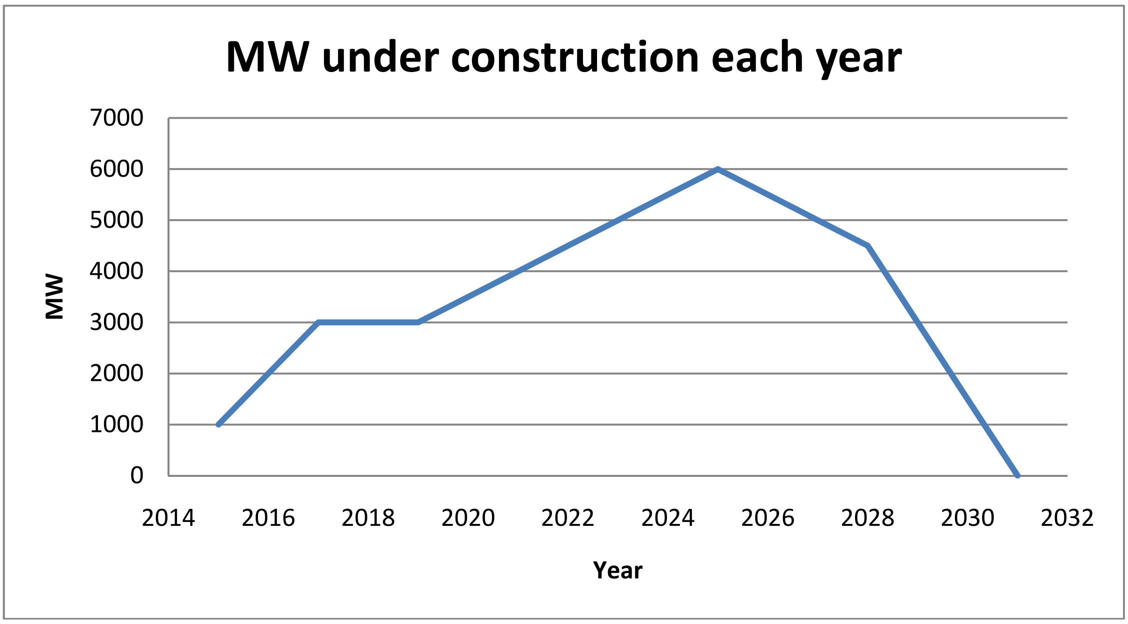

Figure 15. Number of MW under construction until 2030

The resources needed for a larger number of the above mentioned planning and preparation items would be impossible for us to estimate. However, we are able to make estimates on the resources needed related to the consulting work for the design of these plants.

As far as the resources needed from the Owners organization and the Governmental agencies and political system are concerned, our gut feeling and intuition suggest that with the proposed schedule both these would be highly stressed to comply with the demands for high speed processing of plans and approvals.

Assuming that the design process of each of these power plants would be in the range of 3-6 % of the construction costs, we are able to assess the resources needed to do the design of the plants. As can be seen in Figure 5 above, the cost per plant can be calculated based on some actual cost figures and installed capacity. It seems that the cost vary from approximately 0.2 million USD/MW to approximately 2 million USD/MW being the two extreme values of minimum and maximum. In between these extreme values, both the cost estimate for Tonstad (3 million NOK/MW installed capacity) and the project costs for Tianhuangping (5 million NOK/MW installed capacity) fit quite well. A qualitative approach of 1 million USD/MW would be fair to present for further evaluation (equal to 6 million NOK/MW installed capacity).

Assuming a figure of 5 % being related to consulting fees for such a project, we arrive at 0.3 million NOK/MW in consultancies. Further, one man year in average cost would be 1 million NOK which means that a total of 6000 man years would be required to design 20 000 MW. Converting 6000 man years to a relevant number of drawings, we arrive at a total of 240 000 drawings, assuming that each drawing would require 40 man hours for production. This again will be 12 drawings per MW.

Taking the highest recorded costs of 2 million USD/MW and assuming that the annual cost for a man year in consulting is slightly higher than the above estimate; e.g. 1.2million NOK per year, we arrive at 0.5 man year per MW, or about 10 000 man year in consulting services for the entire scheme of 20 000 MW. During a period of 15 years, this will be 700 man years per year. This is considered being the maximum need as far as we are able to assess at this point in time. It means further that at peak production of 6000 MW a total of 72 000 drawings will be needed, which is equivalent to almost 3 million man hours, or close to 2000 man years to cope with the peak demands.

We estimate the total amount of employees in the consulting services in Norway to be about 5000 people, or producing 5000 man years per year. With a demand of 700 man years per year to produce 20 000 MW, we see that some 20 % of the total consulting business will be engaged in this work.

Thus; we conclude that as far as the consulting services are concerned it would be reasonable to expect that the efforts needed can be served within the current business. Consulting work associated with the deliverables of machines and equipment being prepared by the various suppliers themselves is not included in this estimate. However, at peak production there will be a significant stress on the consulting deliveries and careful planning would be strictly required to avoid the consulting services being the bottleneck in the development of 20 000 MW until year 2030.

4.2 Resources related to construction of the 20 000 MW development

The following elements need to be considered in association with construction:

- Owners' organizations
- Governmental agencies and political system
- Local authorities
- Financing and legal advisory
- Consultants
- Suppliers of construction equipment, materials and machines
- Environmental consideration

We base our estimates for the construction period on the same assumptions as for planning and preparations, i.e. a total of 5 power plants of 1000 MW and 60 power plants of 200 MW each built from 2015 to 2030.

Again, we are only able to estimate the resources related to construction, i.e. the organizations of the owners and the contractors.

As far as the resources needed for the Owners organization during construction of a 200 MW power plant, we base the estimate on some simplified assumptions. There are three main items to be constructed: The power house, the tunnels and the reservoir caverns. Assuming an average of 5 persons dedicated to each of these items plus a general management of 10 persons, results in 25 persons employed by the owner for each of the plants during construction. With a construction time of three years resulting in an average of 500 man years per year in the Owners' organizations. A large part of these man years will be drawn from the same human resource pool as those 700 man years for planning and preparation. But we still believe that the total consulting business will be able to supply the necessary capacity.

According to Table 3, the excavation volume per MW is 1735 m^3 for the 250 MW alternative and 1855 m^3 for the 1000 MW alternative. In Section 1.5 it is shown that the corresponding volume based on historical data from around 1980 is 3500 m^3 per MW. Hence, we may expect a more efficient power plant with regard to construction volumes and costs. The main reason for this is the utilization of already existing upper and lower reservoirs, the relatively high head and no need for water transfer tunnels in the upper reservoir system.

In the estimation of necessary recourses, we assume an excavation volume of 2000 m^3 per MW, applicable for both alternatives.

The following volume must be excavated for Alternative 2 of 250 MW:

- Power house and tunnels: 500 000 m^3

Presupposing highly efficient excavation of these volumes in good rock conditions, one may attach the following excavation cost:

- Power house and tunnels: 300 NOK/m^3

When including other costs such as rock support, concrete works, project management and interest during construction, our experience is that the total cost of civil works are roughly twice the excavation cost. For a 250 MW power plant, the civil works will then amount to 300 million NOK.

Assuming that one man year in this type of construction works has a production value of 3 million NOK, one 250 MW power plant will represent 100 man years, and the total of 20 000 MW will represent 8000 man years. With a construction time of 15 years, the average need will be 535 man years per year to construct the tunnels and caverns for the plants. However, the peak construction rate may be as high as 6000 MW in one year, resulting in a need for 2400 man years in that specific year.

The current average production of tunnels is roughly 4 million m^3 per year. Assuming that the average cross section size of these tunnels is 60 m^2, this represents 66.6 km of tunnel per year. If one presupposes a weekly advance rate of 40 m/week and 44 productive weeks per year, it would take one tunneling team 38 years to excavate that tunnel length. A typical tunneling team consists of 30 persons, resulting in around 1140 man years per year in the current Norwegian tunnelling production, corresponding to an excavation volume of 3500 m^3 per man year.

Assuming that the hydro electric power tunnels being analyzed here will be more efficient to excavate than the average tunnel being excavated in Norway today, the excavation volume may be increased from 3500 m^3 to 4000 m^3 per man year. 20 000 MW with an excavation volume of 2000 m^3 per MW gives a total volume of 40 000 000 m^3. Distributed over 15 years, this is an average of 2 700 000 m^3 per year. In the peak year the volume will be 12 000 000 m^3. Hence, the average need will be 675 man years per year and the peak need will be 3000 man years. An issue in any such development would be related to the disposal of the excavated rock material.

According to the two approaches evaluated above, the average need for construction personnel will be between 535 and 675 man years per year, while the peak year will need between 2400 and 3000 man years. Thus; we may conclude that as far as the construction services are concerned, it would be reasonable to expect that the efforts needed cannot be served within the current business without targeted recruitment actions.

Further, we may assume that the capacity of one drilling jumbo is about 125 000-150 000 m^3 (slightly higher for a vertical bench blasting concept than for a horizontal tunnelling jumbo) per year. Given that the yearly required production capacity per plant is approximately 1.1million m^3 and with 6.6 sites going on simultaneously, the total demand would be around 60 jumbos with a 80 % utilization for the 20 000 MW development. This is 1.5 times the number of drilling jumbos in activity today. We have to assume that all other back up services, loading and hauling etc., will have the same factor of multiplication, i.e. 1.5 times the current equipment capacity. Manufacturing of construction machinery is a global industry, and the industry is assumed to have the necessary production capacity to cover the need for machines for the hydro power project discussed here.

5 Cable tunnels

The purpose of establishing such pumped storage hydro electric power projects is to serve Europe with power to balance other power supply sources. This means that cables need to be built from Norway to Central Europe to convey power both ways. During the last year, the discussion on 'Monstermaster' (i.e. high voltage transmission lines) across Norwegian landscape has been a hot issue in the political debate.

To enable such balancing power supply to be established in Norway, it might be a necessity to provide solutions that include cables in dedicated tunnels to avoid the environmental impact and political discussions and possible delays originating from such issues.

Therefore we would like to address the issue in this report to trigger this to be discussed in the CEDREN project.

There might be various solutions to using tunnels for high voltage cables, the two main solutions in our view would be as the following:

1. Dedicated full size tunnels by TBM. Allowing a diameter of 2-2.5 m would be sufficient to include cables and provide access and inspection possibilities. However, such tunnels may have a restricted length, probably up to 5 km from one access point. Increasing the size of the tunnel to e.g. 3.5 m diameter TBM (corresponding to typical TBMs used for hydro electric power development in Norway in the 1980s) would have a range of 15 – 20 km from one access point. It would be possible to utilize the drilll&blast excavation technique, but the length of tunnel from a single access would be very limited with such small cross sections. From the environmental point of view as well as costs and time, these tunnels should have as few accesses as possible.

Figure 16. Hard rock TBM diameter 3.8m courtesy by Robbins Company

This solution allows inspections to be done by individuals, either by foot or by small vehicles if the tunnel inclinations can be overcome. This allows repair works to be undertaken quite easy as necessary man power as well equipment can be brought in by self propelled vehicles.

2. Another possibility would be to drill dedicated small diameter holes, in the range of 0.5 - 1 m in diameter by directional drilling. This means that the drilling unit is remotely operated, but equipped to drill in dedicated directions and can be adjusted to the planned alignment if deviations take place. This technology is not yet developed fully to cope with the demands that would exist for such cable tunnels.

   A. There are various specifications that can be brought forward for such small scale tunnels. Some of these would be as follows:

      a. Drill individual holes for each of the cables with diameter of0.5m - 1.0 m and with a length of 10-15-20 km.

b. Support these tunnels with short rock bolts and/or sprayed concrete if needed based on remote operation. As an alternative, precast concrete segmental lining or steel tube lining could be applied.
c. Pull the cables in and through the small tunnels remotely.
d. Leave the tunnels for the operation time of 50-100 years without inspection and in water filled condition, or filled with other inert fluids.
e. If inspection is required, this could be done by bringing in remote controlled camera, and any repair needs to be done using remote operated vehicles that enter the tunnels.

B. At present the technology may not be developed to such extent that this alternative would be fully applicable today. However, bringing in technology from various industries like the oil industry would likely speed up the process in developing technologies and solutions that enable such small size cable tunnels to materialize in the future.

C. The technology involved in this second alternative for dedicated cable tunnels is not fully developed for this purpose. In addition, there are certain issues or challenges associated with such an approach that need to be further investigated and researched. These are typically related to such items as; ensuring sufficient stability and factor of safety related to collapse and instability in small scale tunnels, maintenance, operational aspects, and particularly in the case of repair works are deemed necessary.

Figure 17. Norhard equipment for drilling 700 mm directional drill hole (Photo: www.norhard.no)

The issue of cable tunnels is far from a fully developed concept. However, the recent discussions on 'monstermaster' suggests that alternative solutions should be considered and carefully elaborated to enable potential balancing power production become a realistic possibility in the future. In that case, a distribution cable network would be required and the possibility of utilizing the tunnel technology in Norway would provide an alternative that is associated with less environmental concerns. Also the issue of excavated rock material and the discharge and permanent disposal would be an issue to solve for such cable tunnels.

6 Alternative solutions (Underground Pumped Hydro electric energy Storage (UPHS))

6.1 Background and references to underground pumped hydro electric energy storage

An alternative solution if it is impossible to find projects in Norway which have sufficient size of upper and lower reservoir, would be the concept of **Underground Pumped Hydro electric energy Storage** (**UPHS**), which is an energy storage method. A surge of interest in this subject happened in the late 1970s and early 1980s, but essentially no new literature on this subject has surfaced for over two decades. On the economic side, most of the literature agrees that UPHS may make economic sense for installations sized between 1000 and 3000 MW. It is of note that no large-scale utility sized UPHS plant has ever been built [1].

In pumped hydro electric energy storage systems, water is pumped to a higher elevation and then released and gravity-fed through a turbine that generates electricity. Most large hydro electric installations rely on hydraulic heads of at least 50 m, with average head of about 140 m. Since head height is proportional to energy, power, and efficiency, a larger head is desirable (within limits). It is also desirable to minimize the transverse length of the water flow path to reduce friction losses.

Underground pumped hydro electric energy storage is an adaptation of conventional surface pumped hydro electric storage that uses underground caverns as the lower reservoir. This alleviates many of the problems with surface pumped hydro electric installations. An underground system may have a vertical water flow path, which eliminates losses associated with transverse water flow. The environmental impact of an underground installation is less than conventional pumped hydro systems because only one surface reservoir is required, also eliminating potential river dams, large power houses on the surface, wildlife habitat disruption, and noise. The impact is further reduced by using an existing reservoir as the upper reservoir of the pump storage facility.

Riverbank Power, a Canadian limited liability company, has developed the so called Aquabank system following the UPHS concept, which uses rock caverns deeply seated below the sea level as the lower reservoir [2]. Three projects of this type have been investigated, of which one is the Wiscasset project. Figure 18 is a sketch of the project layout. The project has 1 GW installation capacity and uses six large underground galleries that would receive the discharge flow from the power house cavern and function together as the lower reservoir. The galleries will have combined capacity to store the discharge flows from six hours of generation in the power house. The galleries are to be connected at their bases by a tunnel for water conveyance. A further series of tubes across the tops of the caverns will provide ventilation and be connected to a single, independent shaft to the surface. Each gallery is to be about 27.4 m wide by 45.7 m high. In total, the combined length of the galleries is to be approximately 4270 m, which would make each, on average, approximately 712 m long. To be excavated in suitable geology, the galleries are to free-stand in unlined rock. The power house includes four reversible pump turbines and the estimated annual energy production from a standard plant is 2190 GWh. Water will be conveyed down four 4 m diameter vertical penstocks, each almost 670 m in length and lined with concrete and steel, to the power house.

Initial design work envisages a 5.9 km long permanent access ramp, constructed with a D-shaped section that is 11.6 m wide and 7.9 m high. The ramp tunnel would have a maximum slope of 10 %. This has been chosen to help reduce the tunnel length. Additionally, separate shafts would be constructed that would not only serve ventilation purposes for the galleries but also allow separate access to, and exit from, the power house complex. The power house is expected to be more than 44 m high, possibly up to 48.8 m.

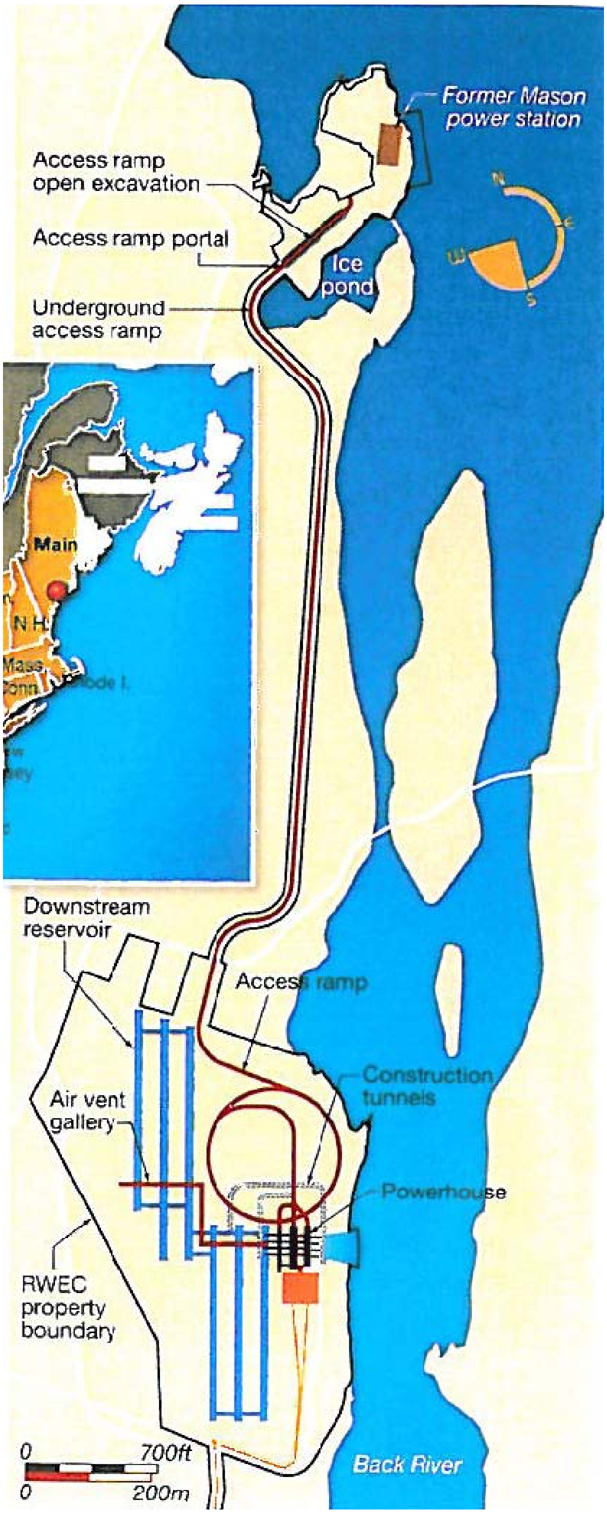

Figure 18. Tunnel layout and location of Riverbank Power's proposed pumped storage project at Wiscasset (Ref. Tunnels & Tunnelling Intnl)

6.2 General layout

For estimating of the resource requirements, the following standard conceptual design is proposed based on the UPHS concept. The lower reservoir is placed in mined unlined rock caverns of large cross section at a low elevation, such providing an enhanced reliability. The power house is located underground in an unlined rock cavern approximately at the same level as the lower reservoir caverns. The reversible pump-turbine-generator units will be used for both electricity generation and water pumping such that the double waterway system is avoided. The installed power generation capacity for a single unit is considered to be 100 MW. The reservoir for an existing hydro electric power station is used as the upper reservoir of the pump storage facility. The headrace and tailrace tunnels are also unlined except the section of the headrace tunnel immediately adjacent to the power house, which has to be lined with steel and concrete. The drill&blast method will be used for excavation of the caverns and most tunnels except the headrace and tailrace tunnel, for which TBM (Tunnel Boring Machine) may be considered in order to reduce the head losses.

With regards to the installation capacity of the standard design, two alternatives have been considered, i.e. 500 and 200 MW with water head 500 and 300 m, respectively. An efficiency coefficient of 0.8 is taken into account and the flow velocity in headrace and tailrace tunnels is taken as 1.2 m/s. The typical layout is illustrated in Figure 19. Basic calculations are listed in Table 4 and a summary of the excavation volume is given in Table 5.

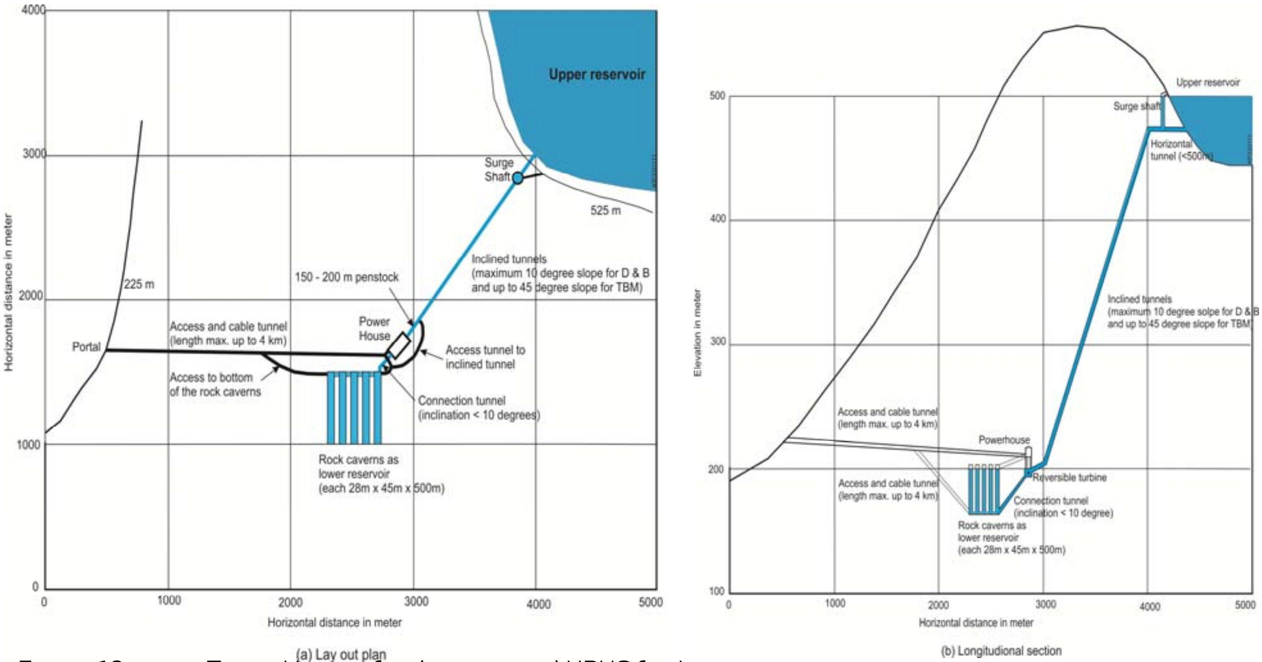

Figure 19. Typical layout for the proposed UPHS facility

Table 4. Basic calculations for 200 MW and 500 MW installations using lower reservoirs in dedicated rock caverns

Power calculation	Unit	ALT 1	ALT 2
Density of water	kg/m3	1000	1000
accelaration	m/s2	9.8	9.8
Water head	m	500	300
Output	MW	500	200
Effyciency co-eficient		0.8	0.8
Flow rate	m3/s	127.6	85.0
Power generation capacity of single unit	MW	125	100
No of units		4	2
Headrace & tailrace tunnels			
pi		3.14	3.14
Flow vilocity	m/s	1.2	1.2
Required tunnel cross section	m2	106.3	70.9
Diameter of single circular tunnel	m	11.6	9.5
Diameter of double circular tunnels	m	8.2	6.7
Tunnel inclination	degree	45	45
Length of Inclined headrace (twin tunnels)	m	1414	849
Length of Tailrace (twin tunnels)	m	500	500
Volume of headrace tunnels	m3	150320	60128
Volume of tailrace tunnels	m3	53146	35431
Lower reservoir			
Continuous discharge time	hour	8	8
Effective volume of lower reservoir	m3	3,673,469	2,448,980
Usage rate		0.90	0.90
Total volume of lower reservoir	m3	4,081,633	2,721,088
Cavern length and cross section			
width	m	28	28
height	m	45	45
length	m	500	500
arch height	m	10	10
cross section area	m2	1,191	1,191
volume of single cavern	m3	595,700	595,700
No of caverns needed		6.85	4.57
No of caverns		7	5
Total length of caverns	m	3,500	2,500
Total volume of caverns	m3	4,169,900	2,978,500
Connection tunnel			
width	m	5	5
height	m	5	5
length	m	168	112
volume	m3	4,200	2,800
Underground powerhouse	m		
Width	m	18	20
Height	m	35	40
Length	m	100	70
Volume	m3	63000	56000
Access tunnels			
Access and cable tunnel (7 x 7 m)	m	4000	4000
Access to bottom of the rock caverns (6 x 6 m)	m	500	500
Access tunnel to the top of cavern (6 x 6 m)	m	250	250
Adit access to inclined headrace bottom (6 x 6 m)	m	350	350
Total length	m	5100	5100
Total volume	m3	183600	183600

Table 5. Summary of excavation volumes

SUMMARY		
	ALT 1	**ALT 2**
Cavern volume (m3)		
Powerhouse	63000	56000
Lower reservoir	4169900	2978500
Total	**4232900**	**3034500**
Tunnel length (m)		
Headrace	1414	849
Tailrace	500	500
Connection tunnel	168	112
Access tunnels	5100	5100
Total	**7182**	**6561**
Tunnel volume (m3)		
Headrace	150320	60128
Tailrace	53146	35431
Connection tunnel	4200	2800
Access tunnels	183600	183600
Total	**391267**	**281959**

Based on Table 5, the following volumes must be excavated for Alternative 2 of 200 MW:

- Reservoir caverns: 2 980 000 m^3
- Power house and tunnels: 340 000 m^3

Presupposing highly efficient excavation of these volumes in good rock conditions, one may attach the following excavation costs:

- Reservoir caverns: 200 NOK/m^3
- Power house and tunnels: 300 NOK/m^3

When including other costs such as rock support, concrete works, management and interest during construction, our experience is that the total cost of civil works are roughly twice the excavation cost. For a 200 MW power plant, the civil works will then amount to 1 040 million NOK.

Assuming that one man year in this type of construction works has a production value of 3 million NOK, one 200 MW power plant will represent 350 man years. With an average of 6.6 plants commencing every year, the average need will be 2300 man years per year to construct the plants. The peak year would require more than four times that number, i.e. around 10 000 man years.

As estimated in Section 4.2, there is around 1140 man years per year in Norwegian tunneling given the current annual production.

Thus; we may conclude that as far as the construction services are concerned, it would be reasonable to expect that the efforts needed to develop 20 000 MW by cavern reservoirs until 2030 cannot be served within the current industry capacity. It would require around two times the man power capacity of today, and 1.5 times the capacity with respect to drilling jumbos and equipment.

6.3 Lower reservoir caverns

The effective volume of the lower reservoir is estimated by the capacity of accommodating 8 hours discharge from the turbine. Considering the unusable space at the cavern roof and the dead volume at the cavern bottom a a conservative number of 75 % of usage ratio is adopted. The cavern dimensions proposed are 28 m wide, 45 m high and 500 m long, making the volume of a single cavern 595 700 m^3. For the two design alternatives, eight and five such caverns are needed.

All caverns are connected to each other with at least one tunnel at the base level of the caverns for water conveyance so that the caverns can work as a united reservoir. The caverns must also be ventilated to the surface to evacuate or supply air during filling or emptying of water in the caverns.

6.4 Other schemes

CAES (Compressed Air Energy Storage)

In compressed air energy storage, off-peak power is taken from the grid and is used to pump air into a sealed underground cavern to a high pressure. The pressurised air is then kept underground for peak use. When needed, this high pressure can drive turbines as the air in the cavern is slowly heated and released; the resulting power produced may be used at peak hours. The caverns may consist of such as aquifers, solution-mined salt caverns, (depleted oil/gas field) and mined rock caverns. A CAES system may have very large capacity up to 300 MW and it has very fast start-up time as short as 9 minutes.

The first utility-scale CAES project was the 290 MW Huntdorf plant in Germany (1978). The second was the 110 MW McIntosh plant in Alabama (1991). Both of these projects use salt domes for air caverns. Currently under development is the Iowa Stored Energy Park, a 270 MW project which will use aquifer-based air storage. A 300 MW project utilizing depleted gas storage is being developed in California, and a 150 MW salt-based project is under development in upstate New York. The first adiabatic CAES project, a 200 MW facility called ADELE, is planned for construction in Germany in 2013.

Another plant currently under development is being designed by Norton Energy Storage LLC in America. Their site is a 10 000 000 m^3 limestone mine 700 m deep, in which they intend to compress air up to 100 bar before combusting it with natural gas. The first phase is expected to be between 200 and 480 MW and cost $50 to $480 million. Four more stages are planned, to develop the site to a possible capacity of 2500 MW. Research has been done in Israel to build a 3 times 100 MW CAES facility using hard rock aquifers.

Use of abandoned mines as the lower reservoir

Investigations have been carried out in recent years studying the use of abandoned mines as the lower reservoir for a pump storage hydro electric power project. Recent examples include the proposed Summit project in Norton, Ohio, and the Mount Hope project in New Jersey, which was to use a former iron ore mine as the lower reservoir. The Marmora project, Ontario, Canada, will use a water-filled abandoned mine and an upper reservoir in a closed-loop configuration. Pump-turbine-generator units will pump water up into the reservoir during off-peak periods and then release it back down into the mine during on-peak periods to generate electricity. The design provides for an average head of 140 m, producing 400 MW of power to enable time-shifting to support renewable energy sources and grid demand patterns.

A new concept is to use wind turbines or solar power to drive water pumps directly, in effect an 'Energy Storing Wind or Solar Dam'. This could provide a more efficient process and usefully smooth out the variability of energy captured from the wind or sun.

7 Summary and conclusions

Through a formal cooperation between two institutes at NTNU and one department of SINTEF, the Gemini centre on Underground technology has prepared a report on the possibility of developing 20 000 MW of hydro electric power production in Norway during a period of 15 years. The client has been the CEDREN project (Centre for Environmental Design of Renewable Energy) through its subproject on HydroPEAK.

In Norway some 30 GW of installed hydro electric power capacity has been developed during a period of several tens of years. This is based on high head, small amounts of water, continuous production. Future power needs will require different concepts in the future, also in Norway. The power supply planned to be developed in this report would be electrical power to balance the European wind production. The report looks at the possibility of producing this development through pumped storage facilities, which are capable of having production durations of a few days to a couple of weeks.

A schedule has been presented with an increment of 1000 to 2000 MW annually during this period of 15 years. This means a peak development of 6000 MW in one given year. The concept is based on utilising the current concessions that exist and to the extent possible use the upper and lower magazines conditionally that they are of such robustness that this possible.

Although future development for such hydro power utilisation may involve some reduction in resources needed compared traditional hydro electric power development in Norway, we asses that a total of almost 2000 m^3 of rock is required to produce 1 MW installation. Such development will have a significant impact on the consulting business as well as the construction business in Norway.

We have been looking at the possibility of developing 5 large production projects, namely 5 projects each with 1000 MW installed capacity, and then 60 projects each having 250 MW installations. The average production in tunnelling excavation is expected to be in the range of almost 3 million m^3 per year, with a peak reaching more than 10 million m^3. This production rate will come in addition to the yearly ordinary production volume within the tunnelling industry. Consequently, as the situation is today in this industry it is hardly believed that the current parties are able to absorb this amount of work with the current manning and equipment. It would be required to increase the capacity of the industry with significant resources to enable such a development to take place. And over the duration of these 15 years one may look at the total need of approximately 30.000 man years during the 15 years period of construction works according to our findings.

8 References

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