Proceedings of the NROCK 2023
The IV Nordic Symposium on
Rock Mechanics and Rock Engineering
ISBN 978-9935-9436-2-0
DOI 10.33112/nrock2023.3

The potential for geothermal energy exploitation in Norwegian tunnels

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ABSTRACT

Renewable thermal energy is a highly sought-after resource in many parts of the world, as a measure to reduce our reliance on fossil fuels and electric power as energy sources for space heating of buildings. Shallow geothermal energy is one of the preferred environmentally friendly thermal energy resources in Norway, where heat stored underground is utilized in conventional heat pump systems via 200-300 m deep boreholes. However, the underground space in our urban areas are under continuous development and puts increasing demand on both surface and sub-surface city planning. The public need for infrastructure tunnels, road or railway tunnels, is most often prioritized rather than development of geothermal systems. Tunnels can thus be a hurdle for the planning and further development of geothermal utilization in cities. In many European countries' tunnels are now increasingly considered as a source of thermal energy in their self. Large volumes of rock mass and groundwater are made available in tunnels and the tunnel can be "activated" for harnessing the heat energy within, so called *Energy tunnels*. The potential for utilizing geothermal energy from Norwegian tunnels via heat pump systems is now being investigated. The tunnels can be activated in several manners, where both passive closed loop systems or active open loop groundwater systems are the two main potential solutions. The applicability of incorporating these systems are here assessed for the Norwegian tunnel design and an initial view on the potential for utilizing our tunnel infrastructure is given. The potential thermal energy available in existing road and railway tunnels alone range in the several TWh scale if all tunnels are activated. The many thousands of kilometers of tunnels in Norway might thus become a future energy resource and a potential pathway to reach our climate goals and to increase the rate of energy transition to renewable energy sources.

KEYWORDS

Geothermal energy; Tunnels; Heating & Cooling Potential; Urban development

1. INTRODUCTION

The Norwegian energy mix in the building sector has traditionally been dominated by electricity generated by hydro power facilities, which for many decades have provided abundant, affordable and environmentally friendly energy. However, the current energy crisis and shortage of electricity and fossil gas in Europe has affected the global energy market and has sparked an increase in energy costs that has never been seen in Norway until now. The cost increase has triggered energy saving actions in all parts of society and we now see an increase in the rate of energy transition to renewables and alternative energy sources. Renewable thermal energy is a highly sought-after resource in all parts of the world, particularly as a measure to reduce our reliance on fossil fuels and electric power as energy sources for space heating of buildings and industrial processes. This is also the case for Norway and it is expected that the rate of geothermal utilization will see a swell in new development in the years to come.

Shallow geothermal energy is one of the preferred environmentally friendly thermal energy sources in Norway, where heat stored underground is utilized in conventional heat pump systems via 200-300 m deep boreholes, so called energy wells. This is deemed favorable because it is a local form of energy production that reduce the load on the power-grids and require less infrastructure development than the traditional high-voltage electricity system. Reduced need for electric power leads to reduced reliance on, and more independence from, economical and political situations that can affect the operational costs of a heating system. In the northern European countries, the need for heating is particularly apparent, but energy utilized for cooling applications and air/surface/process conditioning is increasingly relevant also here, especially for many new buildings in Norway due to the updated building code standards and regulations.

Both a buildings' heating and cooling demand can be realised with shallow geothermal energy systems, and particularly cooling is favorable due to the relatively low annual temperatures in the ground in Norway. A review study carried out in 2011 showed the important role that shallow geothermal energy can play in Norway's energy mix, where essentially all the heating and cooling required by Norway's building mass and industry can be covered by shallow geothermal systems, amounting to a saving of approximately 36.7 TWh of the electric energy annually (Ramstad, 2011). This saving on electric energy can then be made available for utilization in other sectors, which Statnett (the system operator of the Norwegian power system) project to have a significant increase in electric demand towards 2050. In short terms Statnett estimate that Norway's electric energy needs will increase by 24 TWh within 2027, resulting in a negative energy balance in four years. Thus, increased use of shallow geothermal energy now seems even more relevant than ever, especially given the increasing economic competitiveness of heat pump systems due to the high cost of electric and fossil energy on the European market. Today it is estimated that Norway has approximately 60 000 shallow geothermal systems in operation, producing 3.0 TWh of heat annually (Midttømme et al., 2020). The potential for further development is particularly apparent if these figures are compared to the 590 000 shallow geothermal systems in operation in Sweden, producing 17.1 TWh annually (Gehlin et al., 2020).

The underground space in the urban areas around the world are under continuous development and puts increasing demand on both surface and sub-surface city planning. One issue for conventional geothermal systems in urban cities arise when energy wells must compete with other underground infrastructure for the same underground space. The need of the public for infrastructure tunnels is most often prioritized over the geothermal systems of private contractors or building owners. These challenges are now increasingly being met by stakeholder and innovation & research communities by integrating energy systems directly into infrastructural components of buildings, the so-called *energy geostructures,* better known as *energy piles*, *energy walls*, *energy slabs* and so forth. While the thermal yield of such geostructures does not always match that of optimized conventional boreholes, the objective of using sub-surface structures is to potentially reduce the capital costs for shallow geothermal energy systems as well as adopting these systems into urban areas, where land availability is an issue.

Energy tunnels is one such integrated system where the tunnel itself is used for thermal energy production and heat and cold storage purposes. A variety of tunnel types can be employed for this purpose; road and railway tunnels, sewer systems, caves & mines, bomb shelters etc. The main difference of design and utilization rely primarily on how the thermal energy is accessed in these tunnels and at which temperature the heat can be extracted. Norway as a country has long tradition from tunnelling and use of our underground space, with more than 2100 tunnels and caverns nationwide, and today Norway still has a high tunnelling activity in our major urban cities (NFF, 2022). The potential for utilizing our tunnel infrastructure for energy purposes is thus a potential pathway to reach our climate goals and to increase the rate of energy transition to renewable energy sources.

2. ACTIVATION OF TUNNELS FOR ENERGY UTILIZATION

As with all shallow geothermal systems used for heating and cooling applications, tunnels can be activated for energy utilization via two different types of geothermal system designs, namely the *closed loop* system or the *open loop* system. In the closed loop design the tunnel is equipped with embedded heat exchanger elements (Figure 1), e.g. integrated HDPE pipes or steel plate heat exchangers, which circulates a heat carrier fluid within a tunnel piping network. The fluid within these pipes absorbs heat indirectly through these pipe walls and is able to perform also bellow freezing temperatures, as is typical for conventional borehole systems. The open loop design employs a pumping system that extract energy directly from water that is intruded into the tunnel, e.g. groundwater that enter via the fractures in the surrounding rock formation. The main criteria for employing the open loop system rely on the native water temperature within the tunnel, which must be above freezing levels. This inevitably vary depending on the location of the tunnel in question. One example of this variation is e.g. documented by Rybach (2010) whom has shown that in Switzerland the water temperature vary form 10 – 50 °C depending on the tunnel location, length and depth bellow the ground surface. In Norway the climate is colder than in Switzerland, which can pose a challenge for open loop system in situations where the water is close to freezing temperatures during the winter.

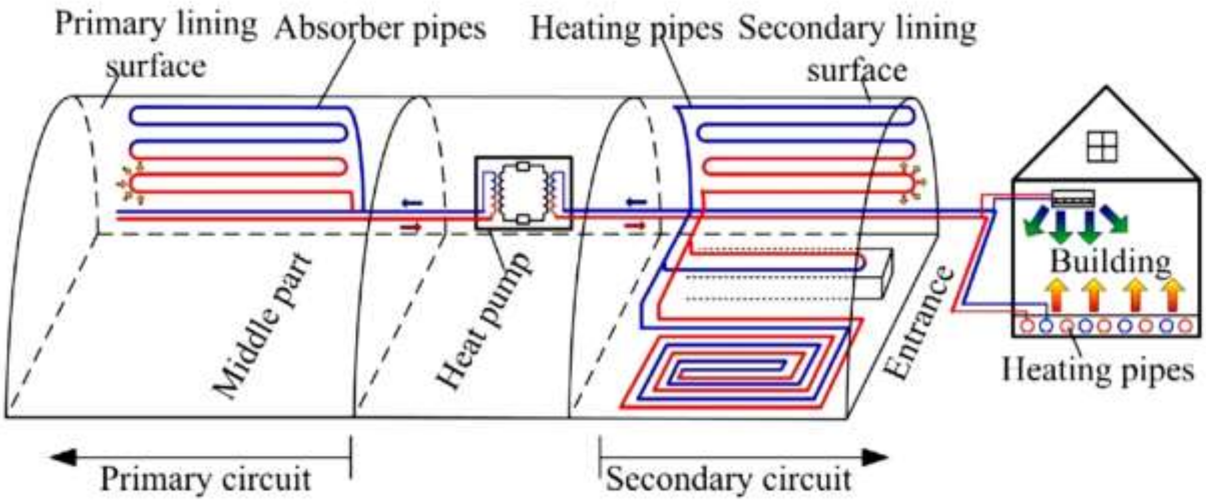

Figure 1: Principles for closed loop tunnel lining embedded heat exchangers (Zhang et al., 2014)

Different uses of the extracted and injected heat are mentioned in the litterateur, such as heating and cooling of subway stations or buildings near the tunnel (Nicholson et al., 2014; Barla et al., 2016; Stemmle et al.; 2022), heating the tunnel lining itself (Zhang et al., 2014), de-icing at the tunnel portals (Islam et al., 2006), road pavements, bridge decks and plattforms (Dupray et al., 2013; Bowers and Olgun, 2013). In Norway the potential for utilizing a tunnel in this manner is not widely recognized. Nevertheless, the concepts are employed in sewer tunnels in several of our largest cities. The VEAS-tunnel in the city of Oslo was equipped for this purpose already inn the 1980's where one of the tunnels in the sewer system is utilized as an open loop heat source for a local 30 MW district heating system, producing approximately 130 GWh annually for the surrounding customers. A closed loop sewer system is employed in the city of Stavanger where a 500-kW heat pump system produce 1,5 GWh of energy each year and provides heating and cooling to the town hall and associated buildings in the city center (Grønnestad, 2017).

The concept of utilizing road and railway tunnels as thermal energy sources was tested already in the early 2000's and world wide there are now reports of test pilot facilities in Japan (Islam et al., 2006), South Korea (Lee et al., 2012), China (Zhang et al., 2014), Germany (Schneider & Moormann; 2010), Austria (Markiewicz, 2004; Unterberger et al., 2004), Switzerland (Stemmle et al., 2022) and Italy (Barla et al., 2014; Insana, 2020;). Recently the concept has seen an increased interest among researchers and stake holders, as is evident by the increasing number of studies that investigate the thermal potential in different countries. Stemmel et al. (2022) has reviewed the current activity on activating road and rail tunnels in Europe and Asia and state that the most common configuration world wide, in view of number of tunnels, is the closed loop design with integrated pipe systems. However, the thermal potential in these installations are not elaborated and most installations seemingly only activate smaller sections of the tunnels, rather than complete and full-scale activation. The largest closed loop installation covers approximately 3 330 m^2 of the Reinstein tunnel B10 (Csesznák, Järschke & Wittke; 2016), where 6 720 meters of 25 mm PEX pipes are integrated into the tunnel wall lining (Figure 2).

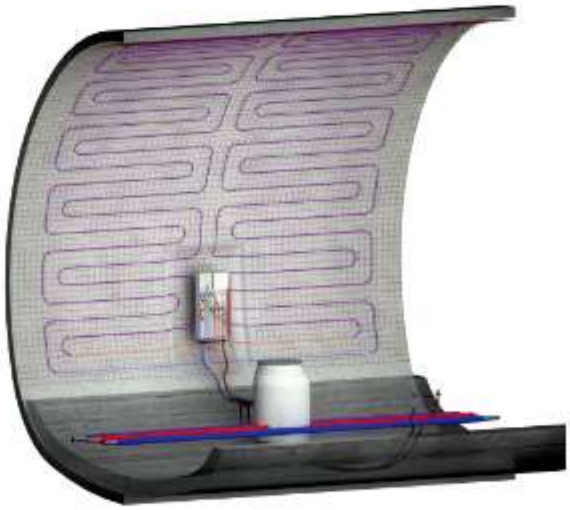

Figure 2: The PEX pipe installation principle in the Reinstein tunnel B10 (Csesznák, Järschke & Wittke, 2016).

The integration of closed loop piping systems in tunnels in a cost-effective manner is perhaps the biggest hurdle for tunnel activation in practice. Tunnel design and construction is mainly governed by other engineering aspects than energy optimization, which inevitably require the piping system to adapt to the construction method of choice. In many European countries the tunnels are designed to cope with soil and soft bedrock conditions, resulting in a tunnel design that rely heavily on concrete lining elements in the tunnel construction. The construction of precast concrete elements with integrated pipes is an advantage for tunnel boring machine (TBM) tunnelling, whereas drill & blast (D&B) tunnelling rely on onsite customisation. In this aspect the differences between countries in engineering tradition and construction customs plays a vital role.

The most straightforward and cheapest form of tunnel heat usage is reported by Rybach (2010) to be open loop systems that collect and transport inflowing waters via ducts to the tunnel portals (Figure 3). The determination of thermal potential of such open loop drainage water systems is quite intuitive, as the thermal power potential (P [kW]) scale proportionally with the amount of water drained (Q [L/s]) and the useful temperature drop (ΔT [°C]) available of the water, as shown in equation (1) (with C_P being the thermal capacity of water (kJ/l,°C)).

$$P = Q \cdot \Delta T \cdot C_P \qquad (1)$$

Rybach (2010) has investigated this thermal potential for 15 road and rail tunnels in Switzerland and report of potential production rates in the range of 150 kW – 11 693 kW thermal power per tunnel. The outflow rates of drainage water are the governing factor for these systems, where the flow rates reportedly vary from 6 – 300 l/s depending on the tunnel in question. The largest drainage rates are reported from the Gotthard road tunnel (120 l/s at 15 °C) and the Grenchenberg Railway tunnel (300 l/s at 10 °C), where the drainage rates are virtually constant all year round. This stable drainage of water at constant temperatures render such open loop systems highly effective and reliant for geothermal exploitation and theoretically, if the thermal energy can be utilized all year round (8750 hours of operation), these two tunnels alone can annually produce energy in the range of 39,5 GWh – 102,3 GWh, respectively.

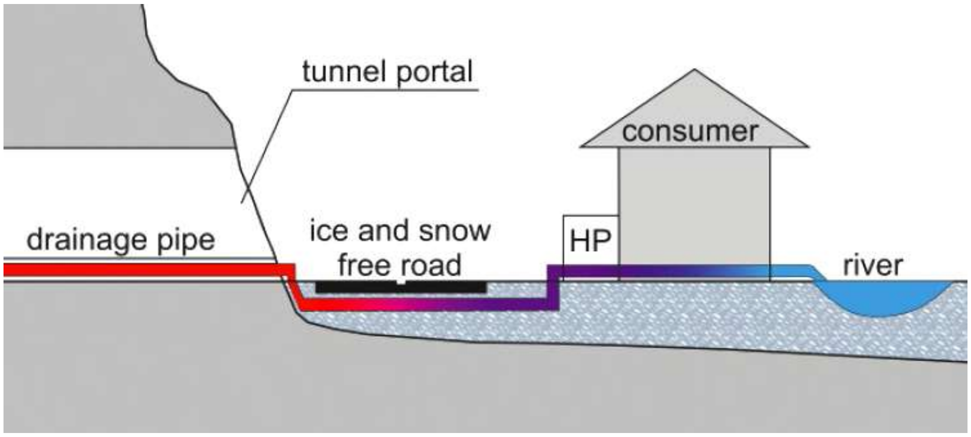

Figure 3: Principle for open loop system and typical examples for heat utilization (Stemmle et al. 2022)

3. NORWEGIAN TUNNELLING ACTIVITY & TUNNEL DESIGN

Historically the tunnelling activity in Norway was centered around the hydropower development in the early 70's towards the late 80's, which culminated in more than 4000 km of hydropower tunnels. The main activity today is related to large infrastructure projects in the major cities across the country, predominantly related to road and railway tunnels. Norway now has more than 1000 road tunnels and 750 railway tunnels totaling more than 3000 km of length (Grøv et al., 2004). The length of tunnel excavated in Norway the last 20 years is approximately 50 – 100 km annually (Figure 4), where roughly 65-70 % of the over-all tunneling volume corresponds to the construction of road and railway tunnels.

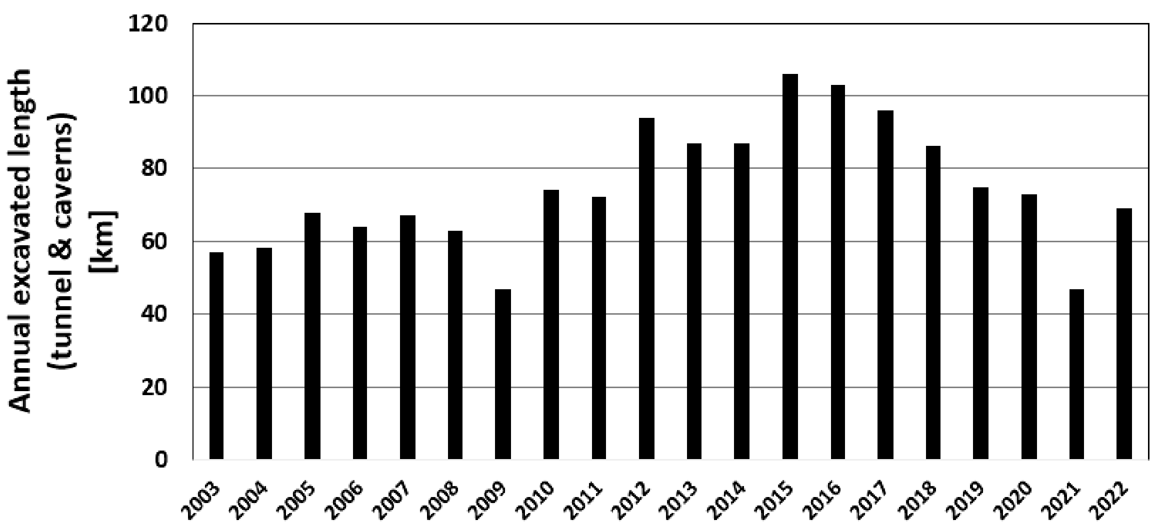

Figure 4: Tunnelling production in Norway (NFF, 2022)

The typical road and railway tunnel concepts are designed with a fully drained structure, where the mechanical stability of the tunnel is primarily supported by rock bolts and sprayed concrete. A water and frost protection system is usually installed as a separate independent freestanding structure via a membrane & insulated pre-cast concrete segment lining. The lining is customized depending on the frost load for the tunnel in question. Water is thus diverted from the carriage-way and guided towards drainage channels in the tunnel invert (Figure 5), which transport inflowing waters via ducts to the tunnel portals or to pumping stations.

Most modern road tunnels therefore have an open space behind this segment lining which is available for thermal activation via the closed loop design. The native rock temperature is found to govern the temperature within this open space, and the tunnel temperature within this envelope is rarely bellow zero degrees even though temperatures in the carriage-way might be much colder in tunnels in certain parts of the country during the winter months (Pedersen & Iversen, 2002). However, the temperature variation in Norwegian tunnels is highly dependent on a variety of factors that can impose limitations on the use of this open space for thermal systems. An optional application is to employ the closed loop system in the tunnel invert, where the drainage of water towards the ducts ensure a continuous replenishment of drainage water with native temperatures from the deeper parts of the rock mass. The annual temperature variation in this part of road and railway tunnels has not been investigated in Norway so far.

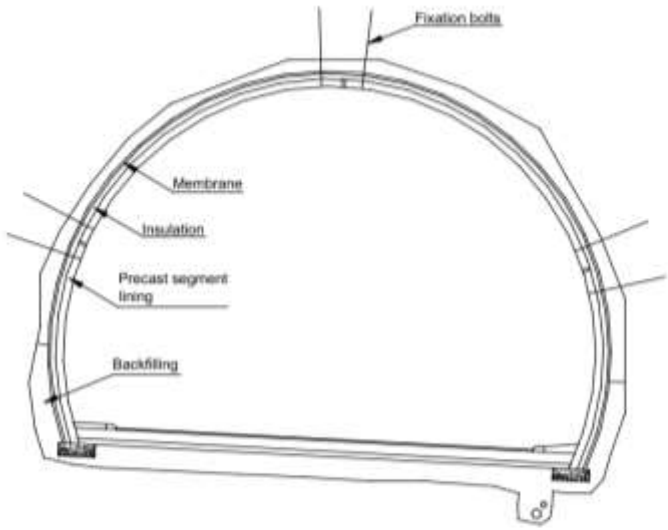

Figure 5: Design principle of pre-cast concrete segment lining for water and frost control (Grøv et al., 2004)

The most straightforward and cheapest form of tunnel heat usage in the Norwegian tunnel design is obviously the same system that is reported by Rybach (2010). The open loop systems that collect and transport inflowing waters via ducts to the tunnel portals is applicable in all tunnels, as the majority of tunnels today have installed drainage systems regardless of the potential for heat usage. The water is now simply diverted to drains and rivers outside of the tunnels. The main limiting factor will be the rate of drainage from the tunnel and whether this rate is continuous or variable throughout the year. Leakage limitations are routinely specified for construction of new road and railway tunnels in Norway, but the actual inflows are not readily available in tunnel statistics. However, inflow limitations are typically set in the range of 5 – 40 l/min per 100-meter tunnel length for most tunnel projects. Strict limitations are particularly given in urban areas to ensure limited risk of subsidence and resulting damage on surface structures. It is therefore possible to evaluate the potential of open loop system with these limitations as guide.

Subsea tunnels are particularly good candidates for open loop systems because all subsea tunnels are equipped with pumping stations at the base of the tunnel for removal of sea water. Unlike conventional tunnels, the subsea tunnels have a continuous inflow of water all year from the sea. Installing compact heat exchanger systems in these pumping systems should therefore not present itself with large additional costs for tunnel activation.

4. POTENTIAL OF GEOTHERMAL EXPLOITATION IN NORWAY

The potential for geothermal exploitation of tunnels in Norway is perhaps best evaluated by comparison with the current market activity and development of conventional borehole heat pump systems. The average size for a "large" borehole heat pump installation in Norway today typically comprise of ca. 10 boreholes of 250 meters drilled depth, totaling about 2,5 km of 40 mm HDPE ground heat exchanger length for these installations (Midttømme et al., 2020). Upon direct comparison with the average tunneling activity in Norway for the past two decades it is evident that the current construction rate of 50-100 km of new tunnels annually is equivalent to 20 – 40 such large borehole heat pump installations being installed, should only one single length of 40 mm HDPE heat exchanger pipe be installed in the invert of these tunnels. In period 2011-2019 Midttømme et al. (2020) report that there are 20 – 100 large borehole heat pump systems, with four or more boreholes, being installed each year in Norway. It is therefore evident that the current tunneling activity is proportional with the over-all large-scale geothermal development in Norway, in view of tunnel length alone.

New tunnels can however be customized in the design phase of projects to include multiple loops of heat exchanger pipes per meter tunnel, to potentially cover larger volumes of rock mass. It is essentially the tunnel size and length that limit the design size, which is perhaps difficult to compare directly to conventional bore hole systems. A conventional borehole heat exchanger is typically installed in a 140 mm wide borehole. Norway's largest geothermal system to date is the 20 GWh system in Ahus hospital in Oslo with 228 such boreholes, each 200-meter deep. These boreholes combined cover a rock surface area equal to 20 000 m^2, which essentially is the contact points towards the rock mass and the effective heat exchanger area of the system. By comparison with the typical T10,5 road tunnel size in Norway, this contact area only adds up to the circumference area of a 600-meter long road tunnel. The potential for installing comparable quantities of heat exchanger pipes in tunnels is thus seemingly not the main issue even for relatively short tunnels. It is therefore rather a question on whether the tunnel is sufficiently adjacent to a building in need of this thermal energy that will determine whether a tunnel should be activated for energy use or not.

To make use of the water in the drainage system is a promising solution in existing Norwegian tunnels due to the relatively low cost of Installing compact heat exchanger systems in existing tunnels. The potential for geothermal exploitation in this manner does primarily rely on the rate of water drainage from the tunnel in question. In practice this type of system would perform best if a given flow quantity of water is guaranteed all year round. In view of the typical inflow limitations of 5 – 40 l/min per 100-meter tunnel length it is apparent that the geothermal potential might vary significantly for each tunnel case and favors long tunnels that guide all available water to the same portal area for disposal. One possible way to evaluate the potential for this system might be to evaluate all 3000 km of road and railway tunnels in Norway in view of these limits via Eq. (1) under the assumption that the useful temperature drop available of the water is $\Delta T = 3°C$. The possible range of geothermal potential will then fall within the range 31 MW – 250 MW of thermal power and 270 – 2 180 GWh of energy for open loop tunnel systems in Norway. Still the question is whether the tunnel portals are sufficiently adjacent to a building in need of this thermal energy.

Further evaluation of these energy tunnel concepts is under way in Norway. One possible and promising tunnel case for further evaluation is the newly built 19 km long Follobanen Railway tunnel in Oslo, which has water drainage towards the center of Oslo. Here there is a pressing need for this energy and the length of the tunnel alone is so long that, even with the strictest inflow limitations, the tunnel still might provide more than 16 l/s of water towards the city and thus potentially provide more than 200 kW of thermal power.

5. CONCLUSIONS

The application and utilization of geothermal tunnel energy is a promising technology that can fit into the Norwegian tunnel design well without the need for substantial alterations of the main design methodology. The technology has a huge potential in Norwegian urban areas in view of current tunnel activity and tunnel design. Preliminary evaluation in this paper suggest that the potential thermal energy available in existing road and railway tunnels alone range in the several TWh scale if all tunnels are activated. The main question is whether the tunnels are sufficiently adjacent to a building in need of this thermal energy. Further evaluation of these energy tunnel concepts is under way in Norway.

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