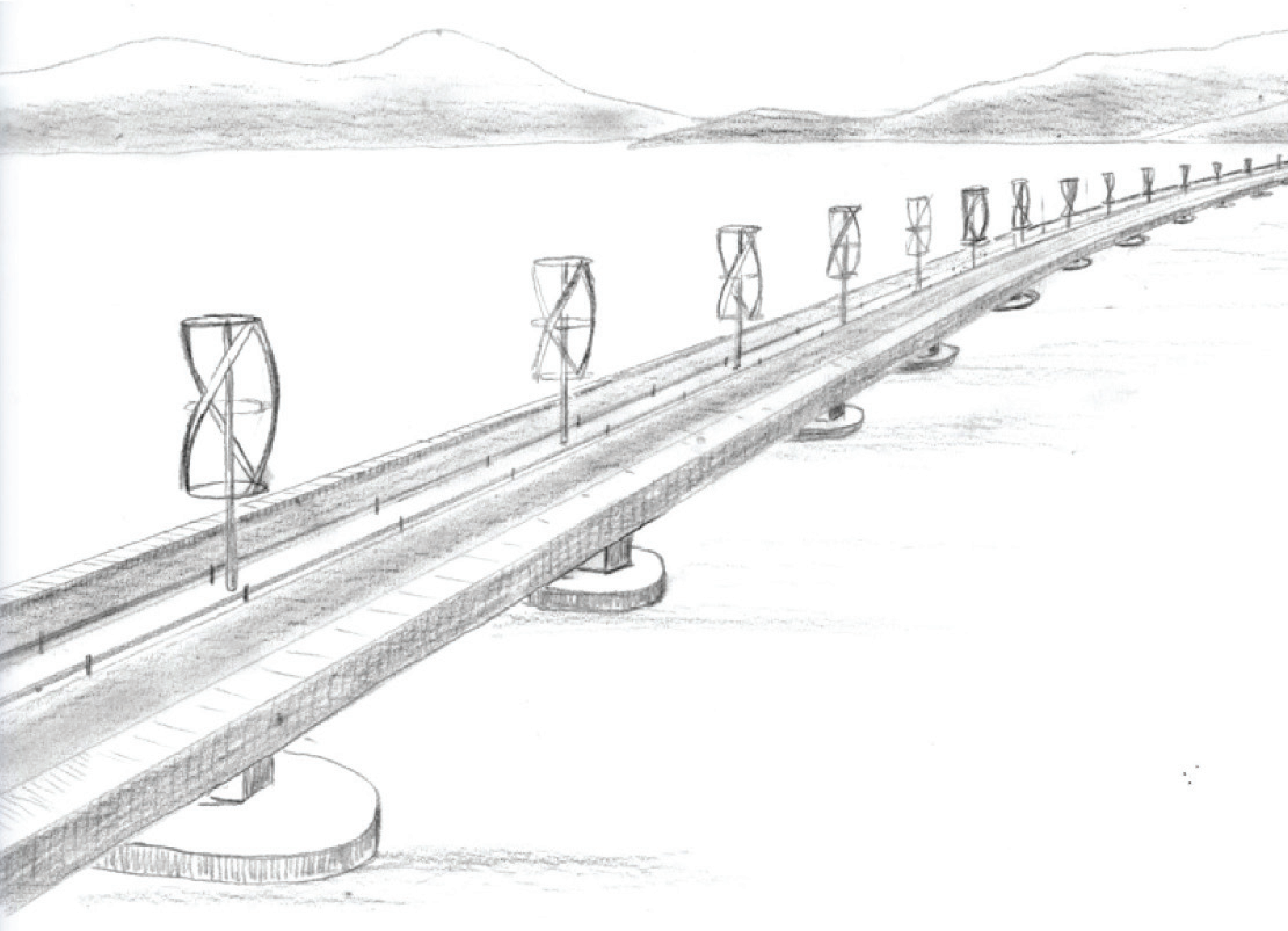
Statens vegvesen

Technology survey for renewable energy Integrated to bridge constructions

Wind and solar energy

Statens vegvesens rapporter

Nr. 110



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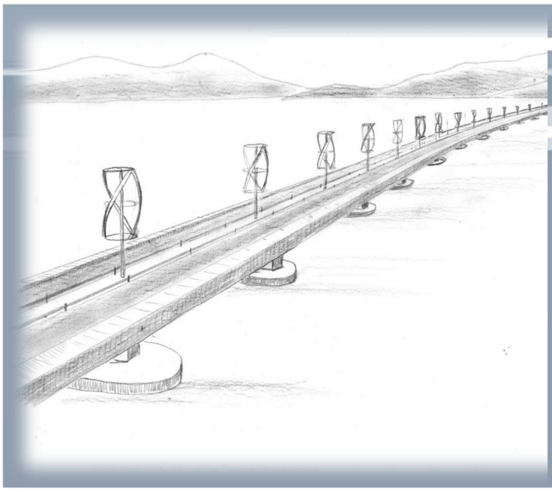
Norwegian Public Roads Administration

Technology survey for renewable energy integrated to bridge constructions

Wind and solar energy

Sub project "Energy" of the project "Ferryless E39"

2012-04-11 Assignment no.: 5120632



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Revision 0	Date: 11.04.2012	Description: Possibilities for installation of renewable energy at new bridges on the "Ferryless E39"	Prepared Eivind Sæta Silje O. Simonsen Joachim Solli Tor Kristian Sandaker Eirik B. Thorsen	Checked Erlend Aamot	Approved Sten-Ole Nilsen

Contents

Summary

This report contains a basic overview study of the possibility of installing wind or solar power on bridges to be constructed on the planned ferryless E-39 along the west coast of Norway.

An inherent issue with these future bridges is that they are placed in locations with great depths, requiring feasible structural solutions like floating bridges or suspension bridges. These are structures for which wind load is often a main governing factor regarding design, and the amount of wind power that can feasibly be installed is therefore uncertain. The resulting overturning moment created by the wind turbines, twisting the road surface, is also likely to be a critical issue.

In addition to this, bridges constitute challenging environments for electrical installations due to pollution from road traffic, salt and humidity from the sea.

Most of the sites studied are found to have relatively poor wind and solar conditions. The report concludes that installation of wind or solar power is unlikely to become economically feasible, as well as being technologically challenging for large installations. The only possible exception economically is installation of wind turbines at Boknafjorden which has average wind speed at 7 m/s, close to what could be found at commercial sites.

Although economically and technically challenging, it is by no means impossible to install wind and solar installations on the bridges studies. Some examples of possible designs are presented in the report. Based on these examples, sample costs and production numbers are estimated. All numbers for potential and cost are very tentative, as they depend completely on how much power it is chosen to install, and what challenges the integration with the bridge will cause.

One example is installation of large wind turbines on a floating bridge at Boknafjorden. Integration to the bridge may be very difficult, but can theoretically have the potential for producing over 200 GWh per year. The most optimistic cost estimates for a large scale project in Boknafjorden suggests costs down to 5 NOK/kWh, but this requires a problem free integration where the bridge provides the majority of the foundation costs. The real cost will most likely be higher.

Another option at the opposite end of the scale is to fill the bridge with many small vertical wind turbines. Depending on the installed capacity, such a concept may produce over 10 GWh at Boknafjorden. The total cost will be much smaller, but the price per kWh will be high and most likely more than 8 NOK/kWh.

A third example is the installation of a double row of side mounted solar panels along the length of the bride. Such a design would be most beneficial for a bridge with a west/east orientation such as at Julsundet near Molde. Installation there could give annual power production up to nearly 800 MWh/year (0,8 GWh). The cost is this installation could be the in area of 14 NOK/kWh excluding mounting system. Including mounting system, the cost could easily increase to more than 20 NOK/kWh.

While the studied installations are unlikely to be economical, they could still be of interest for further work. One reason for this is that environmental consequences for wind and solar installations on bridges are found to probably be smaller than for equivalent conventional installations.

In addition, such a project would be likely to attract much positive attention to the “Ferryless E39” project, and could constitute important research for similar installation at other sites.

As further work, detail studies at one or two sites based on specific bridge designs are recommended. Boknafjorden appears the most suitable for further studies of wind installation, while Julsundet could be a suitable site for further studies regarding solar installation.

1 Introduction

1.1 BACKGROUND

The E39 costal highway runs the length of the Norwegian west coast from Kristiansand in the south to Trondheim in the middle part of the country. The Norwegian Public Roads Administration (NPRA) has been commissioned by the Ministry of Transport to explore possibilities relating to replacement of all ferry links on this stretch with fixed fjord crossings. This task has been organized as a project called "Ferryless E39" with four sub-projects dealing with, respectively: potential for trade, industry, employment and settlement patterns, technological concepts for fjord crossings, renewable energy potential and implementation strategies and contracts.

The sub-project energy has further been sub-divided into one technology survey relating to tidal and wave power and another relating to sun and wind power. Norconsult has been chosen, as one of three companies, to undertake the latter. This report presents the results from the technology survey.

The basic idea behind the sub-project is to use bridges as a platform for extracting renewable energy, thereby utilizing the bridge structure for a second purpose in addition to transportation. This has already been done to some extent in hydropower, where a dam or hatch construction across a body of water sometimes has been used as a bridge. This is not un-common in river hydro power plants in Norway. There is also the famous example of La Rance in France which is a tidal power plant doubling as a bridge.

1.2 RATIONALE

With world energy consumption set to double between 2010 and 2050, and calls for curbing carbon emissions, there is an enormous need for developing new clean renewable energy production.

While there are still technological developments taking place, solar- and especially wind power are relatively mature technologies, and are being developed at a rapid rate. However, two significant challenges present themselves for further installation of these technologies: First, sun- and wind power can still not compete in cost terms with non-renewable energy. Most developments in Europe so far have been due to generous financial incentives such as feed-in tariffs or direct subsidies, and there is a need to reduce costs. Second, the famous NIMBY (not in my back yard) attitude and resulting local resistance to new renewable projects significantly affect the time and difficulty of obtaining necessary building permits in many cases.

Integration of renewable energy in bridge structures could possibly help overcome both these challenges; using the bridge structure as part of the facility can probably reduce the establishment cost, and thereby make the wind or solar plant more competitive with non-renewables. Bridges also, unlike energy production units, are generally well received by local communities. Installation of energy production on a bridge would therefore increase the chances and ease of obtaining permits. These are the basic ideas behind this survey.

1.3 ORGANIZATION

There are currently eight ferry routes on the E39 between Kristiansand and Trondheim, and the project "Ferryless E39" will look at replacing all of these with bridges. Chapter 2 in this report provides a brief presentation of each of the fjord crossings, and defines for basic data with regards to geographical location, orientation and length, that will be used as input for the analysis later. It also discusses the types of bridge structures that are most likely to be used for the crossings.

Chapters 3 and 4 constitute the main part of this report, and discuss the possibilities of integrating wind and solar power, respectively, to the bridges. Each of these chapters start with a technological background, presenting the status of the technology, main types of installations and examples of applications that are relevant for installation on bridges. Next, basic design issues related to installation on a bridge environment are discussed. This includes, for instance, loads on the structures and marine environment. Based on these inputs, some possible design solutions relevant to the E39 case are presented. The chapters then go on to evaluating the fjord crossings with regards to production potential of renewable energy, and corresponding costs, relating to the proposed designs. It should be noted that significant uncertainty is related to the costs at this stage.

In the work with this survey, several technology suppliers for solar and wind power have been contacted in order to gauge interest and collect up to date data. Chapter 7 of chapters 3 and 4 comments briefly on this. Chapter 8 of chapters 3 and 4 presents an evaluation of the potential for installing wind and solar power on bridges, respectively. Chapter 9 provides suggestions for further work.

Chapter 3 and 4 mainly look at technical and economic aspects of the installations. Chapter 5 provides a different angle by discussing environmental consequences.

Chapter 6 introduces some further perspectives, summarizes the findings, and concludes.

2 Fjord crossings on the E39

2.1 OVERVIEW

The "Ferryless E39" project looks at replacing ferry links with fixed crossings at the eight different fjord crossings shown in Figure 1 below. Plans for most of the crossings are at an early stage with regards to exact geographical location and technological solution for the bridge. Some assumptions have therefore been made in this report in order to be able to discuss specific solutions and energy potentials at each site.

Assumptions have generally been based on the status and possible solutions presented by the NPRA to the public on the industry gathering in Bergen 20th January 2012. Several possible crossings and technological solutions were presented for most sites.

In this report, two technological solutions are studied as explained in chapter 2.2, whereas only one crossing (location) is chosen for each site. The assumptions and rational for choice of crossings are explained in sub-chapters 2.3-2.10.

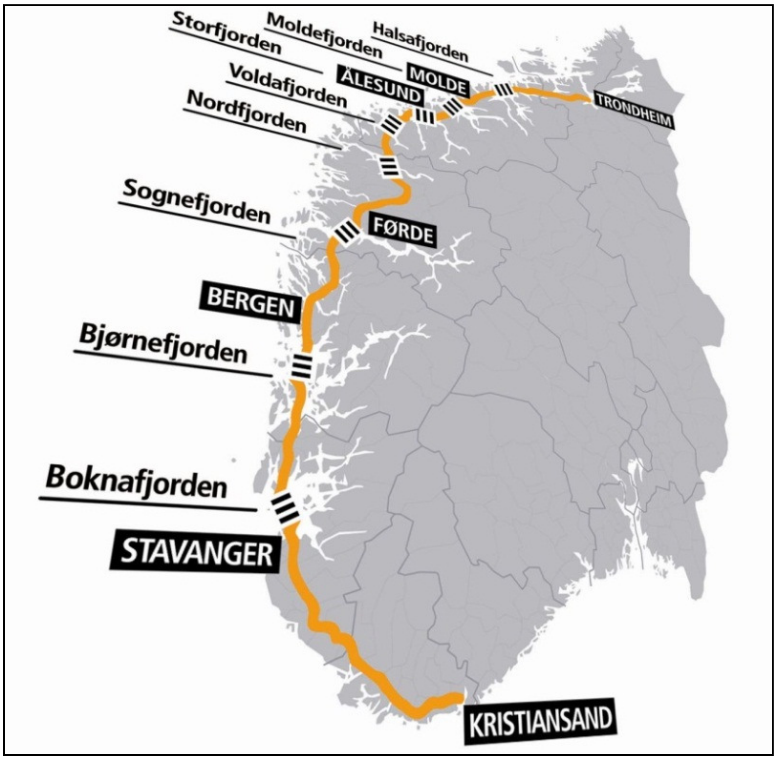

Figure 1. Fjord crossings in the "Ferryless E39" project (source: NPRA)

2.2 TECHNOLOGICAL SOLUTIONS

In the sub-project of "Ferryless E39" dealing with technological solutions for the fjord crossings, four main technological solutions are studied (Figure 2):

- Suspension bridge

- Floating bridge

- Submerged floating tunnel (SFT)

- Sub-sea tunnel

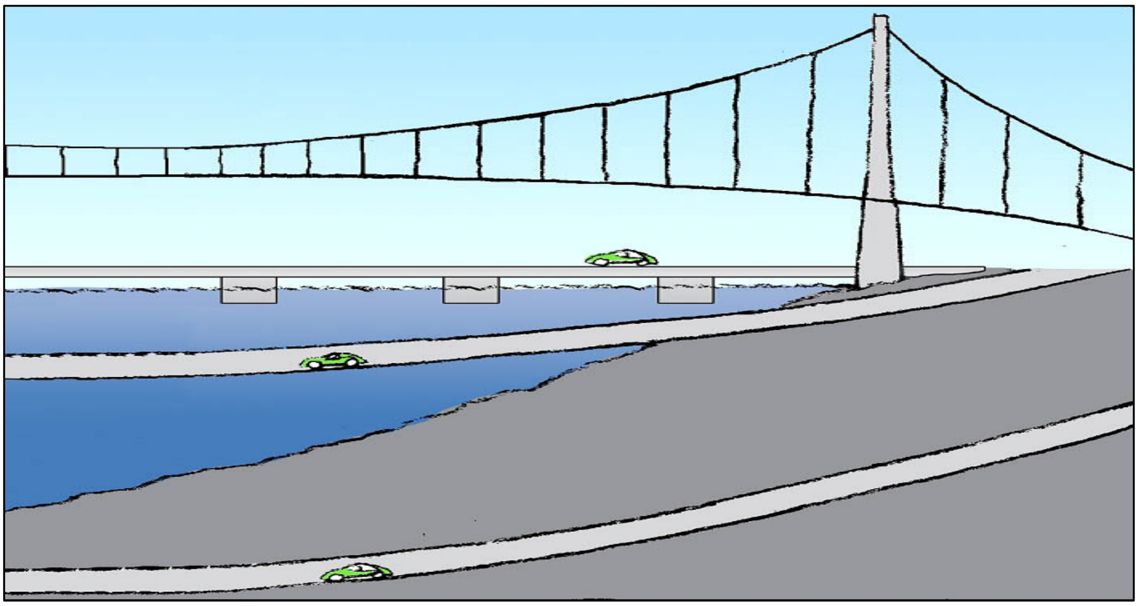

Figure 2. Main technological solutions for fjord crossings for "Ferryless E39" (source: NPRA)

The fjord crossings are technologically challenging because of great depths and widths of the fjords. Bottom fixed bridges are not feasible because of the depths.

Wind and solar power installations must be above the water surface to produce electricity. SFTs and sub-sea tunnels are therefore excluded for this technology survey, and only floating bridges and suspension bridges are considered.

2.3 BOKNAFJORD

The main solution for the Boknafjorden crossing is a 25 km sub-sea tunnel. Detail design is currently ongoing for a tunnel with two tubes 380-400 m below sea level, which may enable start in 2015. Such a solution would not be eligible for installation of sun and wind-power.

An alternative concept however presented by NPRA is a 7,5 km cable-stayed bridge on floating foundations crossing from Moravika to Arsvågen (Figure 3) [1]. The bridge is bottom anchored. This is the concept and location that has been studied in this report. Given the extreme length of the crossing, a suspension bridge concept is considered unrealistic, and has not been considered in this report.

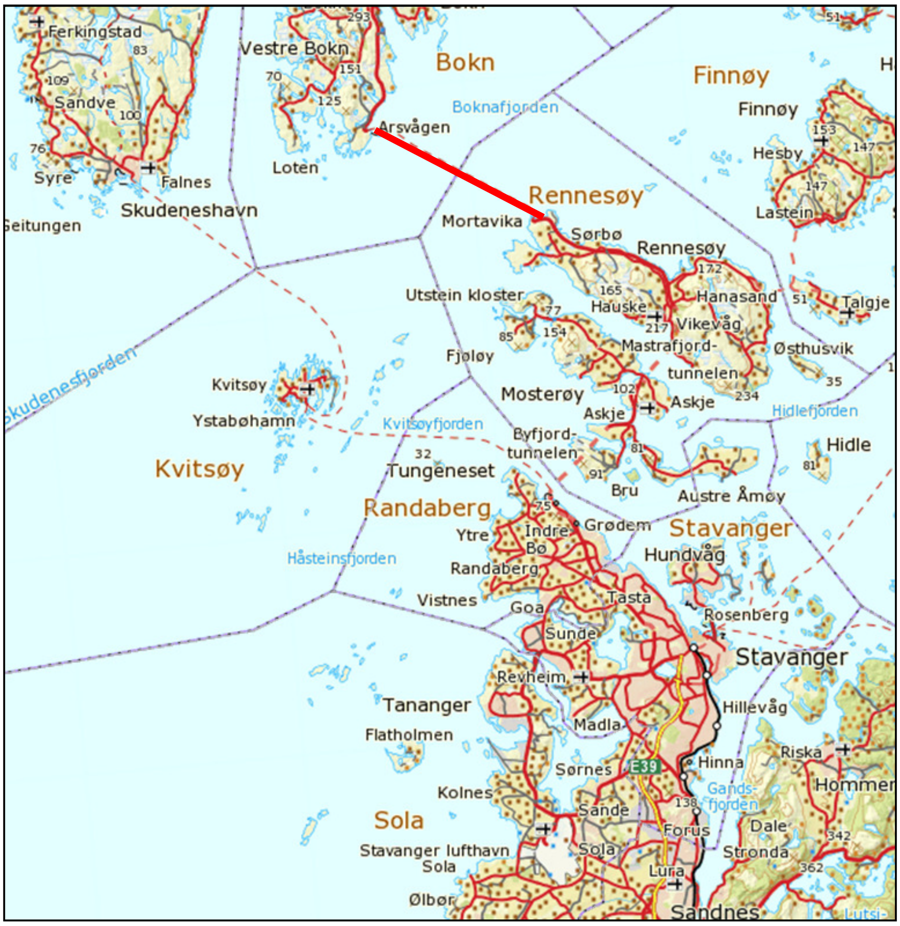

Figure 3. Assumed location of crossing at Boknafjorden

2.4 BJØRNAFJORD

For the Bjørnafjorden crossing, several different corridor concepts have been established (Figure 4).

The most likely routes to involve a suspension bridge or a floating bridge are 1) Corridor K3 with crossing Bakkasund-Sele (distance 2,1-2,5 km) 2) Corridor K5A with crossing Venjaneset-Hattvik (distance app. 2,7 km) and 3) Corridor K5B with crossings Årland-Bogøya and Bogøya Rød (distances for both crossings app. 850 m).

Of these, our understanding is that K5A and K5B are the most likely routes. The Venjaneset crossing has been chosen as the basis for this report because corridor K5A constitutes the shortest corridor of the two, and consequently the one that will lead to the greatest savings in travelling time.

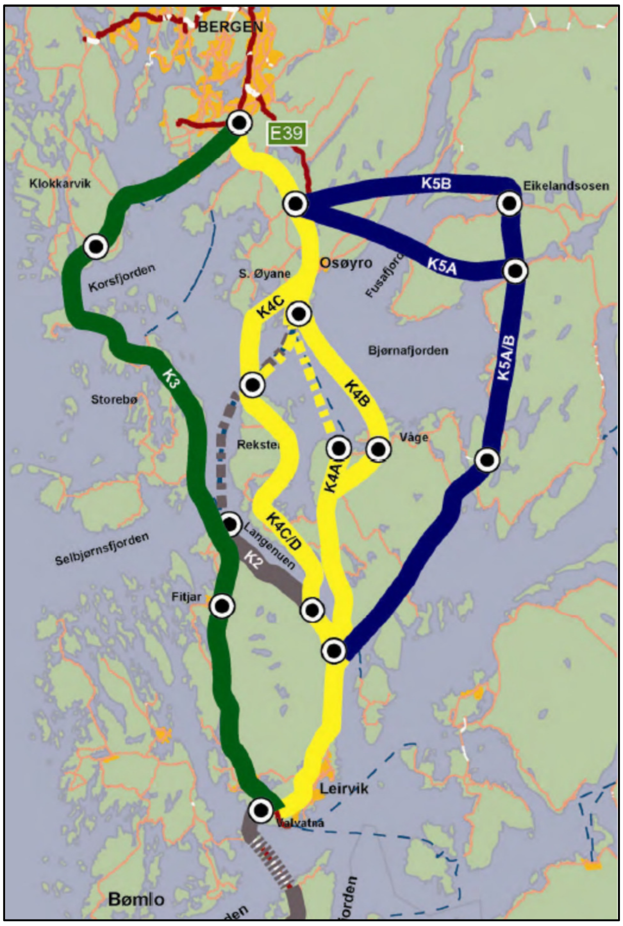

Figure 4. Corridor concepts at Bjørnafjorden. Corridor K5A has been assumed in this study

2.5 SOGNEFJORD

A feasibility study has been published for the Sognefjorden crossing [2] presenting various technological solutions for crossing the Sognefjord between Lavik and Oppedal. The 3,7 km Lavik-Oppedal location has therefore been used as a basis of the current report (Figure 5). Both solutions with a floating bridge and suspension bridge have been evaluated.

2.6 NORDFJORD

Several possible crossings of Nordfjorden have been considered by the NPRA at Anden-Lotsberg and at Faleide near Stryn (Figure 6).

The crossing near Anden crosses the fjord just east of the existing ferry route on the E39. The crossings at Faleide would require a re-rout of the E39, and give a slightly longer road. The Anden-crossing is therefore considered the most likely site for a new bridge, and has been chosen as a basis for this report.

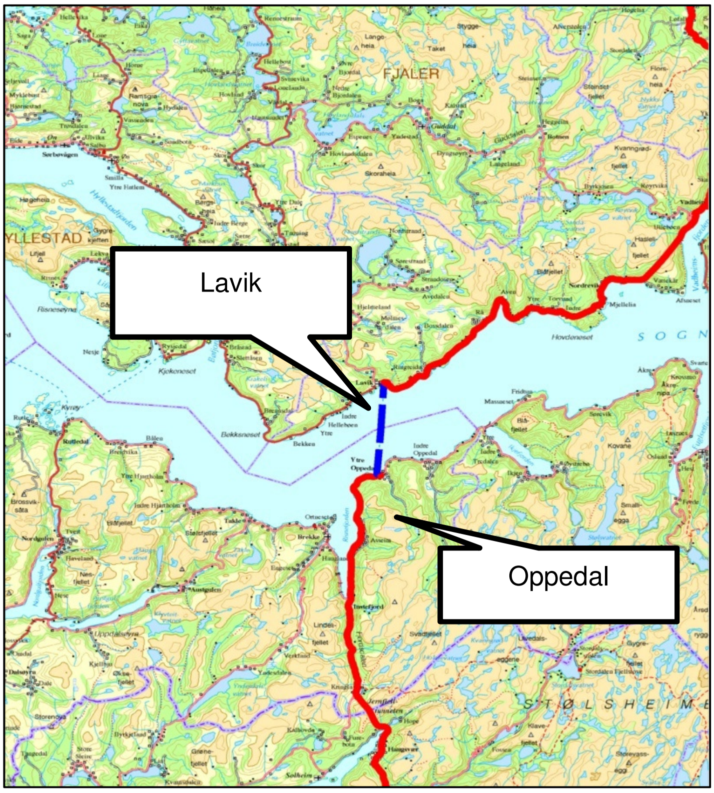

Figure 5. Assumed location of crossing for Sognefjorden.

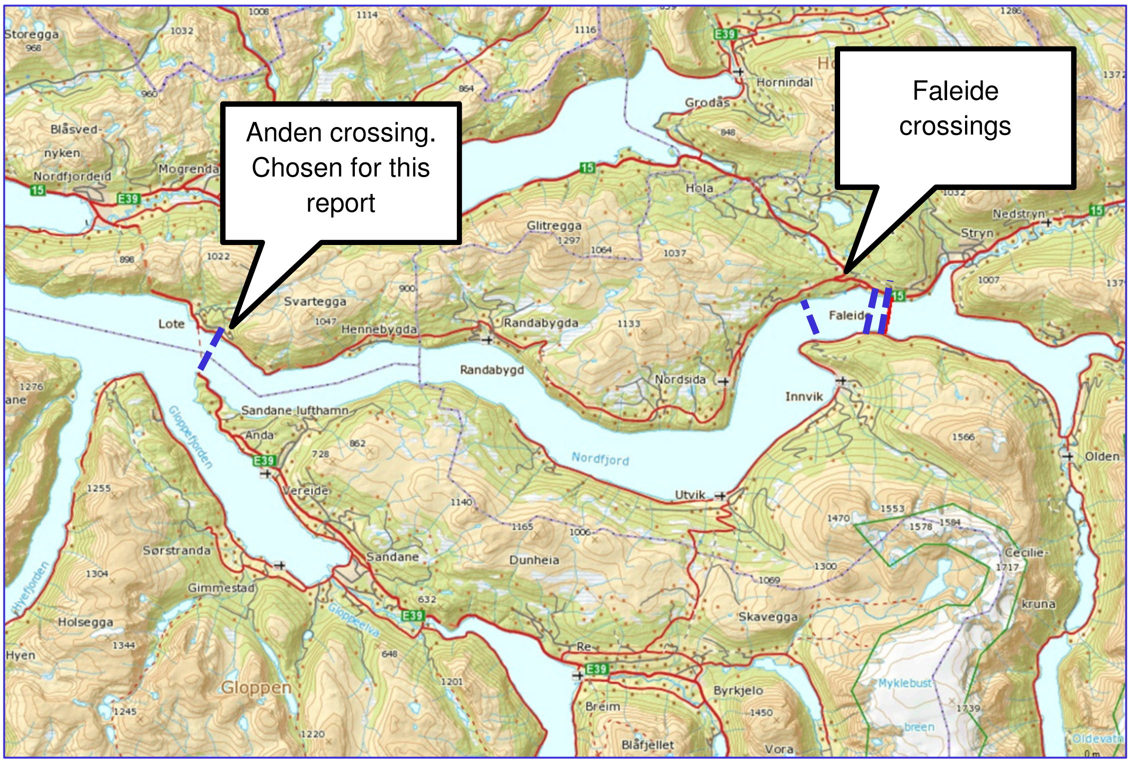

Figure 6. Possible crossings of Nordfjorden. Anden crossing used for this study.

2.7 VOLDAFJORD

For Voldafjorden, little information has been obtained from the NPRA. We have assumed a crossing just north of the existing ferry route Folkestad-Volda which seem a plausible location for a new bridge given proximity to the existing E39 and Volda.

Figure 7. Assumed location of crossing at Voldafjorden

2.8 STORFJORD

The NPRA has considered several concepts for crossing of Storfjorden, including both an outer route over Hareid and an inner route with a crossing at Festøya-Solavågen (Figure 8). The latter is the main alternative, and has thus been used as the basis of this report.

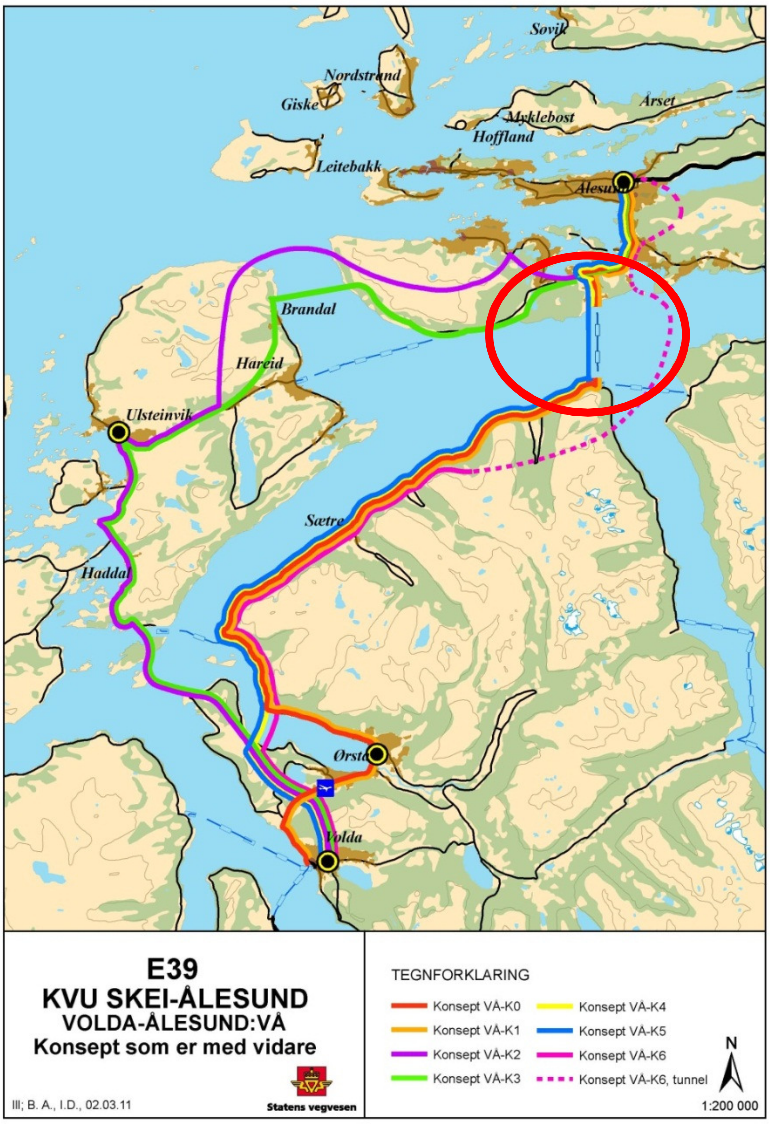

Figure 8. Concepts for crossing of Storfjorden (source: NPRA). Circled alternative with crossing at Festøya-Solavågen is used in this report.

2.9 MOLDEFJORD

As for several of the other crossings, the NPRA has a number of possible concepts for crossing of Moldefjorden (Figure 9). All of the alternative crossings are wide and will probably involve sub-sea tunnels in possible combination with bridges. One possible location of a bridge is at Julsundet. This is used as the basis for studies at Moldefjorden in this report.

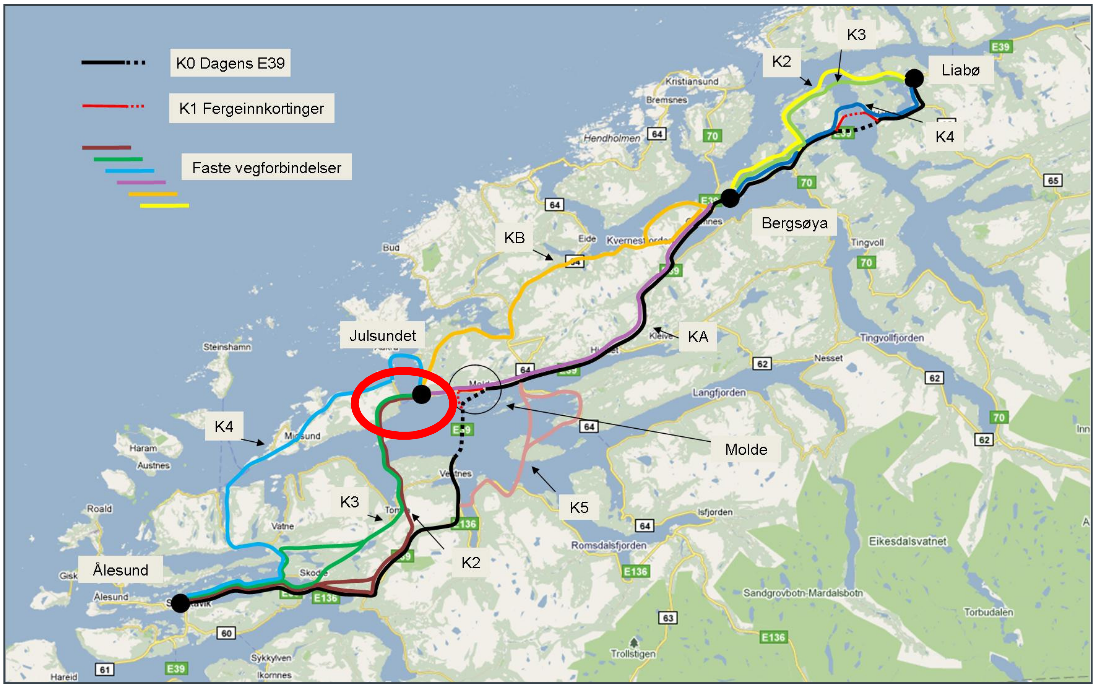

Figure 9. Concepts for crossing of Moldefjorden (source: NPRA). Circled crossing at Julsundet used as basis for this report.

2.10 HALSAFJORD

For Halsafjorden we have assumed a crossing between Hals-Orneset. This is just north of the existing ferry route Halsa-Kanestraum, but significantly narrower.

Figure 10. Assumed crossing of Halsafjorden.

2.11 LENGTHS OF CROSSINGS

Based on the assumed locations of the crossings, approximate bridge lengths are calculated (Table 1). These lengths are used as the basis of calculating energy potential production and costs of installations at the various sites in later chapters. Please note that the lengths are based on straight line crossings. Arched bridges could therefore be somewhat longer.

Table 1. Lengths of crossings

Crossing	Length
Boknafjord	7,5
Bjørnafjord	2,7
Sognefjord	3,7
Nordfjord	1,7
Voldafjord	2,6
Storfjord	3,5
Moldefjord	1,6
Halsafjord	2,0

3 Wind power

3.1 TECHNOLOGICAL BACKGROUND

3.1.1 General

Norway has good wind resources in terms of wind speeds, and significant potential for both on- and off-shore wind power. The technology for on-shore wind is relatively mature and well developed. The costs of installations are, however relatively high compared to hydro power, which is the dominating source of electricity generation in Norway. Hence, only around 540 MW of wind power was installed in Norway by 2011. Growth is nonetheless expected in the period until 2020 as new permits for several projects coincide with the introduction of the Norwegian-Swedish green certificate support scheme.

Off-shore wind technology, on the other hand is still under development. Since the bridges on E39 studied are located in fjords with great depths where bottom fixed foundations are unfeasible, the wind power installations in this study should be considered off-shore in terms of technologies used. A major challenge for such installations is finding foundation concepts that are able to absorb the structural forces from the wind turbine. This challenge profoundly affects the solutions that can be chosen, and will be further discussed throughout this chapter (see chapters 3.1.2.2, 3.3.1 and 3.4).

3.1.2 Technical solutions

3.1.2.1 Types of turbines

There are two main types of wind turbines: vertical axis turbines (VAWTs) and horizontal axis turbines (HAWTs). Main layouts of the two types are illustrated in Figure 11.

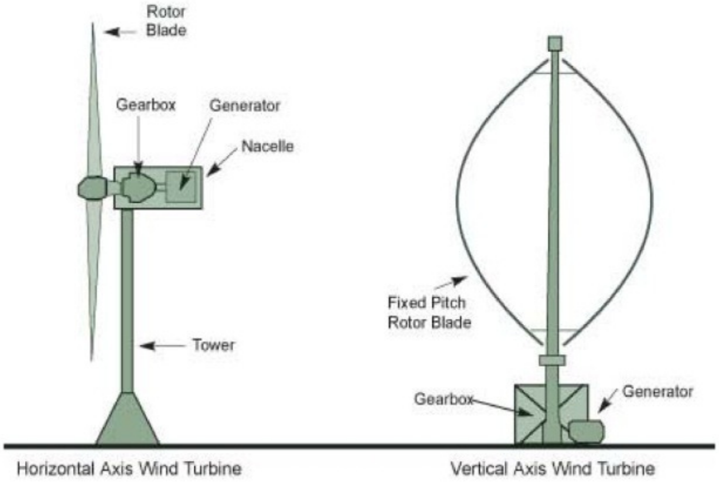

Figure 11. Main types of wind turbines.

Vertical axis wind turbines (VAWT's) are simple. They can be placed close to the ground, and can harvest the wind from any direction without the need for a yaw mechanism. Their major drawbacks are that they are ineffective, cover a relatively small area with their blades, and are commonly not built very large due to structural issues. They are rarely marketed for general power generation to the grid. Their main market is local micro power supply for houses and cabins etc.

All major electricity producing wind turbines connected to the grid are horizontal axis wind turbines (HAWT's). These have higher efficiency, cover a large area with their rotors, and can be built very large. HAWTs are designed for grid integration and large scale power generation. Several offshore models exist.

Wind turbines become more economically feasible with size. Small wind turbines are noticeably more expensive than large wind turbines per unit of produced power. In order to get a financially sound project, the turbine sizes should be large. Typical sizes of commercial turbines today are 2-3 MW.

3.1.2.2 Foundations

Off-shore wind turbines installed until now have been bottom fixed in shallow waters. The only exception is the Hywind floating wind prototype for deep waters, which has been operating since 2009 (Figure 12). It demonstrates that a floating foundation is possible for very large wind turbines (2.3 MW in the case of Hywind demo). It is possible to imagine this type of floating wind turbine in combination with the floating pontoons on a floating bridge.

The Hywind foundation consists of a very long steel tube (up to 100 meters) with massive ballast at the bottom in order to keep the system upright. Even with this ballast, the system tilts several degrees back during normal operation, due to the massive moment force induced by the wind force on the rotor. There are other floating foundations currently in development using other concepts for stability, but Hywind is so far the only one operational, so we will use that as a basis for the discussion of possible designs in chapter 3.3. Off-shore wind foundations for shallow waters are not considered relevant, and will not be discussed in this study.

Figure 12 - Hywind floating foundation.

3.2 EXAMPLES OF APPLICATIONS

There are some constructions with integrated wind power already in existence. The two most famous examples are the Bahrain world trade centre (Figure 13) and the Strata tower in London (Figure 14). Both use HAWT's. Unlike traditional wind turbines, these do not turn to face the wind. Rather they rely on the dominating wind direction and shape of the buildings to provide them with wind. Both buildings are built in a way which forces air in the direction of the turbines. It is said that for the Bahrain case, that the wind can come from up to 45° from either side, and that the turbines will still produce a high power output due to the building shape.

Figure 13. Bahrain world trade centre, with wind turbines.

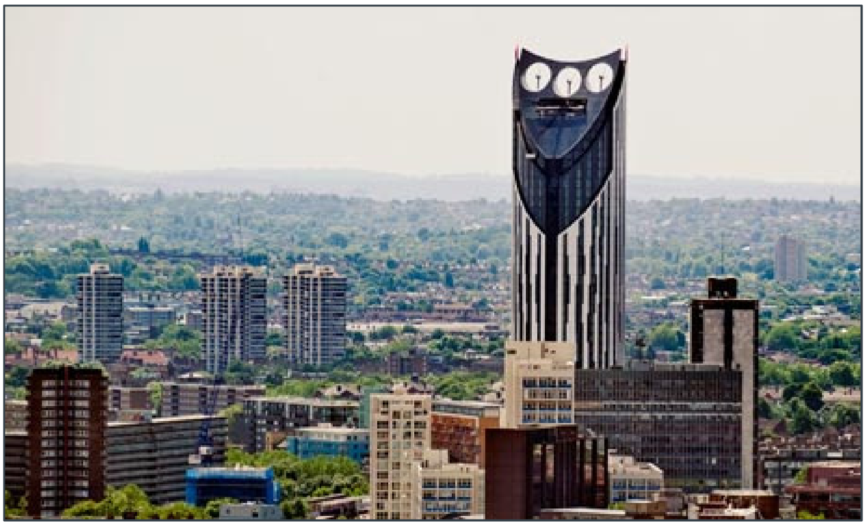

Figure 14. Strata tower in London.

3.3 BASIC DESIGN ISSUES

Certain environmental conditions inherent to fjords where the bridges of this study are to be placed, make design of the installation more challenging compared to conventional wind parks. Some of the most relevant conditions affecting the design are discussed below.

3.3.1 Wind load

For long bridges crossing fjords, wind actions are commonly one of the main governing loads regarding design. Thus bridges are commonly designed in such a way as to minimize wind exposure.

Installing wind turbines on the bridges will increase the exposure of the wind load to the structure. For bottom mounted bridges, this could be solved relatively easily by increasing the dimensions of the pillars and foundations. The bridges in this study are, however, placed in locations with great depths, requiring feasible structural solutions like floating bridges or suspension bridges. These structures are in general more difficult to adapt to increased wind loads.

Wind turbines usually have a cut-out speed at around 25 m/s, above which the turbine shuts down and the blades can be tilted to minimize air resistance. It may be argued that since the bridges are likely to be designed to handle wind speeds up to 40-50 m/s, the operation of wind turbines up until 25 m/s is feasible without surpassing the design resistance of bridge. In addition, the control scheme for the wind turbines can be reconfigured in order to avoid certain load scenarios (although this will affect production negatively). These measures will help alleviate challenges regarding wind actions, but probably not eliminate them.

In addition to the above, adding large commercial wind turbines to a bridge will create an enormous moment force at road level, twisting the bridge. Suspension bridges may have a very low resistance to twisting of this kind. Floating bridges supported on pontoons are in general more suitable for additional loading resulting from installations of for instance wind turbines. Challenges with moment forces can be mitigated with increased dimensions of the supporting structures, and must be kept in mind during design.

3.3.2 Wind direction

In order to obtain optimal production, it is important that the dominating wind direction is across the bridge. If the dominating wind direction is along the bridge, the wind turbines will stand in each other’s shadow and the energy production will be reduced significantly. The placing of the wind turbines (micro siting) is usually done with great care in order to get the best possible production wind onto each turbine.

Also, the surrounding terrain and bridge construction must be of such shape that it does not create very complex and turbulent wind patterns. Large wind turbines are dependent on a relatively homogenous wind for successful operation.

In further work with the project, the common local wind directions should be mapped and taken into account. In this study, however, we have based our considerations purely on the locations shown in chapter 2 and average wind speeds.

3.3.3 *Marine environment*

Placing a wind turbine in the presence of water is not straight forward. The humid air and salt water droplets will aggressively corrode and damage the turbines. A dedicated offshore designed turbine may be needed in order to handle such conditions. The offshore wind turbine market is mostly large multi-MW HAWT turbines.

3.3.4 *Road environment*

The road and traffic dust may also be a problematic pollutant which deposits on wings or contaminates lubricants. It is a general concern that the bridge-environment may be detrimental to wind turbines, resulting in outage, high maintenance costs and shortened life expectancy.

3.3.5 *Icing*

It is important to take into account that temperatures in combination with humidity may promote icing. Ice forming on turbine blades will reduce the efficiency regarding energy production, and may result in dynamic load reactions due to imbalance of the mass distribution in the blades. Icing is also considered potentially dangerous to the motorists on the bridge as blocks of ice may detach and be thrown off the turbine blades at high speeds.

Collecting environmental data like temperature and humidity has not been a part of this study, and icing will therefore not be considered in further detail here. It is however likely that icing will be an issue, and must be dealt with in further work.

3.4 POSSIBLE DESIGNS

Based on the design issues explained above, particularly with regards to wind actions, the following designs are proposed.

3.4.1 *Suspension bridge – small wind turbines*

This solution is based around small wind turbines placed in a row along the road surface (Figure 15). This can be arranged in several ways. The illustration shown proposes using vertical axis wind turbines and utilizing the bridge wires to suspend the top of the wind turbines.

Using small turbines in this manner is assumed to be the only viable way of introducing wind power along the length of the bridge, due to the necessity of keeping overturning moment small (twisting the bridge). In this concept, all forces are extracted at a low height, giving low bending moments. It is also possible to have a similar solution with small horizontal axis wind turbines.

Figure 16 shows an example of a minor HAWT that could be used. In this case it is a ducted rotor, which increases production but can also be assumed to be safer for birds and humans, and may therefore be preferred when installed in such close proximity to human traffic.

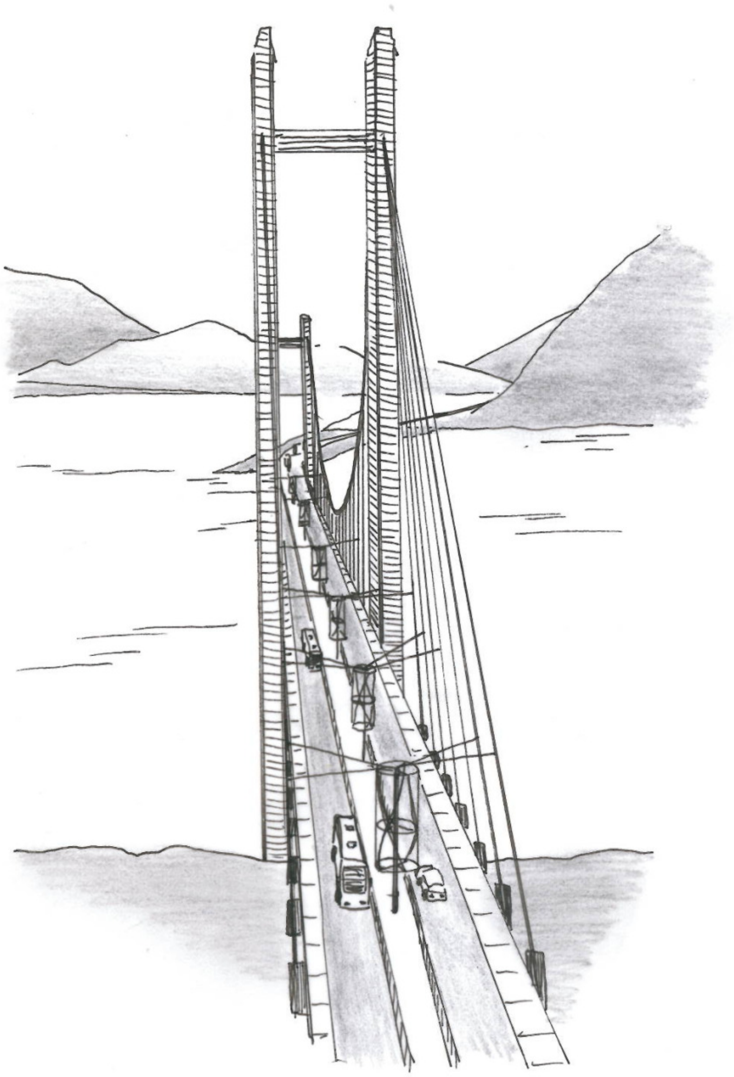

Figure 15. Vertical wind turbines on suspension bridge.

Figure 16. Example of small HAWT, ducted design.

3.4.2 Suspension bridge – large wind turbines

It is difficult to introduce large horizontal axis wind turbines to suspension bridges for several reasons. Large HAWT's needs to face the wind, and must be turned continuously in the right direction. They will therefore come into conflict with the wires on the suspension bridge. One possible solution is to make the wind turbines higher than the wires, but this is likely to give unbearable increased overturning moments.

If the bridge faces the dominating wind direction, it could be possible to install HAWT's in a fixed position on one side of the bridge, similar to what has been done on the Bahrain world centre and Strata tower described in chapter 3.2.

The best way of implementing this concept may be to use the bridge towers and placing the rotors high up, as shown in the figure above. This allows for bigger rotors, and avoids interference with human activities on the ground/sea level. Also, the towers are assumed to be the best suited part of the structure for absorbing the extra load. Still, it will probably be necessary to strengthen the towers to cope with the additional load impact.

The alternative would be to place several smaller HAWT's along the bridge deck on one side, with the rotor being half above and half below the bridge level. This would in theory result in rather small additional bending moment effects and easy access for maintenance. It would however also result in other challenges, such as limited rotor sizes and interference with boat traffic, waves etc.

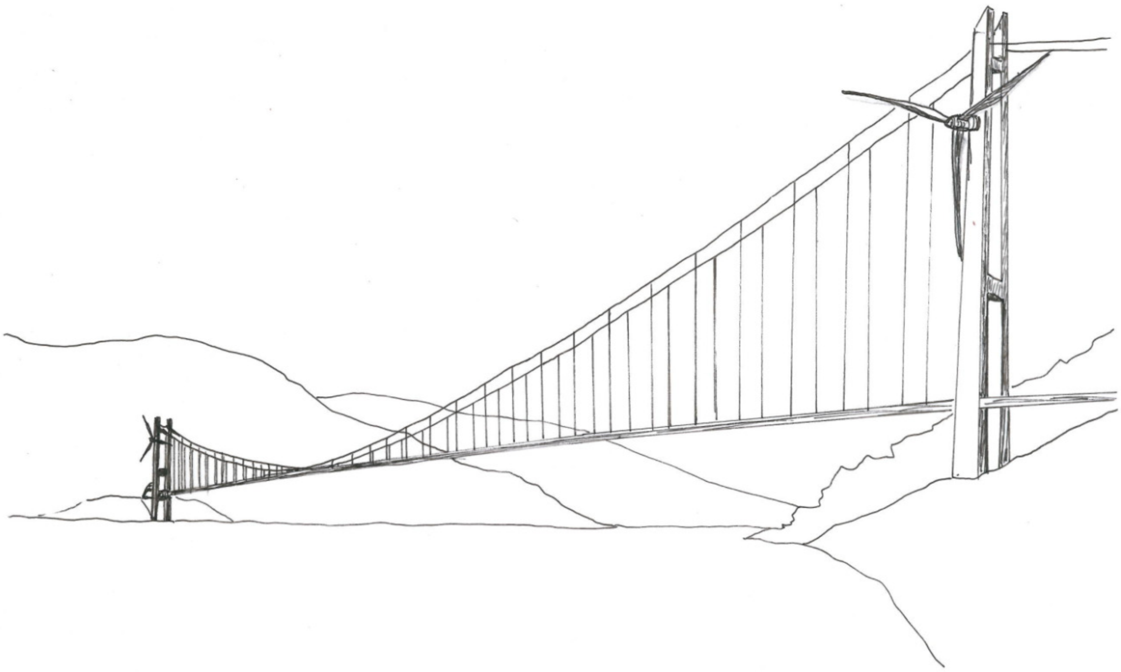

Figure 17. Horizontal wind turbines on suspension bridge.

3.4.3 Floating bridge - small wind turbines

A floating bridge can have wind turbines mounted along the road in the same way as described for suspension bridges.

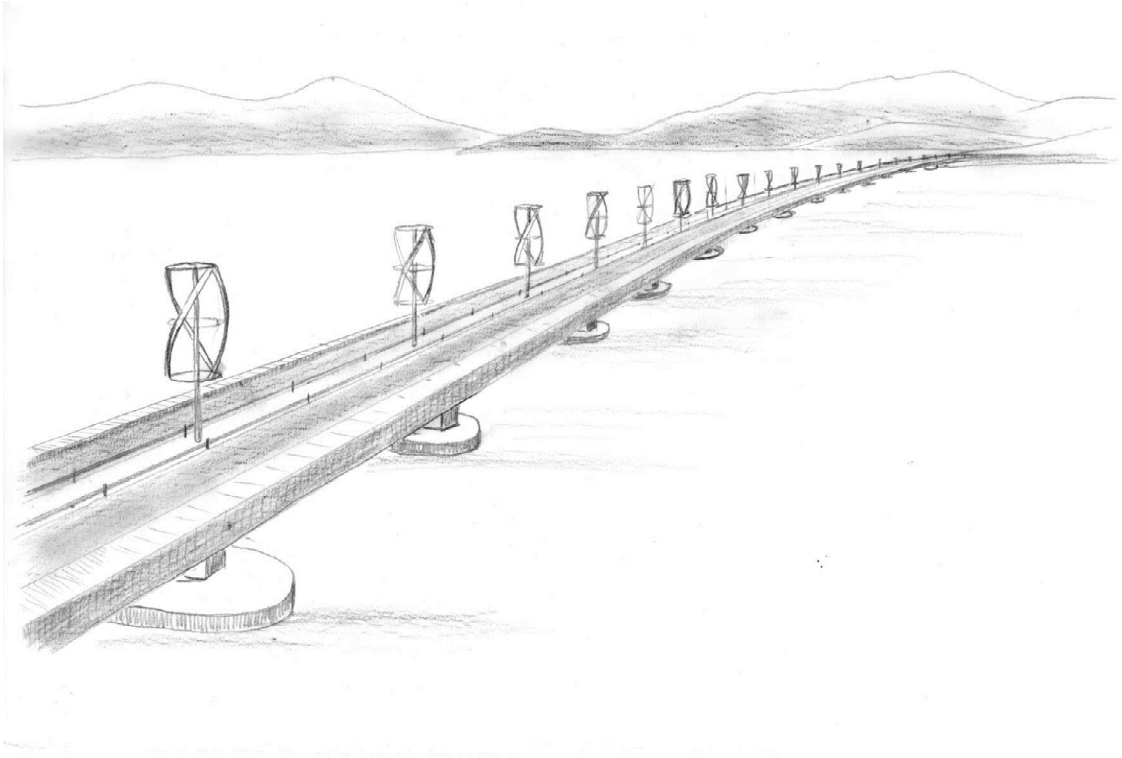

Figure 18. Small VAWT's along a floating bridge

3.4.4 Floating bridge - Large wind turbines

A hybrid solution can be imagined where the pontoons on a floating bridge are enlarged and deepened in order to function both as pontoons for supporting the bridge structure and also act as a Hywind-style foundation for the wind turbine (see chapter 3.1.2.2).

The road surface of the bridge cannot be twisted with the number of the degrees which the Hywind system tilts under normal operation. But it is all a matter of design (and possible use of tension wires) to keep the system within acceptable limits of what the road surface can handle.

The pontoons on a floating bridge are relatively close together. In order to allow for bigger rotors and making the bridge system more economical, it may be a good solution to only enlarge a few of the pontoons to make them suitable as foundations for wind turbines, while keeping the rest in normal dimensions. This would in theory allow for large wind turbines to be placed along the bridge. This is illustrated in Figure 19.

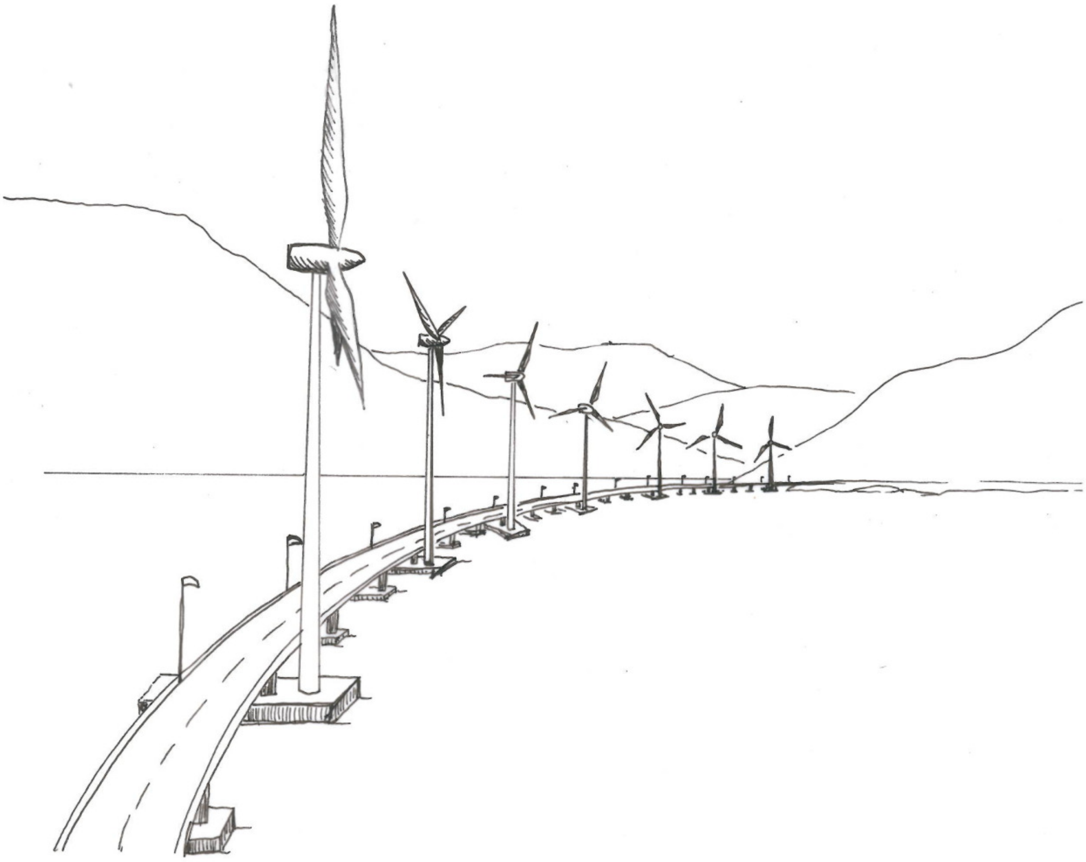

Figure 19. Large wind turbines on floating bridge

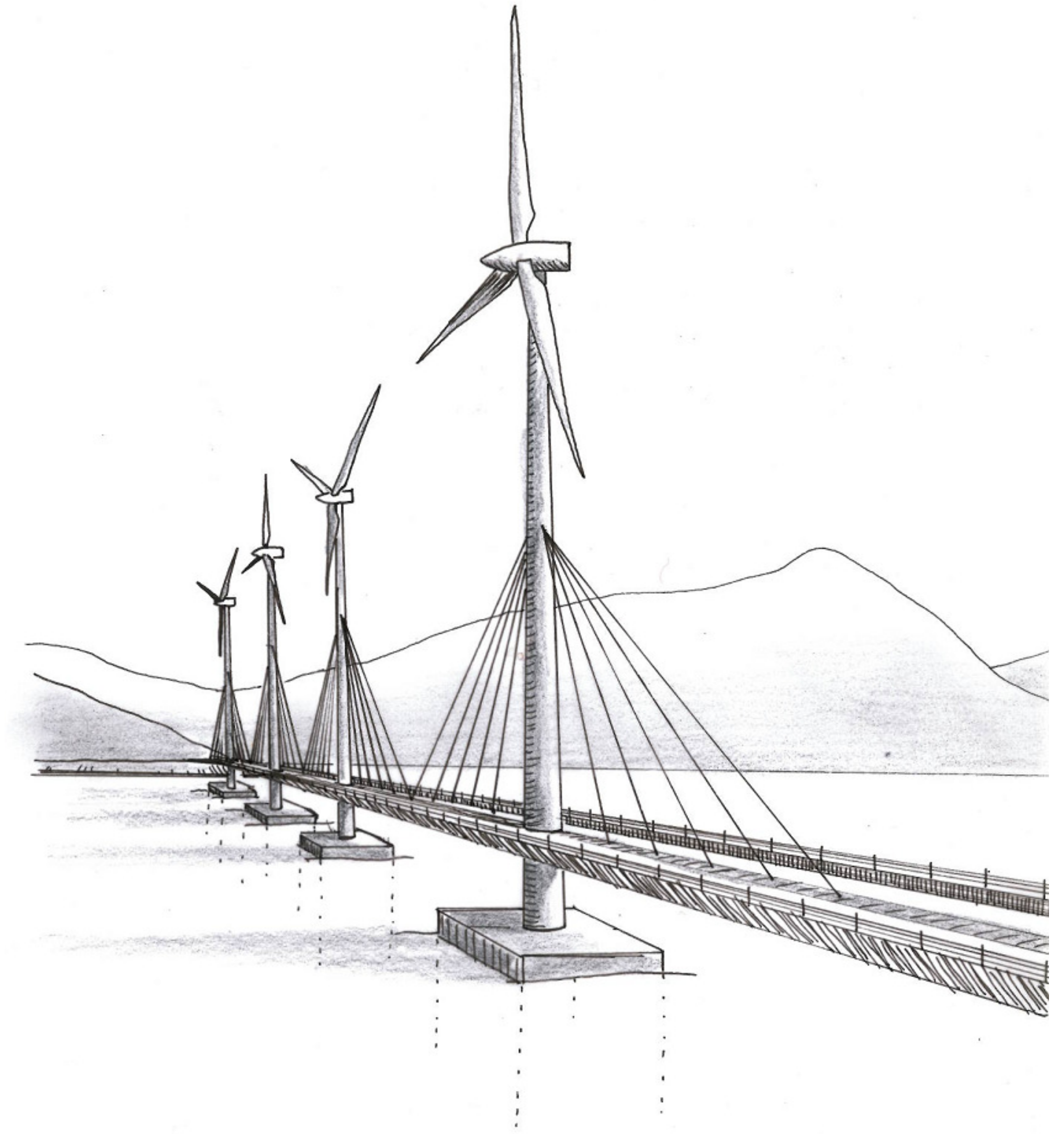

Figure 20. Alternative solution for large wind turbines on a floating bridge

Floating bridges come in different forms. Another solution under evaluation for E-39 (for instance at Boknafjorden) is floating pontoons with towers and suspension wires for holding the superstructure of the bridge. Illustrated in Figure 20 is a solution for such a bridge concept, where the wind turbine towers double as towers for holding the suspension wires.

3.5 POTENTIAL FOR RENEWABLE ENERGY PRODUCTION

Potential for production of renewable energy for the various crossings and designs are evaluated in the following chapters.

3.5.1 Environmental data

Average wind speeds for each of the eight crossings have been derived from wind maps created by Kjeller Vindteknikk for heights of 50 meters (in an NVE founded project). The results are shown in Figure 21.

The crossings are mostly located some distance inland from the coast with high land on all sides which gives shade from the wind. The data shows that most of these crossings have limited potential for wind energy. For a commercial wind park to be interesting the average wind speed should be at least above 7 m/s. Typical for good commercial wind sites is an average wind speed in the region of 8-10 m/s. The only site with some potential on commercial terms is Boknafjorden.

It is common for wind turbines to start producing power at around 4 m/s. Some have even higher cut in speeds. When the average wind speed is close to this, the turbine will obviously be in stand still for large periods of the year, and the energy production will be poor.

The accuracy of the data from Kjeller Vindteknikk cannot be guaranteed. There may be local effects causing wind to be different. More detailed studies need to be performed in the future for accurate results.

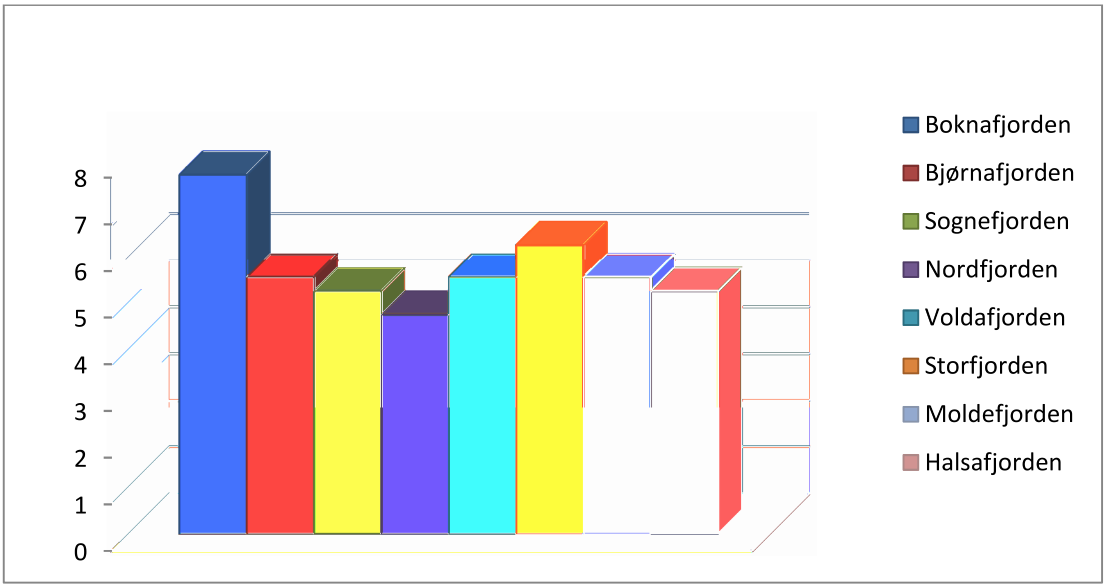

Figure 21. Average wind speeds for the fjord crossings

3.5.2 Energy production vs. rotor area

3.5.2.1 General measure

Wind production at each site is highly dependent on the number and size of wind turbines installed. In theory, very large amounts of energy production capacity could be installed. Turbines are also very different, with varying efficiencies, proportions between rotor and generator, control system etc. It therefore makes little sense to try to calculate the theoretically maximal amount of energy production at each site.

Instead, this survey presents some examples of what may be assumed to be reasonable solutions, and energy potential associated with these.

To arrive at this, it is useful to start by developing a measure of energy production that is independent of turbine size. The result can be seen in Figure 22. This figure presents the correlation between average wind speed (m/s) and expected yearly production (kWh). The yearly production is given per square meter of swept area (rotor size). Standard wind turbine proportions between rotor size and generator size have been used.

Horizontal axis wind turbines are more efficient than vertical axis wind turbines. The figure shows the difference between the two technologies. This model can be used to evaluate the production from any concept and of any size that may be suggested.

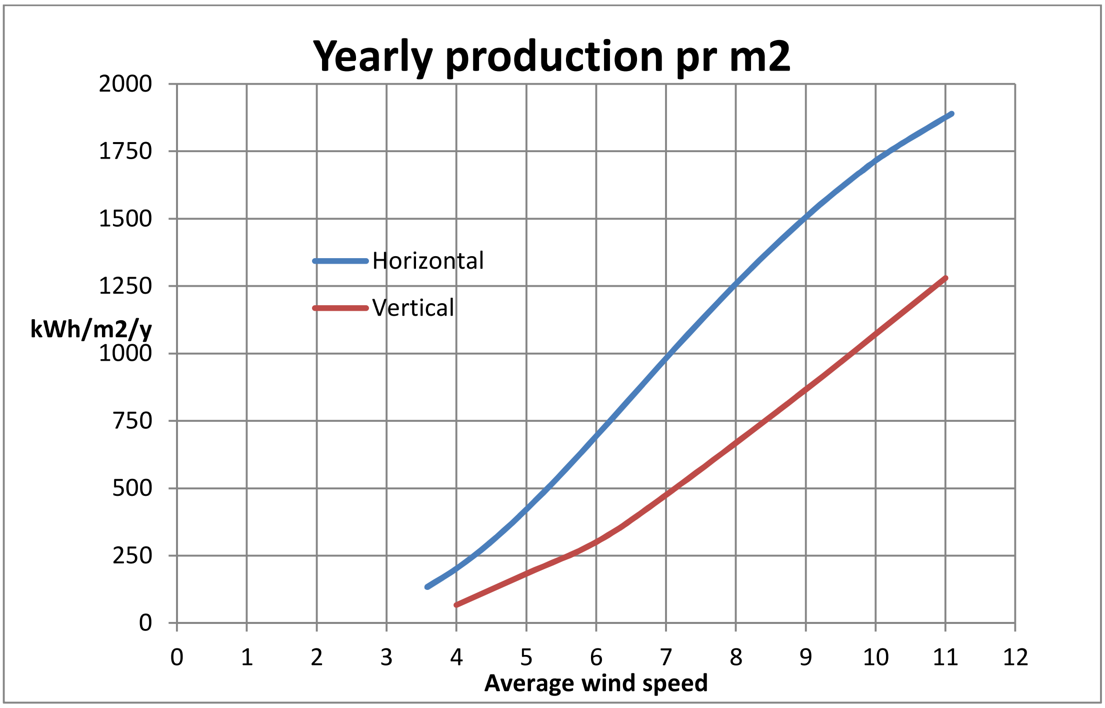

Figure 22. Yearly energy production pr. m2 of rotor area for various wind speeds

3.5.2.2 Site specific numbers

We now use the results from Figure 22 to calculate average yearly energy production pr. square meter of swept area for each specific site, using average wind speeds from Figure 21.

Table 2 shows the result for HAWT's and VAWT's. The table also shows an estimate for the full load hours it will accumulate over a year (based on HAWT numbers). “Full load hours” is an estimate for how many hours the generator must run at full power in order to equal the total yearly production. (This figure varies with turbine design, and is not directly comparable for turbines of different proportions. It should only be used for relative comparisons and not as a universal unit. Standard turbine proportions for HAWT’s have been used to calculate the numbers here). It can be seen in the table below that most of the sites will have less than 2000 full load hours. Storfjorden with 2003 hours, and Boknafjorden with 3138 full load hours are the best sites. However, given that a good wind site for commercial use may have 4000-5000 full load hours per year, it is evident that making wind installations economically feasible at these sites will be challenging.

Table 2. Yearly energy production per. m2, and full load hours for an installation at the various sites

	Wind speed	Production HAWT (kWh/m2/yr)	Production VAWT (kWh/m2/yr)	Full load hrs
Boknafjorden	7,7	1175	610	3138
Bjørnafjorden	5,5	550	235	1469
Sognefjorden	5,2	475	200	1268
Nordfjorden	4,7	350	150	935
Voldafjorden	5,5	550	235	1469
Storfjorden	6,2	750	330	2003
Moldefjorden	5,5	550	235	1469
Halsafjorden	5,2	475	200	1268

3.5.3 Potential – relevant examples

As explained in chapter 3.5.1, the most useful evaluation of the production potential at each site is found by looking at some examples of suggested layouts. The real numbers will depend completely on what layout/designs are chosen. The following is meant only as calculation examples to get acquainted with the size of the numbers involved.

For the case of VAWT’s, we can for instance assume that the designer chooses turbines that are 5 m wide and 7 m tall, and that they can place 8 turbines per 100 m of road. This gives 2800 square meters of swept area per km of bridge.

For the case of HAWT, we can assume a modern offshore wind turbine with 101 m diameter rotor, and that they are placed once per 250 m of road. This gives 32 000 square meters of swept area per km of bridge.

Common practice is to place wind turbines at a distance from each other equal to three rotor diameters. This is done to avoid influence between the turbines which cause lower production. In the examples above, we place the turbines a bit close together than this in order to get a bit more installed power onto the bridge.

Based on the input data above, along with the measure of production pr. swept square meter from Figure 22, we can now calculate annual production at each crossing for the two main technologies. The results are shown in table 3.

Table 3. Annual wind production potential at the different crossings, example

	Length (km)	HAWT - GWh/km	VAWT - GWh/km	HAWT GWh	VAWT - GWh
Boknafjorden	7,5	37,6	1,7	282,0	12,8
Bjørnafjorden	2,7	17,6	0,7	47,5	1,8
Sognefjorden	3,7	15,2	0,6	56,2	2,0
Nordfjorden	1,7	11,2	0,4	19,0	0,7
Voldafjorden	2,6	17,6	0,7	45,8	1,7
Storfjorden	3,5	24,0	0,9	84,0	3,2
Moldefjorden	1,6	17,6	0,7	28,1	1,1
Halsafjorden	2,0	15,2	0,6	30,4	1,1

This calculation example shows the energy potential if using the designs described above. It is possible to increase the numbers further by choosing even larger and taller turbines, and it is possible to reduce them by installing smaller/fewer.

The numbers show the potential for the suggested designs, but realistic production numbers are likely to be lower due to outage, deposits on wings, wind direction, wake effects etc. It is probably necessary subtract ~15-20 % for realism.

One is also dependant on that the dominating wind direction is across the bridge. If the wind comes along the bridge, the turbines will stand in each other's shadow and produce very little. This may cause the production to be significantly lowered.

3.6 COSTS

3.6.1 General

The cost of a wind energy project is normally difficult to estimate at an early stage for several reasons: As for the cost of turbines, prices are not publically disclosed. They are negotiated in each case, and prices are regarded as sensitive information. The prices may differ between different designs, different manufacturers and from case to case depending on how profitable the wind site in question is. Given the unusual nature of the installations in question in this project, what is even more uncertain is the cost of installation work, foundations and grid connection. Operational costs are also highly dependent on the site and turbine.

To arrive at somewhat reliable cost estimates, further design work has to be done for each of the crossings. To have an initial idea of the order of magnitude of the costs of such a project, we have however done some rough estimates based on the information available at this stage. It should be kept in mind that these estimates are highly preliminary.

3.6.2 Cost examples

Boknafjorden appears to be the most suitable place for a wind project. We can estimate some rough numbers from the case in the previous chapter. The large scale HAWT-concept involves about 30 wind turbines along the bridge with a yearly potential for producing about 282 GWh. The cost of the turbines is likely to be in the region of 750 MNOK. The cost of local grid connection, foundation/ integration to the bridge, design, installation work etc. is very difficult to estimate, but we can assume something in the order of 400 MNOK (highly dependent on how simple it is to integrate the turbine into the bridge. This may be much higher if this proves difficult. The hope of keeping it low is that the bridge may be responsible for much of the foundation cost). To account for outage, maintenance, wake effects etc., the yearly production should take into account a yearly loss of up to 20%. Yearly production is therefore set to 230 GWh. In total, we may assume a cost of 1150 MNOK and a production of 230 GWh which gives a cost around 5 NOK/kWh in investment costs. Further, the yearly operational costs may be in the order of 30 MNOK. As mentioned several times before, the uncertainty of these numbers is very high. If the project proves difficult, the costs could easily rise by over 50%. Further study of the concept is needed before exact numbers can be calculated.

Large scale installation of VAWT’s is not common, so there are few numbers available to draw experience from. VAWT’s are typically 3-5 times more expensive than large HAWT’s. Installation costs and foundation work will however be relatively low compared to HAWT's. The concept assumed for Boknafjorden in the previous chapter involves about 600 turbines along the 7.5 km bridge. The price of the turbines may be in the order of 100 KNOK each, giving a total of 60 MNOK. The price is assumed relatively low due to the large quantity ordered. The cost of installation work, foundations and grid connection is likely to be relatively low due to the small scale of the system. This can be set to 22 MNOK (although this may depend heavily on the size and complexity of the turbines). Yearly production including losses and outage is set to 10.25 GWh. This gives an investment cost of about 8 NOK/kWh. Yearly operational and maintenance costs may be in the order of 2 MNOK. The HAWT case is highly dependent on turbine costs, which are uncertain since such large quantities of turbines rarely are bought. They are usually bought one-and-one. It may be possible to get a good deal, thereby noticeably reducing the cost. Again, a far more detailed study must be conducted before exact numbers can be estimated.

3.7 SUPPLIER INTEREST

Unlike wave and tidal power, wind power is an established business with thousands of turbines being installed each year. The turbines have been standardized in order to allow huge production volumes. The companies making wind turbines, therefore, appear not to be very interested in special solutions, such as for bridges. For them to be interested in doing special engineering work there has to be the potential for huge sales volumes in the future. Bridges is a relatively limited and challenging market. However, many manufacturers will want to sell their turbines to such a project, insisting that their turbine is proved acceptable to be installed on a bridge as it is. Finding anyone interested in designing a dedicated solution could be difficult.

One possible exception is Norwin, which is a Danish company famous for doing unique and special projects. They are the designers behind the skyscraper installation shown in Figure 14. They have been contacted and informed about this project, but have not responded to our enquiries.

Another exception that can be mentioned is Norwegian company Innowind AS, which attempts to develop a special ducted design which produces more power with a limited rotor area, thus reducing the rotor size and lowering the moment forces as the rotor centre is closer to the road surface. The company has shown interest in this project. They have, however, yet to document that their concept will work.

3.8 EVALUATION

3.8.1 Economic feasibility

Wind power potential and cost have been evaluated at the eight fjord crossings based on the proposed designs. It appears that wind speeds are too low to make the sites interesting for installation of wind power. The only exception is Boknafjorden.

A (fairly optimistic) evaluation of the Boknafjorden crossing indicate possible installation costs of 5 NOK/KWh for large HAWT's and 8 NOK/KWh for VAWT's. These are fairly decent numbers, given that several hydropower projects in Norway with costs around 5 NOK/kWh are currently being developed. However, possibly challenging design work and high maintenance costs mean that the concepts will struggle to become financially feasible.

3.8.2 Challenges

Even for the Boknafjorden crossing, which could potentially become economically feasible, there are several challenges to be overcome:

-A bridge is sensitive to wind loads, and installing wind turbines on the bridge to catch more of this load may be unfortunate for the bridge design, and especially for suspension bridges and floating bridges. A study of the effect of wind loads on the bridge designs must be conducted in order to answer how many and how large wind turbines can be installed, and how much the bridge structure would have to be changed/reinforced.

-The environment of humid air with salt water droplets and road dust is very detrimental to the life expectancy of wind turbines. In order to survive this, it is probably necessary to have dedicated offshore designed wind turbines. These are rarer and more expensive.

-Safety may also be an issue. Large rotating blades are dangerous both for animals and for humans. Wind turbines are known to kill birds. Falling blocks of ice from wind turbine blades and even entire blades coming loose are some of the problems that can occur. Danger of falling ice blocks could be mitigated by installing non-rotating turbines with rotor planes parallel to the road, but this would severely damage production unless the wind direction at the site is very uniform.

In total, it is our evaluation that the installation of wind turbines on non-bottom mounted bridges, such as floating and suspended bridges, are unlikely to be able to compete with conventional installations from a technical and economic point of view, at least for the sites in question.

3.9 FURTHER WORK

The work conducted so far only takes a basic look at what may be possible. It is necessary to do more precise calculations of economy, aerodynamics and structural loads to get a more accurate evaluation.

The sites should be studied in more detail aerodynamically. It is vital to do a study of wind distribution and wind direction. This will allow proper estimates of how much energy will be produced, and if the bridge is facing in a direction which makes the projects possible. Local wind may be slightly different than predicted by NVE/Kjeller Vindteknikk. Phenomena such as turbulence, wind shear and probability of icing should also be evaluated.

Structural designers of bridges should do an analysis of how much extra force can be put on the bridge designs, and also how much the designs needs to be adapted if applying even larger forces. This will hopefully reveal what is possible within reasonable economical and practical limits.

A few concrete design suggestions should be made, and the practical and economic feasibility should be studied. It may be suggested to do two cases; many small turbines and few large turbines. The economic and practical impact of the two cases will probably be very different.

4 Solar power

4.1 TECHNOLOGICAL BACKGROUND

4.1.1 General

Of all the available renewable energy sources known of today, the sun is the one with the most impact on life on earth. In addition to the possibility of exploiting the solar energy directly, it should be kept in mind that it is the driving force behind all the other renewable energy sources.

The solar energy that hits the earth every year is estimated to be more than 10 000 times the energy consumption. In Norway this value is about 1500 times the energy consumption. Hence, the potential for exploiting this energy is huge.

Sintef Byggforsk and (former) Kan Energi has issued a report named “Mulighetsstudie solenergi” (“Feasibility study solar Energy”) upon request from Enova SF. This report was published in February 2011 and has analysed the potential of realizable solar energy in Norway up to 2020. Some of the basics from the report will be recaptured in this study to justify the alternatives that will be described.

Historically solar energy has been used in many ways, like drying of various products, heating of buildings, production of bio mass and lighting. Available energy is often measured in kWh/m², and will vary greatly according to the following factors:

- Geographical position
- Time of the year
- Local conditions like clouds, shadows etc.

This can be observed in Figure 23 taken from Norsk Solenergiforening (The Norwegian Solar Power Association). The figure shows the insolation (irradiation due to solar radiation) on a horizontal surface in Norway in January and July.

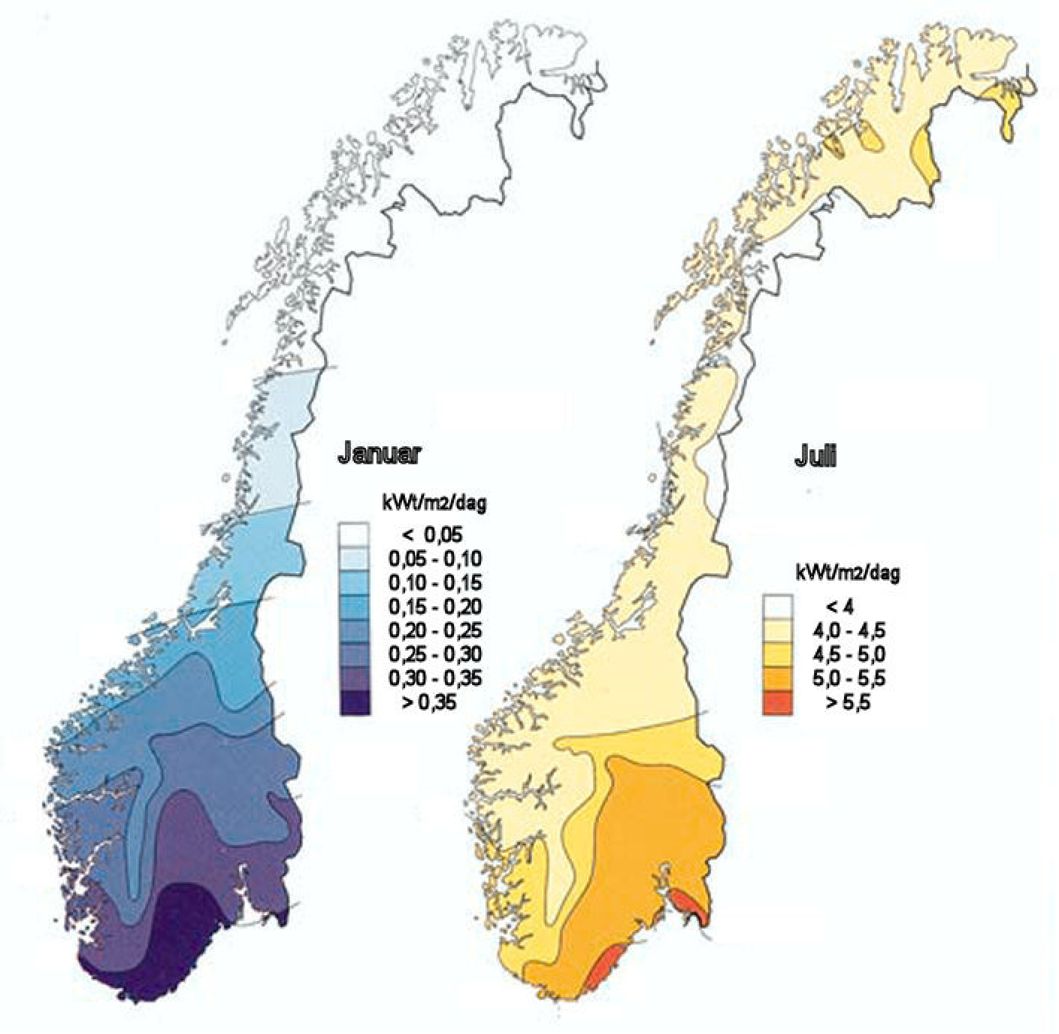

Figure 23. Solar irradiation in Norway, January (left) and July (right)

To achieve the maximum utilization of solar installations the orientation and tilt are crucial factors. The front side of the panel should face true south, while the tilt angle should be adjusted so that most of the solar radiation hits the panel. The optimal tilt will vary according to latitude, but in the southern part of Norway the optimal tilt angle will be around 40 degrees. For solar panels some systems allows for changing both orientation and tilt angle, either manually or by installing tracking systems. Optimal inclination will reduce the difference between the different geographical areas.

Typical solar irradiance in Norway is 700 – 900 kWh/m^2/year.

4.1.2 Technological solutions

Primarily there are two ways of exploiting solar energy directly. It is possible to use the sun for heating purposes, by placing solar “collectors” in direct sunlight. This this called solar heat. The other branch of technology is to convert the radiation into electrical energy directly by using photovoltaic cells.

4.1.2.1 Solar heat

Systems collecting solar heat vary from simply placing a bowl of water in the sun to systems utilizing the direct radiation to produce steam for steam turbines. The most common technology, though, is to install water-filled tubes on top of a building. The water is circulating through the tubes and is being heated by the sun. The hot water is then used as an integrated part of the hot-water system in the building. There are systems in Norway where this technology is implemented.

With relation to bridge constructions, the use of a solar heat technology is considered less optimal because there is little need for heating. Heating of the driveway would be one alternative, but the need for heat will be in the winter, when there are very little direct sunlight. One alternative could be to use the water as a supply to a district heating system. The crossing of the Voldafjord is the only site that seems feasible in this study because one end of the span is in the town of Volda, which is a populated area compared to other places in the region. There have recently been done some investigations regarding installation of district heating mains in this town, because there is a huge potential for using heat from the sea in a district heat pump system. The infrastructure needed for technology is the same as for solar heat. This report does not investigate this possibility further, but it should be looked closer into in further work with the bridge concept at Voldafjord.

High temperature solar heat systems concentrate the radiance to generate steam for production of electricity. There are no known installations of this technology in Norway today.Such installations are not be able to use any of the diffuse radiation, only the direct radiance from the sun. In this part of the world, where a clear sky is rarer than a cloudy one, this is therefore not considered to be a good solution. In general, technologies utilizing solar heat are considered less useful on bridge constructions in this part of the world, and will not be investigated further.

4.1.2.2 Photovoltaincs (PV)

Solar panels are based on a technology that uses semi-conductors to convert solar radiance into electrical energy. The smallest component in a solar panel is the photovoltaic cell, which let alone has a low voltage and is producing a relatively small amount of current. The most common installations delivered today consist of several photovoltaic cells, connected in series and parallel to get a desired output voltage and current. These modules can further be combined to get a desired energy output.

Installations of solar panels can be both stand-alone and grid-connected. In Norway, this technology has primarily been used to produce energy in locations where the grid is not accessible. Stand-alone installations are dependent on energy storage, due to the demand for energy being at night, while the production is during the day. Grid-connected installations in a well-regulated grid are using the grid as a buffer for the production. When the solar panels are producing electricity, other producers with energy storing capabilities are producing less energy. The Norwegian grid, with regulated hydro power as the main energy source, is ideal for integrating solar panels.

Today there are three main types of solar cells available (Table 4).

Table 4. Main types of solar cells

Type	Efficiency*	Advantages	Disadvantages
Crystalline silicon	13-21 %	Cheap and relatively high efficiency. Mature and robust solar cell technology.	Poor utilisation of diffuse radiation
Thin-film	6-14 %	Utilizes both direct irradiance and diffuse radiation	Lower efficiency than crystalline silicon
Third-generation	42 %	High efficiency	Not commercial

*Numbers given by IFE

The output of the solar panel depends on several factors. Two of the main factors directly influencing the panels are solar radiation and temperature. When solar radiation increases, the output of the panel also increases. Changes in temperature give the opposite effect. If the temperature increases the output of the panels actually decreases. Thus, with regards to temperature the solar cell technology is rather suitable in the Norwegian climate.

As third-generation solar panels are not yet commercial, this technology will not be followed in this study, but at the considered bridges will be constructed, the technology will probably have become available and much cheaper. If the solar panel installations are to be installed, the potential of this technology has to be reinvestigated when the building period is closer in time.

4.2 EXAMPLES OF APPLICATIONS

The installation of solar panels on bridges is a relatively unexplored field. Worldwide there are, however, some plants that are being built or are under construction. Three of these are shown below.

Blackfriars Bridge (London, UK). Railway bridge. Currently under construction.
4 400 panels are being installed (Solarcentury)

Kennedy Bridge (Bonne, Germany). Walkway bridge completed 2011
392 panels installed (Solarworld)

Kurilpa Bridge (Brisbane, Australia). Walkway bridge completed 2009.
84 panels installed (Sunpower)

4.3 BASIC DESIGN ISSUES

Solar panels are advantageous in that it is rather easy to find suitable areas to install them. It is possible to produce solar panels in all kinds of shapes and sizes, and this allows for installations in the middle of a city, on a bridge etc. Installation on a bridge, however, involves some conditions that must be taken into account when designing the solar power plant. Some of the most important of these are discussed below. Note that some of the determinant conditions are the same as for wind, but possibly with different effects.

4.3.1 Orientation

The production from a solar panel is largely dependent on the angle at which the sun hits it. The optimal angle is around 40 degrees.

In addition to this, solar panel installations - crystalline panels in particular - are very sensitive to shadowing. In cases where the panels are connected in a series, shadowing will reduce the performance considerably. Even though there is only one photovoltaic cell being shadowed, it will affect the others cells in the same way as the one being shadowed.

It is therefore essential that the panels are installed in such a way as to optimize the tilt angle and minimize shadowing. Design will therefore depend on the geographic orientation of the bridge.

4.3.2 Marine environment

All of the considered fjord crossings are close to the coast. These areas are particularly exposed to wind and weather, and the panels might come into contact with humid air with salt water droplets. While the photovoltaic cells themselves are protected by laminated plastic and glass, the frame of the modules is often made in aluminium, which may be exposed to galvanic corrosion. The extent of galvanic corrosion will depend on the type of solar module type installed and supplier. Some suppliers of crystalline silicon solar cells claim that their products are corrosion-resistant, while others will not give absolute guarantees for this with regards to the close proximity to sea water. If this project reaches a phase of detail engineering, extra protection of the solar cells must be considered.

4.3.3 Road environment

Normally, solar panels have very low maintenance costs compared to other kinds of energy production, which normally involves rotating components that causes wear on bearings. Solar panels do not have any moving parts at all, which is an advantage that should not be underestimated. Maintenance is usually a big part of the life cycle cost (LCC) for an installation, and the economic value of reduced maintenance should be taken into consideration.

In this case however, proximity to the highway (along with the climate) will require more regular than normal cleaning of the panels. This will lead to higher than normal maintenance costs, and installations should be designed in such a way as to minimize pollution on the panels.

4.3.4 Wind load

As explained several places in chapter 3, wind load is likely to be one of the main governing factors regarding design of the bridges in question. Solar panels must therefore be installed in such a way as not to increase the wind load on the structure.

4.4 POSSIBLE DESIGNS

There are several ways of mounting solar panels on highway bridges. It all comes down to the specific design of the bridge. In this study, side-mounted and roof-mounted solar panels have been identified as the most general solutions.

Based on this and on the design issues explained in chapter 4.3, the following designs are proposed.

4.4.1 Side-mounted solar panels

Side-mounted panels will be most beneficial in cases where the bridge is oriented in the East-West direction. In these cases, the whole south-side of the bridge will be available for the installation of solar panels. The bridge crossing the Halsafjord is one of the crossings with this orientation.

It is suggested to place a continuous row of solar cells along the entire south side of the bridge.

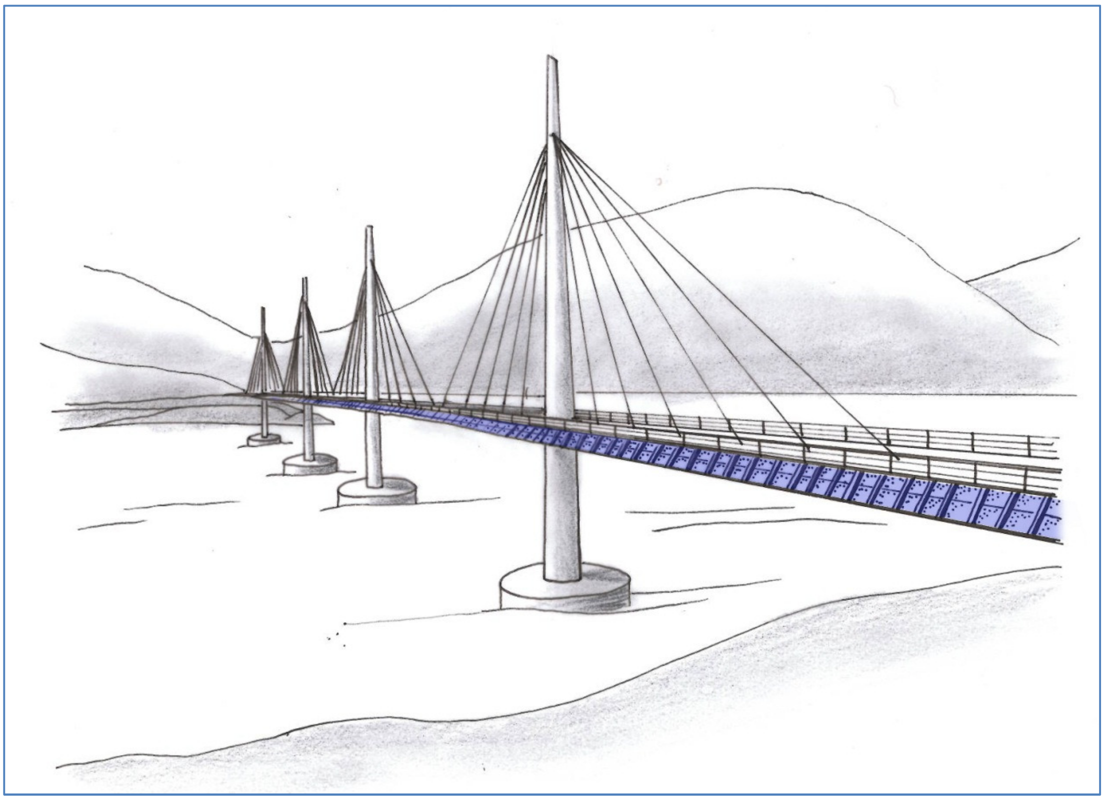

Figure 24. Cable-stayed bridge on floating foundations, with side-mounted panels

A typical cross chapter of the bridge deck (Figure 25) shows that the upper part of the cross chapter edge has a slope close to optimal angle for a solar panel. By making small adjustments to this tilt angle, it will be possible to place the solar panels directly on the bridge. It is possible to extend the available area by mounting racks attached to the construction. In this way, it is possible to get an area of 3,3 m² per running meter of the bridge, using the standard panels from REC (see chapter 4.5.2).

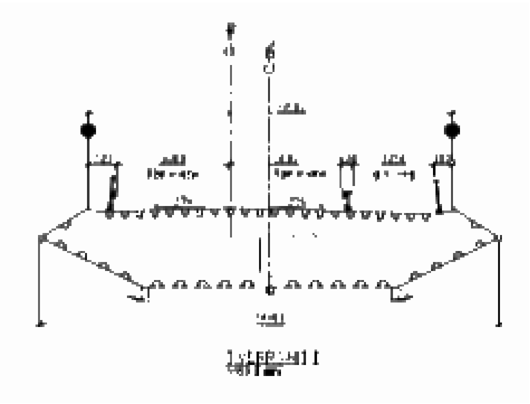

Figure 25. Typical cross chapter of bridge. Example from the Nordfjorden crossing (source: NPRA)

Another concept possible for suspension bridges with an East-West configuration will be to mount the panels on the towers. This is a technically good solution, because there is minimal shadowing in this area of the bridge. Maintenance and inspection will probably be difficult though, and this solution is therefore not considered to be the most optimal.

With a south-north configuration of the bridge, it will also be possible to mount the panels along the side of the bridge, but perpendicular to the bridge. At the middle of the day the sun will shine directly on the panels, but in the morning/evening (depending on east/west mounting) there will be shadows from the bridge. Such a construction would also be more vulnerable to wind, and will be more difficult to clean.

As for the crossing in Nordfjorden, the crossing will be from southeast to northwest. To ensure panels facing south, a zig zag concrete construction can be designed on the southfacing side of the bridge. On each pier a group of panels can be placed together, further connected to the group of panels on the next pier. Seen from south it will appear as if all the panels are placed in one row.

With every configuration of side-mounted panels one should be aware that filth from the highway most likely will fall on the panels during bad weather. They are also more vulnerable to exposure from sea spray, thus it is an advantage if the bridge-height above sea is higher than for a roof-mounted panel.

4.4.2 *Roof-mounted panels*

Panels mounted as a roof above the bridge would give a large available area. Problems with filth from the road will be minimized, and they will be more protected from sea spray than side-mounted panels.

Floating bridges on the E39 are likely to be designed with a shipping lane without pontoons at one end of the bride. This part of the bridge could be arched (see Figure 26), which would be ideal with regards to installation of solar panels because it is a construction with no shadowing. There will be minimal shadowing from the panels on the highway and the panels are high above the sea, minimizing sea spray. The optimal direction of a bridge with this direction will be south-north, with the panels mounted on the south-facing half of the arc. This will also give an inclination to the panels, which will make the relative angle on the panels smaller and thus becoming a more integrated part of the construction. It will also be more visible to the road-users than side-mounted panels, making a good symbolic effect.

It would, of course, also be possible to mount a roof along the entire length of the structure (or parts of the length), giving even more available area. Wind load could however be a challenge for such a solution, depending on design, and must be kept in mind in further work. It should also be added that there might be objections against mounting a roof above the driveway, as the view from the bridge can be minimized. A design with roof without side walls would be preferable, to ensure less impact on the view and the feeling of spaciousness.

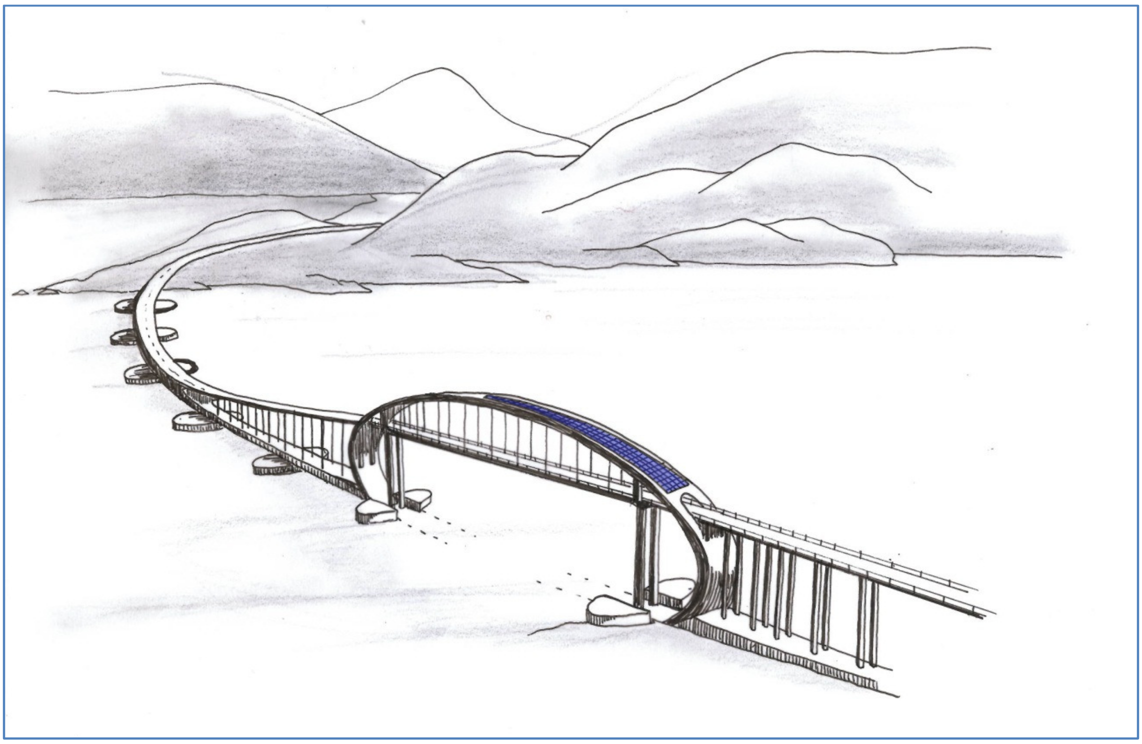

Figure 26. Illustration drawing of floating bridge with arced shipping lane and roof-mounted panels

4.4.3 Floating bridge vs. suspension bridge

Both side mounted panels and roof mounted panels are technically feasible for floating bridges as well as for suspension bridges.

Both bridge types, however, have their advantages and disadvantages with regards to these solutions. On a suspension bridge, panels will normally be installed higher above the sea surface, causing less challenge with sea spray compared to a floating bridge. It is however possible to design floating bridges with driveways raised high above the sea level too.

The main drawback from a suspension bridge would be shadowing effects from towers and cables, which lead to production losses. Shadowing would be most challenging on north/south oriented bridges, and less of a problem for east/west oriented bridges.

4.5 POTENTIAL FOR RENEWABLE ENERGY PRODUCTION

4.5.1 Environmental data

4.5.1.1 General

For optimal utilization of solar energy it is necessary to have knowledge about environmental data in the specific areas in the study of interest. The local climate and solar radiation are typical data that will contribute to evaluate the potential.

The climate in Norway has been registered since the middle of the 19th century. The tendency in the western part of Norway is a mild and wet climate, mainly due to the proximity to the ocean and the high mountains. Due to the varied terrain the climate will vary depending on location.

The public environmental data for solar radiation of the various places in Norway are rather scarce. In Norway there are only a few places measuring the solar radiation levels. In areas where measurements of solar radiation is lacking, interpolation data is found by utilizing existing data for nearby places/cities.

The Joint Research Centre, a part of the European Commission, has developed an instrument for geographical assessment of the solar energy resource called PV GIS (Photovoltaic Geographical Information System). This program has been used to find values for solar radiation and optimal inclination angle in a specific location. The values are not that accurate in the Northern parts of Europe, but can still give a fairly good indication of the sun conditions in a specific area.

Bioforsk is a Norwegian science institute which is doing research related to agriculture, food production, environment and resource management. They have about 50 weather metering stations, located in all of Norway, and some of these stations are located relatively nearby the fjord crossings. Data from these stations are available at their website, and one of the parameters measured is global irradiance on a horizontal surface. This is the sum of direct irradiance on a horizontal surface and diffuse irradiance. Due to the lack of good data from Northern parts of Norway in PV GIS, data from Bioforsk has been chosen to use in correlation with PV GIS.

4.5.1.2 Data

The energy potential has been estimated with data from both PV GIS and Bioforsk.no. The data from both sources coincides very well, with the PV GIS material being consistently lower than the Bioforsk data, but no less than 9%, and mostly about 5%. The one exception is “Bjørnefjorden”. According to met.no [3] there shouldn’t be more precipitation in this area than the others. The difference will not be discussed further in this report because it does not have a significant impact on the result. If one were to go through with any of the suggested ideas in Bjørnefjorden, this issue should be investigated closer. The resulting data for the different sites are shown in Figure 27

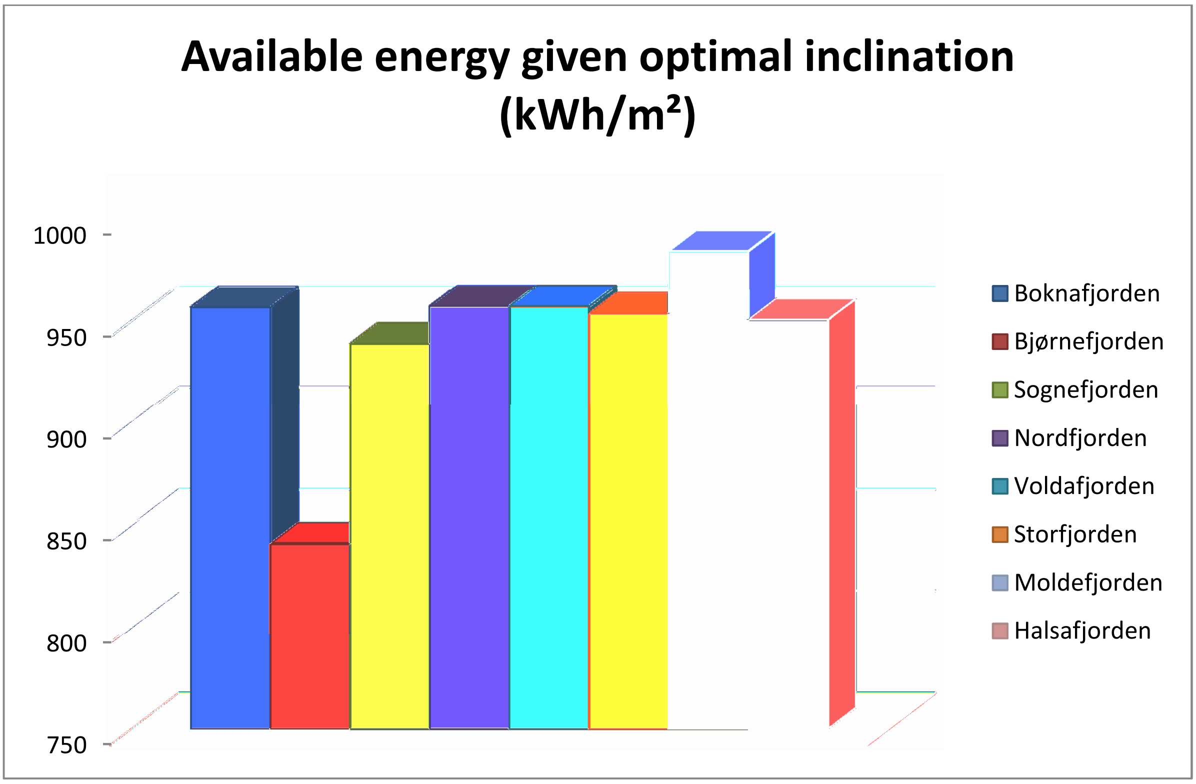

Figure 27. Available solar energy at the fjord crossings

4.5.2 Electricity production per area

As for wind energy, it is useful to develop a generalized measure of energy production, in terms of energy per m^2 covered with solar panels. To arrive at this, we have looked at specific examples of panels from suppliers.

Vendors in the solar panel market largely deliver solutions based on crystalline silicon or thin film technologies. A standard crystalline panel from the REC with a nominal power at 245 W_p will have the dimensions 1,00m x 1,65 m. The efficiency is 14,8 %.

Schüco is another vendor of Solar Panels, specialized in delivering large-scale installations. They deliver thin-film panels with an efficiency of 9,2 %, nominal power of 135W and physical dimensions of 1,30m x 1,10m with an area of 1,43m^2.

There is a significant difference in efficiency between the two technologies, but it should be kept in mind that the crystalline panel will vary much more according to inclination and the quality of the radiance than a thin-film panel.

Based on an average solar radiation of 925 kWh/year, a production of approximately 136,9 kWh/m^2 is possible with a crystalline panel, and 85,1 kWh/m^2 with a thin-film panel. It should be noted that this production is due to direct radiation. Diffuse radiation is not taken into account, which means that the thin-film panel might have a potential of producing more than 85,1 kWh/m^2.

4.5.3 Thin-film vs. crystalline

All fjord crossings studied are situated in the western part of Norway, which in turn implies that the weather might be rather rough. In fact, considering the weather conditions in the southern half of Norway, the west-coast is the least favourable area to install solar panels.

The climate statistics and the sun conditions suggest that solar panels installed in this part of the country should be installed optimized for production in the summer time. This in turn means panels facing south and with an optimized tilt angle. It is beneficial that the solar panel is able to utilize both direct radiance and diffuse radiance. The reason for this is that the diffuse radiation component in the global radiation in this area is rather large. This means that even though the sun-energy that hits the west-coast is not that low compared to the east-coast, a crystalline silicon panel will not be able to transform the same amount of energy into electricity.

A thin-film panel, on the other hand, will be able to convert both diffuse and direct radiance. For some of the bridge designs, the possibility to place the panels directly on the surface will be an aesthetically big advantage. This will result in a non-optimal tilt, but thin-film panels are not as sensitive to this as crystalline silicon panels. The colour of the panels might also be of importance when choosing type of solar cell technology. The crystalline silicon cells are normally dark blue of colour, while thin-film cells are black with varying transparency. However, black crystalline cells can also be offered, but with slightly reduced efficiency.

Taken in consideration the flexibility with relation to tilt and weather the thin-film technology might seem like the best choice for this project. Also from an aesthetic point of view this technology is often favoured. However, all relevant suppliers presented with the scope of the project recommend crystalline silicon panels. In addition to having higher efficiency under ideal conditions, this technology has the advantage of being older, more well-proven and robust than thin-film.

Historically the cost of producing thin-film technology has been less than for crystalline silicon, and this has been one of the main advantages of choosing this technology. Due to the drastic cost reduction of crystalline silicon the recent years (see next chapter) the cost is no longer an advantage. Another less advantageous aspect of thin-film technology is the expected lifetime, which is 10-15 year compared to at least 25 years for crystalline silicon. As the access to a system installed on a bridge construction is more challenging than to a ground- or roof-mounted (on buldings) system, a technology with higher expected lifetime is preferred.

Both technologies can be assessed possible for this type of installation, but with today’s technology the advantages of crystalline silicon appears greater than those of thin-film.

4.5.4 Potential –relevant examples

As argued in chapter 3.5.3, potential production at a given site is largely dependent on the number and size of units installed. The following are some relevant examples of what could be done.

We base the examples on installation of the 245 W panel from REC described in chapter 4.5.2. If one were to install a double row of side-mounted panels on a bridge, the nominal output would be:

$$245\,W/panel \cdot 2\,panels/m \cdot 1000\,m/km = 490\,kW/km$$

Given an average potential of 925 kWh/year and an efficiency of 14,8 % the yearly production of a panel would be

$$925\,kWh/(m^2year)\cdot 1{,}65m^2/panel\cdot 0{,}148\approx 226\,{}^{kWh/year}\!\big/_{panel}$$

and

$$226\,{}^{kWh/year}\!\big/_{panel}\cdot 2\,panels/m\cdot 1\,000\,m/km = 452\,{}^{MWh/year}\!\big/_{km}$$

Based on the input data given in Figure 27 the total installed effect and annual production potential per unit length of the bridge is calculated for the different fjord crossings. The majority of the crossings will have a bridge orientation from east to west, and in this case the panels are assumed to be placed directly along the side of the bridge, facing south.

As for the crossing in Sognefjorden and Storfjorden the orientation will be from south to north. The estimates are done assuming panels placed perpendicular to the bridge, as explained in chapter 4.4.1, with two times two panels placed in each row. For the crossing in Nordfjorden a zig zag construction is assumed, with four panels grouped together at each pier. The results are shown in Table 5.

Table 5. Annual solar production potential at the different crossings, example

	Length (km)	Side-mounted - kW/km	Side-mounted - kW	Side-mounted MWh/km	Side-mounted MWh
Boknafjorden	7,5	490	3 675	467,4	3505,5
Bjørnafjorden	2,7	490	1 323	410,7	1 109,0
Sognefjorden*	3,7	653	2 417	305,7	2 262,5
Nordfjorden	1,7	516	877	492,0	836,4
Voldafjorden	2,6	490	1 274	467,4	1 215,2
Storfjorden*	3,5	653	2 287	621,2	2 174,4
Moldefjorden	1,6	490	784	480,6	768,9
Halsafjorden	2,0	490	980	464,5	928,9

*This alternative assumes installations on both sides of a floating bridge, with no shadowing

This calculation example shows the energy potential if using the designs described above. It is possible to increase the numbers further by increasing the numbers of panels installed. Realistic production numbers are likely to be lower due to variation in solar radiation, some shadowing (for Sognefjorden, Nordfjorden and Storfjorden) and the fact that the actual available area for installing the solar panels might be less than assumed.

As for the alternative of roof-mounted panels, similar calculations have not been done. The proposed designs for the floating bridges are expected to vary significantly; hence the available area for installation will vary accordingly. A rough estimate based on the suggestion in Figure 26 can be done. Assuming covering a trapeze-shaped area with a width of 10 meters at the top of the arc and 20 meters at the bottom and a length of approximately 125 m, gives an area of 1 875 m^2 possible for installation of panels. Using the numbers given in section 4.5.2 (based on an average solar radiation of 925 kWh/year), an installation of this size can theoretically produce 160 MWh/year (thin-film technology) or 262,5 MWh/year (crystalline silicon). These numbers are valid given 100 % coverage of the area, that means an effective area of 1 875 m^2. For crystalline silicon the production can be assumed to be less, mainly due to the varying tilt angle.

4.6 COSTS

4.6.1 Background

Solar power has for a long time been one of the most expensive energy sources. Competing with hydro power in Norway, the solar technology has mainly been reserved for use where other energy sources have not been available, such as in isolated buildings in the mountains.

In recent years there has been an increase in manufacturers, which have resulted in a dramatic cost reduction for solar panels. In the last five years, the price for silicon has been lowered around 85 %. One of the main reasons for this is the recent mobilisation in China. Government subsidies and lower wages than in most European countries have led to an industry of mass production of high quality solar modules with low material costs.

In the future years it is expected that the costs will fall even more. This together with probable increased module efficiency will facilitate for a higher competitiveness than of today.

4.6.2 General

When considering installation of solar panels on bridge constructions, the design of the bridges will be very normative for the area available for solar panels. The required equipment will be the same as for a regular ground-mounted or roof-mounted solar power plant, but the mounting systems will be a greater challenge. Considering the location and shape of the bridge constructions compared to the foundations of regular solar power plants, the mounting systems must necessarily be specially designed according to the bridge design. This might be expensive, and will depend on to which extent the bridge construction can be altered to integrate the solar panels, type of solar technology that is used etc. The cost of installation will also very depending on whether a design with solar panels on the roof or on the side of the bridge is chosen.

Arriving at accurate cost estimates for such installations considered in this project is rather difficult, especially at such an early stage. The prerequisites as mentioned for wind in chapter 3.6.1 also apply for solar power. Negotiation of prices, different designs and manufacturers will influence the final cost. For solar power the system integration cost is normally constitutes more than 50 % of the total cost. Given that information about the existing grid in the different locations is not known it is hard to give accurate estimates for the total system cost. However, some rough estimates has been done, comprising the costs of solar panels, inverters and electrical works (material costs). The costs for mounting system, power cables and assembling are not included.

Cost estimates are presented for side-mounted solar panels. These estimates are based on use of crystalline silicon, due to the fact that several suppliers have recommended this alternative. Thin-film technology can of course be considered for some of the bridge concepts, but it is expected that this choice will require a lot more considerations regarding protection due to the environment.

4.6.3 Cost example

Using the same sample installation as for calculating production in chapter 4.5.4, with a double row of side mounted panels, the following costs estimate can be made.

Unit cost for the REC panels are 1,2 €/W_p (similar prices have been obtained from Scatec Solar), which gives a cost of 294 €/panel (178 €/m^2) for 1,00m X 1,65m panels. This gives a cost pr. installed kilometre of panels of

$$294\,€/panel \cdot 2\,panels/m \cdot 1000\,m/km = 588\,000\,€/km$$

The installation will also require switchgear for connection to the grid. A nominal power of almost 500 kW will in many cases require a new transformer to be installed to be able to transfer the power to the grid. This will have to be evaluated in each case, and if there is enough capacity in the existing grid, connection can be coordinated with the bridge installation thus saving costs. The total cost of a 500 kVA transformer and switchgear is roughly estimated to be NOK 500 000 or €65 000. If there is no need for a transformer the cost will be about 300 000 NOK or €40 000. This cost is not linear, and will be relatively reduced with a larger installation. Based on the above mentioned assumptions, the total cost of panels, inverters and electrical works can be seen in Table 6.

Table 6. Cost of solar panel, inverters and electrical works at the different crossings, example

	Length (km)	Material cost NOK
Boknafjorden	7,5	33 957 000
Bjørnafjorden	2,7	12 224 520
Sognefjorden	3,7	22 336 160
Nordfjorden	1,7	8 102 021
Voldafjorden	2,6	11 771 760
Storfjorden	3,5	21 128 800
Moldefjorden	1,6	7 244 160
Halsafjorden	2,0	9 055 200

A total cost estimate for the fjord crossing in Moldefjorden has been roughly estimated to give an overview of what this type of installation would cost. The final number includes solar panels, inverters, electrical works, power cable, transformer and switchgear and is found to be approximately 8,7 MNOK. Adding an installation cost of about 20 % will give a final result of 10,5 MNOK. This is based on an assumption that the transformer and switchgear is placed close to one side of the bridge. Further connection to existing grid is not taken into account.

Note that mounting systems are not included in this estimate, as the price for this is very uncertain. A supplier has carefully suggested a number for a mounting system for this type of installation to be about 1 200 kr/m^2. Using the fjord crossing in Moldefjorden as example, with 3,3 m^2 installed solar per running meter of the bridge, a total area of 5 280 m^2 can be covered. This is equivalent to a cost of 6,3 MNOK (7,5 MNOK including a 20 % installation cost). Compared to the cost given in Table 6, this value suggests that the mounting system alone will cost almost as much as the panels, inverters and electrical works combined. The unit value of 1 200 kr/m^2 can only be considered as a qualified guess, based on the assumption of a specially designed mounting system. A more realistic value can first be established after a further study based on a chosen bridge concept. Depending on the design, the mounting system could probably be less expensive than implied, especially if the bridge construction is adjusted to create a suitable foundation for the solar installations.

4.7 SUPPLIER INTEREST

Some suppliers of solar panels have been contacted in connection with this survey in order to gauge interest and collect additional data. Most suppliers contacted via Norwegian offices have been rather helpful sharing relevant data in the extent possible. The suppliers of the projects in London (Solarcentury) and Bonn (Solarworld) has been contacted, but no responses have been received.

As the sun conditions are more beneficial in latitudes further south and production costs in Norway are quite high, most supplier headquarters and production sites are found abroad. Worldwide there are many suppliers of solar technology which might be interested in such a project. As an example following suppliers can be mentioned: REC, Scatec Solar, Shüco International KG, Sunpower, Solarwold, Sanyo, Getek AS.

Getek AS and Shüco International KG have previously delivered solar systems in Norway, of the building integrated type. Getek AS installed a plant on the new Oseana Art & Culture Center in Os municipality in 2011, while Shüco International KG is the supplier of a solar plant one of the facades of the Opera House in Oslo.

The recent years the largest supplier present in Norway has been REC, the Renewable Energy Corporation, with several offices and production sites around the country. Due to overproduction and the drastic cost reduction the corporation has been forced to close down several factories and offices throughout the country. As from May 2012 the Norwegian headquarter no longer exists, and the supplier itself encourages further contact taken directly with the office in Germany.

Scatec Solar is another corporation present in the Norwegian market. However, their main focus is on system deliveries of a certain size, mainly to foreign countries.

There are many suppliers available, and it seems like suppliers find the project interesting. However, due to the early stage of the project it is challenging to get a real engagement.

Presenting the suppliers to a more concrete concept, and inviting them to participate in an Ideas Competition might increase the interest.

4.8 EVALUATION

4.8.1 Economic feasibility

The average cost pr. kWh of annual production for the solar installations in Moldefjorden, is estimated to be 13,7 NOK. This cost does not include mounting system. Including the price for mounting system discussed in chapter 4.6. 3 will increase the number to more than 20 NOK. Although the estimates are uncertain, it is still improbable that the installations could become economically feasible in the foreseeable future. Cost pr. unit will vary somewhat between the sites, but even for Moldefjorden with the highest solar intensity, costs estimates are high.

4.8.2 Challenges

Compared to wind installations, challenges related to installing solar panels on bridges appear to be less severe. The study has shown that panels probably can be installed without significantly increasing wind load on the bridge structures. Also, icing is not a safety issue for the solar panels.

Still, challenges relating to maintenance remain. Sea water and road pollution will lead to increased need for cleaning. The saline environment is also likely to reduce the lifetime of parts of the installations. In addition installations on a bridge are likely to be harder to access than ones on land, making repairs etc. more costly.

In total, it is our evaluation that the installation of solar panels on the bridges in question are unlikely to be feasible as pure production systems for delivery on the grid. Pilot installations could however still be of interest if non-economic and non-technical issues are taken into account, as will be seen in the last two chapters of this report.

4.8.3 Further work

The work conducted so far has been focusing on collecting data about the existing technology and to find possible solutions seen from a technical point of view. The cost estimates are mainly based on experience data for regular solar power plants, and it is necessary to do more precise calculations when the bridge designs have come to a more detailed stage.

Seen as the aesthetics probably will be an issue, it is recommended to include an architect in the further designing. At the same time suppliers should be closer involved. In this report it has been recommended to use crystalline silicon cells. In a further investigation the use of this technology compared to thin-film technology should be studied more closely, hopefully revealing the real potential for the different technologies for this type of installation. Studying in which extent diffuse sunlight can be utilized might be of great interest.

As the bridge designs and orientation are chosen for each site, a few concrete design suggestions can be made. This should preferably be done in cooperation with architects and structural designers. Then it will be easier to decide what type of installation and type of solar cell technology will be best suited for the specific site, regarding both the technical and economic aspects.

5 Environmental considerations

This chapter provides a brief discussion of environmental consequences associated with the installations studied, and compares briefly with conventional installations.

Conventional wind turbines or wind farms may effect local or regional environment and society in various ways. Descriptions of how the turbines will affect the following themes are normally requested:

- the visual landscape and its values
- cultural heritage and environment
- outdoors activities and traffic
- habitats and vegetation
- birds and other animals
- intervention free areas
- noise
- shadow cast and reflection
- likelihood for unforeseen accidents and icing
- value creation locally and regionally
- tourism
- land use
- aviation and communication systems

Since the turbines in this case are planned mounted on bridges crossing fjords, many of these themes are not relevant. The most actual consequences here are likely to be how the turbines will affect the visual landscape, birds, unforeseen accidents and value creation.

5.1 POTENTIAL CONFLICTS

Solar - and wind energy generation are different when it comes to potential conflicts with environmental issues. Wind turbines may increase mortality rates, especially among birds and bats, due to collision, loss of habitat, noise, other disturbances and barrier effects. Loss of habitat, noise and disturbances are not considered relevant in this study, due to the assumption that the bridges themselves will influence these aspects considerably, with or without the incorporating of solar or wind power. Hence the focus will stay with the risk of collision and possible barrier effects of wind turbines for birds.

Both solar panels and wind turbines can impose visual landscape and architectural challenges. Wind power generation is considered the most potent of the two, given its rotating movement and any requirements of warning lights for aviation.

5.2 WIND TURBINES AND BIRDS

A location with a few wind turbines will generate small effects, compared with an extensive wind park. If there are large wind parks nearby, the cumulative effect could be controversial anyway. It is therefore important to know the distribution of built and planned wind turbines in any specific area. Distribution and densities of different species in any particular area is also crucial information. Information about key areas, such as nesting sites, moulting sites, resting areas and migration routes will indicate potential challenges. Special attention should be given species which are known to be vulnerable in this aspect and species listed threatened in *The 2010 Norwegian Red List for Species*, for instance birds of prey and species within the orders *Galliformes* and *Charadriiformes*.

Large horizontal axis wind turbines are known to kill birds from several locations, but there is little knowledge about wind turbines mounted on bridges crossing fjords and conflicts with birds. It is however likely that the bridge structure itself and the passing traffic will make many species of birds avoid the site altogether. If so, bridge mounted turbines may cause less a problem than conventional turbines on land or at sea. Other species may be attracted to the structure and attempt crossing the stretches of water above it, with increased mortality as a result. Further studies will probably be needed, if the large turbines are chosen.

The smaller turbines, both the horizontal and vertical, are likely to pose minor problems in connection with bird collisions. Faster rotation and shorter blades probably makes them easier to see and avoid.

5.3 CONCLUSIONS ON CONSEQUENCES

Solar panels or small wind turbines mounted on bridges will probably not induce any major conflicts in relation to environmental issues. The large wind turbines, introduced to suspension bridges or floating bridges are more likely to create some challenges, in relation to the visual landscape, collision risk for birds and unforeseen accidents.

It is also clear that installation on bridges will lead to reduced consequences compared to conventional installations due to the fact that the bridge in itself will already have caused many of the consequences normally associated with such installations.

6 Conclusions

The eight fjord crossings included in “Ferryless E39” have been studied in order to find possible technical solutions for integration of wind and solar power installations to the bridges.

For wind power, a major concern has been to find designs that do not overly increase wind loads on the structures. This is important for long bridges that are not fixed to the ground along the length of the structure, such as the floating bridges and suspension bridges considered here.

Wind speeds are found to be relatively low at the sites. This is probably a result of them being placed some distance inland in fjords with elevated terrain on all sides, and means that most of the sites are not suited for wind power installation. Boknafjorden is an exception with relatively good wind conditions. Cost and production estimates show that an installation of large horizontal axis wind turbines there could possibly be economically feasible there.

Solar power installations on the bridges are not found to be economically feasible for any of the sites. In terms of investment, however, installation on bridges may not differ much from on-land installation, but maintenance costs are likely to be higher.

When looking at environmental conditions, our conclusion is, as expected, that consequences of installations on bridges will likely be smaller than equivalent installations elsewhere. Wind power at the Boknafjorden crossing will however still face challenges relating to birds.

Although installation of renewable energy appears economically unfeasible at the sites studied, other sites with better solar and wind conditions, and/or easier conditions with regards to foundations, could well be better suited for this. If such an installation were to be built, it would surely attract significant (likely positive) attention and interest. For the sake of promoting the “Ferryless E39” project as a whole, pilot installations at one or more of the sites could therefore be of interest. Such a pilot could then serve as a basis for refining the designs for such installations, which again would facilitate installation of feasible, low consequence installations at other and more suited sites.

If it is desirable to go further with this project, Norconsult’s recommendation is to select one site for wind installation, and one site for solar installation for further studies. Such a study should be a multi discipline study in which renewable energy experts work together with bridge designers to find specific designs that can be used as a basis for more detailed calculations. See also the discussions under further work.

For wind power, Boknafjorden appears to be the best site to study, depending on further design choices there in terms of tunnel vs. bridge. For solar power, a study of Julsundet in Moldefjorden is recommended.

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