Statens vegvesen

Technology survey for renewable energy Integrated to bridge constructions

Wind energy

Statens vegvesens rapporter

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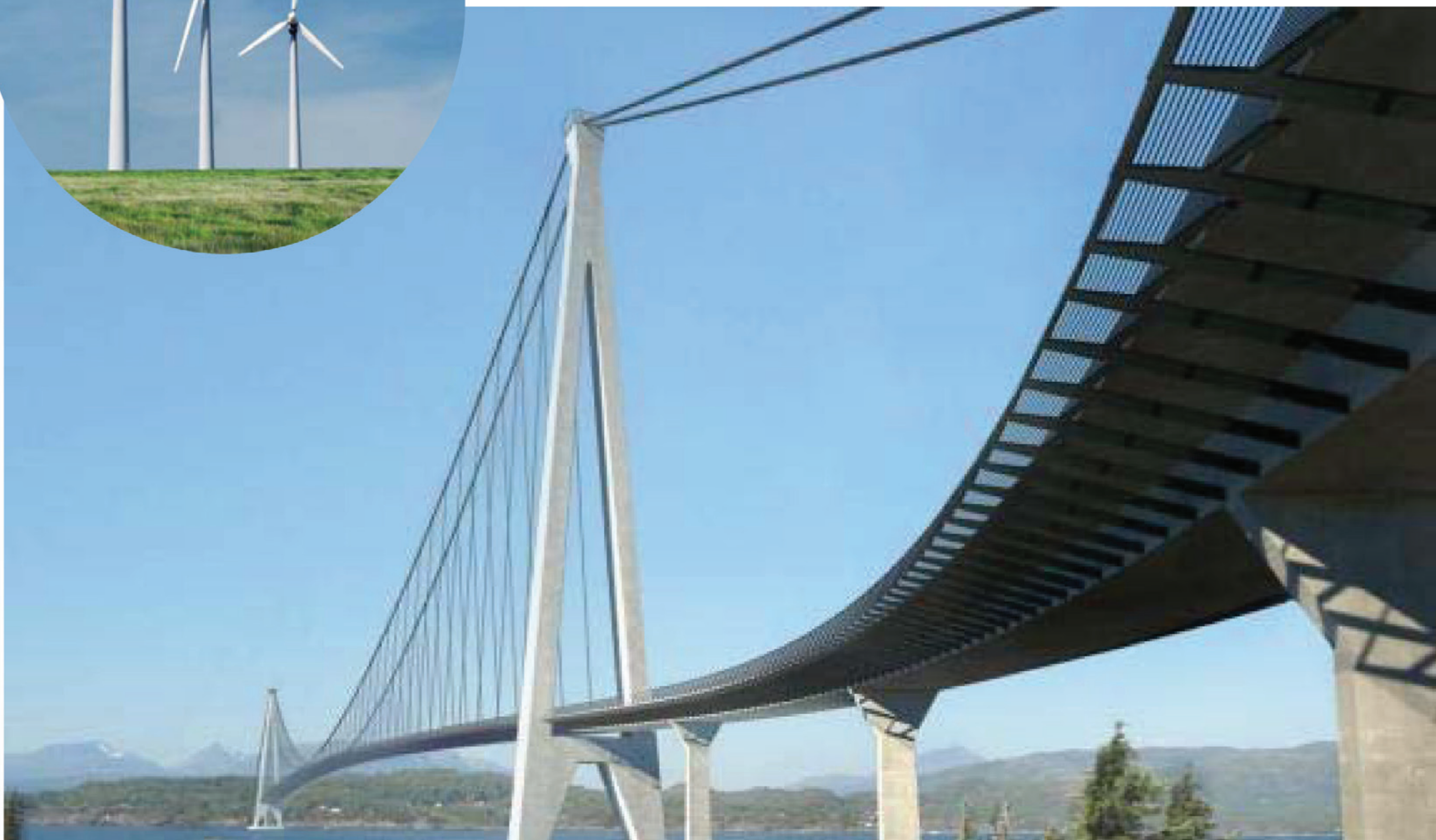

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Wind Energy Technology Survey for Ferry Free E39 Project

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SP Structural and Solid Mechanics

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Executive summary

E39 is a road located along the west coast of Norway with a number of fjords with ferry crossings along its entire length from Kristiansand in the south to Trondheim in the north. The fjords crossings range from 1.5 km to 25 km in length and have depths down to 1300 m. Proposed "Ferry Free" solutions for the fjord crossings consist of suspension bridges, floating bridges and submerged floating tunnels. This feasibility study reports how the bridge structures can be utilized for wind energy generation.

The wind energy production potential for the eight fjords shows high variation between the different fjord crossings. There are fjords that have very good wind resources and there are fjords with very low wind energy potential.

The essential assumption for this energy production potential assessment is based on the performance of a 10 kW DAWT-turbine with an maximum outer duct diameter of 3,1 m which has been installed with 215 turbines per km (1,5D spacing between turbines) and that 80 % of the length of the bridges have been equipped with wind turbines.

The initial result of the wind energy potential assessment shows that if the wind turbines are installed at 50 m above the sea level, the annual energy production would be about 59-71 GWh. The wind turbine height of 50 m corresponds to suspension bridges only.

On the other hand, if the wind turbines are installed at the low level 10 m the annual energy production potential would be reduced to about 29-37 GWh. It is assumed that a height of 10 m corresponds to floating bridges and submerged tunnels.

Looking at the energy contribution from each individual fjord, the study shows that the three fjords Boknafjord, Bjørnafjord and Moldefjord account for over 70 % of the total energy production potential for all fjords.

For comparison, a standard 2 MW wind turbine annual energy production is about 5 GWh while the bridge wind energy potential 30-70 GWh.

An important assumption for the integration of DAWT turbines in the bridge structure is that the bridge load capacity does not need to be increased due to the wind turbines.

It is recommended that future work should be focused on the DAWT-technique and how the DAWT-module can be integrated in the bridge structure with maintained optimal performance. Work should be performed to define the DAWT-turbine as a standard building component manufactured in a highly modularized industrialized process. It is also recommended that the DAWT-module influence on the bridge structures from mechanical vibrations, stress and fatigue aspects should be investigated.

1 Introduction

E39 is a road that is located along the west coast of Norway and extends from Kristiansand in the south to Trondheim in the north. Currently, a number of ferry crossings are required to traverse its entire length. The Transport Ministry has given a mandate for the project "Ferry Free E39" to assess the technological solutions for the crossing of eight large fjords without ferries. The fjords crossings range from 1.5 km to 25 km in length and have depths up to 1300 m. Proposed solutions for the crossings that are under consideration consist of suspension bridges, floating bridges and submerged floating tunnels.

The **Energy** part of the project is to consider how the construction of the crossings can be combined with devices that produce energy from **waves, tides, wind and the sun.** The idea is that by using the bridge construction as part of the facility**, the production cost of renewable energy can be reduced** and therefore become more competitive with non-renewable energy sources.

SP Technical Research Institute of Sweden has been commissioned by the Norwegian Public Roads Administration to perform a technology survey and generate a summary of the current state of the art wind energy conversion technologies. A request for information "Questionnaire wind power and bridge structures" was sent to the majority of the wind turbine manufacturers in order to obtain the most up to date information about the current technology status and performance data and conditions of functionality for each of the devices.

The thoughts behind the questions asked in the request for information, results of the survey as well as a recommendation for wind turbine integration with bridge structures and an assessment of the wind energy production potential are presented herein.

2 Wind energy conversion technologies

The natural power in the wind is proportional to the air density, the swept area and the wind speed cubed. The power output from a wind turbine is proportional to the air density, the swept area and the wind speed cubed multiplied by the power coefficient. The theoretical maximum of the power coefficient for a horizontal axis wind turbine without duct is 59,3 % [Ref 1]. Most wind turbines will only reach 30-40 % of the natural wind power but the most optimized wind turbines will reach 45-50 % of the free natural power at the most optimal wind speed 8-9-10 m/s.

To increase the power output from the wind turbines the research and development work has been focused on increased swept area for the common horizontal axis wind turbine, increased efficiency of the wing blades and increased wind speed through the rotor plane.

The technical development during 30 years has been focused on achieving larger rotor diameters. Today's big MW-wind turbines have very large diameters to increase the swept area to increase the power output. The multimegawatt wind energy industry is today a mature line of business with many manufacturers all over the world.

The technical development for the Small Wind Turbines (SWT) has been focused on safety, quality and increased power output by using ducts to increase the wind speed through the rotor. The IEA Wind organization has in 2011 completed an international safety and quality improvement project called "Labeling of Small Wind Turbines". The result of this work will be part of the international safety standard IEC 61400-2 for small wind turbines.

IEA Wind is now working with Built-Environment Wind Turbines (BWT) in urban areas. The wind turbines in urban areas has been given high attention due to the awakening interest for "green publicity" from companies and the public. The IEA Wind organization is aware of the increasing demand for urban wind power and building integrated wind turbines and has started the new task "Recommended Praxis on testing and design for the Built-Environment Wind Turbines".

2.1 Technology classification information

All wind turbines are divided in the two major wind turbine groups, the horizontal axis wind turbines (HAWT) and the vertical axis wind turbines (VAWT).

Horizontal Axis Wind Turbine

The wind turbine market of today (2011-2012) is dominated by the standard onshore 2-3 MW horizontal axis wind turbine (HAWT). The offshore wind turbines rated generator power are now 3-5 MW and 6 MW coming during 2012.

Diffuser Augmented Wind Turbine

The ducted horizontal axis wind turbine is also called a Diffuser-Augmented Wind Turbine (DAWT) which can provide high power output with less rotor area due to increased air velocity through the rotor plane.

Vertical Axis Wind Turbine (H-rotor and Darrieus-rotor)

The vertical axis wind turbine was used before the horizontal axis type. It is called a Darrieus type of rotor and was patented 1931. Once the horizontal axis wind turbine was developed it became very popular and most of the research and engineering research was focused on the horizontal axis wind turbine type. In the last ten years there has been a growing interest for the vertical axis wind turbine due to the its simplicity and many small VAWT turbines up to 10 kW have been marketed by different manufacturers. The Swedish company Vertical Wind AB in cooperation with Uppsala University has been one of the design groups working with the VAWT H-rotor type of wind turbine. The first 200 kW H-rotor wind turbine from Vertical Wind AB is now in operation and connected to the Swedish national electricity grid for energy export. The advantage of the VAWT is a simple technical design and less noise due to reduced wing blade speed.

Savonius rotor

The Savonius type of rotor is a VAWT type of rotor (after the Finnish inventor S Savonius 1924). This type of wind turbine has low speed and therefore low power output because it is a drag type of turbine but it has high starting torque. With the introduction of low power LED-technology one can expect that the Savonius type of wind turbine can be used in more low power applications such as streetlights etc. The rotor speed is limited to the wind speed. The Darrieus and H-rotor type of turbines can be difficult to start and the Savonius rotor can be used as a starting turbine.

2.2 Technology status and future trends

Horizontal Axis Wind Turbine

The average rated generator power for the Swedish onshore wind turbine installations during 2011 was 2,13 MW with a total of 755 MW new installed wind power capacity. The global wind power installation was about 42 GW during 2011 adding up to over 240 GW installed capacity worldwide. The growth rate in the global wind power market has been around 25 % for some years and the industry continues to grow with new manufacturers entering the wind power market.

The large multimegawatt turbines of today are growing so large that there will be problems around installation onshore. Wing blades of 60 m and more are difficult to handle for a road transportation and solutions with air transportation is studied. It is feasible to believe that there will be a limit for onshore wind turbines due to logistics. For the offshore wind industry the wind turbines will continue to grow. Today’s turbines with rated power of 5-6 MW and rotor diameters of 150 m will be replaced within some years by installations of 10 MW wind turbines with 200 m rotor diameters. These 100 m long wing blades can easily be handled within the offshore industry with much less restriction on logistics compared to onshore installations.

Vertical Axis Wind Turbine

The technical development of the vertical axis wind turbines has not been following the “big” wind power trend. The Swedish company Vertical Wind AB has developed a 200 kW turbine which is in operation on the west coast of Sweden. Most other manufacturers have developed small VAWT turbines for urban applications. The advantage of the VAWT turbine is less noise and a simple mechanical design for low cost. The disadvantage is lower efficiency compared to the traditional horizontal axis wind turbine.

Diffuser Augmented Wind Turbine

Many engineers have been experimenting with different technical solutions to “speed-up” the wind speed in order to increase the power output for small wind turbines (SWT) for some time. When the “big” wind power grew bigger the obvious drawback with extremely long wing blades was clear and some design engineers started to implement the DAWT-technology for industrial sized wind turbines like Innowind.

For the small wind turbines (SWT) there have been numerous of design examples during the years, some more or less successful concepts, from Swift to donQI, Enflow and others.

The final report 2009 from the micro wind turbine field test project by Encraft Warwick Wind Trials in UK [Ref 2] disclosed some facts of building integrated micro wind turbines. The report concluded that the micro wind turbine technology need to be improved; the micro wind turbines produce energy at high cost and the life expectancy of small wind turbines are shorter than for big turbines.

2.3 Performance and economy

The big HAWT wind turbines are “standard” industrial products available from many manufacturers. The design life time is normally 20 years for all wind turbines. The energy production performance is more or less equal among the different manufacturers within the same wind class.

The production cost per kWh for onshore wind energy has dropped the last two years.. For a typical 2 MW wind turbine installed 2010 the “turn-key-price” was 6-7 SEK/kWh. With the low energy price (NordPool + green certificate) together with the introduction of more manufacturers from China with lower wind turbine price the Swedish market “turn-key-price” has dropped to 5-6 SEK/kWh which corresponds to about 1400-1600 KEUR/MW installed capacity.

At the Swedish Energy Administrations conference “Energiutblick 2012” in March 2012”, the wind turbine industry expects the wind energy production cost to be reduced down to 0,04 EUR/kWh within a few years. The price will drop due to new wind turbine manufacturers entering the market.

The MW-turbine cost level can be compared with the UK feed-in-tariff generation price for SWT wind turbines up to 100 kW which has been proposed to 21 p/kWh which is about 0,23 EUR/kWh. The UK FIT-scheme [Ref 3] shows the importance of FIT-tariffs for small wind turbines (SWT). The energy production cost level for SWT and PV solar energy is today about the same level due to PV cost reductions.

2.4 Future technology prospects

The traditional large multimegawatt HAWT turbines of today are growing so large that there will be logistic problems around installation onshore. Wing blades of 60 m and more are difficult to handle on road transportation and solutions with air transportation is studied. It is feasible to believe that there will be a limit for onshore wind turbines due to logistic limits.

For the offshore wind industry the wind turbines will continue to grow. Today’s turbines with rated power of 5-6 MW and rotor diameters of 150 m will be replaced within some years by installations of 10 MW wind turbines with 200 m rotor diameters. These 100 m long wing blades can easily be handled within the offshore industry with much less restriction on logistics compared to onshore installations.

More wind turbine manufactures design engineers are looking in the direction of direct drive technology trying to design out components with high failure rates like high speed gear boxes.

The DAWT-technology development will continue to be in focus. Many advantages can be expected from the DAWT turbines compared to the traditional HAWT turbine.

3 Wind energy technologies

3.1 Technology survey from questionnaire

The “Questionnaire wind power and bridge structures” (see Appendix 3) was emailed to sixty-six different wind turbine manufacturers with request for information and invitation to the Workshop in April in Trondheim. The main purpose was to gain information about technology and reference projects.

The multimegawatt wind turbine industry is now days an established industry with standard wind turbines in the product range. This situation became very clear when most of the manufacturers responded “thank you for your interest but our commitment is in the multimegawatt wind turbine product range”.

The multimegawatt wind turbines are unsuitable for integration to bridges, they are simply too big. Following manufacturers represent traditional HAWT-turbines but their product range includes small and medium sized wind turbines:

Table 1: Manufacturers with small and medium wind turbines

Manufacturer	Webb site	Wind turbine type and power
Turbowinds, Belgium	www.turbowinds.com	400, 600 kW, HAWT
Wind Technik Nord, Germany	www.windtechniknord.de	200, 250, 500, 600 kW, HAWT
Norwin, Denmark	www.norwin.dk	200, 225, 500, 750 kW, HAWT
Wind Energy Solutions, The Netherlands	www.windenergysolutions.nl	70, 80, 100, 200, 250 kW, HAWT
Northern Power Systems, USA	www.northernpower.com	100 kW and 2,3 MW, HAWT
Bornay, Spain	www.bornay.com	3, 6 kW, HAWT

The only manufacturer that had experience in building-integrated wind power was Norwin from Denmark.

The Norwin company had been involved in erecting wind turbines 225 kW and 29 m rotor diameters between the Bahrain World Trade Centre towers. Each one of the three wind turbines were installed on a dedicated steel structure between the two tall tower buildings (see Figure 1).

Figure 1: Top: Bahrain World Trade Centre; Below Strata Building in London (Photo: Norwin)

The other project is from the Strata Building in London where three (3) 9 m diameter wind turbines were integrated straight through the building.

The remaining five companies can together offer traditional horizontal axis wind turbines from 3 kW up to 750 kW.

3.2 Other technology status

This section shows wind turbines with less common technical solutions and new concepts.

Vertical Wind AB, Sweden (www.verticalwind.se)

The Swedish company Vertical Wind started 2002 with the vertical axis wind turbine concept with the 12 kW H-rotor wind turbine. From this prototype the company scaled up and manufactured the first 200 kW vertical axis wind turbine (VAWT) with H-rotor. The first prototype was erected in 2009 in Falkenberg on the west coast of Sweden.

Figure 2: VerticalWind 200 kW at Falkenberg, Sweden.

The company has plans to enter the multimegawatt wind turbine range and a 3 MW H-rotor turbine is under development.

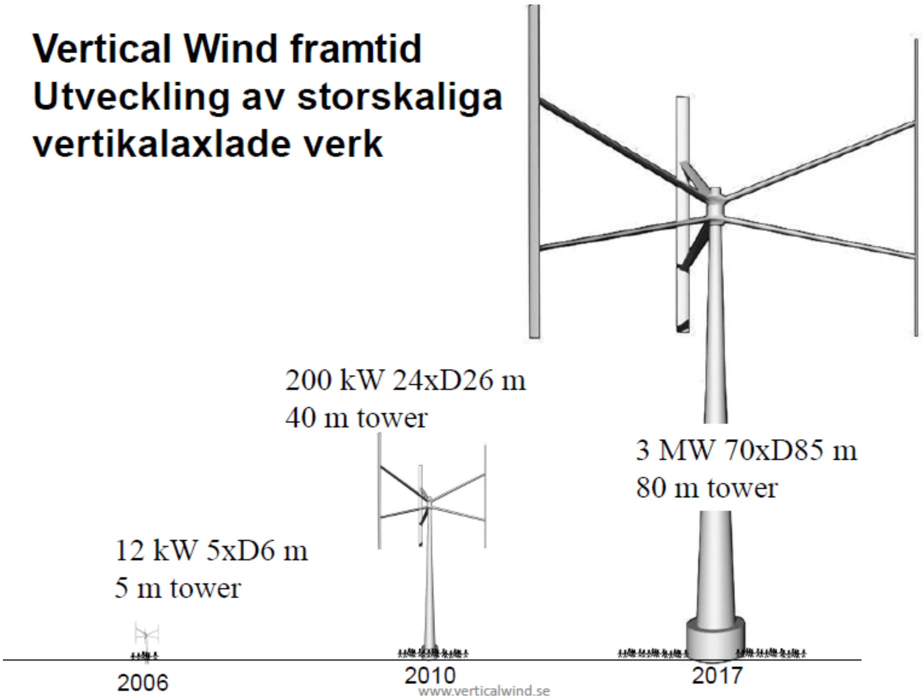


Figure 3: Vertical Wind development plans (picture Vertical Wind).

Performance

The performance of the H-rotor turbines has to be verified. As of today very limited test data are available from the prototype testing.

The VAWT turbines of Darrieus type have a more narrow power efficiency curve compared to the 2- and 3-bladed HAWT turbines. The drawback is poor starting torque and sensitivity to high turbulence intensity in the wind.

Relevance to the Ferry Free E39

The Vertical Wind H-rotor concept has improved power efficiency performance compared to the original Darrieus rotor but the company will not recommend the H-rotor for the bridge applications due to the wind speed turbulence around the bridge structures.

Hexicon, Sweden (www.hexicon.eu)

The Swedish company has developed a floating platform concept called Hexicon. The platform can be manufactured at land and then towed and anchored on the windy sites to reach higher capacity factors. The platform can be equipped with both wind turbines as well as wave energy devices.

Figure 4: The Hexicon concept (Hexicon)

Performance

The Hexicon concept is new and will require a lot of engineering work and validation work. The concept is very attractive since it is a floating concept and can be anchored where the wind energy resources are as most favorable. The engineering challenge is to cope with the very big wave forces on these windy sites.

Relevance to the Ferry Free E39

The Hexicon platform concept is of minor relevance to the Ferry Free E39 project.

Innowind, Norway (www.innowind.no)

The Innowind concept is very interesting concept with many ducted wind turbines (DAWT) installed on a floating platform. Due to the decreased rotor dimensions the floating platform can be equipped with a large number of turbines which will bring down the production cost per kWh.

Figure 5: The Innowind concept for offshore (Innowind)

The Innowind concept is based on the ducted augmented wind turbine type that can increase the speed of the wind. Innowind claims that the power output can be 6 times higher for the Innowind DAWT compared to a traditional HAWT turbine. The Innowind operating principle is to design the duct to increase the velocity of the air.

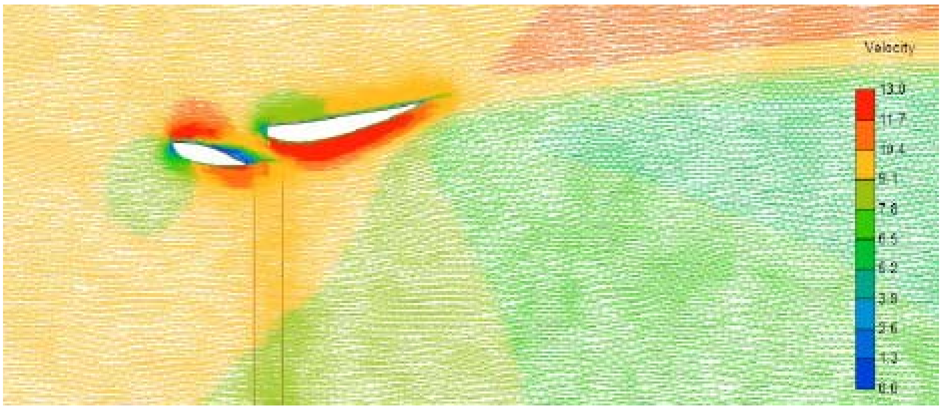


Figure 6: Wind velocity for the duct (Innowind)

The high velocity air is sucked through the slot in the duct and passes through the outer parts of the rotor blades which will be forced to rotate at a very high speed.

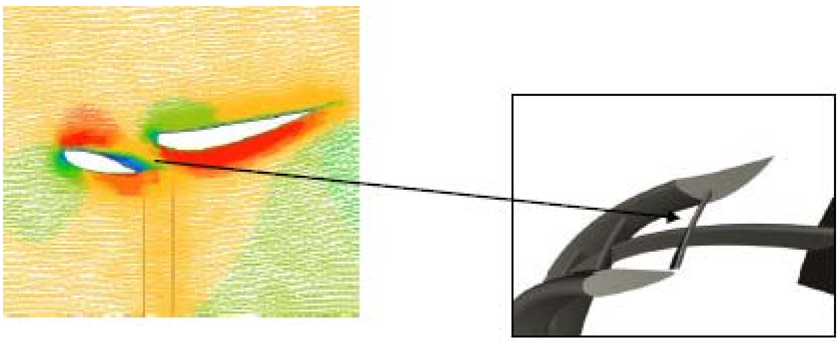


Figure 7: Wind velocity and rotor blade tips (Innowind)

Figure 8: Part of the rotor and the outer rotor blade tips which will be rotating at high speed (Innowind)

Performance

The Innowind concept is very new and like other DAWT turbine concept will require engineering work to verify and validate the DAWT turbine performance. The Innowind DAWT technique is interesting and shows potential for robust wind energy production in the future.

Relevance to the Ferry Free E39

The Innowind concept is interesting for the Ferry Free E39 project. The Innowind DAWT turbines can be adopted for building structures.

donQi, The Netherlands (www.donqi.nl)

Type: donQi Urban Windmill 1,5

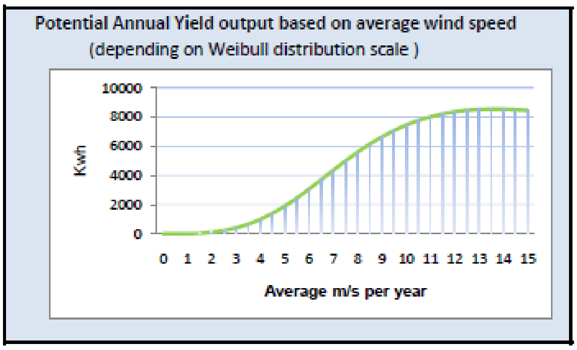
Figure 9: donQi Urban Windmill (donQi)

Ducted small wind turbine (DAWT) for max power 2,3 kW.

Rotor diameter 1,5 m (swept area 1,77 m2); outside duct max diameter 2,0 m.

donQi 1.5 Venturi Windmill - PV Curve

Performance (break at 20m/s	
Windspeed meter/second	Power kW
1	0.000
2	0.000
3	0.019
4	0.044
5	0.087
6	0.150
7	0.238
8	0.355
9	0.505
10	0.693
11	0.922
12	1.197
13	1.522
14	1.901
15	2.300
16	2.300
17	2.300
18	2.300
19	2.000
20	2.000
21	0.800
22	0.800



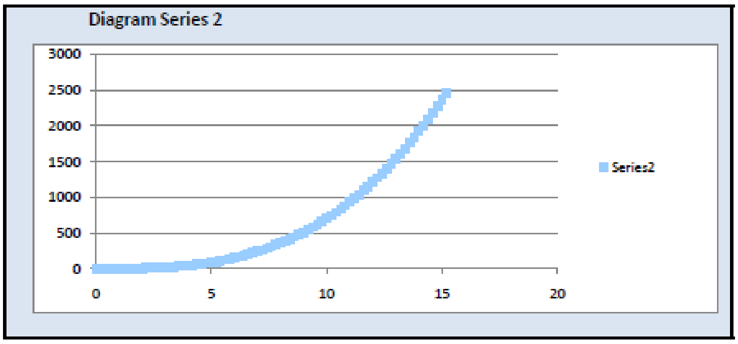


Figure 10: Power curve and potential annual energy production AEP (donQi).

Performance

The DAWT concept is new and like other DAWT turbine concept will require engineering work to verify and validate the DAWT turbine performance.

Relevance to the Ferry Free E39

The donQi-concept is interesting for the Ferry Free E39 project and the donQi DAWT turbines can be adopted for building structures.

3 Description of bridge types and locations

3.1 Suspension bridge

Figure 11: Illustration of Hålogalandsbrua (cowi/Satatens vegvesen)

Suspension bridges have been assessed as the optimal structure for integration of wind turbines to the bridge structure. The wind energy production potential assessment has been calculated for a height of 50 m above the sea level.

3.2 Floating bridge

Figure 12: Concept of Floating bridge crossing Björnafjorden(Lmg Marin)

Floating bridges have been assessed to accommodate wind turbines on a much lower height compared to suspensions bridges. The wind energy production potential assessment has been calculated for a height of 10 m above the sea level which theoretically corresponds to 75 % of the wind speed or only 42 % of the energy at 50 m height. .

3.3 Submerged floating tunnel

The wind energy production potential has not been calculated for the submerged floating tunnel. A submerged floating tunnel can be comparable to a floating bridge structure but with less length since only the pontoons of the submerged tunnel can be used for DAWT turbine installations.

3.4 Locations

The different locations of the fjord crossing are on the road E39 that stretches from Trondheim in the north to Kristiansand in the south of Norway. The length of the crossings vary from 1500 up to 5000 meters. Each crossing has different conditions and possibilities and demands unique and state of the art technical solutions.

Figure 13: Road E39 from Kristiansand to Trondheim with eight fjord crossings.

The locations of the bridges across the fjord crossings have been proposed as the shortest route along the E39 road. The suggested locations, bridge direction, length and wind speed maps can be seen in the Appendix 2. Input data and assessment criteria.

The risk for bridge – ship collisions has been estimated by SSPA Sweden AB, see report [Ref 4] based on the bridge locations in Appendix 2.

3.5 Wind speed in the fjords

For each fjord crossing the corresponding wind speed data has been used based on Kjeller Vindteknikk wind speed maps for 50 m height above ground/sea.

The Kjeller Vindteknikk wind speed maps [Ref 5] show good wind energy resource in the coastal region and at the orifice of the fjords. But the wind speed is reduced when entering deeper into the fjords.

An illustrative example how the deep fjords affect the average wind speed can be seen in the Figure 14 from the area south of Trondheim. The wind speed in the coastal region is around 6-7-8 m/s but dropping down to about 3 m/s in the fjords.

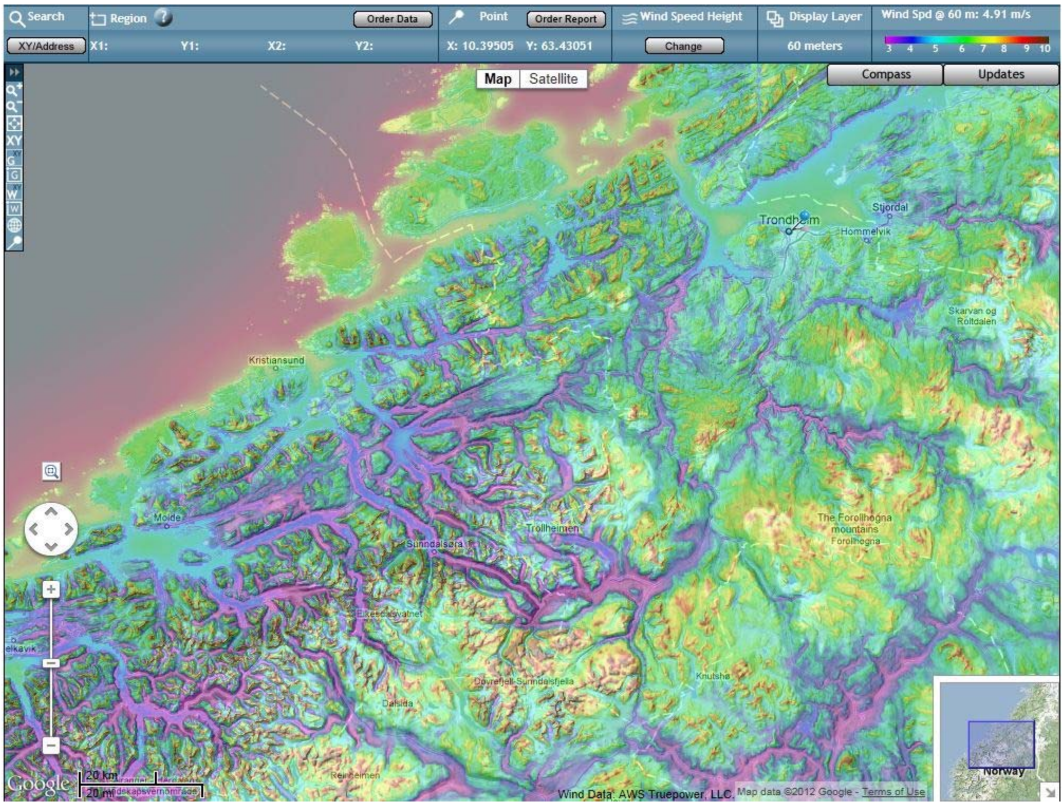


Figure 14: Wind speed at 60 m height (Photo by Google by courtesy of Northern Power Systems, USA)

The Figure 14 shows the average wind speed dependence with the distance from the coast when leaving the coastal region and entering into the fjords.

4 Basic recommendation for integration of wind turbines in bridge structures

4.1 Relevance to Ferry Free E39

Neither the traditional HAWT wind turbine nor the VAWT turbine have been considered for the bridge integration application. The main reason and draw backs why HAWT and VAWT are unsuitable is

- Moving parts above the road level must be avoided because of the traffic risk when the car drivers focus is diverted from driving
- The risk of falling ice and other “hard” components must be avoided
- The turbulent wind speed regime around the bridges are not suitable for ordinary HAWT and VAWT wind turbines.
- The traditional HAWT turbine is less efficient than the DAWT for a given rotor diameter.

4.2 Recommended solution

Due to the listed draw backs with the HAWT and VAWT turbines together with bridge structure it is recommend that DAWT turbines should be integrated with bridge structures.

The DAWT turbine can be integrated in very large numbers in the bridge structure in a standardized, modular and flexible way. The DAWT-module can be manufactured in 1000-quantities and can become “a low cost standard wind turbine” for bridge and building integrated structures.

The bridge structure should be designed from the very beginning to accommodate the modularized DAWT-turbine modules in “apertures/openings” in the structure. The bridge structure must not be modified in any other aspect than provide apertures/openings for the DAWT-modules. The structure does not need to be reinforced in any way to accept the DAWT turbine since the DAWT turbine can be stopped at very high wind speed. A stopped wind turbine will minimize the aero dynamic forces on the structure at high wind speed. The bridge structure construction will have a load safety margin anyway to withstand the wind loads at very high wind speed.

The bridge structures need not to be reinforced or designed with higher mechanical stresses than normal. The only restriction of the construction of the bridge is that the bridge structure shall have “apertures” for the DAWT-modules as a natural part of the bridge structure. The following pictures shows an example of a bridge with large number of DAWT-modules.

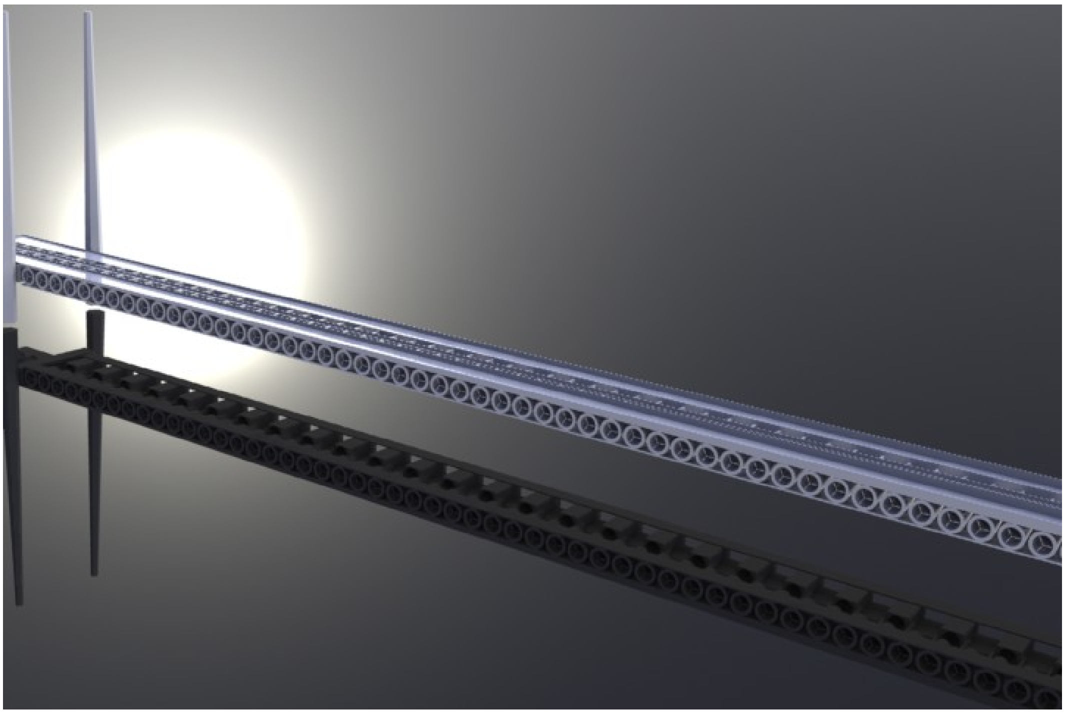


Figure 15: An illustration of wind turbines and suspension bridge.

The Figure 15 and 16 shows the DAWT-modules as modules attached to the suspension bridge structure. The fundamental "vision" is that the DAWT-modules will fit into "opening or apertures" in the bridge structure. The DAWT-module is easily replaced from the bridge.

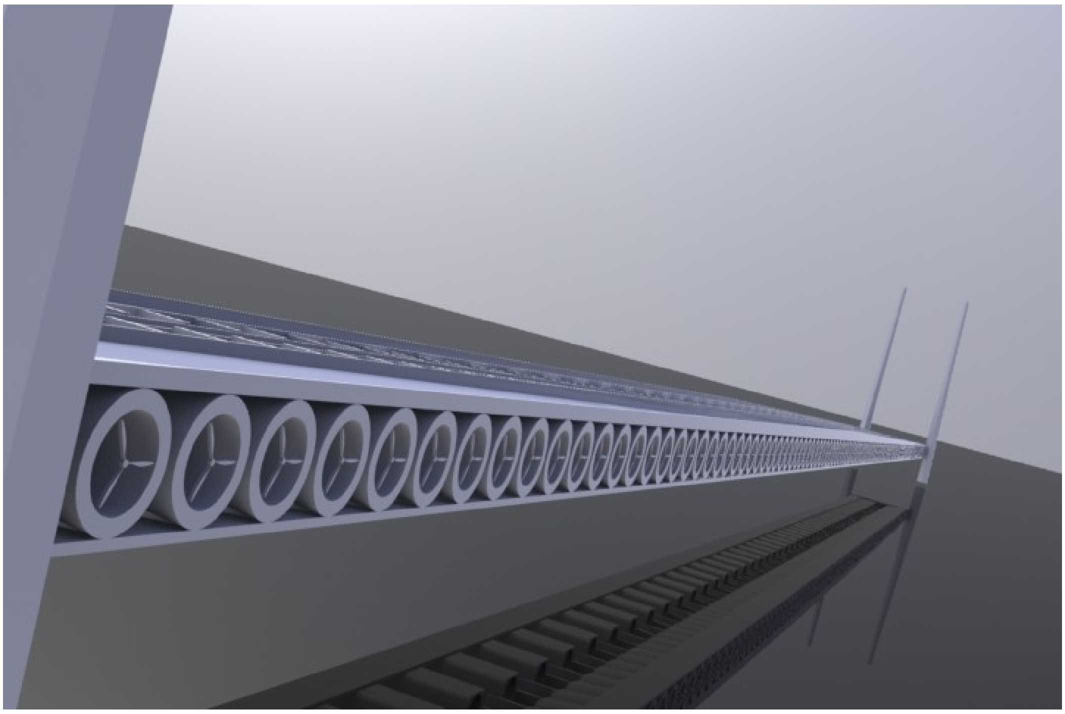


Figure 16: Bridge structure and DAWT modules

4.3 Basic conditions for the wind energy production calculations

Wind energy production potential has been calculated for the fjords at 50 m and 10 m height above sea level and the result is presented in section 5. The basic assumptions and conditions for the calculations are listed below:

Wind turbines

The wind turbine used in the energy production potential assessment is a diffuser augmented wind turbine DAWT-25/31-10 kW. The generator rated power is 10 kW. The diffuser inner diameter is 2,5 m equal to the rotor diameter and the maximum outer diameter of the diffuser duct is 3,1 m. The speed-up factor for the DAWT-turbine is 1,7. The number of DAWT-modules has been calculated with a factor 1,5 spacing between each module giving a c/c-distance of 1,5 x 3,1 = 4,65 m or 215 DAWT-modules per km bridge length. The actual DAWT-dimensions will be optimized together with the bridge construction.

Wind frequency distribution and wind resource maps

The annual energy production (AEP) is calculated for the Weibull wind frequency distribution with the shape factor C = 2,0 also called the Rayleigh distribution. The actual shape factor C depends on the terrain. For comparing the wind energy potential for the different fjord crossings it is a good approximation to use the Rayleigh distribution for all fjords. The average wind speed is varied according to the specific conditions for each fjord according to Kjeller Vindteknikk wind resource maps for 50 m height (kartbok1c_4144_50m) [Ref 5].

The AEP-calculation has been carried out with the Excel-sheet "Weibull_production_E39", see Appendix 1

Table 1: Power curve for DAWT-25/31-10000

	DAWT-25/31-10	
v	P	AEP
(m/s)	(W)	(kWh)
0	0	0
1	0	0
2	0	0
3	155	191
4	379	501
5	740	924
6	1300	1383
7	2100	1739
8	3082	1827
9	4313	1694
10	5708	1378
11	7392	1020
12	9146	672
13	10000	365
14	10000	170
15	10000	74
16	10000	30
17	10000	11

18	10000	4
19	10000	1
20	10000	0
21	10000	0
22	10000	0
23	10000	0
24	10000	0
25	10000	0
26	10000	0
27	10000	0
28	10000	0
29	10000	0
30	10000	0
	AEP =	**11985**

Annual Energy Production (AEP) compensation

The annual energy production AEP-value = 11 985 kWh calculated with the Excel-sheet (Appendix 1) represents the 12 months energy production with average wind speed 5,0 m/s at the hub height and that the direction of the nacelle is always pointing into the wind direction.

Since the DAWT-module is fixed to the bridge structure it is necessary to compensate for the direction of the bridges together with the direction of the prevailing wind. The DAWT-turbine duct has the ability to guide and “line up” the wind and lead the wind through the rotor plane in a more optimized way compared to traditional HAWT-turbines. The DAWT-turbine can for the same reason also accept higher turbulence intensity in the wind with maintained good performance.

DAWT hub height compensation

For the energy production calculation the average wind speed at the hub height is very important and must be calculated for each bridge type. For the suspension bridge the 50 m hub height is used and which is equal to the wind maps height. But for the floating bridge we must reduce the height and the wind speed will drop accordingly. A hub height of 10 m has been used for all floating bridges and all other installations that are not a suspension bridge.

The average wind speed will be reduced according to the exponential relation with α = 0,18. The wind speed at 50 m height is reduced to 10 m height by the factor $[(10)/(50)]^{\alpha}$ = 0,75. Since the power or energy is proportional to the cube of 0,75 the energy potential will be reduced to about 42 % of the energy at the height of 50 m.

4.4 Bridge conditions for the wind energy production

For each fjord crossing the following parameters are assessed and given as input conditions for each fjord calculation.

Table 2: Clarification of the table parameters

DAWT-hub height	Hub height for the wind turbines when the DAWT modules are installed in the bridge structure
Average wind speed interval at DAWT hub height	The average wind speed interval at hub height used for the AEP calculation and derived from Kjeller Vindteknikk 50 m wind maps.
AEP-interval per DAWT-unit	The Annual Energy Production AEP calculated for the average
Direction of the prevailing wind for the bridge	The direction of the prevailing wind for the west coast of Norway has been set to the sector 135-315° (half circle sector SE to NW).
Direction of the bridge	The direction of the suggested bridge
Correlation Factor wind - bridge	Value 0,1 – 0,5. If the bridge direction is within the prevailing wind sector the correlation factor is set to 0,5.
Other Correlation Factor	Value 0,1 – 1,0 Local variations that will influence the wind direction across the bridge. It is known that valleys and fjords will act like “guides for the wind” and the wind will change direction and blow along the “channel”.

Table 3: Boknafjord

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	7,5 – 8 m/s	5,6 – 6 m/s
AEP-interval per DAWT-unit	30181 – 33725 kWh	16287 – 19001 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	298°	298°

Correlation Factor wind – bridge	0,5	0,5
Other Correlation Factor	1,0	1,0
Bridge length (m)	8 416	8 416
Number of DAWT-modules if 80 % of bridge length is used (installed power)	1 448 (14,5 MW)	1 448 (14,5 MW)
Energy potential (MWh/year)	21 851 – 24 416	11 790 – 13 756

Table 4: Bjørnafjorden 2

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	6,5 – 7 m/s	4,9 – 5,3 m/s
AEP-interval per DAWT-unit	22715 – 26 448 kWh	11 252 – 13 627 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	6°	6°
Correlation Factor wind – bridge	0,44	0,44
Other Correlation Factor	1,0	1,0
Bridge length (m)	5 732	5 732
Number of DAWT-modules if 80 % of bridge length is used	986	986
Energy potential (MWh/year)	9 854 – 11 474	4 881 – 5 912

Table 5: Bjørnafjorden 1

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	6,5 – 7 m/s	4,9 – 5,3 m/s
AEP-interval per DAWT-unit	22715 – 26 448 kWh	11 252 – 13 627 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°

Direction of bridge	32°	32°
Correlation Factor wind – bridge	0,44	0,44
Other Correlation Factor	1,0	0,9
Bridge length (m)	1600	1600
Number of DAWT-modules if 80 % of bridge length is used	275	275
Energy potential (MWh/year)	2 748 – 3 200	1 225 – 1 484

Table 6: Sognefjorden

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	5,0 – 5,5 m/s (50%) 5,5 – 6,0 m/s (50%)	3,8 – 4,1 m/s (50%) 4,1 – 4,5 m/s (50%)
AEP-interval per DAWT-unit	11985 – 15343 kWh 15343 – 19001 kWh	5288 – 6955 kWh 6955 – 8975 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	325°	325°
Correlation Factor wind – bridge	0,50	0,50
Other Correlation Factor	1,0	1,0
Bridge length (m)	3810	3810
Number of DAWT-modules if 80 % of bridge length is used	328 328	328 328
Energy potential (MWh/year)	1965 – 2516 (50%) 2516 – 3116 (50%) 4481 - 5632	867 – 1140 (50%) 1140 – 2944 (50%) 2007 - 4084

Table 7: Nordfjorden

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	4,5 – 5,0 m/s	3,4 – 3,8 m/s
AEP-interval per DAWT-unit	8975 - 11985 kWh	3882 - 5288 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	28°	28°
Correlation Factor wind – bridge	0,44	0,44
Other Correlation Factor	1,0	0,9
Bridge length (m)	1700	1700
Number of DAWT-modules if 80 % of bridge length is used	292	292
Energy potential (MWh/year)	1153 - 1540	448 - 611

Table 8: Voldafjorden

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	5,5 – 6,0 m/s	4,1 – 4,5 m/s
AEP-interval per DAWT-unit	15343 – 19001 kWh	6955 – 8975 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	40°	40°
Correlation Factor wind – bridge	0,35	0,35
Other Correlation Factor	1,0	1,0
Bridge length (m)	2014	2014
Number of DAWT-modules if 80 % of bridge length is used	346	346
Energy potential (MWh/year)	1858 - 2301	842 - 1086

Table 9: Storfjorden

Type of bridge	Suspension bridge	Floating bridge
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	6,0 – 6,5 m/s	4,5 – 4,9 m/s
AEP-interval per DAWT-unit	19001 – 22715 kWh	8975 – 11252 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	345°	345°
Correlation Factor wind – bridge	0,5	0,5
Other Correlation Factor	1,0	1,0
Bridge length (m)	3400	3400
Number of DAWT-modules if 80 % of bridge length is used	585	585
Energy potential (MWh/year)	5557 - 6644	2625 – 3291

Table 10: Moldefjorden

Type of bridge	Suspension bridge	Floating bridge
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	5,5 – 6,0 m/s	4,1 – 4,5 m/s
AEP-interval per DAWT-unit	15343 – 19001 kWh	6955 – 8975 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	355°	355°
Correlation Factor wind – bridge	0,5	0,5
Other Correlation Factor	1,0	1,0
Bridge length (m)	8034	8034
Number of DAWT-modules if 80 % of bridge length is used	1382	1382
Energy potential (MWh/year)	10602 – 13129	4806 – 6201

Table 11: Halsafjorden

Type of bridge	**Suspension bridge**	**Floating bridge**
DAWT hub height	50 m	10 m
Average wind speed interval at DAWT hub height	5,0 – 6,0 m/s	3,8 – 4,5 m/s
AEP-interval per DAWT-unit	11985 – 19001 kWh	5288 – 8975 kWh
Direction of the prevailing wind	112 – 337°	112 – 337°
Direction of bridge	75°	75°
Correlation Factor wind – bridge	0,44	0,35
Other Correlation Factor	1,0	1,0
Bridge length (m)	1829	1829
Number of DAWT-modules if 80 % of bridge length is used	314	314
Energy potential (MWh/year)	1655 – 2625	581– 986

5 Results from wind energy potential assessment

Summarizing the wind energy production potential from the eight fjord crossings in the following table gives the high end figure if all bridges were suspension bridges with the DAWT-turbines at the height of 50 m. If all bridges were floating bridges the turbine hub height is reduced to 10 m giving the lower end of the energy potential interval, see table 12.

Table 12: Summary of wind energy potential from table 3 – 11.

Fjord crossing	**Suspension bridge** **50 m height**	**Floating bridge** **10 m height**
Boknafjorden	21851 - 24416	11790 - 13756
Björnafjorden 2	9854 0 11747	4881 – 5912
Björnafjorden 1	2478 - 3200	1225 – 1484
Sognefjorden	4480 - 5632	2007 – 4084
Nordfjorden	1153 - 1540	448 – 611
Voldafjorden	1858 - 2301	842 – 1086
Storfjorden	5557 - 6644	2625 – 3291
Moldefjorden	10602 - 13129	4806 - 6201
Halsafjorden	1655 - 2625	581 - 986
Total (MWh/year)	**59488 - 71234**	**29205 - 37411**

Note: The wind energy production potential assessment for the bridges is based on the performance of the DAWT-25/31-10000 turbine with a wind-speed-up factor of 1,7.

Another DAWT-turbine with larger diameter and rated power will result in higher wind energy production potential.

6 Conclusions and future work

The wind energy production potential for the eight fjords shows high variation between the different fjord crossings. There are fjords with very good wind resource potential and there are fjords with very low wind energy potential.

The initial result of the wind energy potential assessment shows that if the wind turbines are installed at 50 m above the sea level, the annual energy production would be about 59-71 GWh. The wind turbine height of 50 m above sea level corresponds to suspension bridges only.

On the other hand, if the wind turbines are installed at the lower level of 10 m above sea level the annual energy production would be reduced to about 29-37 GWh. The lower level of 10 m corresponds to floating bridges and submerged tunnels.

Looking at the energy contribution from each individual fjord, the study shows that the three fjords Boknafjord, Bjørnafjord and Moldefjord account for over 70 % of the total energy production.

The essential assumption for this energy production potential assessment is based on the performance of a 10 kW DAWT-turbine with an maximum outer duct diameter of 3,1 m which has been installed with 215 turbines per km (1,5D spacing between turbines) and that 80 % of the length of the bridges have been equipped with wind turbines.

It is interesting to compare the bridge wind energy potential 30-70 GWh with a typical standard 2 MW onshore wind turbine annual production of 5 GWh per year.

Based on the DAWT-concept with “standard DAWT wind turbine modules for building-integration” it is recommended that future work is focused on how the DAWT-module can be integrated in the bridge structure in an “industrialized” process with maintained optimal energy production performance.

Together with the bridge construction design, the DAWT-module influence on the bridge structures from mechanical vibrations, stress and fatigue aspects should be investigated.

It is further on recommended to investigate the new DAWT-technique and to optimize the performance from the DAWT turbine and the wind capture performance from DAWT-turbines when they are installed in the bridge structures.

7 References

[1] http://en.wikipedia.org/wiki/Betz_law#Assumptions

[2] http://www.warwickwindtrials.org.uk/2.html

[3] http://www.decc.gov.uk/en/content/cms/meeting_energy/Renewable_ener/feedin_tariff/feedin_tariff.aspx

[4] SSPA Sweden AB report: Probability estimate of ship collision with planned E39 bridges. SSPA Report No.: 20126158

[5] http://www.vindteknikk.no/norges-vindressurser-kartlagt/?nav=framside

Appendix 1 Weibull production E39

The Excel-sheet Weibull_production_E39 has been used for calculation of the DAWT-turbine annual energy production AEP.

		Weibull							
		parametrar							kWh
		A=	5,65			AEP-DAWT-25/31-10000 =			11985
		C=	2						
	Intervallbredd		1		Summma f17-f22:		73,38%		
					E-82:	3019	MWh/år		
resultat	medelv		5,00	m/s	E-53:	1261	MWh/år		
Vindens energiinnehåll			1293	kWh/m2/år	421	0,325			
beräknad NWP 1000			963	MWh/år				Area=	4,91
			0,745103						
								DAWT-25/31-10000	
	Vindhast		Vindhast	Vindhast	frekvens	v*freq	Vindenergi	P	AEP
	[m/s]		[m/s]	[m/s]			[kWh/m2/år]	(W)	(kWh)
								0	0
	0,0	-	1,5	0,8	6,81%	0,0511	0	0	0
	1,5	-	2,5	2,0	10,98%	0,2195	5	0	0
	2,5	-	3,5	3,0	14,09%	0,4227	20	155	191
	3,5	-	4,5	4,0	15,10%	0,6041	52	379	501
	4,5	-	5,5	5,0	14,26%	0,7131	96	740	924
	5,5	-	6,5	6,0	12,15%	0,7287	141	1300	1383
	6,5	-	7,5	7,0	9,45%	0,6616	174	2100	1739
	7,5	-	8,5	8,0	6,77%	0,5414	186	3082	1827
	8,5	-	9,5	9,0	4,48%	0,4034	175	4313	1694
	9,5	-	10,5	10,0	2,76%	0,2755	148	5708	1378
	10,5	-	11,5	11,0	1,58%	0,1733	112	7392	1020
	11,5	-	12,5	12,0	0,84%	0,1007	78	9146	672
	12,5	-	13,5	13,0	0,42%	0,0542	49	10000	365
	13,5	-	14,5	14,0	0,19%	0,0271	29	10000	170
	14,5	-	15,5	15,0	0,08%	0,0126	15	10000	74
	15,5	-	16,5	16,0	0,03%	0,0055	7	10000	30
	16,5	-	17,5	17,0	0,01%	0,0022	3	10000	11
	17,5	-	18,5	18,0	0,00%	0,0008	1	10000	4
	18,5	-	19,5	19,0	0,00%	0,0003	1	10000	1
	19,5	-	20,5	20,0	0,00%	0,0001	0	10000	0
	20,5	-	21,5	21,0	0,00%	0,0000	0	0	0
	21,5	-	22,5	22,0	0,00%	0,0000	0	0	0
	22,5	-	23,5	23,0	0,00%	0,0000	0	0	0
	23,5	-	24,5	24,0	0,00%	0,0000	0	0	0
	24,5	-	25,5	25,0	0,00%	0,0000	0	0	0
	25,5	-	26,5	26,0	0,00%	0,0000	0	0	0
	26,5	-	27,5	27,0	0,00%	0,0000	0	0	0
	27,5	-	28,5	28,0	0,00%	0,0000	0	0	0
	28,5	-	29,5	29,0	0,00%	0,0000	0	0	0
	29,5	-	30,5	30,0	0,00%	0,0000	0	0	0
					100,00%	5,00	1293		11985

Weibull production E39 calculation sheet for average wind speed 5,0 m/s and C = 2,0. By changing the amplitude A-, and the shape C-parameter values the AEP can be calculated for different wind speed frequency distributions.

The Weibull shape parameter C = 2,0 for the Rayleigh distribution is kept constant at C = 2,0 but the amplitude parameter A is varied and the annual energy production AEP is calculated for the different average wind speed conditions according to Kjeller Vindteknikk wind maps (Ref 4] for the various bridge locations.

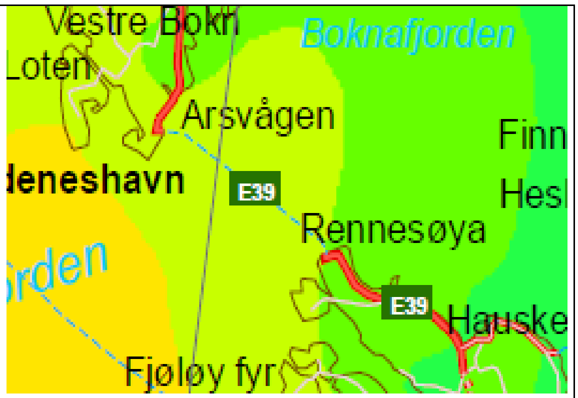
Average wind speed (m/s)	**AEP (kWh/year)**	**A-parameter**	**C-parameter**
3,4	3 882	3,84	2,0
3,8	5 288	4,25	2,0
4,1	6 955	4,66	2,0
4,5	8 975	5,09	2,0
4,9	11 252	5,52	2,0
5,0	11 985	5,65	2,0
5,3	13 627	5,93	2,0
5,5	15 343	6,21	2,0
5,6	16 287	6,36	2,0
6,0	19 001	6,78	2,0
6,5	22 715	7,34	2,0
7,0	26 448	7,90	2,0
7,5	30 181	8,47	2,0
8,0	33 725	9,03	2,0

AEP for a single DAWT 25/31-10000 unit with the average wind speed at hub height.

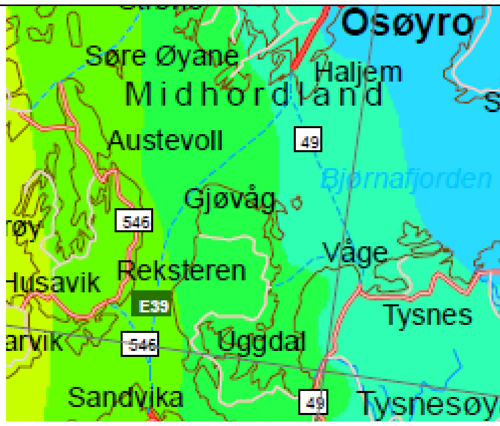
Appendix 2. Input data och assessment criteria

Wind maps from Kjeller Vindteknikk at 50 m heights have been used for the different fjord crossings.

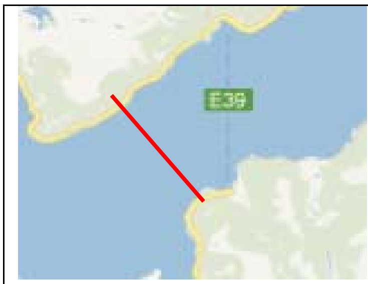
Boknafjorden, Mortavika – Arvsvågen, NV Stavanger

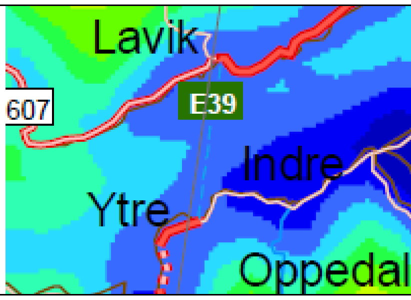
	
Bridge direction: SE to NW (298°)	Wind speed 7,5 – 8,0 m/s at 50 m
Length shortest crossing: 8 416 m	

Bjørnafjorden, Sandvikvågen - Halhjem

	
Bridge 1 direction: SW to NE (32°) Bridge 2 direction: S – N (6°)	Wind speed (1) and (2): 6,5 – 7,0 m/s at 50 m
Bridge 1 length shortest crossing: 1 600 m Bridge 2 length shortest crossing: 5 732 m	

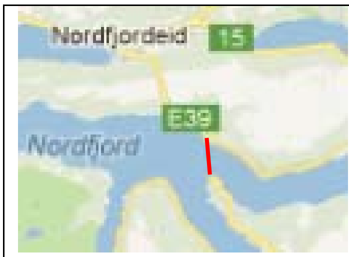
Sognefjorden, Opedal - Lavik

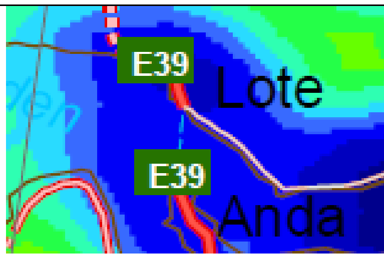




Bridge direction: SE – NW (325°)	Wind speed: 5,0 – 5,5/5,5 – 6,0 m/s
Length shortest crossing: 3 810 m	Split 50/50

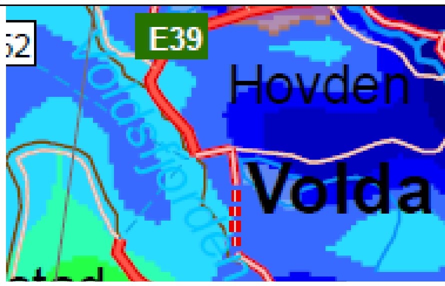
Nordfjorden, Anda - Lote





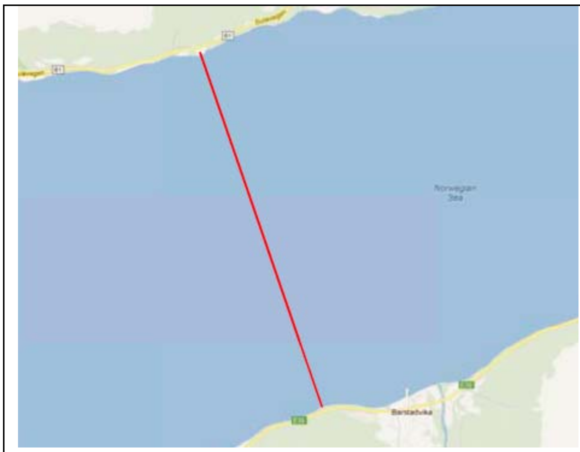
Bridge direction: S – N (28°)	Wind speed: 4,5 – 5,0 m/s
Length of shortest crossing: 1 700 m	

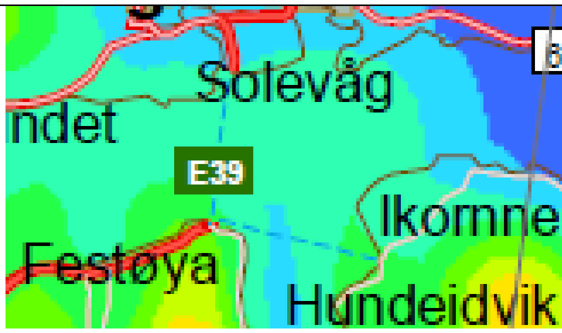
Voldafjorden



Bridge direction: SW – NE (40°)	Wind speed: 5,5 – 6,0 m/s
Length of shortest crossing: 2 014 m	

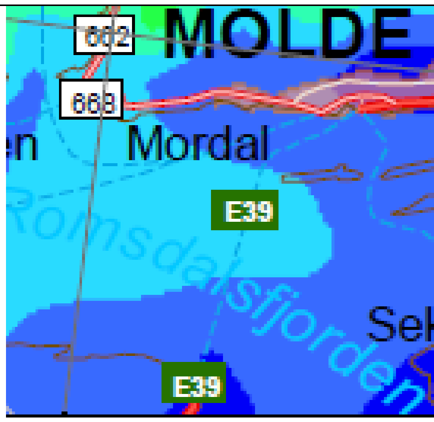
Storfjorden





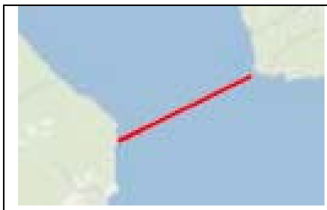
Bridge direction: SW – NE (345°)	Wind speed: 6,0 – 6,5 m/s
Length shortest crossing: 3 400 m	

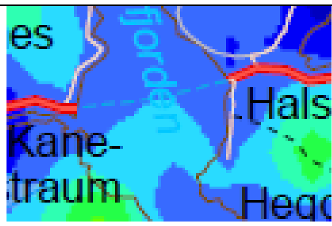
Moldefjorden



Bridge direction: SW – NE (355°)	Wind speed: 5,5 – 6,0 m/s
Length shortest crossing: 8 034 m	

Halsafjorden





Bridge direction: SW – NE (75°)	Wind speed: 5,0 – 6,0 m/s
Length shortest crossing: 1 829 m	

Appendix 3. Questionnaire wind power and bridge structure

Dear Sir/Madam,

Please forward to Research and Development department. We are especially interested in building integrated wind turbines.

SP Technical Research Institute of Sweden has been commissioned (together with two other companies) by the Norwegian Public Roads Administration in a project that will potentially utilize a large number of renewable energy conversion devices i.e. for wind, solar, waves and tidal energy. The Ferry Free E39 project is a giant road project involving eight (8) fjord crossings with a project budget of over 13 billion Euros and 20+ years project time. The project will involve "state of the art" bridge construction – and building integrated renewable energy production facilities. For more information about the project itself, please see the following link to Statens Vegvesen

http://www.vegvesen.no/Vegprosjekter/ferjefriE39

We at SP are currently in the process of performing a technology survey to determine the capabilities and characteristics of wind turbines suitable for integration with bridge constructions. We are approaching your company to find out and investigate how wind turbines can be used together with a bridge construction or buildings in order to increase the potential for renewable energy production. We are very interested to hear your thoughts and innovative ideas in building integrated wind turbines. If your company has been involved in a similar project(s) before, we would appreciate if you can give us a short description of and references to the project(s).

We have included a short questionnaire and we would very much appreciate if you can reply to the questions and return to me. Your reply will be included in a "state of the art" technology report. We would appreciate it if you can return your reply not later than February 28th. If you are lacking information for any of the questions, simply state that in your reply.
The results of this technology survey will be presented as part of the workshop/conference scheduled for April 19th, 2012 in Trondheim, Norway. Your company is invited to participate at the workshop/conference April 19th in Trondheim.

Questionnaire	**Reply**
Company	
Country	
Web address	
Device Type (HAWT/VAWT/Ducted/Other type)	
Development status (Prototype/Pilot series/Commercial)	
Rotor diameter	
Weight of wind turbine structure (kg)	
Rated power output (kW)	
Wind speed at rated output power (m/s)	

Power curve (reply with pdf)	
Annual Energy Production (AEP) at 5 m/s wind speed	
Estimated date commercially available	
Estimated production cost per rated unit (EUR)	
Have environmental impact studies been performed	
Discuss the survivability of the device and whether or not it has been tested.	
Technical publications	
Figures/photographs of device have been attached to reply	
Is it possible to combine this device with a fjord crossing like a suspension bridge, a floating bridge or a submerged floating tunnel and if so, how?	
Reference constructions from other similar projects where wind turbines have been integrated with buildings and other constructions; please describe and specify web address.	

Project Background

E39 is a road that is located on the west coast of Norway and extends from Kristiansand in the south to Trondheim in the north. Currently, a number of ferry crossings are required to traverse its entire length. The Transport Ministry has given a mandate for the project "Ferry Free E39" to assess the technological solutions for the crossing of eight large fjords without ferries. The fjords crossings range from 1.5 km to 25 km in length and have depths up to 1300 m. Proposed solutions for the crossings that are under consideration consist of suspension bridges, floating bridges, submerged floating tunnels, and sub-sea rock tunnels. Part of the project is to consider how the construction of the crossings can be combined with devices that produce energy from waves, tides, wind and the sun. The idea is that by using the bridge construction as part of the facility, the costs of the renewable power plants could be reduced and therefore be more competitive with non-renewable energy sources. If it is not possible to combine certain technologies with the actual bridge construction, the possibility will also be considered to install the devices in other locations, such as offshore.

If you have any questions about the questionnaire or, if you would like more detailed information about the project, then feel free to contact me by replying to this email or calling at the telephone numbers given below.

I would appreciate your reply not later than February 28th, thank you.

Borås 2012-02-22

Lars Åkesson

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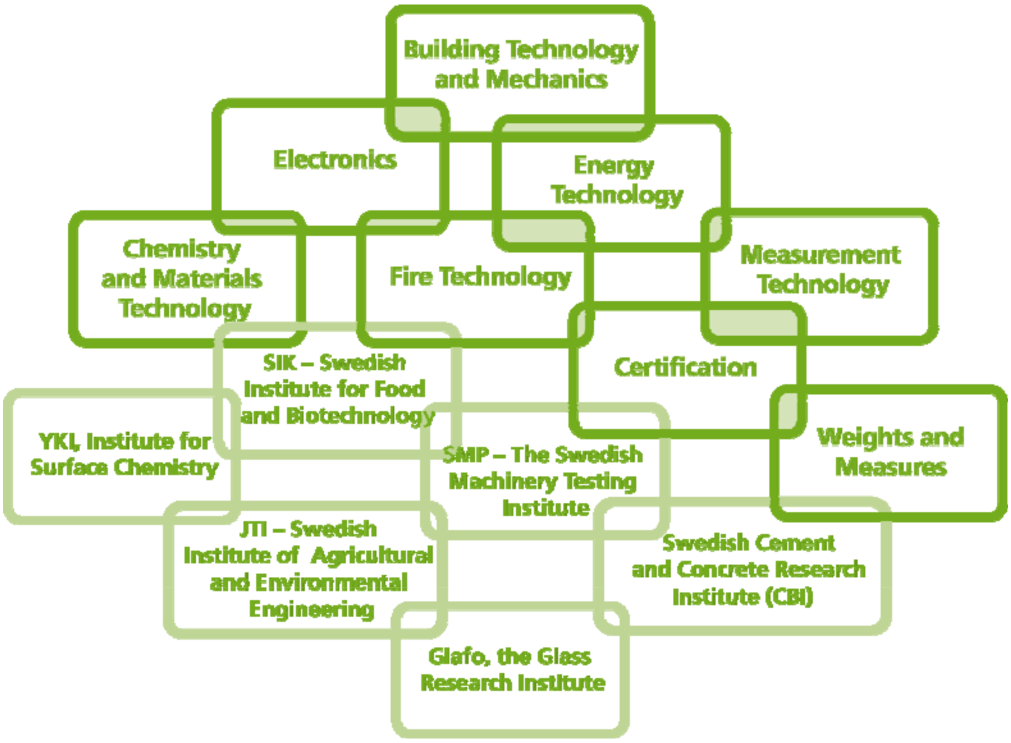

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