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FERJEFRI
E39

Contents

Executive summary

The possibility of integrating energy production devices in bridge structures along Coastal Highway Route E39 has been investigated. Feasibility studies have been carried out by the NPRA (Norwegian Public Roads Administration), Norconsult, Rambøll and SP Technical Research Institute of Sweden, resulting in five reports. The studies assessed the renewable energy potential and explored how bridge structures can be utilised for power generation. The main advantage of integrating energy conversion devices in bridge structures is the reduction of costs compared to stand-alone devices. A bridge construction could be used as a foundation, a mooring point or provide dry surroundings for the electrical works of the production devices. Easy access to the production site could also reduce installation and maintenance costs. The main challenge would be to find the location with the optimal energy resource for power production.

Integrating energy conversion devices in bridge structures may have negative impact on the environment and on the bridge construction. Most of the devices studied would mean additional loads due to forces from wind, wave and tidal current or from their own weight. The potential environmental impacts associated with renewable technologies are the consequences for bird life or marine fauna at the fjord crossing locations, as well as noise and visual impact.

The most suitable locations for wind power production are at the Boknafjord and Storfjord crossings. The wind average speed could reach 7-8 m/s and the full load hours could be more than 3000 hours at Boknafjorden. The added value from integrating wind turbines in the construction is expected to be low for most of the suggested technologies. The costs of integration will most likely be increased due to modification and increased loads. However, there are some exceptions. Integrating Ducted Augmented Wind Turbines (DAWT) in a bridge construction, for example, could be very cost effective and increase the potential for power production.

Due to the limited amount of direct sunlight in Norway, integrating solar panels to the bridge constructions along the E39 does not add value. Solar panels mounted as a roof over the roadway could produce almost 2 GWh/km/year, but the investment costs would be very high. However, it could be of interest to investigate the potential of solar power in the future, since cost reduction and efficiency enhancement are expected for solar power during the next 5 – 10 years.

Lack of energy resource data has made it impossible to estimate adequately the expected power production from waves and tidal currents. SP has made some rough estimates based on the number of devices and their rated power, showing power production in the range of 20-236 GWh/km/year from waves and 16-105 GWh/km/year from tidal currents at the fjord crossing locations Boknafjord, Moldefjord and Bjørnafjord. This is based on the assumption that the significant wave height is greater than one metre and the current velocity is greater than 0.5 m/s. Most likely the potential for power production would be in the lower range of this interval.

It is also expected that investment costs could be reduced by about 40% if the devices could be integrated into the construction. These predictions indicate that there is substantial potential for extracting power from the fjords if the waves and/or the currents are powerful enough. Further study is recommended, and energy resource data should be collected at Boknafjord, Moldefjord and Bjørnafjord. This would make it possible to estimate more adequately the feasibility of power production from waves and tidal currents.

The situation in the energy market has not been considered in this study, but should be taken into account in future studies. Energy prices and subsidised measures for renewable energy are vital factors when determining the viability of renewable energy production.

1. Background

The E39 on the west coast of Norway connects Kristiansand in the south to Trondheim in central Norway. The Ministry of Transport and Communications has given the project «Coastal Highway Route E39» a mandate to assess technological solutions for fjord crossings. The project has also been mandated to investigate how the bridge constructions can be exploited to produce energy from wind, sun, waves and tidal currents.

The project consists of four components:
- Social impacts
- Fjord Crossing
- Energy
- Implementation strategies and types of contracts

Norway is a world leader in the construction of bridges and tunnels and has long experience in renewable energy production. Norway is also a substantial producer of renewable energy, primarily due to abundant hydropower resources (more than 99% of mainland Norway's electricity production is from hydropower plants). Even so, there is still vast untapped potential in wind, tidal, and wave power. (Norway has limited resources in solar energy, but is one of the world's largest producers of solar grade silicon and silicon solar cells, much thanks to the activities of Renewable Energy Corporation.) Producing electricity from additional renewable energy sources will reduce the Norwegian carbon footprint and contribute to the Norwegian government's goal of carbon neutrality by 2050.

One of the challenges for renewable energy is to develop technologies that are cost competitive with non-renewable energy. In addition, there are technical challenges associated with large-scale exploitation of energy sources. Using the construction as part of the energy-producing facility can probably reduce the establishment costs and thus increase the potential for the development of renewable power plants.

This report deals with how bridge infrastructures can be utilised for producing electricity from the renewable sources wind, solar energy, waves and tidal currents. The potential for energy production from the approximately 16,000 existing river bridges managed by the NPRA has also been considered.

The energy component of the project «Coastal Highway Route E39» is managed by the Traffic Safety, Environment and Technology Department at the NPRA Directorate in Oslo.

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2. Objective

The main objective has been to investigate the possibilities of using bridge constructions and submerged tunnel to increase the potential for producing renewable energy. Two feasibility studies have been carried out by Rambøll, Norconsult and SP Technical Research Institute of Sweden. The purpose of these studies was to investigate the potential for producing energy by integrating devices into the road infrastructure on fjord and river crossings and to explore the technical challenges and opportunities. The studies have identified the most suitable technical solutions available on the marked and have attempted to estimate the potential for power production from each energy source for each fjord crossing (based on the available resource data). One of the objectives was to use the results of the feasibility study to set priorities and recommendations for further work and possible proposals for a case study or pilot testing in the near future.

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3. Feasibility study

A literature survey was carried out earlier to identify the technological solutions currently available for renewable energy. Completion of this survey, based on mapping «state of the art» technologies, was part of the feasibility study. The suitable technologies were mapped and complementary information was collected from different technology providers. This provided information about established knowledge, research and projects that are in progress or already realised.

The study was divided into two parts:

- Feasibility study for renewable energy from wind and sun
- Feasibility study for renewable energy from wave/current and tidal energy

Access to energy resource data is essential when investigating the potential for energy production from each source of energy. This data is also necessary in order to evaluate which of the energy production alternatives would be most suitable for each fjord crossing. Both the literature survey and the work of gathering the available data (with a focus on the fjord crossings on the E39) were part of the feasibility studies.

The feasibility studies have been published as separate NPRA reports [1], [2], [3], [4] and [5]. The results were presented for representatives from research institutes, universities, consultants, technology suppliers and industry in the field of renewable energy at an international workshop in Trondheim on 19 April 2012. The technical issues, challenges and potential for renewable energy production were discussed [6]. This report summarises the outcomes from the feasibility studies.

3.1 Crossing locations

The following crossing locations have been considered in the feasibility study:

- Halsafjord (Kanestraum – Halsa)
- Moldefjorden (Vestnes – Molde)
- Storfjord (Festøy – Solavågen)
- Voldafjord (Volda – Folkestad)
- Nordfjord (Anda – Lote)
- Sognefjord (Opedal – Lavik)
- Bjørnafjord (Sandvikvågen – Halhjem)
- Boknafjord (Mortavika – Arsvågen)

Two alternatives have been proposed for crossing the Bjørnafjord, one short and one long.

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3.2 Consequences for the bridge construction

The study investigated the impact the additional loads from each proposed technology might have on the bridge construction. However, there is a need for further studies to estimate the exact impact on the construction. This is especially important for long bridge constructions that face the challenge of withstanding horizontal loads from wind, currents and waves.

3.3 Environmental consequences

As with all energy resources, renewable energy resources may also affect the environment. For the time being we have few real world examples and limited experience from bridge constructions equipped with power production devices. The primary challenges are noise and visual impact, the effect on the marine environment and marine fauna or bird life.

The Norwegian government has established a goal of 30 % reduction in CO_2 emissions by 2020 compared to 1990-values and carbon neutrality by 2050. As a result of the political compromise on climate policy (Klimaforliket 2012), the government is looking at possibilities for making Norway carbon neutral by 2030. This compromise also calls for reductions in Norwegian greenhouse gas emissions of 15 – 17 million tonnes CO_2-equivalents by 2020. About 2/3 of the emission reductions are to be taken within the country, not by projects abroad [7]. In addition to the governmental goal for Norway's carbon footprint, the renewable energy directive from the European Union should be taken into consideration. By 2020, the EU as a whole shall obtain at least 20 % of its overall energy supply from renewable energy sources. For Norway this means that the share of renewable energy has to be increased to 67.5 % [8]. To achieve this increase, the country will have to install renewable energy production plants in the range of 13 TWh [9].

Road salt is used in Norway to melt snow and ice from slippery roads for traffic safety proposes. This has an environmental downside that can affect a widespread area long after winter has passed. The road salt has also negative impact on bridges, increasing the risk of corrosion. Instead of using road salt, it is possible to use the generated power for heating to de-ice the roads. This would be a more efficient and environmentally friendly method of promoting traffic safety.

3.4 Energy prices

The price of energy will be one of the determining factors when deciding which of the alternatives for extracting energy is the most suitable. If a certain percentage is saved in energy costs when installing power production devices on bridges, this will be very advantageous if energy prices climb, but not interesting at all if they drop. A review of the energy market was not part of the feasibility studies, but will be incorporated in a later phase of the project.

4. Wind energy

4.1 Energy resources

There is substantial potential in wind power and offshore wind power in Norway. Average wind speed at 50 metres height in a well-exposed coastal area can be 7 – 9 m/s. The physical overall wind power potential in Norway is estimated to be thousands of TWh/year, but a great deal of the potential is not available for exploitation because of environmental and economic circumstances [10].

A good commercial wind site should have an average wind speed in the region of 7 – 11 m/s [11]. It is common for wind turbines to start producing power at 3 – 4 m/s [12]. Full load hours vary from almost 1000 hours in the Nordfjord to more than 3000 hours in the Boknafjord, making these two fjords the most suitable locations for wind power [3]. The average wind speed at 50 metres height for the different crossings varies from 8 m/s above the Boknafjord to 5 m/s above the Nordfjord [13].

4.2 Technology

Onshore wind technology is relatively mature and well developed, while offshore technology is still under development. The offshore technologies are more of interest for this project, since bridges located in the fjords would face similar environmental challenges, such as bottom-fixed foundations due to the great depths.

There are three main types of wind turbines that could be of interest for the E39 project:

- Horizontal Axis Wind Turbines (HAWT)
- Vertical Axis Wind Turbines (VAWT)
- Ducted Augmented Wind Turbines (DAWT)

Figure 1: Vestavind Kraft, HAWT [31], Quietrevoultion, VAWT [33] , donQi, DAWT [32]

The improvement of DAWT-technology will continue to be in focus, as there are many advantages that could be expected from this type of turbine compared to the traditional horizontal turbines.

A number of ideas have been launched for how to combine wind turbines and bridge constructions, for example placing the turbines on the extended pontoons of a floating bridge [1] or integrating DAWTs in the roadway [5]. For a list of integration ideas with illustrations see Appendix A: Integration alternatives for wind turbines.

4.3 Potential for power production

The estimated power production for the crossing locations varies from 0.3 – 2.6 GWh/km/year for suspension bridges and 0.3 – 30 GWh/km/year for floating bridges. The greatest potential for power production is at the Boknafjord crossing. The table below shows the estimated energy production at the Boknafjord crossing (assuming 8.4 km length [5]).

Turbine type	Floating bridge [GWh/km/year]	Floating bridge [GWh/year]
HAWT (small) [1]	2.7	23
HAWT (large) [3]	30	252
VAWT [3]	-	-
DAWT [5]	1.4	12

Table 1: Estimated energy production from wind power

The highest value for floating bridges is based on installation of HAWTs with a diameter of 101 m placed every 250 m bridge [3]. This alternative will subject the bridge to extreme additional loads, which is considered unrealistic at this stage. For suspension bridges, DAWTs integrated in the roadway seem to be the best alternative [5]. However, suspension bridge is not possible at Boknafjord crossing. For detailed calculations, see references [1], [3] and [5] and Appendix E: Calculations.

4.4 Costs

The cost for integrated DAWTs is approximately 2 NOK/kWh for the turbines. The installation costs and annual operation and maintenance costs for these turbines are not known [5]. For VAWTs the cost is around 6 NOK/kWh for the turbines, 8 NOK/kWh when 20 % loss of energy, installation and maintenance costs are included. For HAWTs the turbine and installation cost will be lower, around 5 NOK/kWh, and the annual operation and maintenance cost could be in the range of 0.1 NOK/kWh [3]. An estimate of approximately 1 NOK/kWh is proposed for the 45 kW HAWTs; the installation costs and annual costs are not known [1].

The table below shows a probable cost distribution for a typical wind turbine installation [1].

Wind turbine investment cost distribution	
Turbine, rotor, generator	65 %
Tower and foundation	15 %
Internal grid and cabling	3 %
Grid connection	7 %
Mounting, construction, logistics and engineering	10 %

Table 2: Wind turbine investment cost distribution

The costs for the tower, foundation, construction, logistics, engineering, internal grid, cabling, grid connection and mounting could be reduced 20 % by integrating wind turbines into the bridge construction [1].

4.5 Summary

For most of the suggested technologies, the added value and synergies gained by integrating wind turbines in the construction is expected to be low. The costs of integration will most likely be increased due to necessary modification and increased loads. However, there is an exception: Using DAWTs integrated in the construction could be more cost effective and has great potential for power production.[5]. Other options that might be viable are to attach turbines as shovels around the pillars or installing VAWTs in the zone near shore [1].

Advantages	Challenges
- Reduction in costs if the bridge is used as tower or/and foundation for the turbines - Existing infrastructure can be used for transport and mounting of turbines - Construction machines and equipment being used for the bridge can be used for the wind turbine installations - Shared surveillance and control facilities - Utilization of existing electrical grid in connection with the bridge construction - Reduced visual noise compared to other wind turbines due to the bridge construction - For DAWTs, reinforcement of the bridge is not necessary, since they can be stopped at very high speeds	- In most cases increased costs to reinforce bridge construction - Increased design and engineering costs - Increased visual noise compared to a stand-alone bridge - Because of the humid air, salt water droplets and road dust, it is probably necessary to have offshore wind turbines, which are more expensive

Table 3: Advantages and challenges of wind energy

If wind turbines are to be integrated in a bridge construction it is important that this is taken into account in the design phase of the project.

4.6 Further work

Collecting adequate data on resources at the Boknafjord crossing is necessary in order to analyse wind distribution and wind direction more precisely. This would provide essential information for proper estimation of potential power production and the opportunity to address the key challenges and consequences for the bridge structure. There is also a need for further investigation and development of the new DAWT-technique: optimisation of these turbines' performance in terms of wind capture and efficiency when integrated in bridge structures is necessary.

5. Solar energy

5.1 Energy resources

Typical solar irradiance in Norway is 600 – 1000 kWh/m2/year [14], which corresponds to about 1500 times the total annual energy consumption. The potential for exploiting this energy is vast, but little direct sunlight limits the actual power production potential. However, there is much indirect, diffuse sunlight that might lead to some production

5.2 Technology

There are two main types of solar energy conversion technology. Solar thermal technology uses the sun for heating purposes by placing collectors (e.g. water-filled tubes) in direct sunlight, while photovoltaic (PV) panels convert solar radiance into electrical energy. Thin-film panels have lower efficiency than crystalline silicon panels, but thin-film panels can utilise both direct irradiance and diffuse radiation [3].

PV panels would be more suitable than solar thermal installations, since these fjord crossings are located in sparsely settled areas; the heat generated would have to transported long distances, which is not a viable option. Electricity, on the other hand, can easily be connected to the grid and transferred to a remote point of use. Thus such restrictions do not apply for PV panels. However, solar water heating could be used for tap water heating, defrosting and snow melting that may be needed on or near the bridge [2].

A number of ideas have been launched as to how the solar panels could be integrated in a bridge structure. For a list of integration ideas with illustrations, see Appendix B: Integration alternatives for solar panels.

5.3 Potential for power production

The following table presents the estimated power production for different mounting alternatives of the solar panels. The calculations have been carried out by SP and are based on a 45o tilt angle for optimal utilisation of the irradiance. The assumption is that there is no large variance for the estimated power production at the different fjord crossing locations.

Type of mounting	Suspension bridge [GWh/km/year]	Floating bridge [GWh/km/year]
Side mounted	0.6	0.6
Roof mounted	1.9	1.7
Mounted on wires	8.4	-
Mounted on pylons	0.3 per pylon	-

Table 4: Estimated energy production solar power

Solar panels mounted on the wires of a suspension bridge give the greatest potential for power production. However, this alternative would most likely increase the additional wind loads on the bridge structure and therefore is not recommended. For detailed calculations, see references [1], [2] and [3] and Appendix E: Calculations.

5.4 Costs

The estimated cost for PV panels is around 2500 ± 450 NOK/m2 for large panels (>10 kW) [2] and 1300 NOK/m2 [3] for smaller crystalline panels. This corresponds to average panel costs of nearly 11 NOK/kWh for side-mounted panels, 20 NOK/kWh for roof/wire-mounted panels and 30 NOK/kWh for pylon-mounted panels. These cost estimations are based on the calculated energy production and the prices of large panels.

The total cost for small panels (245 W) is more than 20 NOK/kWh [3]. This is a rough estimation as it is difficult to predict the cost of mounting systems. A rough estimation of the investment cost distribution based on the costs mentioned above is presented in table 5.

Estimate of investment cost distribution for 245 W solar panels	
Panels	40 %
Inverters, electrical works, power cable, transformers and switchgear	20 %
Mounting system and installation	40 %

Table 5: Estimate of investment cost distribution for 245 W solar panels

The estimations of mounting system and installation costs for the solar panels are very uncertain. However, there is potential for a substantial cost reduction if the bridge is designed for mounting and installation of solar panels in an early design phase.

5.5 Summary

A solar power plant could be easily installed on a bridge with relatively small added value. The solar panels could be mounted directly on the construction without using any other mounting systems if this is planned in the design phase. This would reduce the total costs.

Advantages	Challenges
- Large available areas on bridge shoulder and pillars with relatively easy access for maintenance - Existing constructions can be used without major modifications - Can be used to reduce wind loads and turbulence and protect the roadway and pedestrians - Reduction in costs if the panels can be mounted directly on the bridge construction	- Low sunlight intensity in Norway will result in low amounts of energy produced, but the rapid development of solar cells technology and heat applications could make the installations much more competitive within 5 – 10 years - The cost of solar panels is very high

Table 6: Advantages and challenges of solar energy

Solar panels on the bridges along the E39 are unlikely to be feasible as production systems for delivery to the grid based on the today's solar power technologies and market. If the panels are mounted on the sides, as a roof, on the pylons and on the wires, the energy production would be in the acceptable range. The panels mounted on wires would account for around 75 % of the total production [2], but since this is the mounting alternative that gives the greatest additional load, all-round mounting is not an optimal solution. However, pilot installations could be of interest in order to gain new knowledge through experience and to contribute to the further development of solar panels.

5.6 Further work

The efficiency of solar panels will increase during the next 5 – 10 years and their price will decrease in the same period [1]. The assessment of energy production and costs should be updated and taken into consideration in the future.

The use of thin-film panels should be studied further, revealing their potential for the different technologies. It might be of great interest to investigate to what extent diffuse sunlight could be exploited.

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6. Wave energy

6.1 Energy resources

Wind-generated waves are a huge, largely untapped energy resource, and the potential for extracting energy from waves is considerable. Waves have a very high energy concentration and are a natural store of kinetic energy that can travel thousands of kilometres with little energy loss [15]. Wave power is one of the most abundant energy sources on Earth. It is estimated that the contribution of wave energy to the Norwegian energy portfolio could reach between 12 to 30 TWh per year [16].
Waves vary with time and location. Wave energy scatter diagrams typically contain information about annual distribution of the significant wave heights (Hs in metres) and peak wave period (Tp in seconds).Data from at least one year is required to ensure that seasonal differences in the energy flux are accounted for.

6.2 Technology

Some basic design principles for wave energy conversion (WEC) devices are presented below, for more technical information and other principles see [4].

- Attenuator: floating device that is able to ride over the waves
- Point absorber: the floating part of the device oscillates with the waves and the relative motion between floater and the rest of the structure is converted into electrical energy
- Oscillating water column: takes advantage of the increased pressure as a wave passes the device

Several ideas have been put forward as to how to combine WEC devices with a bridge construction, for example mooring the device to the bridge or integrating the device in the structure. For more examples of integration ideas with illustrations, see Appendix C: Integration alternatives for wave power.

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6.3 Potential for power production

It is impossible to do exact calculations of the expected power production, as there is not sufficient wave statistic data from the fjord crossing locations. However, rough calculations have been carried out by SP based on the rated power and the number of installed WEC devices. The results presented in table 7 are based on the most suitable and applicable devices, listed in [4], which could start producing power when the significant wave height is below one meter. These calculations are not adequate, but they do give an indication of the expected power production (if the significant wave heights are high and long enough (Hs > 1 m, Tp > 3-4 sec)).

The results show that the highest potential for power production is found in the Moldefjord, the Boknafjord and the Bjørnafjord (long crossing). Assuming that the crossing with the greatest wind speed also will have the most powerful waves, the Storfjord crossing could also be a crossing location with a potential for extracting wave energy. It is most likely that the power production would be in the middle or lower range of these intervals. However, it should be expected that the significant wave heights would be more than one metre in the Boknafjord. The results show that there is significant potential for producing energy from waves if the significant wave height is more than one metre. For detailed calculations, see references [1], [4] and Table E4 in Appendix E: Calculations.

Crossing	Suspension/ floating bridge [GWh/km/year]	Submerged tun-nel [GWh/km/ year]	Suspension/ floating bridge [GWh/year]	Submerged tun-nel [GWh/year]
Halsafjord	15 – 193	13 – 163	27 – 347	23 – 293
Moldefjord	**20 – 235**	**17 – 200**	**160 – 1880**	**136 – 1600**
Storfjord	18– 218	16 – 185	61 – 741	54 – 629
Voldafjord	16 – 198	13 – 168	32 – 396	26 – 336
Nordfjord	15 – 188	13 – 160	26 – 320	22 – 272
Sognefjord	18 – 221	16 – 188	67 – 843	59 – 717
Bjørnafjord (short)	15 – 184	13 – 157	24 – 295	21 – 251
Bjørnafjord (long)	**20 – 230**	**16 – 196**	**114 – 1320**	**91 – 1122**
Boknafjord	**20 – 236**	**17 – 201**	**168 – 1986**	**(143-1688)***

Table 7: Estimated potential for WEC devices producing energy at Hs<1 m and Tp<3-4 s.

6.4 Costs

The costs of installing WEC devices depend on the device chosen. There are many different types that are already on the market or being developed. A production cost of 1.5 – 3 NOK/kWh is expected, based on experience with the market [1]. The costs for WEC devices would be reduced if they are integrated into the bridge construction. The cost reduction could be expected to be about 40%, which corresponds to a production cost of 0.9 – 1.8 NOK/kwh.

Table 8 presents an example of the investment cost distribution of installing several WEC devices. These costs will change over time due to developments in technology, the cost of raw materials and components and experience gained in manufacturing and deployment [17].

Example of investment cost distribution wave energy conversion device	
Structure	27 %
Mechanical and electrical	49 %
Mooring	5 %
Grid connection	4 %
Project management and installation	15 %

Table 8: Example of investment cost distribution for wave energy conversion device

6.5 Summary

There are many advantages when combining WEC devices and bridge constructions, especially in terms of cost reductions. The main challenges are the reliability of the energy resource and the additional loads on the structure. It is crucial that the integration of WEC devices be included in an early phase of the bridge design.

Advantages	Challenges
- Cost savings related to - Installation and maintenance because of easy access to the devices, installation vessels would not be required and maintenance could be coordinated with the bridge maintenance - Using the bridge structure as attachment point for mooring lines or as part of the device - Generators and electrical systems could be placed in dry surroundings - Some WEC devices can be used as break-waters or dampening devices, which could help reduce the loads from waves on the bridge structure	- Increased design and engineering costs - Reliability of the energy resources - Additional loads to the bridge structure - The depths of the fjords could pose some limitations to the size of the devices - Data sharing, not all developers are willing to share their data - The contractors will not "waste money" devel oping concepts or products that the NPRA is not looking for - Introduction of the possibility of a health and safety hazard to passing vessels - Marine growth and corrosion on the devices

Table 9: Advantages and challenges of wave energy

6.6 Further work

Mapping of the wave resource data for all the fjord crossings and collecting data for the locations of greatest interest is essential. These data should include both significant wave height and peak period. The expected power production could be estimated more adequately when the wave statistics are known, and the designs of the WEC devices could be optimised. With this information in hand, comparisons could be made between the different technologies and the most suitable technology could be chosen. This should be a part of the design stage of the bridge so that interdisciplinary challenges are minimised and the advantages and possible synergies are exploited.

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7. Tidal energy

7.1 Energy resources

The tides, being a result of the periodic variations of the Earth-Moon-Sun system, are more predictable than other renewable energy sources. The predictability of tidal energy is seen to be a major advantage in light of the variations in generation and consumption across the electrical grid.

The theoretical global potential for exploiting the tidal currents for power production has not been calculated precisely, but it is estimated to be in the range of 1000 TWh/year. In 2008 Norway used 228 TWh, and of this the NPRA used around 1 TWh [18]. Two studies of the technical tidal current energy resources of the Norwegian coast have been carried out. Based on these studies, the estimated potential for annual tidal power production is between 0.5 TWh and 1 TWh [16], [19]. The main focus in our study was on kinetic tidal current energy, which was not considered in the above studies.

7.2 Technology

Technologies that convert kinetic tidal current energy are referred to as Tidal In-Stream Energy Conversion (TISEC) devices, Marine Current Energy Converters (MCECs) or marine current turbines. The optimum current velocity for traditional technologies is between 1.5 – 3.5 m/s, but several technologies have been developed for velocities down to 0.5 m/s.

Most of the TISEC devices are similar to wind turbines. Some common design principles are presented below; for more technical information, see [4].

- Horizontal axis turbine: similar to vertical axis wind turbine
- Cross-axis turbine: similar to horizontal axis wind turbine
- Enclosed tips turbine: similar to ducted augmented wind turbine
- Oscillation hydrofoil: the passing water generates a lift on the hydrofoil which makes it oscillate

Several ideas have been launched as to how to combine TISEC devices with a bridge construction, for example by mooring the device directly to the bridge or mounting the device directly on a submerged floating tunnel. For more examples of integration ideas with illustrations, see Appendix D: Integration alternatives for tidal power.

7.3 Potential for power production

There is a great lack of data on currents and tidal current velocity at the sites of interest, which makes it impossible to do exact calculations of the expected tidal power production. The available data indicates an average current velocity of less than 0.25 m/s, with a maximum of 1 – 1.5 m/s [20]. We could not find any data available for Moldefjord, Voldafjord, Nordfjord and Boknafjord. However, a rough estimation has been carried out by SP for these four crossings based on the number of devices and their rated power. The results presented in table 10 are based on the possible number of devices integrated in the construction and their nominal rated power. Only devices that are designed to produce power when the current velocity is below 0.5 m/s are included [4]. This is a rough calculation to give an indication of the expected power production if the tidal current velocities are sufficiently great (vcurrent > 0.5 m/s).

Crossing	Suspension/ floating bridge [GWh/km/year]	Submerged tunnel [GWh/km/year]	Suspension/ floating bridge [GWh/year]	Submerged tunnel [GWh/year]
Moldefjord	**16 – 105**	**13 – 89**	**128 – 840**	**104 – 712**
Voldafjord	13 - 88	11 – 74	26 – 176	22 – 148
Nordfjord	12 – 83	11 – 71	21 – 145	19 – 142
Boknafjord	**16 – 105**	**13 – 89**	**136 – 893**	**757**

Table 10: Estimated potential for TISEC devices producing energy at v< 0.5 m/s

Moldefjord and Boknafjord are the crossings with the highest potential for tidal energy transformation. It is likely that the power production would be in the lower range of these intervals, since the calculations are based on nominal power production, which is usually at vcurrent > 0.5 m/s. Taking this into account, the results still show significant potential for retrieving energy from tidal currents. For detailed calculations, see references [1], [4] and Table E6 in Appendix E: Calculations.

7.4 Costs

An example of a tidal current turbine investment cost distribution is shown in the table below [1].

Example of allocation of investment cost for a 1 MW tidal current turbine	
Turbine and generator	30 %
Anchoring and foundation	35 %
Internal cabling and grid connection to shore	15 %
Project management and installation	20 %

Table 11: Example of allocation of investment cost for a 1 MW tidal current turbine

The investment cost depends on the TISEC device chosen and may be reduced when using the bridge as a foundation for the devices. The investment costs for a 1 MW tidal current turbine have been calculated to be 1.36 NOK/kWh when assuming 3000 full load hours per year. Taking into account the savings that can be realised from anchoring and foundation, internal cabling, grid connection, turbine and gear, project management and installation, the price decreases to 0.87 NOK/kWh [1]. This corresponds to a 36 % reduction in costs.

7.5 Summary

The investment cost depends on the TISEC device chosen and may be reduced when using the bridge as a foundation for the devices. The investment costs for a 1 MW tidal current turbine have been calculated to be 1.36 NOK/kWh when assuming 3000 full load hours per year. Taking into account the savings that can be realised from anchoring and foundation, internal cabling, grid connection, turbine and gear, project management and installation, the price decreases to 0.87 NOK/kWh [1]. This corresponds to a 36 % reduction in costs.

Advantages	Challenges
- Cost savings related to - Installation and maintenance - Significantly reduction in required time for vessels and divers - Bridge structure used as part of the foundation instead of having individual foundations for each device - Mooring lines can be reduced by mooring the devices directly to the bridge - The possibility of shorter and more effective cable runs - Generators and electrical systems can be placed in dry surroundings - The device installation depth can be better optimised regardless of the depth of the fjord when the bridge is used as an attachment point for the device - The shape of the bridge structure itself can be used to increase the flow rate to the devices, leading to higher energy output - The blockage effect of multiple turbines could create a small pressure head difference across the devices, further increasing their performance - The devices can be designed to increase the stiffness or damping of the bridge structure	- The structure will be subjected to additional horizontal and torsional loads. These can be alleviated by taking advantage of the over-capacity that is built into the bridge design. - Attaching the devices to the bridge structure could pose a health and safety risk for passing vessels - Increased design and engineering costs - Data sharing (not all developers are willing to share their data) - Little is known about lifecycle costs of tidal turbines - Contractors will not want to «waste money» developing concepts or products that the NPRA is not looking for - Marine growth and corrosion on the devices

Table 12: Advantages and challenges of tidal energy

7.6 Further work

More tidal resource data must be collected for Moldefjord, Voldafjord, Nordfjord and Boknafjord. The energy resource data should be gathered over a significant period of time (at least one year) to ensure that seasonal variations in the current velocity are accounted for.

The potential for power production can be determined when detailed data about the annual distribution of current velocities is available. Then it will be possible to assess the added value and compare costs and energy output. These comparisons will provide a better understanding and background for making the decision on whether a tidal current power plant is viable. The next step would be to consider which technology or combination of technologies should be utilised for the different fjord crossing locations.

8. Other renewable energy sources

There are also other technologies for producing renewable energy in connection with bridge structures. The use of piezoelectric material and ocean thermal energy conversion are two possibilities.

By integrating piezoelectric tiles in the roadway, it is possible to produce energy from weight, motion, vibration and temperature changes from the passing vehicles. When a vehicle passes over a road, the road deflects vertically and this deflection is released as thermal energy. The deflection is proportional to the weight of the vehicle and the asphalt stiffness. For a road with embedded piezoelectric generators, part of the energy the vehicle utilises on road deformation is transferred into electric energy via direct piezoelectric effect instead of being wasted as thermal energy. This technology does not increase the vehicles' fuel consumption or affect the road infrastructure. While producing energy the integrated tiles can register the vehicles' speed and weight. Assuming 1000 trucks per hour with an average speed of 72 km/h, the expected energy production from pilot testing is 100 kW/km/lane [21]. This technology may be more interesting if integrated on roads with a greater number of passing vehicles than expected on the bridges along the E39.

Ocean thermal energy conversion is based on exploiting the difference in temperature between the cold bottom water and the warmer water at the surface. The temperature difference makes it possible to produce electricity with turbines. To achieve sufficient efficiency, a temperature difference of 20o C or more on a yearly basis is needed. These conditions are found in tropical and subtropical climates [22]. Although this technology has been in use since the 1930s, it is still considered an emerging technology. The main technical challenge is to generate significant amounts of power from small temperature differences [23].

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9. Other suitable locations

In the vicinity of the E39 fjord crossing locations there are several strong tidal currents where it may be possible to produce tidal energy with turbines. Examples of such sites are Skjoldastraumen in Rogaland, Lukksundet in Hordaland, Skodjestraumen near Ålesund and Vestnesstraumen in the Romsdalsfjord. In the most narrow and shallow sections of these courses, the current velocity may be in the range of 2 – 3 m/s. This corresponds to an energy flux of 4 – 14 kW/m2, but the cross-sectional areas are relatively small, limiting the potential amount of produced energy [20].

10. Possible pilots

Cantilever bridges have a significant reserve capacity and are therefore suitable as pilots for renewable energy production. This reserve capacity could be used and the additional load caused by the integrated energy conversion devices does not necessitate reinforcement of the bridge construction. Examples are the Ognasund bridge in Bokn (Rogaland) and Lukksund Bridge in Hordaland. At the Ognasund bridge the average wind speed is around 7 m/s [13] which is in the lower range of what is required for a viable wind farm. The tidal current velocities near the Lukksund bridge are in the range of 1.5 – 2 m/s [20]. This means that most of today's devices could be used at this site.

The Nordhordland bridge consists of 1246 metres floating bridge and almost 400 metres of cable-stayed bridge above the shipping lane. The floating bridge has additional horizontal capacity with respect to the wind and wave forces at the site. The construction is designed to withstand losing one pontoon. The bridge has also vertical reserve capacity. A TISEC device for low current velocities could be installed on this construction, for example Deep Green developed by Minesto [24] which starts producing energy at 0.5 m/s. The Nordhordland bridge might also be used as a pilot for solar and wave power production. The average wind speed is 6 m/s [13] which is not favourable for traditional wind turbines.

Other possible locations for pilots are the Gjemnessund bridge in Møre og Romsdal, the Bømlo bridge in Hordaland, and the locations described in section 9. In addition, pilots for current energy production in rivers may be of interest.

Cost and production estimates are essential before the pilots are established. Establishing contact with possible joint venture partners should also be considered before realisation of a pilot project is possible.

11. Energy utilisation

The energy produced could have several ranges of applications depending on the bridge type. For suspension bridges, floating bridges and submerged tunnels it could be feasible to utilise the energy for road lighting, corrosion prevention and delivery to the grid. Submerged tunnels have a critical need for power for ventilation fans and pumps to discharge incoming water. In the case of suspension bridges and floating bridges, heating of the road to prevent icing is a possible use of energy. If the bridge is designed so that some parts have to be raised for passing vessels, this also requires energy [25].

The table below presents estimated energy consumption for the different utilisations. The energy consumption per kilometre road increases when the road width increases.

Energy consumption	GWh/km/year
Lighting [26]	0.05 – 0.1
Corrosion prevention [25]	0.05 – 0.1
Water discharge, fans and lighting for subsea tunnel [27]	0.3 – 0.5
Heating of the roadway [27]	1.0 – 2.0

Table 13: Energy consumption

Conclusion

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Power production in connection with bridge constructions poses many challenges. The greatest challenge, and the one that is more or less impossible to overcome, is the limitation imposed by the selection of bridge site location. With this in mind, it is crucial to choose energy production devices which are optimised for the existing conditions at the site. It is also very important to plan the integration of devices in an early design stage of the construction in order to optimise added value.

When considering power production from wind and waves, the Norwegian climate has a great advantage. The strongest winds and most powerful waves occur in the winter, when the national energy demand is at its highest. The opposite applies for solar energy, which means that the energy generated needs to be stored or additional energy sources are needed during the winter months. The tidal currents vary with the phase of the moon, but there are also some seasonal differences. In general the variation in water level is higher during the winter than in the summer, but the extent depends on local conditions [28].

The energy conversion technology for waves and tidal currents is relatively immature compared to other renewable energy technologies. Increased efficiency and decreased costs are expected within the next 10 – 20 years. Energy conversion technology for wind and solar power are more mature, and improvement of existing technology is expected.

For both wave and tidal currents there is a great lack of energy resources data. It is crucial that further work is focused on collecting energy resources data. The prospects are best for producing wave power, since the investigations into tidal currents at some of the fjord crossing locations have concluded that the current velocities are below 0.25 m/s. There are few energy conversion devices that start producing power from 0.5 m/s and upward. The power output for devices operating in this range is expected to be low. However, harnessing tidal energy by using current turbines is closer to a commercial breakthrough than wave power plants [1].

Exact calculations of the expected power production are not possible before the actual locations and exact directions of the bridges are determined. The estimated energy production for Boknafjord is presented in the table below. Boknafjord is the fjord crossing location that has shown the highest potential for exploiting the energy sources discussed in this report, and it is the best suitable location for wind power production. For solar power there is no large variation in the estimated power production between the different fjord crossing locations. The calculations performed in section 5.3 show that the expected wave energy production for Boknafjord, Moldefjord and Bjørnafjord (long crossing) is within the same range. The highest estimates for tidal power are at Boknafjord and Moldefjord; the estimates for these two locations are almost the same.

Energy source	Suspension bridge [GWh/km/year]	Floating bridge [GWh/km/year]	Submerged tunnel [GWh/km/year]
Wind	2.6	2.7	-
Solar	1.9	1.7	-
Wave	6.7 – 236	6.7 – 236	5.7 – 201
Tidal	16 – 890	16 – 890	13 – 756

Table 14: Estimated energy production from all energy sources

The estimated energy production from wind is based on DAWTs integrated in the roadway of a suspension bridge and small HAWTs placed along the road of a floating bridge. The horizontal turbines will, even though they are relatively small, subject the bridge construction to additional load. This means that the bridge needs to be reinforced to cope with the additional loads, increasing the costs.

By contrast, the bridge structure does not need to be modified in any other way than providing apertures/openings for the modules when DAWTs are installed. Reinforcement of the bridge structure to cope with additional loads and stresses is not necessary, since the DAWT-modules can be stopped at high speeds. A stopped wind turbine will minimise the aerodynamic forces on the structure at high wind speeds [5].

Solar panels should be roof mounted to achieve the highest power output without applying excessive external load to the bridge construction. The estimates for wave and tidal energy conversion depend on the device chosen. For the crossing locations considered, it is likely that production would be in the lower range of the intervals presented in table 14.

The greatest potential for renewable energy harnessing is found for wave and tidal energy even when the lower range of the intervals is considered. This is based on a consideration of whether the waves and current velocity at the crossing locations are powerful enough for the devices in question to produce energy. If the energy resources for wave and tidal energy production are insufficient, wind energy is the more favourable of the two remaining resources.

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Glossary

HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
DAWT	Ducted Augmented Wind Turbine
PV	Photovoltaic
WEC	Wave Energy Conversion
TISEC	Tidal In-Stream Conversion
Piezoelectricity	Electricity resulting from pressure, the charge that accumulates in certain solid materials in response to applied mechanical stress [29].
H_s	Significant wave height, this is the average of the 1/3 highest waves in a time series [30]
T_p	Peak period, the time between two wave peaks [30]
Energy flux	Rate of energy transfer per unit area, W/m2 [20]

<u>Energy units:</u>

Watt [W]	Unit of power, Nm/s
kW	Kilowatt
kWh	Kilowatt-hour, unit of energy production
MW	Megawatt, 1 MW=1 000 kW
GW	Gigawatt, 1 GW=1 000 000 kW
	1 GWh corresponds to the annual energy consumption of 50 Norwegian households, assuming an average consumption of 20 000 kWh (0.02 GWh), or lighting of around 25 km 4-lane road [26].

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References

[1] E. B. Christophersen, "Technology survey for renewable energy integrated to bridge constructions," Rambøll, 2012.

[2] P. Kovacs and P. Wahlgren, "Solar energy technology survey for ferry free E39 project," SP Technical research institute of Sweden, 2012.

[3] Sæta, Simonsen, Solli, Sandaker and Thoresen, "Technology survey for renewable energy integrated to bridge structures," Norconsult, 2012.

[4] D. Vennetti, "Wave and tidal energy technology survey for ferry free E39 project," SP Technical research institute of Sweden, 2012.

[5] L. Åkesson, "Wind energy technology survey for ferry free E39 project," SP Technical research institute of Sweden, 2012.

[6] Panel discussion Trondheim workshop, April 19th, 2012.

[7] "Norske klima og energimål," fornybar.no, 2012. [Online]. Available: http://fornybar.no/sitepageview.aspx?sitePageID=1777. [Accessed 11th July 2012].

[8] "EU og 2020-målene," fornybar.no, 2012. [Online]. Available: http://fornybar.no/sitepageview.aspx?sitePageID=1776. [Accessed 11th July 2012].

[9] A. C. Bøeng, "Fornybardirektivet - Hva betyr dette for energybransjen?," Statistisk sentralbyrå for Energi Norge, 2012.

[10] "Vindressursen i Norge," fornybar.no, 2012. [Online]. Available: http://fornybar.no/sitepageview.aspx?sitePageID=1740. [Accessed 4th July 2012].

[11] American wind energy association, 2012. [Online]. Available: http://www.awea.org/learnabout/utility/transmission/index.cfm. [Accessed 4th July 2012].

[12] Wind Power Program, 2012. [Online]. Available: http://www.wind-power-program.com/turbine_characteristics.htm. [Accessed 4th July 2012].

[13] "Vindkart for Norge, Kartbok 1c: Årsmiddelvind i 50 m høyde," Kjeller Vindteknikk, 2009.

[14] "Solenergiressurser i Norge," fornybar.no, 2012. [Online]. Available: http://fornybar.no/sitepageview.aspx?sitePageID=1648. [Accessed 5th July 2012].

[15] "Ocean energy conversion in Europe: recent advancements and projects," Wave energy centre, 2006. [Online]. Available: http://www.wavec.org/client/files/OceanEnergyConversionEurope_CRES.pdf.

[16] Sandgren, Hjort, Miranda, Hamarsland and Ibenholt, "Potensialstudie av havenergi i Norge," SWECO Grøner for Enova SF, 2007.

[17] J. Callaghan, "Future Marine Energy - Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy," Carbon Trust, 2006.

[18] M. Hoseini, "Grunnlagsnotat for en mulighetsstudie, ferjefri E39 - delprosjekt 3, energi," Statens vegvesen, 2011.

[19] E. Fröberg, "Current Power Resource Assessment: A study of selected sites in Sweden and Norway," Master thesis, Uppsala universitet, 2006.

[20] B. Gjevik, E. Gundersen and H. C. Sandbo, "Vurderinger av potensialet for kraftproduksjon i forbindelse med bruer langs ferjefri E39," Statens vegvesen, 2012.

[21] Innowattech, 2012. [Online]. Available: http://www.innowattech.co.il/index.aspx. [Accessed 2nd July 2012].
[22] "Utnyttelse av havvarme og havstrømmer," fornybar.no, 2012. [Online]. Available: http://fornybar.no/sitepageview.aspx?sitePageID=1736. [Accessed 12th July 2012].
[23] "Ocean thermal energy conversion," Wikipedia, 2012. [Online]. Available: http://en.wikipedia.org/wiki/Ocean_thermal_energy_conversion. [Accessed 12th July 2012].
[24] "Deep Green Technology," Minesto, 2012. [Online]. Available: http://www.minesto.com/deepgreentechnology/index.html. [Accessed 27th July 2012].
[25] Conversation with Bjørn Ivar Isaksen, July 17th, 2012.
[26] O. C. Torpp, "Håndbok 264: Teknisk planlegging av veg- og gatebelysning," Statens vegvesen, 2008.
[27] Correspondance by email with Svein Rune Vie, August 1st, 2012.
[28] "Vannstand.no," Kartverket, 2012. [Online]. Available: http://vannstand.no/index.php/nb/statistikk/midler. [Accessed 13th July 2012].
[29] "Piezoelectricity," Wikipedia, 2012. [Online]. Available: http://en.wikipedia.org/wiki/Piezoelectric_material. [Accessed 25th July 2012].
[30] D. Myrhaug, TMR4182 Marin dynamikk: Uregelmessig sjø, Institutt for marin teknikk, NTNU, 2007.
[31] Vestavind Kraft, 2010. [Online]. Available: http://www.vestavindkraft.no/Aktuelt/Artikkel/tabid/7993/smid/17240/ArticleID/999/reftab/7991/Default.aspx. [Accessed 16th July 2012].
[32] DonQi, 2012. [Online]. Available: http://donqi.nl/en/news/impressies/category/1-donqi-windmill.html. [Accessed 13th July 2012].
[33] Quietrevolution, 2012. [Online]. Available: http://www.quietrevolution.com/qr5-turbine.htm. [Accessed 13th July 2012].
[34] European wind energy association, 2012. [Online]. Available: http://www.ewea.org/index.php?id=1639. [Accessed 4th July 2012].

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Appendices

Appendix A: Integration alternatives for wind turbines

Ideas proposed by Norconsult:

VAWTs placed in a row along the road surface, utilizing the bridge wires to suspend the top of the wind turbines.

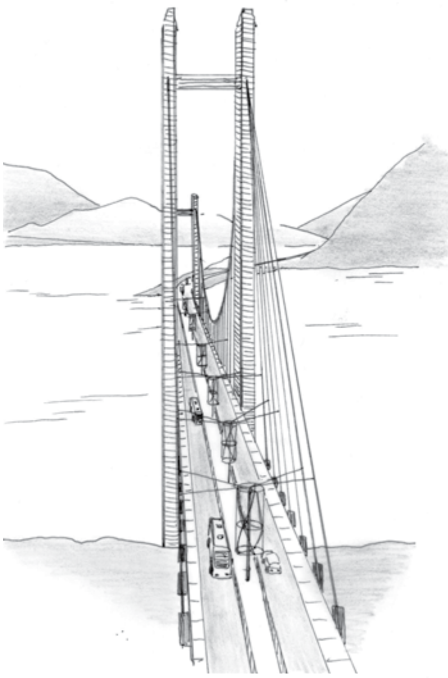

Figure A- 1: VAWTs placed along the road surface of a suspension bridge, Norconsult

Large HAWTs placed high up on the towers.

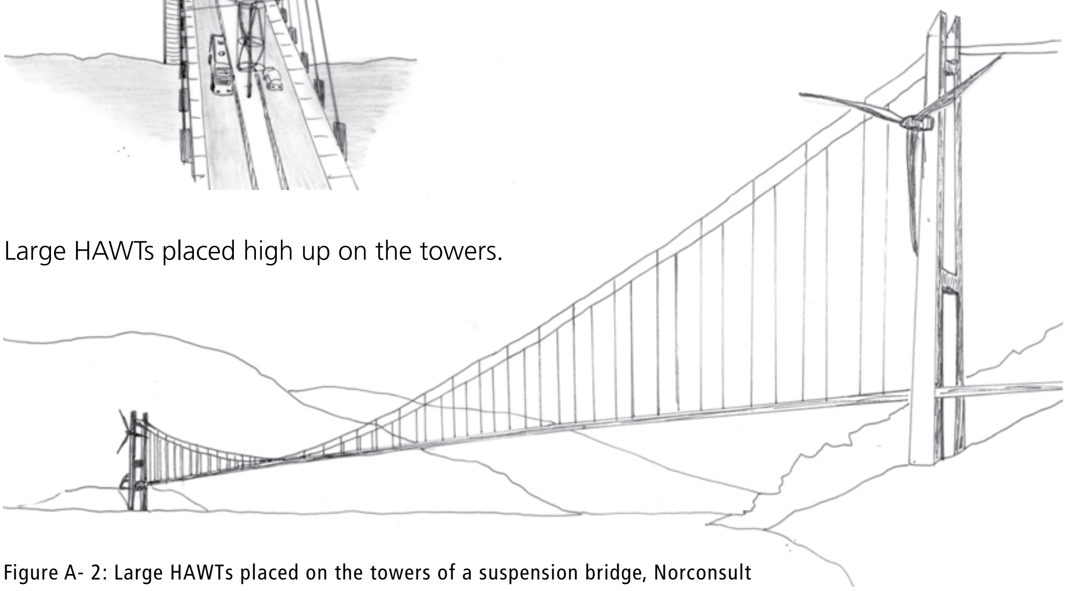

Figure A- 2: Large HAWTs placed on the towers of a suspension bridge, Norconsult

VAWTs placed in a row along the road surface.

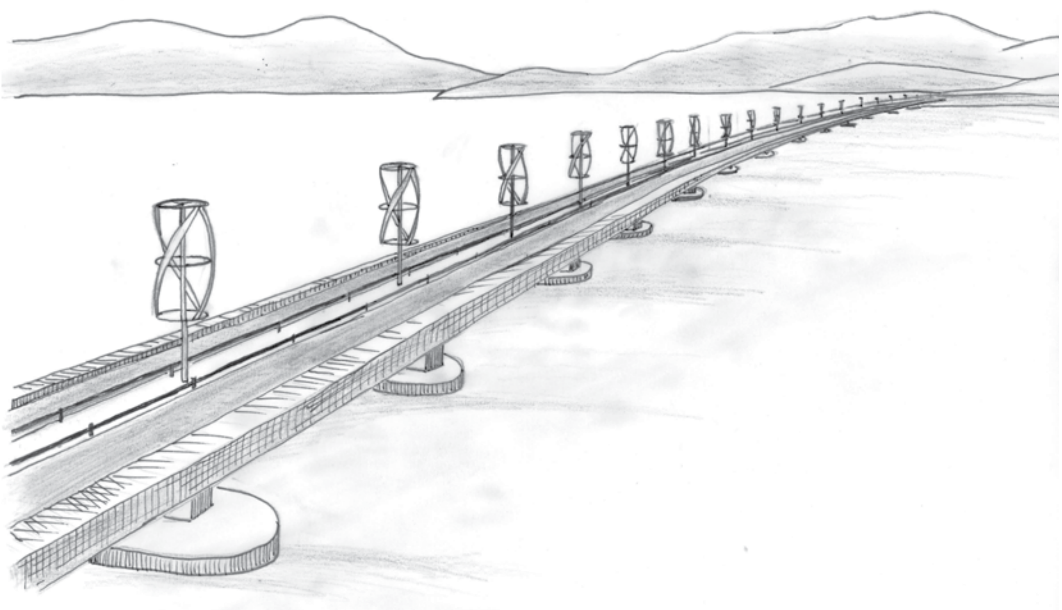

Figure A- 3: VAWTs placed along the road surface of a floating bridge, Norconsult

Large HAWTs placed on enlarged pontoons.

Figure A- 4: HAWTs placed on the enlarged pontoons of a floating bridge, Norconsult

Large HAWTs where the wind turbine tower is placed on pontoons and double as towers for holding the suspension wires for a floating bridge

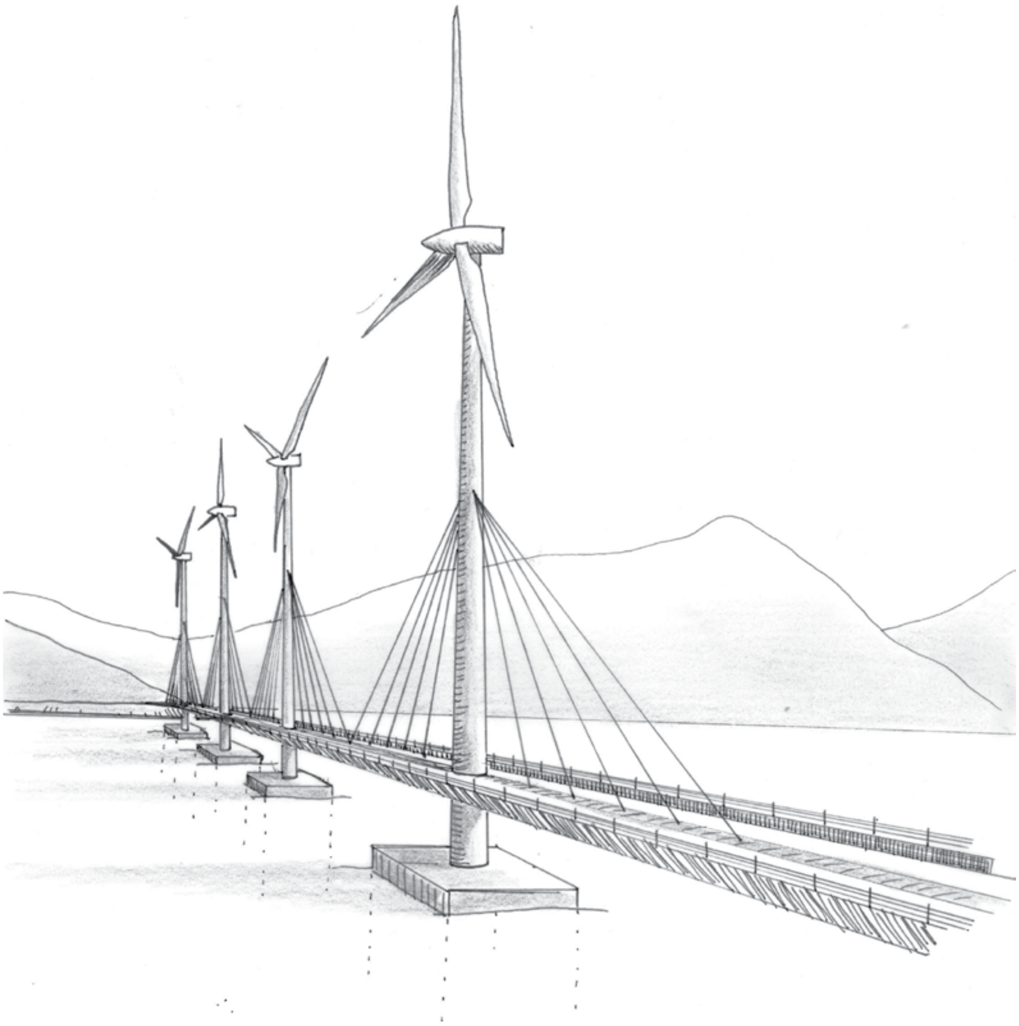

Figure A- 5: Wind turbine tower doubles as towers for holding suspension wires of a floatin bridge, Norconsult

Other ideas:

- Small HAWTs along the bridge deck on one side of a suspension bridge with the rotor being half above and half below the bridge level.

Ideas proposed by Rambøll:

Small HAWTs placed close to the roadway.

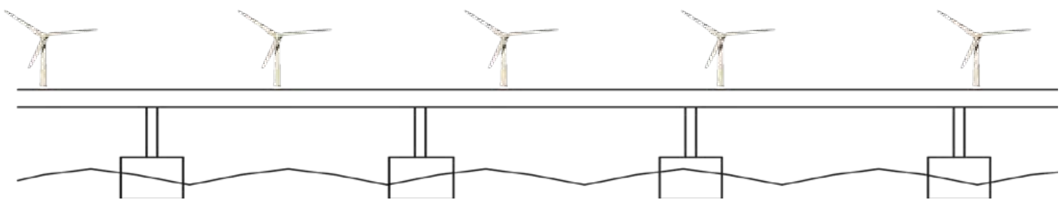

Figure A- 6: HAWTs placed close to the roadway of a floating bridge, Rambøll

Other ideas:

- VAWTs placed on top of the pylons.
- Wind turbines installed in the immediate vicinity of the bridge
- Attaching turbines as shovels around the pillars

Ideas proposed by SP:

DAWTs integrated in the roadway, possible for both suspension and floating bridge.

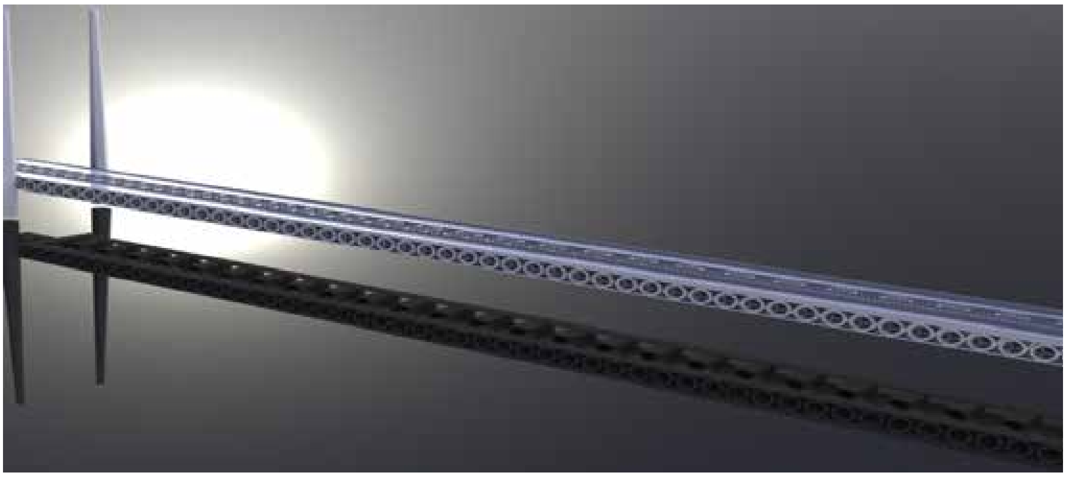

Figure A- 7: DAWTs integrated in the roadway of a suspension bridge, SP

Appendix B: Integration alternatives for solar panels

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Ideas proposed by Norconsult:

Panels mounted on the side(s) of the bridge.

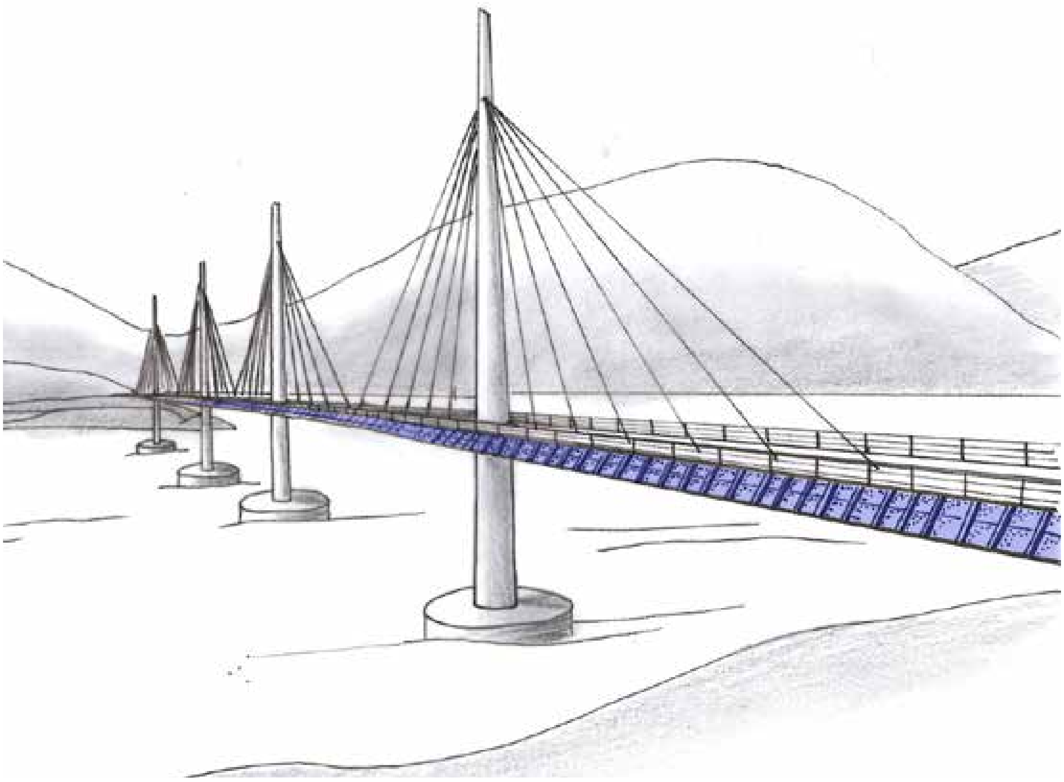

Figure B- 1: Panels mounted on the side of a suspension or floating bridge, Norconsult

Panels mounted as a roof over the driveway, over some parts or the entire length of the bridge.

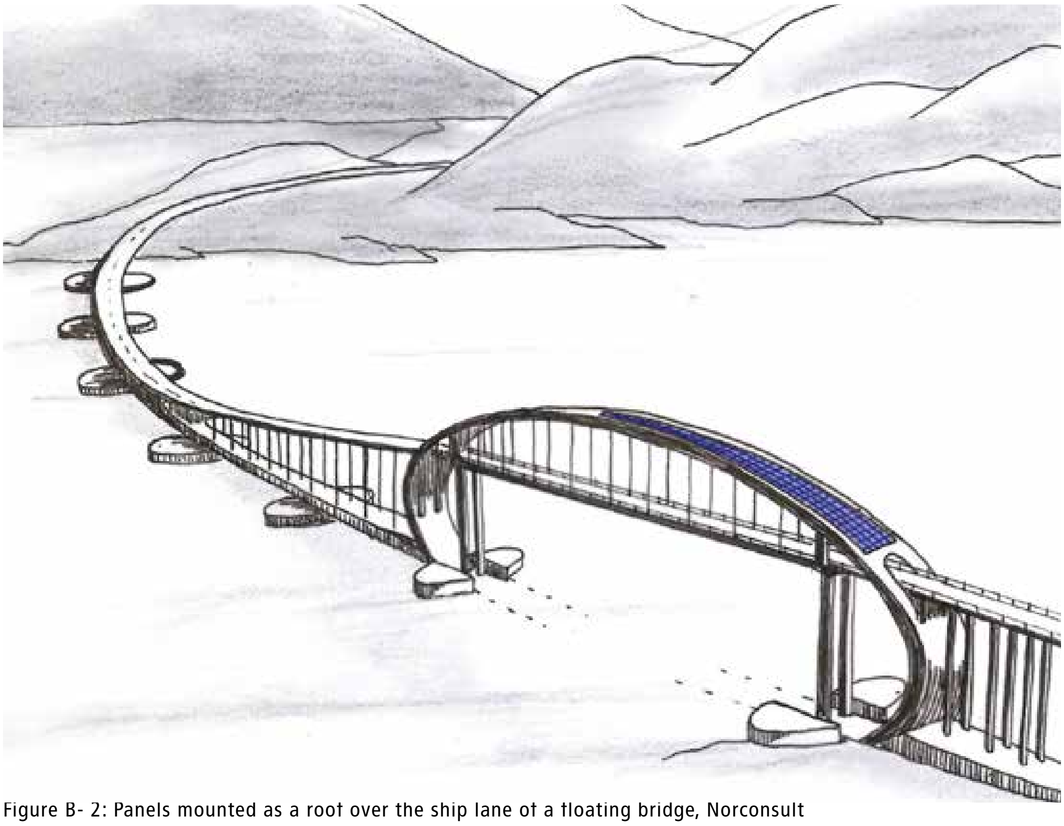

Figure B- 2: Panels mounted as a roof over the ship lane of a floating bridge, Norconsult

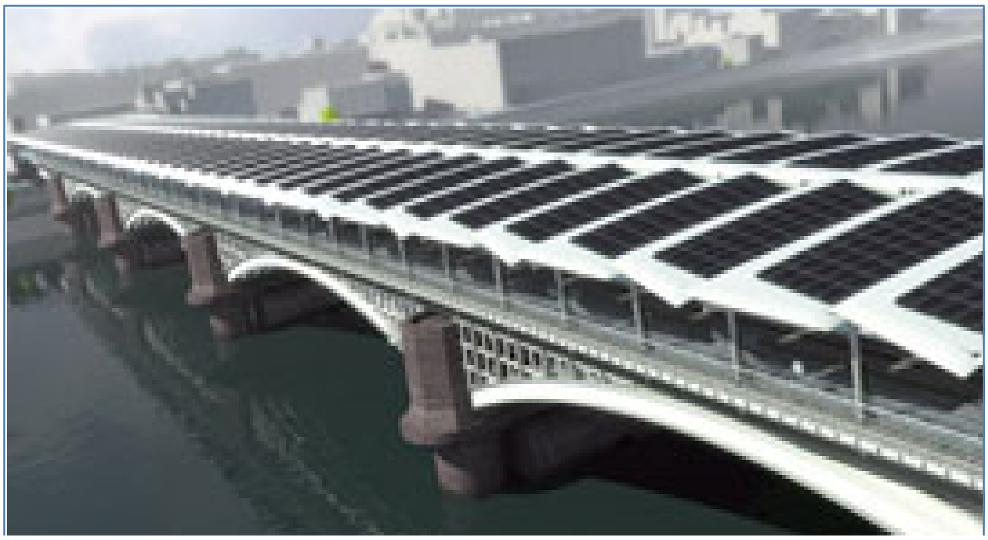

Figure B- 3: Panels mounted as a roof over the roadway of a suspension or floating bridge, Norconsult

Ideas proposed by Rambøll:

Panels mounted on the pylons and on the sides of a suspension bridge.

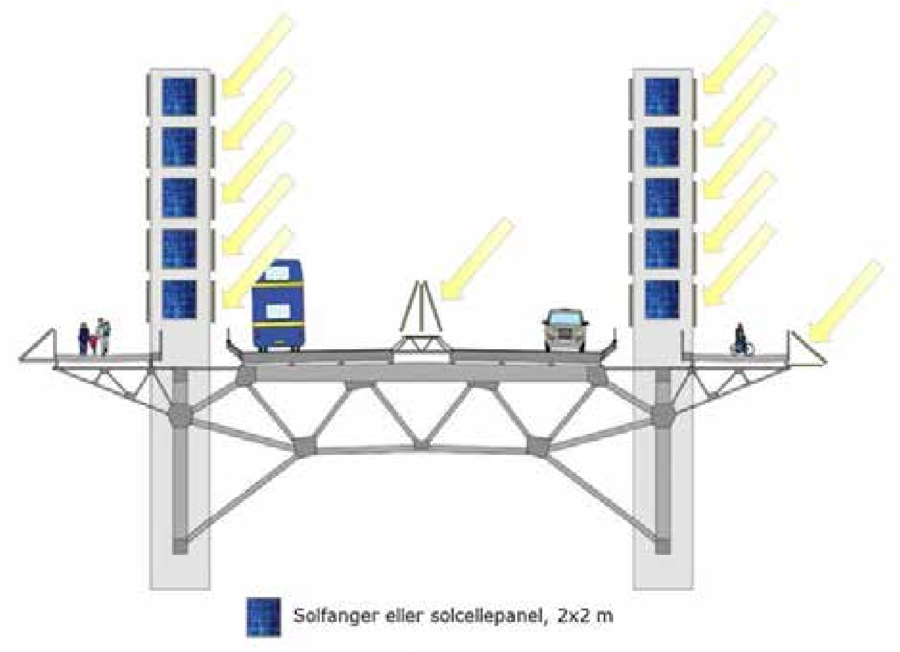

Figure B- 4: Panels mounted on the pylons and the sides of a suspension bridge, Rambøll

Ideas proposed by SP:

Panels mounted on the wires of a suspension bridge.

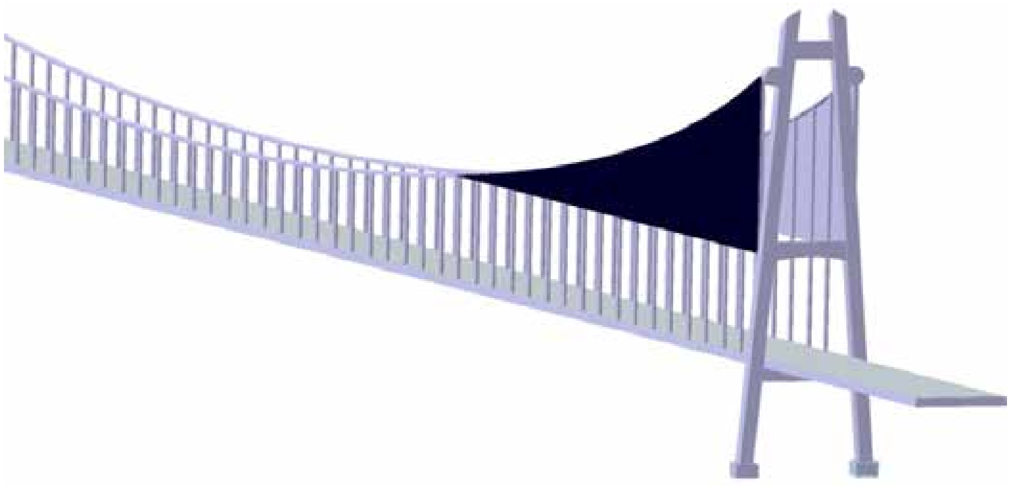

Figure B- 5:Panels mounted on the wires of a suspension bridge, SP

SP has also presented the ideas of mounting the panels on the side, as a roof or on the pylons of a bridge.

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Appendix C: Integration alternatives for wave power

In the following some of the ideas of integration alternatives are presented. For more examples the reader is referred to reports by Rambøll [1] and SP [4].

Ideas proposed by Rambøll:

Point absorbers integrated in floating bridge.

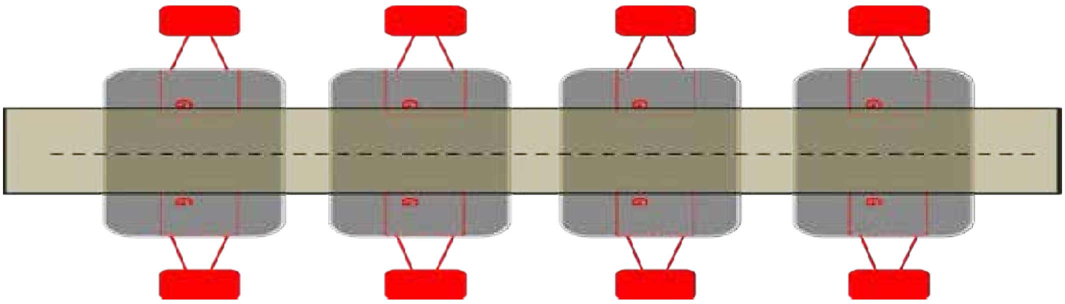

Figure C- 1: Point absorbers integrated in a floating bridge, Rambøll

Wavestar, developed by Wave Star A/S. Point absorber, can use a floating bridge as foundation.

Figure C- 2: Point absorber, could use a floating bridge as foundation, Rambøll

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Ideas proposed by SP:

SurgeDrive, developed by AquaGen Technologies, point absorber moored to the bridge.

Figure C- 3: Point absorber, could be moored to all three bridge types, SP

Drakoo, developed by Hann-Ocean Energy Pte Ltd. Twin-chamber water column. The device has no moving parts outside and can be attached to other marine structures.

Figure C- 4: Twin-chamber water column, could be moored to all three bridge types, SP

Other ideas:

- Integrating the WEC devices into the bridge structure
- Integrating just the power take-off of the device into the bridge structure
- Integrating the WEC device into a floating platform, which is then moored to the bridge structure
- Using the WEC as a breakwater that is installed adjacent to the bridge structure
- Replacing a typical mooring line with a lever arm that can be directly attached to the bridge structure

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Appendix D: Integration alternatives for tidal power

In the following some of the ideas of integration alternatives are presented. For more examples the reader is referred to reports by Rambøll [1] and SP [4].

Ideas proposed by Rambøll:

Current turbines integrated in floating bridge.

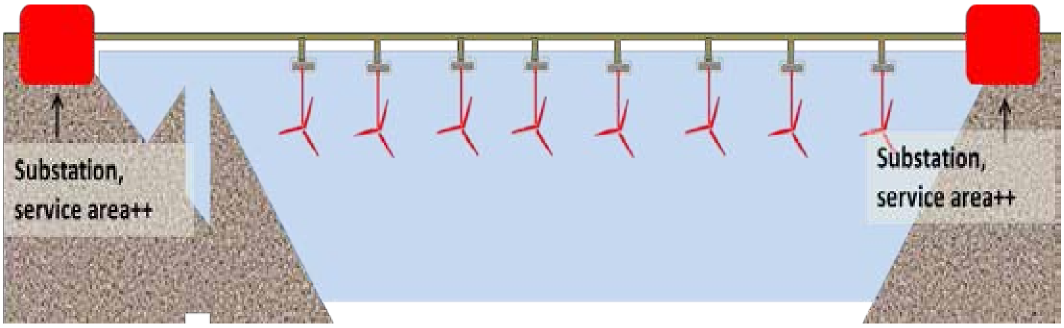

Figure D- 1: Current turbines integrated in a floating bridge, Rambøll

Current turbines mounted to submerged tunnel.

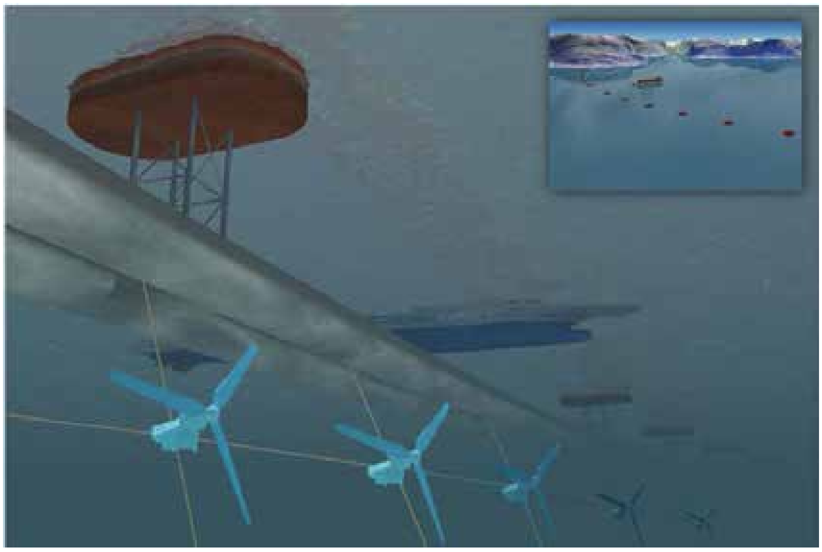

Figure D- 2: Current turbines mounted to a submerged tunnel, Rambøll

Ideas proposed by SP:

Solution developed by Oceanflow Energy Ltd, tidal current turbines mounted under a floating bridge.

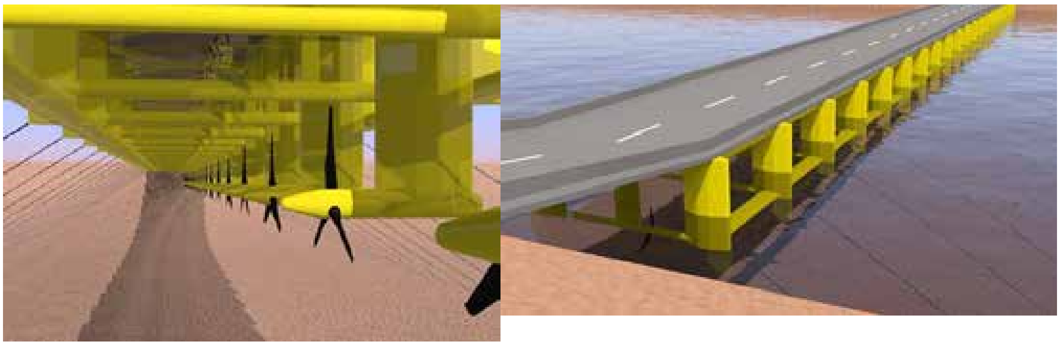

Figure D- 3: Current turbines mounted under a floating bridge, SP

DeepGreen, developed by Minesto, can be moored to the bridge structure.

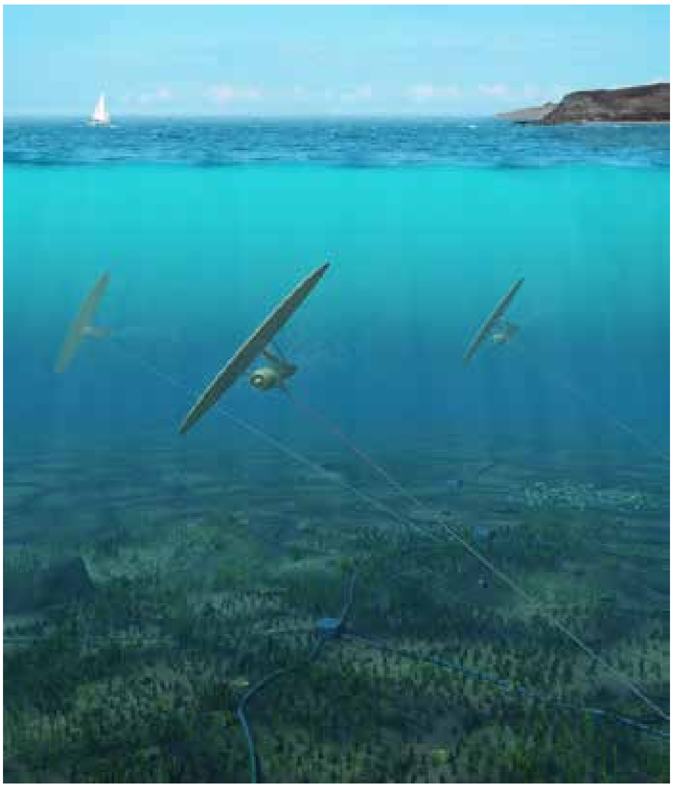

Figure D- 4: Moving wind turbine, could be moored to all three bridge types, SP

Suspending the TISEC devices from the bridge using a rigid frame. Possible for floating bridge and submerged tunnel.

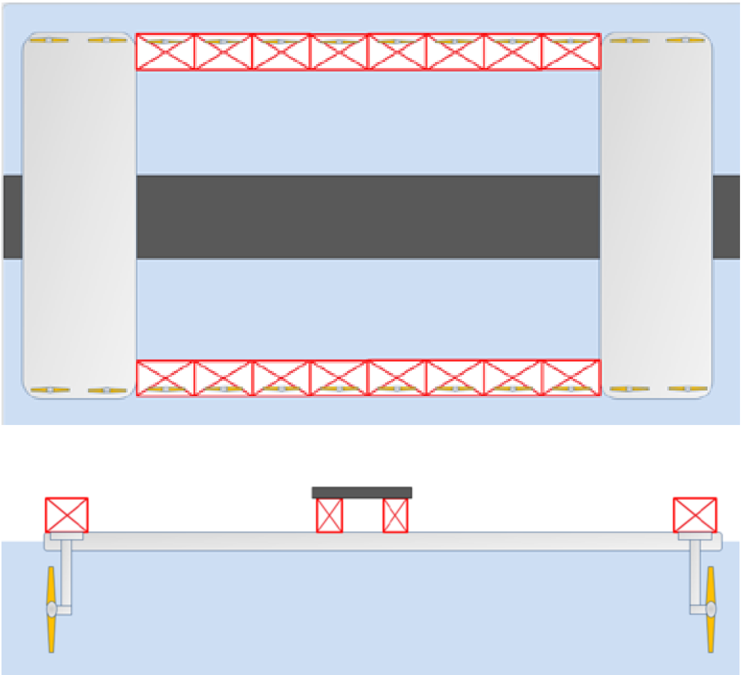

Figure D- 5: Suspending TISEC devices from a floating bridge or submerged tunnel using a rigid frame, SP

Tocardo T200, developed by Tocardo International BV. Turbines can be attached directly to a floating bridge or submerged tunnel.

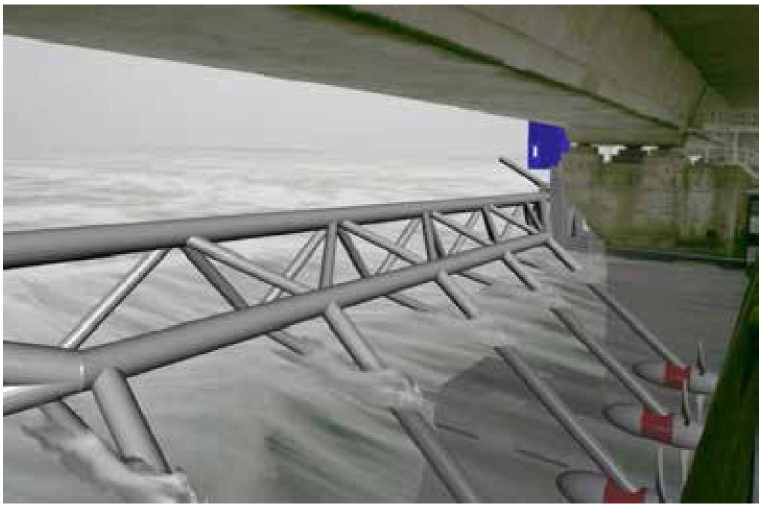

Figure D- 6: Current turbines, can be attached directly to a floating bridge or submerged tunnel

Power tower, developed by Flumill.

Figure D- 7: Current turbine, can be moored to a floating bridge or submerged tunnel, SP

Other ideas:

- Suspending the TISEC devises from the bridge structure using inverted pylons
- Attaching the TISEC devices to the bridge piles or foundations
- Connecting the TISEC devices to floating platforms which are moored to the bridge
- Integrating the TISEC device into the bridge structure itself
- Mounting the TISEC devices directly to the submerged floating tunnel (either above or below)

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Appendix E: Calculations

WIND ENERGY

Suspension bridge
VAWT/DAWT
GWh/km/year

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	0,90	1,32	1,63	0,92	0,68	1,18	1,55	1,72	2,60
Norconsult	0,48	0,56	0,72	0,56	0,32	0,48	0,56		1,36
Rambøll	no calculations for suspension bridge								

lowest production value used for SP

Floating bridge
HAWT/DAWT
GWh/km/year

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	0,32	0,60	0,77	0,42	0,26	0,53	0,77	0,85	1,40
Norconsult	12,16	14,08	19,2	14,08	8,96	12,16	14,08		30,08
Rambøll	each turbine is estimated to produce 90 000 kWh/year --> 2,7 GWh/km/year								

Table E- 1: Calculations for wind energy production

SOLAR ENERGY

Suspension bridge and floating bridge side mounted, 45 tilt

GWh/km/year

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	0,56	0,59	0,59	0,58	0,58	0,59	0,58	0,59	0,57
Norconsult	0,46	0,48	0,62	0,47	0,49	0,31	0,41		0,47
Rambøll	no calculations have been done, but a rough estimate states that 1000 m2 of panels will produce something in the range of 75 000 kWh/year, corresponding to 0,1875 GWh/km/year with a height of 2,5 m								
values when assuming 2,5 m height for Norconsult									
Norconsult	0,35	0,36	0,47	0,35	0,37	0,23	0,31	0,00	0,35

Norconsult have assumed an irridiation of 925 kWh/m2/year, which is higher than what SP has used in their calculations (they have generated values for each site)
SP does not say anything on what kind of panels they have based their calculations on, and I dont understand 100 % how they have done the calculations wrt specific production

Suspension bridge roof mounted

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	1,88	1,88	1,88	1,88	1,88	1,88	1,88	1,88	1,88
Norconsult	no calculations have been done								
Rambøll	no calculations have been done								

Suspension bridge mounted on wires

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	1,88	8,57	8,55	8,39	8,48	8,47	8,44	8,55	8,26
Norconsult	no calculations have been done								
Rambøll	no calculations have been done								

Suspension bridge mounted on pylons

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	0,73	0,17	0,39	0,67	0,79	0,35	0,84	0,23	0,16
Norconsult	no calculations have been done								
Rambøll	no calculations have been done								

Floating bridge roof mounted

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	1,68	1,69	1,69	1,68	1,69	1,69	1,69	1,69	1,68
Norconsult	no calculations have been done								
Rambøll	no calculations have been done								

Table E- 2: Calculations for solar energy production

WAVE ENERGY

Suspension bridge or floating bridge
GWh/km/year

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	249,32	320,01	293,53	259,68	246,47	298,16	240,00	311,58	321,41
Norconsult	wave energy not considered in their feasability study								
Rambøll	no calculations have been done								

Submerged floating tunnel
GWh/km/year

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	211,59	272,59	245,88	213,51	207,06	252,76	200,00	264,31	272,69
Norconsult	wave energy not considered in their feasability study								
Rambøll	no calculations have been done								
Difference	1,18	1,17	1,19	1,22	1,19	1,18	1,20	1,18	1,18

the energy production is in the range of 20 % higher for suspension bridge

Extreme values, only SP
Suspension bridge
or floating bridge
MINIMUM

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	5,47	6,60	6,18	5,46	5,29	6,30	5,00	6,45	6,65
	10	53	21	11	9	24	8	37	56
MAXIMUM									
SP	2490,43	3271,10	2988,82	2609,73	2473,53	3034,91	2408,75	3178,82	3289,21

Submerged floating tunnel
MINIMUM

Crossing	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
SP	4,37	5,60	5,29	4,47	4,12	5,25	4,38	5,58	5,70
	8	45	18	9	7	20	7	32	48
MAXIMUM									
SP	2107,16	2791,39	2473,53	2087,88	2061,18	2575,07	1971,25	2689,81	2789,57

Table E- 3: Calculations for wave energy production

Technology producer				suspension bridge/floating bridge								
Hs min	Tp min	Hs nom.	Tp nom.	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nord-fjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
Hann Ocean				103	132	121	108	103	123	101	128	132
0,2	2	1-1,3	.4-5									
Ocean Harvesting Technology				15	20	18	16	15	18	15	19	20
1	3	.8-10	.3-4									
Oweco				193	235	218	198	188	221	184	230	236
1	3	.0-4										
Perpetuwave				111	140	130	115	109	131	108	137	141
0,5	4	3	11									
Wavestar				15-193	20-235	18-218	16-198	15-188	18-221	15-184	20-230	20-236
0,25	1,5	4,75	4,5									

submerged tunnel									
	Halsafjord	Moldefjord	Storfjord	Voldafjord	Nordfjord	Sognefjord	Bjørnafjord a	Bjørnafjord b	Boknafjord
Hann Ocean	88	112	103	90	86	105	83	109	112
Ocean Harvesting Technology	13	17	16	13	13	16	13	16	17
Oweco	163	200	185	168	160	188	157	196	201
Perpetuwave	95	119	109	98	91	111	89	116	120
Wavestar	13-163	17-200	16-185	13-168	13-160	16-188	13-157	16-196	17-201

Table E- 4: Calculations for WEC devices that statr energy production at Hs<1 m

Energy resource; Tidal current						
			Expected Energy production GWh/km/year			
cut-in speed<1 m/s			**Floating bridge**			
	cut in	rated	Moldefjord	Voldafjord	Nordfjord	Boknafjord
tocardo international	0,4	.2-4	21	17	16	30
hydro-gen	0,5	4	50	42	40	50
Neptune renewable	0,5	5	81	68	64	81
Norwegian ocean power	0,5	2,6	105	88	83	105
ocean renewable power	0,5	3	16	13	12	16
			16-105	**13-88**	**12-83**	**16-105**

Table E- 5: Estimated potential for TISEC devices producing energy at v< 0.5 m/

FERJEFRI E39

Comparison of the different energy productions

GWh/km/year

Suspension bridge

crossing	Halsafjord		Moldefjord		Storfjord		Voldafjord		Nordfjord	
	max	min	max	min	max	min	max	min	max	min
wave	2490,43	5,47	3271,09	6,60	2988,83	6,18	2609,73	5,46	2473,53	5,29
tidal			2215,58	15,68			1844,09	12,91	1772,35	12,35
wind	0,91	0,48	1,32	0,56	1,63	0,72	0,92	0,56	0,68	0,32
solar	8,19	0,47	8,57	0,17	8,55	0,39	8,39	0,47	8,48	0,49
max values:	wave:	Vigor wave energy AB			**min values:**	wave:	Atmocean			
	tidal:	Tidal sails AS				tidal:	Ocean renewable power company			
	wind:	DAWT (SP)				wind:	VAWT (Norconsult)			
	solar:	panels mounted on wires				solar:	side mounted		mounted on pylons	

Floating bridge

crossing	Halsafjord		Moldefjord		Storfjord		Voldafjord		Nordfjord	
	max	min	max	min	max	min	max	min	max	min
wave	2490,43	5,47	3271,09	6,60	2988,83	6,18	2609,73	5,46	2473,53	5,29
tidal			2215,58	15,68			1844,09	12,91	1772,35	12,35
wind	12,16	0,32	14,08	0,60	19,20	0,77	14,08	0,42	8,96	0,26
solar	1,68	0,47	1,69	0,48	1,69	0,62	1,68	0,47	1,69	0,49
max values:	wave:	Vigor wave energy AB			**min values:**	wave:	Atmocean			
	tidal:	Tidal sails AS				tidal:	Ocean renewable power company			
	wind:	HAWT (Norconsult)				wind:	DAWT (SP)			
	solar:	roof mounted				solar:	side mounted			

Submerged floating tunnel

crossing	Halsafjord		Moldefjord		Storfjord		Voldafjord		Nordfjord	
	max	min	max	min	max	min	max	min	max	min
wave	2107,16	4,37	2791,39	5,60	2473,53	5,29	2087,89	4,47	2061,18	4,12
tidal			1884,11	13,32			1566,04	10,92	1504,71	10,59
wind										
solar										
max values:	wave:	Vigor wave energy AB			**min values:**	wave:	Atmocean			
	tidal:	Tidal sails AS				tidal:	Ocean renewable power company			

Table E- 5: Comparison of the four energy production sources

Sognefjord		Bjørnafjord a		Bjørnafjord b		Boknafjord	
max	min	max	min	max	min	max	min
3034,91	6,30	2408,75	5,00	3178,82	6,46	3289,21	6,65
						2219,11	15,68
1,18	0,48	1,55	0,56	1,72		2,60	1,36
8,47	0,31	8,44	0,41	8,55	0,23	8,26	0,16

Sognefjord		Bjørnafjord a		Bjørnafjord b		Boknafjord	
max	min	max	min	max	min	max	min
3034,91	6,30	2408,75	5,00	3178,82	6,46	3289,21	6,65
						2219,11	15,68
12,16	0,53	14,08	0,77		0,85	30,08	1,40
1,69	0,31	1,69	0,41	1,69		1,69	0,47

Sognefjord		Bjørnafjord a		Bjørnafjord b		Boknafjord	
max	min	max	min	max	min	max	min
2575,07	5,25	1971,25	4,38	2689,81	5,58	2789,57	5,70
						1886,05	13,43

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