Turbine design and field development concepts for tidal, ocean, and river applications

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Abstract
This paper discusses tidal, ocean, and river free turbine functional design parameters and general considerations associated with tidal field developments. A particular focus is on the importance of considering mechanical fatigue and the associated calculation method when designing a turbine for the challenging hydrodynamic environment. The balance between high-fatigue resistances, costs associated with designing components, and potential for reduced turbine efficiency is discussed in regards to the potential energy extracted from a field site. A novel flexible foil vertical turbine concept with high-fatigue resistance, and simple installation and retrieval methods is shown to have a low kWh cost per production output compared to other hydrodynamic turbine concepts. Three possible field development concepts for the flexible foil turbine are described herein for river, ocean current, and tidal applications.

Introduction
Achieving a carbon neutral future depends on the development of renewable energy resources like tidal energy [1]. The significant commercial potential of renewable energy production from free flow hydrodynamic turbines is not yet realized. Few prototype or commercialized turbines have been tested in field hydrodynamic environments [2–6]. To date, lack of robust and alternative concepts, challenging environmental conditions, high installation and maintenance costs, and limited financial investment have prohibited widespread commercialization of free flow turbines for tidal, ocean current, and river applications.

The challenging hydrodynamic conditions require considerable emphasis on operational, structural, and mechanical fatigue aspects of turbine design [7, 8]. Blade and structural failures have been caused by inadequate design and/or manufacturing defects that cannot withstand the harsh underwater conditions [7]. Unsteady flow due to turbulence, wave activity, and depth variations causes unsteady blade loading, resulting in fatigue [9, 10]. Marine and river environments require robust machinery that can tolerate these challenging and dynamic conditions. Optimizing turbine output into the available power utility distribution grid also needs to take into consideration the field-specific environmental and social conditions (e.g., field locations, distance to available grid, tidal and seasonal variations, waves, multiple turbine interactions, ice and debris, commercial and recreational traffic, and marine industry).

The tidal turbines tested to date generally have high manufacturing, installation, and maintenance costs associated with extracting energy from such a challenging environment. To date, the free flow turbine industry has not been focusing enough on cost-effective turbine installation and retrieval techniques as well as mechanical fatigue aspects. Indeed, several turbine projects have failed in field conditions due to mechanical fatigue, with detrimental results and costs. Consequently, many investors are reluctant to invest in free flow turbine technology. Tidal turbine blade and structural component failures are not uncommon and more robust turbine technology is required to endure the demanding hydrodynamic conditions.
conditions [7], which can vary between sites and also within a given site [9, 11].

To improve the economic potential of turbine concepts, the fabrication, installation, retrieval and operation of the turbine and associated equipment need to be robust and cost-effective, even if these aspects will reduce the actual turbine energy extraction efficiency. This paper discusses essential factors that need to be addressed when considering the development of robust, cost-efficient turbines. A particular focus is on fatigue-related issues and calculation, which are based on the author’s experience in pioneering techniques addressing fatigue aspects related to subsea oil and gas wellheads and manifolds. Furthermore, three potential multi-turbine field development concepts are proposed for a novel, flexible foil vertical-axis turbine designed for hydrodynamic environments, also addressing particular fatigue aspects: (1) permanent installation fixed to a river bottom or sea floor, (2) suspension from a floating structure on a mobile barge or vessel, and (3) permanent installation on a fixed structure such as a bridge or a platform.

**Considerations for Turbine Design and Field Development**

**Field site conditions**

The turbine concepts discussed herein are applicable for ocean, tide, and river applications. Typical river applications could be downstream of hydroelectric power stations where free turbines would be applicable. Ocean currents in excess of 0.4 m/sec are readily available at many sites, and are thus a significant untapped energy resource. Tidal energy extracted from periodic tidal current phenomena in various naturally occurring channels represents an energy potential of ~700–1200 × 10^6 MWh per year (~20% in Europe), although only a fraction of this can be effectively extracted. A few tidal sites with high peak currents have high-energy potential and are sought by most developers, but concepts yielding cost-effective solutions at medium to low current rates should also be more seriously considered.

Turbine efficiency also depends on interactions between the turbine and the site geography and/or interactions between turbines. These blockage effects will affect the individual turbine performance [12–14]. Narrower channels or the blockage and flow effects from other turbines may improve turbine efficiency by funneling a higher flow speed into the blades of the turbine. Groups of fish can use the “schooling effect” to increase their hydrodynamic efficiency, just as vertical-axis turbines can work together to more efficiently harness the kinetic energy in a tidal current [15]. A field development of vertical-axis turbines, typically with flexible foils, should therefore be positioned so the schooling effect will take place. Vertical turbine concepts could be better optimized for such interactions between turbines, because vertical turbines represent a “projected” rectangular area whereas horizontal-axis turbines have a more circular “projected” area of influence. The use of the schooling effect in a field development with vertical-axis turbines will increase the energy/area density and thus reduce the development cost [15].

Figure 1 shows a typical cross section of a tidal site in Norway with high currents, showing significant variation in current speed across the channel as well as with water depth. The general hydrodynamic forces and variations must be carefully analyzed and considered in the design of the individual turbines, as well as when determining the location of each turbine in the flow. Variation in flow speeds at different positions within a field and at different water depths, caused by topology and interaction with other structures, result in varying vertical and lateral forces along the height and width of the turbine, which will affect turbine performance and mechanical fatigue. Such global and local flow speed variations and turbulence can typically be semi chaotic in behavior, with local variation and superimposed random and nonrandom super waveforms. The effect can be significant with respect to the local applied hydrodynamic forces and corresponding structural fatigue. These effects should be
measured on site and the effect may then be defined as discrete relevant hydrodynamic loads in a time domain, applied as superimposed loads and/or load factors. These factors (typically as high as factor 2) can be used for the locally applied structural hydrodynamic forces beyond that of the generally established global forces. Thus, turbine design criteria must include consideration of additional horizontal and vertical forces, local and global turbulence, and nonsymmetric bending and torsional forces. Ideally, a turbine design will be adaptable to different velocities experienced at different geographical sites, and also within the nonhomogenous conditions along the height and width of an individual turbine.

The occurrence and impact from various types of debris and ice must be considered when designing the turbine and field development layout, thus accepting that objects may hit the hydro-dynamically optimized profiles and other structural elements. Risk assessments are required on the effects that damaged turbine elements might have on turbine performance, including the potential detrimental impacts that larger objects will have on the turbine rotational functionality. Thus, the design must cater for a potentially unbalanced condition causing significant vibration, with the means also of detecting such unbalances.

Hydrokinetic devices such as turbines can impact organisms directly (e.g., blade strikes, pressure differentials) or indirectly (e.g., altering the local chemistry, electromagnetic field, noise, flow hydraulics, or bottom habitats), with seasonal and temporal variations in biotic and abiotic conditions [6, 16]. The turbine and associated equipment can create positive or negative habitats for different species [16], including providing surfaces for detrimental marine growth (see below). An optimal turbine site would have minimal biological, social, and economic impacts on wildlife and human use of the area (e.g., commercial shipping, recreational activities). The Norwegian government proposes a minimum ~18 m depth for infrastructure in shipping routes. Ideally, the turbine field would be positioned in areas that would avoid biologically rich regions such as fish habitat, and also major shipping and recreational boating routes.

**Fatigue analyses for optimizing turbine design and performance**

The challenging hydrodynamic conditions necessitate a robust turbine design that can withstand the intended environment and life cycles without oversizing turbine components and costs associated with weight, fabrication, transportation, and installation. Many of the tidal turbine concepts and pilots developed and/or actually tested to date have focused primarily on obtaining a high coefficient of power (an objective to some degree inherited from hydro turbine developments), designed with a safety factor on a selected maximum design load. Tidal turbine technology has not adequately addressed the time-dependent fatigue aspect of rotating subsea turbines needed to scale up for actual commercial developments. The tidal turbine industry must undertake a more significant effort to adequately perform fatigue analyses of the structural components as a means of ensuring a robust design and also assessing ongoing performance in the field. An appropriate guide for fatigue calculations of subsea structures and tidal turbines could be based on the described method herein and recommended praxis DNV-RP-C203 [17] and [18], although with suggested alterations as discussed below.

To date, turbine design engineering often apply a set design load/force safety factor, typically 6–10 for normal operating conditions versus a factor of 1 for harsh/extreme conditions [7]. However, in general this practice is not recommended because this does not reflect the actual material and design details and fabrication method used in the design, nor does it reflect the time-dependant design life and/or stress cycles to which the equipment is subjected. Instead, the method described herein is based on the use of S-N curves (graphical representation of the dependence of fatigue life [N] on fatigue strength [S]) for the actual design and material, in combination with superimposed hydrodynamic forces. This gives a more targeted approach, reflecting the inherent statistically generated fatigue capability of the materials and design used, in combination with the selected fabrication method. Appropriate industry tested and statistically defined S-N curves can therefore be used for structural design details and materials used in the turbine design. This approach can be used on local and global structural elements made from composites and alloy materials, and is relevant for machined, welded, friction and bolted connections, and other structural transitions.

**A general fatigue analysis method**

Figure 2 shows a general, and computation-effective, method for assessing and calculating turbine fatigue for a vertical turbine, although it is also relevant for horizontal turbines and other turbine concepts.

The establishment of the applied hydrodynamic forces could be based on properly scaled model test results (recommended), or analytical results from a full computational fluid dynamic (CFD) model, blade element momentum (BEM) theory [19], quasi-static BEM theory [20], or using a rapidly optimizing iterative analysis such as the Cascade theory (D. H. Zeiner-Gundersen, unpubl. data). Hydrodynamic analyses (Fig. 2, blue boxes) should establish the dynamic forces as a function of the applied conditions, which in turn can be input into the fatigue analysis. This will ensure that the design is a robust one, capable of performing satisfactorily for the intended life cycle.
environmental loads, based on variable flow velocities and directions. A tidal, ocean, or river field check should be done to evaluate the recorded field-specific potential variations in incoming water speed along and across the turbine in order to establish representative load cases. Accurate superimposed characterization of such hydrodynamic forces should be established versus height and azimuth angle. This also reflects unsteady oscillatory hydrodynamic loads, as characterized by static and dynamic profileblade stall and special turbine functionality features (e.g., passive spring force profileblade movements, pitching, local and global component dynamics, and eigen frequencies). Such hydrodynamic forces and the global and local flow field speed variations should be defined into discrete 3D representations of variable hydrodynamic forces versus the vertical and horizontal (azimuth angle) position, representative for the induced water flow velocities. Variable hydrodynamic forces based on local vortices and depth/width variations should be superimposed onto the hydrodynamic load as a variable load and as a function of the rotational azimuth angle and time. If these speed variations and vortices are chaotic by nature, a statistical application reflecting the measured field-specific occurrence of these loads can be applied. The superimposed loads acting at various positions on the structural elements are used in determining relevant variable stresses in structural critical design hotspots on each structural element, such as the blades, and the resulting effect determined for the turbine arms and turbine axis or structure.

Finite element analysis (FEA) calculations should be used in investigating the appropriately defined local design hot spots and the development of a set of transfer functions in the design with respect to the (1) applied variable unit forces, (2) relevant directional application of such force, (3) representative design configuration, and (4) generated resulting vectorized stress (Fig. 2, green box). These stress transfer functions should be established in a 3D configuration to cater for variation in the direction of the superimposed forces for the most critically structural design hot spots. The transfer functions will thereby represent unidirectional stress graphs for each
predefined design hot spot in a specific structural turbine component. The number of transfer functions for the turbine’s components should, however, be limited in magnitude and complexity. This would reduce the complexity of the dynamic calculations of the stress counting simulation using dynamic analysis of the stepwise turbine rotation and applying the external superimposed forces onto the turbine. Thus, sound engineering judgment should be applied in defining the number, complexity, and variations in the transfer functions.

A set of quasi-static turbine analyses (iterative rotational steps vs. time to determine relevant variable stresses peaks at defined design stress hotspots) should be executed (Fig. 2, green box) based on rotational azimuth angle and applied hydrodynamic forces. These analyses are based on the use of the applied superimposed hydrodynamic forces and use of the stress transfer functions established by 3D FEA in determining the stresses and the number of stress peaks at a specific design hot spot for each component. The superimposed dynamic force and related variation in stress peaks versus time histories should then be used to calculate the predicted fatigue “damage” for each defined hotspot (Fig. 2, red boxes). The stress time series for each design hot spot are then rainflow counted. The appropriate stress concentration factors (SCFs) for each hotspot should then be applied, and the appropriate design and material S-N curve used, as given by Equation (1). Equation (2) shows the Miner Palmgren’s rule that is used to calculate the predicted fatigue “damage” for each design stress hot spot.

**S-N curves and Miner Palmgren’s rule**

A typically designed S-N curve, including the thickness effect, is defined as

\[
\log N = \log \bar{a} - m \log \Delta \sigma _{a} \left( \frac{t}{t_{\text{ref}}} \right) ^{k}
\]

where \(N\) is the predicted number of cycles to failure for the stress range (\(\Delta \sigma\)), \(\log \bar{a}\) is the intercept of the log N axis with the S-N curve, \(m\) is the negative inverse slope of the S-N curve, \(t\) is the thickness through which a crack will most likely grow \((t < t_{\text{ref}})\), \(t_{\text{ref}}\) is the reference thickness typically for tubular joints (32 mm; 25 mm for other welded connections and bolts), and \(k\) is the thickness exponent of fatigue strength, as defined in the DNV-RP-C203. The S-N curves defined in DNV-RP-C203 should be used with caution due to the high number of load cycles that the turbine components are exposed to both locally and globally. Fatigue life calculation based on rainflow counting using a continuously downward sloping S-N curve should be upheld as a recommended method (rather than a cutoff at \(10^{7}–10^{9}\) stress cycles). This is due to the excessive high number of local and global cycles to which the turbine components are subjected, even when maximum stress amplitude levels (as stated within DNV-RP-C203) define acceptable threshold values that in theory should provide “infinite life.” Extrapolation beyond \(10^{7}\) cycles in the high-cycle fatigue regime should, as a minimum, use the \(m = 22\) slope for the S-N curve [18].

The fatigue damage for each design stress hot spot is calculated using Miner Palmgren’s rule:

\[
D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{a} \sum_{i=1}^{k} n_i \cdot (\Delta \sigma_i)^m \leq \eta,
\]

where \(\bar{a}\) is the intercept of the designed S-N curve with log \(N\) axis, \(m\) is the negative inverse slope of the S-N curve, \(k\) is the number of stress blocks, \(n_i\) is the number of stress cycles in stress block \(i\), \(N_i\) is the number of cycles to failure at constant stress range \(\Delta \sigma_i\), and \(\eta\) is the usage factor. The long-term stress range distribution is thereby expressed by a stress histogram, defined by constant stress range blocks \(\Delta \sigma_i\) each with a number of stress repetitions \(n_i\). The number of stress blocks \(k\) should be high enough in order to achieve a sufficient numerical accuracy. For more detailed usage, see the criteria and equations defined by DNV-RP-C203 [17].

**Additional considerations relevant for a turbine design**

Tidal, ocean, and open river turbines are typically designed from composites or carbon steel. Proper cathodic protection with optimized positioning of anodes should be selected. Additionally, adequate allowance should be made for general corrosion on unpainted components and surfaces, including the foundation and internal structural elements. Vent holes should be included in all structural components to avoid collapse from hydrostatic pressure. It is important to maintain electrical contact between all components, independent of the type of material used [21]. Typically, this can be achieved using miniature electrical jumpers or bare metal friction washers with proper connections between all components. Aspects such as hydrogen-induced stress cracking (HISC) should be carefully considered for critical components such as fasteners, nuts and bolts in duplex and martensitic corrosion-resistant alloys, as well as high-yield carbon steel.

For high-fatigue resistance, forged metal components would be preferred in critically stressed areas. Preloaded friction-based connections should preferably be used as attachments between components, avoiding welds whenever possible. Adequate turbine manufacturing accuracy and carefully considered transitions should be used, such
as properly rounded corners, grinding of weld roots and surfaces, and limited eccentricity between components. Welding should in general only be used on noncritical components and low-stressed areas on major load carrying components. The positive effects of such design and manufacturing improvements would reduce the expressed SCFs and use of enhanced S-N curves, thus increasing the mechanical fatigue design life.

For fatigue performance analysis, a design fatigue factor (DFF) of 10 on fatigue life is typically recommended for nonretrievable components such as the foundation, with a relative uncertainty in the defined hydrodynamic loads. A DFF factor of 5 may typically be applied if there is high confidence on the established load cases such as monitoring the turbine loads by load cells and accelerometers. This high DFF factor is due to the inherent statistical characteristics of the established S-N curves, inaccuracy in calculation methods, methods used in establishing SCFs, level and possibility of nondestructive testing (NDT), and the final acceptable reliability level. In general, the factor can be reduced if there is no possible loss of human life. A DFF of 3 would be acceptable if there is continuous monitoring of the strain and stress monitored in the foundation critical design hotspots during operation, provided that the turbine foundation operating acceptance criteria is not exceeded. A DFF of 3 is recommended for retrievable elements such as the turbine itself, where NDT inspection is possible and can be performed on a periodic basis. Planning for regular maintenance of the turbine is an important element that should be a vital design parameter. Thus simple installation, retrieval, inspection, and replacement techniques are essential. A 5-year retrieval frequency is typical for inspection of a turbine’s rotational elements. All critical welded connections should be NDT examined during such inspection in accordance with the best praxis.

The fatigue analysis will generally give very low acceptable peak stress in the material, reflecting the fact that local design stress hot spots for a turbine are subjected to a very high number of lifetime cycles, typically $10^7$–$10^{10}$. The acceptable stress peak levels will therefore typically represent only a fraction of the material’s specified yield capacity. Thus, the selected overall turbine design and vital elements such as hydrodynamic blades will be significantly affected by properly addressing fatigue. This would therefore typically reduce the turbine power coefficient by introducing less efficient but tougher or more dynamic blade designs, and strengthening other structural components.

Particular fatigue considerations associated with local vortex-induced vibrations (VIV) should be done on structural elements and components, such as for local effects on wing blades, support and structural elements, cables, pipes/flexible hoses, and the control umbilical. This aspect should also be considered when reviewing the effect of nonhomogeneous current flow paths across the turbine, as typically shown in Figure 1. Local effects from cavitation should be carefully considered when selecting overall operating parameters such as the tip speed ratio and the detailed design of components that would reduce the negative impact of cavitation. Cavitation may also cause undesirable design hotspots with time, which needs to be considered in the local FEA analysis.

Effects from waves are not implemented into considerations for a tidal turbine because the top of the turbine would typically be 15–18 m below the surface, as required by the Norwegian government regulations. Wave refraction and fatigue must typically be addressed if the turbine depth $(D) < L/2$, where $L$ is the wavelength, because there is very little perceptible wave motion below this depth. Wave action and corresponding loads would typically be a concern for turbines suspended from bridges, platforms, and barges due to the proximity of the turbine to the water surface.

Ventilation can occur for a turbine at a shallow depth below the free water surface, which should typically be considered for river applications. As the water velocity increases, the dynamic pressure energy is converted to kinetic energy, the surface level drops, and the pressure also drops by an amount defined as the velocity head. Thus, the local velocity is accelerated to get around the convex side of a profile, resulting in lower pressure that may cause air to be sucked from the free surface into the water. However, this is not significantly applicable for tidal applications due to the turbine’s depth below the surface, but should be considered in particular for free stream river turbines with high RPM or for turbines suspended from bridges, floating structures, and platforms.

In general, structural components, supports, and cantilevers that undergo flexing oscillations in water are called wet frequencies and must account for the added mass induced by the motion and acceleration in the fluid, thus producing a hydrodynamic pressure and additional force on the structure [22].

The turbine’s local and global mechanical frequency response and related eigenvalues should be carefully analyzed with models such as ANSYS. The components and system structural elements exposed to cyclic variation from local and global hydrodynamic forces and VIV should be designed with eigen frequencies well outside the general imposed force generating excitation spectra. If such imposed force frequencies are close to the eigen frequency, they may tend to be shifted closer to and/or match the structural eigen frequency. The structural eigen frequency of structural elements for new turbine designs should typically be measured during construction by tapping on various structural elements and measuring the response frequency. Such measurements and eigen fre-
frequency verification are beneficial when reviewing the analytical results prior to commissioning, so that corrective design actions can still be implemented. The final design and operating limitation criteria will benefit from these early tests during construction.

The foundation design at the seabed/riverbed must consider soil stability, static and dynamic soil capacity, settlement, and structural interactions to ensure proper functionality. The representative simulation of the foundation must carefully consider boundary modeling conditions such as fixation points, rotational elements, and the model springs used to simulate the vertical and horizontal soil interaction in the analytical model. Furthermore, it is important to determine the fatigue effect of global turbine dynamic movements on interfacing constituents such as general long-term soil stability, seabed pipes, and/or the power and signal umbilical.

The cause and effect of failure of various structural parts (e.g., foil, blade, arm, shaft), generator, or other harmful failures should be listed and analyzed to ensure that typical failure modes do not detrimentally impair the functionality and/or structural integrity of the turbine and/or foundation. A complete risk management matrix ranking failures versus consequences and required actions is a useful tool in visualizing and organizing this process. This risk management matrix can be further enhanced by actions taken based on instrumentation and monitoring.

Considering fatigue aspects methodically when designing a commercial turbine would ultimately increase the actual field energy output by maximizing turbine lifespan while reducing the costs of oversizing components. However, this would likely also reduce the overall hydrodynamic turbine performance and energy output of the actual turbine. Thus, a commercial turbine intended for a field development would therefore likely have a different design compared to that of an optimized test or pilot turbine, which are often designed for maximum energy efficiency rather than maximum durability.

**Fatigue analysis done on a pilot vertical-axis turbine with flexible foils**

A set of fatigue calculations was performed on a full-scale (7 m tall) test pilot turbine with flexible foils that was tested in a river environment in Norway (see below, and unpubl. data). These analyses, together with accumulated experience from offshore oil and gas wellhead fatigue and manifold piping FIV fatigue analyses, were contributing factors to proposing the analytical method described in Figure 2.

The establishment of the hydrodynamic forces for the full-scale pilot turbine was based on appropriately scaled-up forces on lift, drag, and momentum derived from a set of model tests performed in a cavitation tunnel at SSPA Sweden AB, Goteborg [23]. Finite element 3D models of the turbine components were created using Siemens NX Ideas 6.1 (Siemens PLM Software, Plano, TX, USA; e.g., Fig. 3A and B). For the quasi-static analysis, the flexible multi-body dynamics software FEDEM (Fedem Technology A.S., Trondheim, Norway) was used (Fig. 3C), and the fatigue damage for each stress hot spot was calculated using Miner Palmgren’s rule (eq. 2). A required DFF of 3 was set as the acceptance criteria because of the good turbine retrieval ability as well as “non-submerged” NDT inspection available on a regular basis. A relatively extensive iterative analysis and design enhancement process was executed in order to determine an appropriate design for the full-scale pilot test turbine.

An example of the FEA is given for the profile/blade and supporting structures located in the middle of the turbine (Fig. 4). The analysis was performed for 2.1 m/sec incoming water velocity (extreme conditions), 8 RPM, and a 3-year fatigue lifespan safety factor, which was considered adequate for the pilot turbine. The analyses showed that the region of the profile/blade-supporting bracket to the arm had the maximum cyclic stress (Fig. 4A; $7.6 \times 10^7$ Pa, 670 day fatigue life). The flexible foil blade showed the maximum stress near the mid region of the profile/blade support structure (Fig. 4B, arrows). The turbine was designed to normally operate between 0.6–1.6 m/sec with optimum operation at 0.8 m/sec and a 0.369 coefficient of power, thus giving the structural components a higher operating fatigue life than required for this particular test pilot turbine.

During the on-site testing of the pilot flex foil turbine at 1.6 m/sec current, high-frequency VIV were observed on a 1” secondary noncritical rod to a support bracket, with fatigue failure experienced after just 1 week of operation. These results illustrate the importance of seriously considering VIV during turbine design.

An envelope configuration comparable to NACA 0013 (i.e., a relatively slender configuration) was implemented for the profile/blade design. The implementation of a flex foil NACA 0013 was chosen after analyzing cavitation tunnel test results for coefficients of lift, drag, and momentum. These results were balanced with the fatigue life, structural strength, flexible foil parameters, passive spring coefficients, incoming water velocity, and turbine parameters. The NACA 0013 provided good lift/drag performance for the turbine RPM, blade design, and water velocity, although its narrow profile had less mechanical strength capacity, which was challenging for structural optimization. Dynamic simulation of forces was performed on a profile/blade for one revolution (Fig. 5). At 14 sec, the foil was situated downstream with a normal force component of 40,000 Nm, and later had a peak normal force of 137,000 Nm at 72–81°C. A higher flex foil NACA profile such as NACA 0018 would
likely be more robust and tolerate more variation in induced water velocity angle, but would lower overall turbine efficiency. The fatigue analysis also showed that the loads in the structure were highly sensitive to pitch flexibility and flow coefficients.

Monitoring the turbine during operation

To accurately monitor turbine performance, fatigue, and mechanical vibrations, a turbine (and in particular a pilot turbine) should be properly instrumented with strain and vibration monitoring equipment (accelerometers) capable of handling a wide range of frequencies (typically 0.5–100 Hz). Such equipment may transmit the information in situ (instantly) back to the shore through an umbilical, or a remote operating subsea vehicle (ROV) can be used to retrieve one or several power and signal data collectors located on the turbine after a few tidal cycles. Such data can then be used to verify and “tune” the cyclic hydrodynamic forces and stresses assumed in the analytical mod-
These tuned fatigue analytical models can then be used to accurately calculate the tidal turbine’s predicted design fatigue life, thus potentially also accepting a reduction in the selected DFF.

The instrumentation and monitoring equipment may also be used for constant surveillance as a risk, safety, and maintenance measurement system. On site onshore data processing may be executed based on remote data acqui-
sition from the turbine, land generator, hydraulic pump, or turbine generator. This information can be used to adjust functional parameters to be within optimum and acceptable design criteria. These performance measurements will typically include RPM, water velocity, torque, local strain and stress, hydraulic flow, pressure, profile pitch, turbine rippling, global and local vibration effects, power output, transmission and generator loss, and loss of hydrodynamic performance as a function of marine growth.

Overall system functionality and performance can therefore be monitored during operation for optimized production, planned maintenance, and replacement of the underwater turbine systems and/or onshore facility systems. Such monitoring could also be used to compute and calculate actual and forecasted minimum mechanical fatigue life for a number of critical components based on input data (e.g., bearings and blade stresses, resonance phenomena, and stress amplitude data at selected structural design hotspots). The presence of a monitoring system would also be a valuable tool in assessing safety, risk levels, and required actions, taken in consideration of biological, fishing, maritime, and recreational activities.

**Energy conversion**

Evaluation of selected strategies for power development of a hydrodynamic turbine system depends on many factors such as (1) optimal kWh cost and profitability of the project, (2) variation in energy utilization, (3) environmental and local regulatory requirements, and (4) investment costs related to risk, operation, and maintenance. In order to obtain a competitive kWh price, the field development concept should aim to obtain a low absolute kWh cost for a sensible development strategy rather than maximizing the possible extracted kWh. Hence, the individual turbine and locations would be selected based on where the power and depth are optimal using concepts that are technically compatible.

Typically, most tidal turbines transmit energy by means of electrical power generation on the turbine, which is transmitted to shore for further voltage and frequency conversion. An alternative and robust method for tidal and shore field development concepts is to equip each turbine with a hydraulic motor for hydraulic energy transfer (using pumps) through individual pipelines to shore. A manifold on shore would be used to combine the flow to operate one or several hydraulic motors converting hydraulic energy into electrical energy, as shown in Figure 6. Such combined circuitry would also include inherent hydraulic dampening and accumulators that can assist with uneven and rippling rotational effects typical of vertical-axis turbines. Operating turbines could be easily isolated from the system manifold while being subjected to maintenance. The concepts would be based on hydraulic to electrical energy conversion systems onshore that are industrially available, together with off-the-shelf components that require minimal research and development.

**Marine growth on turbine components**

Marine growth can represent a significant problem for tidal turbines even in moderate conditions, and hence can significantly impact hydrodynamic performance. For example, although not typical, subsea structures recovered

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*Figure 6. Schematics for a typical multi-turbine hydraulic/electric system. The HP control unit would direct controlled pressure and flow supply to the appropriate hydraulic motors driving generators by means of directional regulating valves.*
by the author from the Santa Barbara channel in California after 20 years of operation were covered with ~80 mm tall barnacles [21]. Various techniques to remove/assess marine growth include built-in high-pressure flushing, special coatings, mechanical scraping methods, periodic inspection and removal by an ROV, or periodic turbine retrieval for maintenance. Thus, the design of a turbine and a turbine field development must consider local conditions for such marine growth and a marine growth removal strategy.

The foil material, surface finish, and dynamics of the flexible foil vertical-axis turbine (D. H. Zeiner-Gundersen, unpubl. data) may have a positive impact on limiting marine growth on its surface. The author observed this when large flexible fresh water storage bags (tanks) composed with elements made of similar material was towed between Turkey and Cyprus. The ability of the material to prevent marine growth over time will be assessed in future studies.

A Novel Vertical-Axis Turbine with Flexible Foils

A novel vertical-axis turbine using flexible double-cambered profiles, with relatively high performance and a passive blade regulation system, has been developed to optimize hydrodynamic performance for river, ocean, and tidal applications (Fig. 8; D. H. Zeiner-Gundersen, unpubl. data). A vertical-axis turbine design was chosen because its function is independent of flow direction, has relatively low installation costs, and thus would be suitable for tidal applications. Vertical-axis turbines are generally more easily installed and retrieved from a field site, and they can have more positive effects from adjacent turbines compared to horizontal-axis turbines. Typically, commercial field developments may spend up to 50% of the project cost on installation and foundation, and thus optimizing these aspects are important. Optimizing turbine interactions within a multi-turbine field is important for maximizing efficiency and minimizing the impact on the environment [24]. Individual vertical-axis turbines in a specific field arrangement can positively influence each other to efficiently harness tidal energy, similar to groups of fish using the ”schooling effect” to increase their hydrodynamic efficiency [15].

The flexible foil turbine concept is partially based on simulating natural flexible hydrodynamic thrust characteristics of aquatic and flying creatures. ”Morphing blade” concepts that use flexible material can increase wind and hydrodynamic turbine efficiency, while reducing turbine fatigue and operational costs compared to fixed blade turbines that require more complex pitching mechanisms [25–31]. The flopping motions of the flexible foils and passive spring pitching mechanisms reduce turbine vibrations and variations in RPM versus water speed. Consequently, the turbine also emits a low-dominant frequency noise (≤2 Hz), which may cause less impact on biological organisms. Little is known about the effect of different noises on wildlife like fish and birds [6], and this needs to be further studied. The flexible foil turbine described herein was designed to be inexpensive and robust. It used several features including easy installation and retrieval techniques, and embedding the energy conversion system within the turbine structure to protect it from the environment. The turbine design was based on using friction and mechanically preloaded connections rather than welded components in order to increase its mechanical fatigue life.

The novel flexible foil turbine had a low kWh cost compared to current-free turbine power plants in tidal, ocean, and river applications. The flex foil turbine can be designed to extract energy at currents as low as 0.20 m/sec, while still covering a wide range of current velocities. The turbine, infrastructure, and installation cost estimates are based on experience from engineering and construction costs of a 7-m pilot turbine installed in Sarpefossen, Norway with an associated hydraulic energy conversion unit. The quoted onshore/inshore installation costs for this particular foundation structure have been used for establishing the installation cost, and the operating cost assumed a 5% downtime per year. Provided a minimum ~30% subsidization of the project costs by government renewable energy programs and a good tidal site, the estimated project and operating cost of a 4 MW peak producing tidal turbine operating at 2.5 m/sec would be ~$US 0.065/kWh.

Field Development Concepts

Table 1 compares the advantages and disadvantages of the three-field development concepts discussed herein.

Permanent installations anchored to a river bottom or seabed

This concept involves permanent bottom foundations for stand-alone turbines anchored using a pile-drilled conductor cemented into the river bottom, with power extraction either above or below water with electrical or hydraulic transmission. Ideally, these installations would occupy areas that would not be in conflict with shipping or other purposes, and would preserve the site’s biodiversity. With this approach, the number of turbines installed could be increased to best fit the location and may be configured so that individual turbines positively influence each other.
The turbine would typically be installed on a center pile, which serves as the main axle. The pile must have the strength to withstand general and fatigue-related moment forces, as it will bear all flow forces imposed by the turbine and the load torque that occurs between the turbine and generator or hydraulic motor. Piles that define the positions of individual turbines would be installed by a barge or rig pulled to the appropriate position, secured with wires between the mainland and holes/wells drilled or excavated into the river bottom or seabed bottom. The foundation pile/conductor for the individual turbines would then be cemented in place, much like methods used in the oil and gas industry. The turbines must be preassembled at the nearest available site to allow the turbines to be transported to the site via a barge.

Individual or multiple turbines could be installed at field sites. For example, a single turbine could be installed in a river channel adjacent to a preexisting power plant (Fig. 7). Figure 8 shows an example of a subsea multi-turbine concept consisting of multiple satellite underwater turbines with pipes and hoses connected to an onshore utility site containing the hydraulics, generator, and frequency and power converter. Each turbine would be site-specific but could typically be 40-m high with a 20–30 m diameter. For a typical high-energy tidal current application, each turbine could deliver ~10 GW per year. The turbine would be fully submerged, with ~20 m from the turbine top to the sea surface level at low tide. The turbine would be outfitted with cathodic corrosion protection for 20–30 years based on a system with galvanic electrical contact between all components, thus more easily utilizing various types of materials.

On each turbine, a high-pressure pump would transfer the turbine’s rotational energy, by means of high-pressure fluid, to land through a pipe/hose that would be weighted down onto the seabed. On land, a high-pressure motor/engine would convert the hydraulic energy into rotational energy to drive a generator. Onshore facilities would consist of the high-pressure engine, generator, transformer, and frequency converter and controller facilities. The pipelines running from the underwater turbines to the onshore facilities, and possibly the cables connecting the transformer to the distribution network, would be buried in the shoreline and on land.

The dynamic behavior of the turbine foundation versus the static cable or pipe loop and umbilical situated on the seabed should be assessed with respect to fatigue on such items. Additionally, VIV should be addressed for such interfacing components, as they typically will be exposed to currents and are relatively long and slender with a small diameter and limited support.

### Mobile floating structure on a barge

A floating barge with turbines installed along the barge sides would have the advantages of being locality independent, easily mobilized and anchored, and the turbines could be easily extracted from the barge for maintenance. The structurally adapted barge could potentially be visually unflattering and would hold a limited number of turbines, thus limiting the kWh generated. Barge maintenance (typically after ~10 year) would also temporarily halt kWh production (Fig. 9).

| Table 1. General evaluation criteria for the field development concepts. |
|-----------------|-----------------|-----------------|
| **Option**      | **Advantages**                           | **Disadvantages**                          |
| Seafloor mounted structure | 1. Low visual interference 2. No limitations in number 3. Possibility of including a greater number of turbines to better fit the location | 1. Number of turbines must be decided early to keep installation cost low 2. Development phases must be decided before piles are mounted 3. Locality decision for each turbine |
| Floating structure | 1. Locality dependent 2. Easy mobilization and anchoring 3. Easy extraction from the barge for maintenance | 1. Functional, but not flattering for the environment 2. Requires a structurally adapted barge to hold turbines 3. Limited number of turbines, thus less kWh |
| Installed structure | 1. Utilizing an intended bridge, which can also be used by the local population 2. Cost sharing between power project and bridge development 3. Have local politically positive aspects | 1. Locality dependent 2. Limited numbers of turbines and a large construction to cater for a high number of turbines would become very expensive 3. Could be combined with seafloor mounted freestanding turbines 4. Would require municipal/political approval |

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A flat top barge could be an appropriate floating support structure for turbines because these barges are common units and available in variable sizes for river or inshore applications. Turbines could be fitted along one or both sides of the barge, with the size of the barge determining the number of turbines and vice versa. The turbine spacing along the barge length is determined by the optimal influence of flow from one turbine into the adjacent turbine. The minimum barge width would typically be twice the turbine diameter. A typical 8-m barge with a 35–50 m length would enable installation of 12 turbines (with 4-m diameter) on the barge. The turbines would be suspended under the barge. Hence, the turbine height would need to be designed to avoid contact with the river or ocean floor during low water levels but also reflect on effects such as ventilation and wave forces.

Suspending the turbines on an out-rigging from the barge would allow simpler maintenance, although barge stability must be considered. Such a custom-built mechanical structure attached to the barge side could have a pivot mechanism so that the turbine could be turned 180° along the vertical axis, bringing the turbine upright out of the water for maintenance (Fig. 10). A small deck-mounted gantry crane on the platform would be necessary for handling the equipment and accessing the turbine height.

During periods of extreme conditions or planned major maintenance, the barge would be moved to a suitable location.

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**Figure 7.** A single turbine concept located within a river channel near a power plant facility. This structure could also be suspended from a bridge.

**Figure 8.** Diagrammatic representation of a subsea field development site, showing multiple turbines and their associated infrastructure connecting to an onshore utility web.
A barge solution would have minimal impact on the natural surroundings and minimal land infrastructure. The power would be transferred to land by a single air-suspended cable with a “safe release” link or by underwater cable. The barge land anchor load profile would be calculated based on the local maximum and minimum tide and flow velocity, with the anchoring truss/wire/rope or winch arrangement adjusted to the maximum load profile. The barge would be anchored with two mooring lines in each corner and amidships on each side. An anchor could potentially also be drilled into the river or ocean floor.

When analyzing for fatigue, the superimposed load cases should also include the general dynamic movements of the barge and wave-induced loads. It is important to check the eigen frequencies of the preexisting structures and/or floating barge in order to avoid coherent interaction between the attached turbine(s), rotating machinery, and the barge with resulting fatigue that may have severe consequences. Ventilation and standing waves caused by vortices should be considered when selecting the structural system design layout. Fatigue on support structures and spring devices should be carefully selected and analyzed in combination with design, routing, and support of the cable, pipes or jumpers used for the energy transmission and controls. A probabilistic design assessment and check versus applicable impact forces onto the turbine, such as from ice and/or timber, is also relevant.

**Permanent installation on fixed structures such as a bridge or oil and gas platforms**

The turbines could be installed on a preexisting bridge structure or a newly designed structure with cost sharing between the power project and other funds (community or private) for bridge development and maintenance. The number of turbines would depend on the size of the bridge and would be limited to a row on each side of the
bridge (Fig. 10). Similar to a floating structure, the turbines could be swung up when needed. However, unlike the barge option with turbines located under the hull, the turbines on the bridge can make full use of the total river depth. Public safety and protecting the installation from damage and vandalism must be ensured.

An alternative concept is the utilization of existing oil- and gas-producing platforms, which may assist in providing a turbine attachment point and facilitate power conversion and/or usage. This may also extend the useful life of the platform. Typically, the platform can act as a support structure with turbines mounted horizontally onto the shafts and/or legs on permanent platforms, or extending down from the center or side into the sea from anchored floating platforms. All of the above-mentioned options could use either a hydraulic/electrical system or just an electrical system for power extraction and distribution. The load cases, eigen frequency issues, and related potential fatigue issues discussed above are also relevant for these concepts.

Conclusions

Achieving a carbon neutral future depends on developing renewable energy resources such as tidal energy [1]. There is a huge potential for worldwide renewable energy production using free flow turbines in hydrodynamic environments. The significant offshore oil- and gas-producing countries, such as Norway, have many potential sites with predictable tidal and ocean currents. If there is the political will to increase renewable energy production, the considerable experience in offshore construction work could be used in tidal power plant development [32] within Europe, China, India, Brazil, Canada, and the U.S.

The limiting factors for commercialization are the ability to (1) design cost-efficient turbine systems that are robust enough to withstand the challenging environmental conditions, (2) properly address general mechanical fatigue, and (3) find alternative cost-effective turbine installation techniques. Potential investors are wary of turbine technology because of fatigue-related issues like blade failure [7]. A proposed method for fatigue calculations has been included. This method addresses the actual hydrodynamic forces in play, limits the complexity of calculations by using transfer functions, reflects the actual design configuration, and uses appropriate statistically defined S-N curves on structural design details for material ranging from composites to alloy materials. The fatigue life on tidal turbines should be a minimum of 25 years.

The flexible foil turbine concept discussed herein attempts to optimize the interactions between the environment and machinery, while maintaining low production, installation, operation, and maintenance costs. The proposed field development strategies provide a general framework for facilitating large-scale commercialization of concepts like the flexible foil vertical-axis turbine.

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Conflict of Interest

None declared.

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