Marine Current Resource Assessment
Measurements and Characterization

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**Abstract**

The increasing interest in converting energy from renewable resources into electricity has led to an increase in research covering the field of marine current energy, mainly concerning tidal currents and in-stream tidal turbines. Tides have the advantage of being predictable decades ahead. However, the tidal resource is intermittent and experiences local variations that affect the power output from a conversion system. The variability is mainly due to four aspects: the tidal regime, the tidal cycle, bathymetry at the site and weather effects. Each potential site is unique, the velocity flow field at tidal sites is highly influenced by local bathymetry and turbulence. Hence, characterizing the resource requires careful investigations and providing high quality velocity data from measurement surveys is of great importance. In this thesis, measurements of flow velocities have been performed at three kinds of sites.

A tidal site has been investigated for its resource potential in one of all of the numerous fjords in Norway. Measurements have been performed to map the spatial and temporal variability of the resource. Results show that currents in the order of 2 m/s are present in the center of the channel. Furthermore, the flow is highly bi-directional between ebb and flood flows. The site thus have potential for in-stream energy conversion. A model is proposed that predicts peak current speed from information on tidal range at the site. A corresponding model can be set up and implemented at other similar sites affected by tides, i.e. fjord inlets connecting the ocean to a fjord or a basin.

A river site serves as an experimental site for a marine current energy converter that has been designed at Uppsala University and deployed in Dalälven, Söderfors. The flow rate at the site is regulated by an upstream hydrokinetic power plant nearby, making the site suitable for experiments on the performance of the vertical axis turbine in its natural environment. The turbine has been run in uniform flow and measurements have been performed to characterize the extent of the wake.

An ocean current site was a target of investigation for its potential for providing utilizable renewable energy. A measurement campaign was conducted, mapping the flow both spatially and temporally. However, the site was shown to not be suitable for energy conversion using present technique.
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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## Nomenclature

<table>
<thead>
<tr>
<th>Notations</th>
<th>Description</th>
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<tbody>
<tr>
<td>H</td>
<td>Tidal range</td>
</tr>
<tr>
<td>$H_i$</td>
<td>Tidal amplitude for tidal constituent i</td>
</tr>
<tr>
<td>N</td>
<td>Number of pings per ensemble</td>
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<tr>
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<td>Period</td>
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<tr>
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<td>Power density</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
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1. Introduction

1.1 Layout of thesis
This licentiate thesis describes the work performed on characterizing marine currents in three types of sites; a river site, a tidal site and an ocean current site. The main contribution of the author has been to perform measurement surveys of current velocities at these various locations and through analysis of measurement data describe flow characteristics and/or resource potential. The most important work in this thesis is presented in Paper I and II, which covers a tidal site in Norway that has been investigated as a potential tidal energy site. Paper III and IV covers a river site which is part of the Söderfors project. In Paper V, variability of renewable resources are reviewed.

Ch. 1 provides the reader with background to marine current power, the characteristics of tides and the instrument used for current measurements. In Ch. 2, general aspects of the methodology for resource potential assessment are described. In Ch. 3 site specific methodology from field work is presented, and the results are given in Ch. 4 for each type of site.

1.2 Marine current power
Conventional hydrokinetic power plants have long been used to generate electric power. Lately, the interest in and aim for using other forms of water motions as a resource of renewable energy has intensified. Especially for in-stream converters of tidal currents the technical development has progressed rapidly. Other sources of marine currents are unregulated rivers and ocean currents where the same technique could be used.

The understanding of tidal hydrodynamic kinetic energy and the effect of extracting such energy with single turbines or larger farms has been developed by e.g. [1]–[5]. The first step in such projects is resource assessment. Around the world, numerous investigations have been performed where the water velocity field has been measured and characterized, see e.g. [6]–[16]. Different aspects have been discussed such as directionality, tidal asymmetry and non-tidal effects of tides and currents (winds, waves and pressure).

The hydrokinetic power density, \( P \), per cross-sectional area is given by

\[
P = \frac{1}{2} \rho U^3 \quad \text{(W/m}^3) \quad \text{Eq. 1}
\]
The power available in streaming water is scaling up fast with horizontal velocity, $U$, due to the cubic relationship, but even at low velocities the power is substantial due to the high density of water, $\rho$ (1025 kg/m$^3$, corresponding to 800 times that of air).

At Uppsala University the marine current group is working on a project with the aim to develop and test a full size marine current energy converter. The converter is based on a robust technique, i.e. a vertical axis, marine current turbine and a permanent magnet synchronous generator, intended to operate in speeds of about 1 m/s and depths from around 7 m \cite{17}, \cite{18}. The flow at the site was investigated by Lalander et. al in \cite{19}, \cite{20}. The site is located just downstream of a hydro power plant. Thus, it is a suitable site for performing experiments since the flow in the channel is regulated by the hydro power plant and can be kept steady during experiments.

One important aspect of any renewable energy resource is its variability. To get a firm electric power output, the resource should preferably be of equal magnitude all of the time and easy to forecast. Tides, for example, are easy to forecast (see Section 1.3) but they are by nature fluctuating from peak speeds to near zero velocities several times per day, thus, resulting in a varying power output from a conversion system.

\section{1.3 Tides and tidal currents}

Tides are the periodic variations of sea level elevations. It is due to gravitational forcing from the Sun and the Moon in interaction with the rotation of Earth. The tidal regime is most commonly semi-diurnal with two highs and two lows each day, but can also be diurnal with one high and one low or a mix of the two \cite{21}. As a renewable energy resource, tides has the advantage of being predictable decades ahead. The predicted astronomical tide, $h$, at a site can be expressed as a sum of harmonic constituents representing variations of different amplitude and time scale, according to:

$$h = h_0 + \sum_i H_i \cos \left( \frac{2\pi}{T_i} + \phi_i \right)$$

where $h_0$ is the reference water level relative to the mean sea level and each constituent $i$ corresponds to a tidal amplitude $H$, period $T$ and phase $\phi$. Information and forecasts of tidal heights are publically available in tidal charts for most areas around the world.

The moon exerts the strongest forcing. The principal lunar semi-diurnal constituent is called $M_2$ and has a period of 12 hours 25 min. The principal solar semi-diurnal constituent $S_2$ has a period of 12 hours. These are in phase every fortnight (14.76 days) forming spring tides, with neap tides in between
(when the misalignment is 90°) [22]. Multiples of these or shallow water constituents further alter the symmetry and phase of the tidal cycle. To resolve all relevant constituents, at least 29 days of observations are needed.

The tidal waves propagate around the oceans, with a smooth variation over distances on the order of 100 km, and give rise to floods and ebb in the coastal areas. The rising and falling sea levels produce tidal currents. Strong currents occur if a large amount of water is being pushed through a strait, a fjord inlet, a sound between two islands or around a headland. These currents are enhanced in areas where depth and width are restricted due to bathymetry.

Tidal currents at a site need to be measured to be correctly characterized since they are altered by effects such as drag from the bottom creating turbulence and changing the flow path as well as the vertical profile. As shown in [23], the velocity field can only be interpolated about 100 m. Reflecting waves in estuaries also alter the flow speeds by changing the phase resulting in current speeds that does not follow a sinusoidal pattern or is out of phase with the tidal wave (see Figure 1).

Weather effects such as variations in air pressure or strong winds creating surface waves also affect the flow pattern [21]. Additionally, the drag force induced by wind stress, that is proportional to the square of the wind speed, can push the water on or off shore and alter the sea level and consequently the tidal currents.

![Figure 1. Illustration of the phase shift between tidal height and current at the sill of a fjord.](image)

### 1.4 The instrument: ADCP

The instrument used for measuring current velocity is an acoustic Doppler current profiler (ADCP) from Teledyne RD Instruments of the type Workhorse Sentinel ADCP of 600 kHz\(^1\). The instrument transmits acoustic pulses from four transducers at a certain frequency and interval. The sound pulses are sent out in bursts of a number of pings and reflects on particles in the water.

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The Doppler shift in the frequency of the returning signal is used to calculate the flow speed and the time it takes for the signal to return corresponds to the distance from the transducer head to the middle of the depth cell. The obtained velocity profiles give information of flow velocity along the four beams for equally spaced depth cells. The beam velocities are transformed to earth-coordinates by the instrument giving the output as north (\(u\)), east (\(v\)) and vertical (\(w\)) velocity so that \(U = (u, v, w)\).

The transducers are separated with an angle of 20° from the centerline, thus, the distance between the beams is increasing with depth, see Figure 2.

![Figure 2. Sketch of ADCP operating in upside down mode from a boat.](image)

The ADCP assumes a horizontally homogenous velocity field when calculating the water velocity from its three (or four) beams. Thus, any small scale turbulence is averaged out. For an observation to be of good quality, at least three good beams, i.e. beams with a high correlation, are required in the solution. The fourth beam is to ensure better quality. For each burst of \(N\) number of pings, an ensemble average is calculated by the instrument. The Doppler noise uncertainty can be large but is decreased by a factor \(1/\sqrt{N}\).

Inbuilt sensors give information on the physical status of the ADCP. A pressure sensor provides the depth at the transducer, a compass gives the heading and a gyro gives information about the tilt of the ADCP (pitch and roll depending on around which axis the tilt occurs).

When used in the upside down mode, an extra Bottom Tracking pulse can be transmitted. It has a longer wave length and tracks the speed of the bottom with high accuracy.
2. Resource assessment methodology

2.1 Site selection

In this chapter, resource assessment methods will be discussed from a tidal energy point of view. When searching for a site with potential for in-stream tidal energy conversion, an area where the flow is constricted in some way, and thus accelerated, is favorable. The higher the flow speed, the more available energy (Eq 1). For developers of marine current energy converters of the first generation, flow speeds exceeding 2 m/s and depths of about 20-50 m are required. For 2nd and 3rd generation turbines, where lower velocities and shallower sites are also interesting [9], the number of potential sites around the world is increased.

The first step taken in a resource assessment survey is to find a promising site with sufficient depth and water speeds. Such information may be available in ship navigation charts (e.g. [24] in Norway). Promising sites can also be found by analyzing nautical charts. Areas to look for are, for example, narrow and shallow fjord inlets in areas with tides and a large enough basin inside the sill where sufficient flow speeds, with a high energy content, may occur.

The second step is to choose measurement method. Normally, this is done by first performing a transect measurement survey to conclude whether the site has sufficient water speeds (>1m/s) and if so, map the spatial variability at the site. Often, the most energetic area is found and explored further through long-term measurements of current speeds.

2.2 ADCP configuration

Each measurement survey needs to be carefully planned in advance. The instrument needs to be calibrated and configured according to the chosen measurement method and the characteristics of interest. Software packages provided by Teledyne RDI is used to “talk” to the instrument (for example BBTalk or PlanADCP). The compass needs to be calibrated in advance of each measurement survey [25].

The ADCP can either be run in real-time mode by keeping it connected to the computer during the measurements, or operate self-contained by programming it in advance and connect it to one or more batteries. The user needs to consider the required measurement accuracy when setting up the ADCP. In a
self-contained deployment, the power consumption is dependent on the measurement intervals and number of pings in each measurement.

The parameters that need to be set by the user are

- Ensemble interval
- Pings per ensemble (N)
- Time between pings
- Vertical bin size
- Number of vertical bins
- Bottom tracking (and depth range)

### 2.3 Transect measurements

To investigate the spatial variance of a flow stream in a watercourse (river or tidal strait), a common way is to measure the velocity profile in cross-sections, along transects perpendicular to the flow direction. The ADCP is then mounted upside down in a floating vessel (Figure 3), Riverboat\(^2\), and towed across the watercourse with a small boat navigated with help of a GPS or by following leading lines marked at the shoreline (as in Paper IV).

The ADCP can then be configured with the software VmDas and measurement data is monitored in real-time through the software WinADCP provided by the manufacturer. The inbuilt function Bottom Tracking records the speed of the ADCP relative to the sea- or riverbed, and subtracts this speed from the flow speed measurements.

A Garmin EchoMAP 50 has been used to log the GPS-positions during the transect measurements. It has also been used with an echo sounder to investigate the bathymetry (as in Paper I).

When high accuracy position data was required (for the wake measurements, Paper IV, see Section 3.2) a Global Navigation Satellite System (GNSS) receiver was mounted on top of the ADCP (seen in Figure 3). The Real Time Kinematic (RTK) technique used, gives a precision down to 1 cm.

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2.4 Long-term measurements

To get the temporal variation of flow speeds at a site, the ADCP can be mounted in a foundation and placed on the seabed (or bottom of the river). Foundations designed at Uppsala University are used for deployments. The foundations are made of stainless steel and weighs about 10 kg (Figure 4). The ADCP is screwed to the bottom plate of the foundation to stay steady. Ballast weights of 10 kg each is attached onto the foundation with screws. This was either done in advance in the boat, or by divers at the seabed.

Figure 3. ADCP mounted upside-down in a RiverBoat with a GNSS receiver mounted on top.

Figure 4. Photo of ADCP mounted in the foundation and ballasted with four weights.
It is important that the ADCP is placed steady and horizontally with a small tilt (pitch and roll) to ensure good accuracy. The practical aspects of deployment of an ADCP for long-term measurements needs to be well planned in advance. The depth of the site determines the length of the ropes used when lowering the instrument and when marking it with a buoy. The expected flow speeds affects the required ballast weight.

2.5 Data analysis

The output data from the ADCP, used to describe the flow characteristics, includes flow velocity profiles (north, east, vertical) and flow direction for each depth cell, together with vectors of depth and time (year, month, day, sec, hundreds of sec). A number of data quality parameters are also given for each observation including (but not limited to):

- Error velocity
- Percent good (PG1-PG4)
- (Bottom tracking speed)
- Echo intensity
- Correlation between beams
- Heading
- Pitch and roll
- Battery

The analysis of ADCP data starts with a quality screening. First observations marked ‘bad’ by the ADCP, shown as spikes, are removed. Observations where the sum of the parameters PG1 (percent of observations of good three beam measurements) and PG4 (percent of observations of good four beam solutions) are at least 75% are kept, corresponding to measurements where at least 75% of the pings in the ensemble come from three or more good beams³. The error velocity should be less than 1 m/s and the average correlation between beams more than 64. Data close to the seabed or surface (depending on whether measurements are performed downwards or upwards) are interfered with noise and therefore removed according to $\text{noise} = h \cos \alpha$ where $\alpha = 20^\circ$ for the ADCPs used [26].

Heading, pitch and roll give information about how steady the ADCP has been during the measurement period. It can be used to analyze whether the instrument has been moved during the deployment, would it be because of strong currents or other external forces, and thus have changed the location or tilt angle inducing measurement errors.

When the data has been quality checked, there are many aspects of the flow characteristics that can be studied. One approach is to calculate standardized, characterization metrics that with a single figure of merit can be compared to other sites, as in Paper II. Among these (as proposed by Gooch et al. [27]) are mean speed, maximum sustained speed for 10 minutes, ebb/flood asymmetry and vertical shear describing the velocity field and principal axis, standard deviation from the principal axis and ebb/flood direction asymmetry describing the directionality; together with mean power density and ebb/flow power asymmetry describing the energy content. All of these metrics are calculated at expected hub height, which has been proposed to be in the middle of the water column [28].

It is also of importance to analyze the speed frequency distribution function for a typical month or for a year. Furthermore, a vertical profile plot allows for interpolation of the speeds from hub height. An understanding of the weather effect on tidal range, and thus current speed, at a site may be important for a full resource characterization. Weather effects may be substantial, especially at high latitudes where travelling low pressure systems are common during parts of the year.

For transect measurements it is common to divide the transects into smaller horizontal bins and analyze the data that fall into each bin to form mean values or time series for a specific part of the surveyed site as in Paper I.
3. Field work

3.1 Tidal site

Tidal sites along the coast of Norway are numerous because of all the fjords. The tidal height in Norway reaches from about 0.5 m in the south up to a maximum of 2.5 m in the north [29]. The tidal site that has been investigated is located in the Folda Fjord, in Korsnesstraumen at the sill to its inner part, Innerfolda (see map in Figure 5).

Two measurement surveys were conducted at the site. The initial spatial mapping of the speed variance and expected maximum velocities are presented in Paper I. From these results, the most energetic area was chosen and long-term measurements were planned and performed during the year after, see Paper II.

![Figure 5. Overview map of Norway and in detail over the inner part of the Folda Fjord and Korsnesstraumen. Measurements in Transect 1-4 are shown. The star marks the location of ADCP deployment.](image)

Four transects were investigated during the initial survey in August 2013 (Figure 5). Each transect was addressed three times during flood and three times during ebb. The measurements were performed in tracks from west to east...
then back again. Each track took about 10 minutes to complete. During this
time, the tidal currents are assumed to be constant. For each track, horizontal
bins of about 50x50 meters were defined and the depth averaged speed within
that area was calculated. An area in the west part of the fjord inlet, between
Transect 2 and 3, was chosen for further investigation due to its uniformly
high speeds during ebb and its high peak speeds during flood.

The ADCP was deployed for long-term measurements in June 2014 with
assistance of a team of scuba divers who secured it horizontally on the seabed
and then mounted the 60 kg of ballast on the foundation. The ADCP was re-
covered later on in August, after 54 days of measurements.

![Image](image.png)

*Figure 6. During transect measurements, the ADCP is mounted in a RiverBoat and
towed across the stream.*

3.1.1 Simple prediction model

A simple model is proposed where peak current speeds can be predicted from
tidal chart data in a tidal strait connecting the ocean to a fjord. A linear rela-
tionship is assumed between tidal range and peak current speed, $U_{max}$. When
the linear relationship is found, the model allows readily available tidal eleva-
tion data to be used to predict long time series of peak current speed. This is
done in Paper II.

The model is performed in a number of steps. First tidal chart data, often
given as an interpolated value from nearest gauge station, is calibrated to the
site specific tidal range. The tidal range, $H$, is calculated as the difference be-
tween each high and low tide and vice versa. Then, predicted tidal range is
compared to measured tidal range to ensure a small deviation. Then, the linear
relationship between measured tidal range and peak current speed is estab-
lished.
The model accuracy is estimated with the standard deviation in $U_{\text{max}}$ for increments of 0.2 m tidal range. Weather effects on tidal range and thus current speed are quantified. The model is evaluated for two other heights above the seabed, except for the hub height (6.1 m). Also the effect on the model of a shorter measurement period is investigated to find the shortest possible measurement period. The correlation coefficient between measured tidal range and peak speed has been analyzed as well as the slope and y-intercept from the linear regression.

3.2 River site

A marine current energy converter was deployed in March 2013 at the river site in Dalälven in Söderfors, as described in Paper III (see Figure 7). Simultaneously deployed were three ADCPs to monitor the flow upstream and downstream of the converter. The turbine is 5-bladed and 3.5 m high with a diameter of 6 m. It is mounted on a generator which is then attached to a tripod foundation (for design, see Fig.2 Paper IV). Since the deployment, the control system has been tested and improved so that the system can be operated in flows from about 0.6 m/s for different rotational speeds (rpm) (Paper IV).

Figure 7. Photo from the deployment of the turbine in Söderfors.
The wake behind the converter has been investigated in Paper IV for a case when the turbine was rotating at a tip speed ratio of approximately 5.6. Measurements of vertical velocity profiles were performed across and along the flow by slowly towing an ADCP behind a small boat to get cross-sections of the flow speed. Leading lines were established on shore to ensure that the measurements were performed at the same location each time. The ADCP was set up to measure 5 pings/ensemble with 1 Hz sample frequency.

The reduction of flow speed compared to the undisturbed flow, \( v_{norm} \), downstream of a turbine is called speed deficit, \( v_{def} \), and is defined as

\[
v_{def} = 1 - v_{norm}
\]

The aim of the investigation in Paper IV was to evaluate the survey and data processing methods, and to get a first idea of the extent and characteristics of the wake.

3.3 Ocean current site

Two measurements surveys were conducted to investigate a possible high energy currents site in the Stockholm archipelago. High currents had been experienced by some of the locals in a sound between two islands east of Finnhamm. The tide in the area is negligible so the currents were assumed to be ocean currents, i.e. thermally induced, due to pressure and wind or fresh-water runoff from the mainland.

The first survey was conducted on November 20, 2014. Water current velocities were measured in cross-sectional transects and in transects along the flow. Mean speeds are plotted, where they were collected, across and along the flow (Figure 8). The flow speeds were slow that day, ranging from 0 – 0.6 m/s, in a bin corresponding to about 6 m from the surface. From those measurements, two areas were chosen for long-term measurements. One in the south end of the sound (A1) and one in the north (A2).

For the second survey, two ADCPs were deployed at the seabed and performed measurements for about a month between December 17, 2014 and January 29, 2015. Information about the long-term measurements are seen in Table 1. Data was collected in 1 ping/s and was stored in 30 s ensembles once each minute. Flow speeds were analyzed for 30 s values and 10 min mean values. The measured speeds are presented for hub height, i.e. the middle of the water column.

The measurements show low mean speeds, \(~ 0.1 \text{ m/s}\), and maximum speeds of less than 0.7 m/s for both sites. The direction of the flows follow the sound and are thus mainly northwesterly and southeasterly.

The site was not considered to have potential for energy conversion.
Figure 8. Mean speed from transect measurements, calculated at the depth 5.5-6.5 m (from the surface). Mean speed is given by colors (in m/s). The areas for deployment of the two ADCPs, A1 and A2, are marked with stars.

Table 1. Information from long-term measurements of ocean currents.

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<td>Mean depth</td>
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<td>22.1 m</td>
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<tr>
<td>Hub height</td>
<td>6 m</td>
<td>11 m</td>
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</table>
4. Results and discussion

4.1 Tidal site: Korsnesstraumen

The results from the transect measurements in Korsnesstraumen in Paper I are shown in Figure 9 where it is seen that the highest and most uniform speeds are found in the west part of the sound, in the area between Transects 2 and 3. This area was further investigated in Paper II and an additional transect was addressed (Transect 2b) close to where the ADCP then was deployed, as seen in Figure 10.

The resultant time series from the long-term measurements is seen in Figure 11 for current speed at assumed hub height (at 6.1 m from the seabed). It is seen that the currents does not follow the same strictly sinusoidal pattern as the tide (cf. Figure 1). This confirms that the currents are more unpredictable and requires measurements to be characterized properly. The frequency distribution of speeds is seen in Figure 12 for all measurements and for a typical month, chosen as 7 July – 5 Aug 2014. The mean speed at hub height is the same for flood and ebb, 1.02 m/s, but the maximum speed sustained for 10 min is higher for ebb, 2.06 m/s compared to 1.86 m/s for flood. The cumulative distribution shows that the velocity is more than 0.6 m/s during 72.7% of the time (corresponding to cut-in speed for the vertical axis turbine in Paper IV), and exceeding 1 m/s for 38% of the time. The peak speed measured was 2.17 m/s.

The vertical profiles in Figure 12 are 10 min mean values at peak flows, for flood and ebb during spring and neap (marked in Figure 11). They show a larger shear in the lowest half of the water column, and rather uniform flow in the upper part. Around hub height, the vertical shear is on average 0.05 m/s per meter for ebb and half of that for flood (see Paper II Table 4).

The channel-like bathymetry of the site results in an almost completely bi-directional flow, which is favorable for most tidal energy converters (see Paper II fig 6).
Figure 9. Mean speed and standard deviation for each transect, calculated for horizontal bins, for ebb and flood respectively (Fig. 4 in Paper I).

Figure 10. Flow speeds in transects near the location of the stationary ADCP (marked with a star) Bathymetry is shown, where darker shading corresponds to deeper sea (Fig. 15 in Paper II).
4.1.1 Simple prediction model

The results from the simple prediction model show that the measured tidal range is typically 3% larger than the predicted but otherwise show a small deviation from the linear relationship. The linear relationship between tidal range and peak current speed (Figure 13) is shown to be strong with a correlation coefficient of 0.98 at hub height (6.1 m), and the standard variation in the measurements is less than 10 cm/s from the linear relationship given by

\[ U_{\text{max}} = 0.647H + 0.165 \text{ m/s} \]  

The non-tidal effects (of ±30 cm on tidal range) would give ±0.19 m/s difference in peak speed at hub height following the linear relationship (Eq. 1). The maximum expected peak speed is 2.12 m/s at hub height.

The result of the evaluation of varying hub height show that closer to the seabed (3.1 m), the current peak speeds are lower and the linear regression is not as steep as for hub height (6.1 m). Closer to the surface (9.1 m), peak
speeds are higher but the linear relationship is similar. Furthermore, the evaluation of the effects of measurement period length show that at least 9 days of measurements are needed to reach a correlation coefficient of at least 0.9 and reduce the relative error in peak speed to 3%. After 29 days of measurements, the relative error is less than 1%, but the error is expected to vary depending on where in the monthly tidal cycle the survey begins (see Paper II, Fig. 11 and 12).

![Figure 13. Linear relationship between tidal range and peak speed for three different heights above the seabed (Fig. 10 in Paper II).]

These results, although site specific, show that the simple prediction model can be used to predict peak current speed from information on tidal range on this and similar sites, i.e. tidal straits connecting the ocean to a bay or fjord. It is suggested to measure for at least 1/3 of the tidal cycle. If the measurement period is short, is it furthermore suggested to focus on performing measurements around the largest spring tide to make sure to catch both smallest and largest tidal ranges and thus smallest and largest peak speeds.

4.2 River site: Söderfors

Figure 14 shows depth mean velocity for several measurement runs, downstream of the turbine (marked with a circle), plotted where it was collected. The depth mean velocity, indicated by colors, has been normalized by the undisturbed depth mean speed. Each grid square corresponds to one turbine di-
A wake is prominent as a higher speed deficit, i.e. lower speeds, behind the turbine and were seen to extend some 5 to 6 turbine diameters downstream.

To give a more realistic appearance, the transects were projected along straight lines. Figure 15 shows the cross-sectional velocity profiles for three of the across-flow transects (C1, C2 and C3) at 1.3, 5.4 and 9.7 turbine diameter distance respectively (c.f. Fig. 5 and 6 in Paper IV).

Figure 14. Depth mean speed (in m/s) as measured in transects downstream of the marine current energy converter. Circle denotes the turbine. Each grid square equals one turbine diameter. Wake is visible as lower mean speed (Fig. 7 in Paper IV).

Figure 15. Cross-sectional velocity profiles for three transects at 1.3, 5.4 and 9.7 turbine diameters respectively (Fig. 9 in Paper IV).
5. Conclusions

5.1 Tidal site: Korsnesstraumen

There are many indications that the potential for marine current energy from tides is large in various areas around the world. Especially when the development of tidal turbines progresses towards turbines operating in more diverse flow conditions and depths. The measurement surveys performed at the tidal site Korsnesstraumen show that the site provides truly bi-directional flows with mean currents up to 2.06 m/s. Thus the site has potential for in-stream energy conversion. Similar conditions, a fjord inlet connecting the ocean to a basin, are expected at numerous sites along the Norwegian coast. It is thus probable that the potential for marine current energy is large in Norway.

The method of measuring along transects at a tidal site is a time and cost efficient way to perform an initial characterization of the natural flow. At sheltered sites, it is both convenient and sufficient to use a simple small sized boat to navigate across the site and to tow the ADCP. The instruments, i.e. the ADCPs, have performed well during the different measurement surveys. However, the importance of planning any measurement survey in detail and perform careful calibrations of the instrument are emphasized.

5.1.1 Simple prediction model

A simple prediction model was set up with the aim to predict peak current speed from tidal range. The assumption that the predicted tidal range in the charts coincides with the tidal range at the sill and that the tidal range controls the peak velocities at the site is shown to hold true. The proposed simple prediction model shows a strong linear relationship between tidal range and peak speed and allows prediction of peak speeds in the channel center within ±0.12 m/s. These results, although site specific, show that the model can be used to predict peak current speed from information on tidal range at this and similar sites, i.e. tidal straits connecting the ocean to a bay or fjord.

Measurements of current velocity is always required when characterizing a tidal site and a shortened measurement period is economically beneficial. The model is shown to accurately (within 3% deviation) predict peak speeds in the channel center after 9 days of measurements. When implementing this model at another similar site, it is thus suggested to perform measurements for at least 1/3 of the lunar tidal cycle around the time for the largest spring tide to make
sure to catch both smallest and largest tidal ranges and thus smallest and largest peak speeds.

5.2 River site: Söderfors

The river site in Dalälven, Söderfors, is very suitable as a test site due to the vicinity to the upstream hydrokinetic power plant. The power plant regulates the flow rate which results in steady and controllable flow speeds in the channel downstream. The successful deployment of the in-stream energy converter allows for important research on a full size test station in its natural environment.

The performed measurement survey provides first results showing that the wake can be measured with the proposed technique, i.e. transect measurements following leading lines with positions recorded by a high accuracy positioning system. The wake can be seen to propagate approximately 5 to 6 turbine diameters downstream. However, more detailed studies are required to fully characterize the wake.
6. Future studies

Resource characterizations at tidal current sites are still important for the understanding of tidal flows. Thus, a large scale measurement campaign quantifying the number of sites with potential for in-stream tidal current converters along the Norwegian coast would be interesting to perform.

Required measurement methods are site specific, but the development of standardized techniques could still be beneficial. Further development of a model that take the relationship between tidal range and current speed into account could also be of interest.

The next step in the Söderfors project is to continue performing extended wake measurements as well as measurements of turbulence at and around the turbine and in the wake. Available data from velocity measurements logged upstream and downstream of the turbine in Söderfors can be used to investigations of the natural flow affecting the turbine, e.g. distribution of current speeds.
7. Summary of papers

**PAPER I**

A tidal energy site in the Folda fjord in Norway was investigated as a first step in evaluating its potential as a renewable energy resource. Transect measurements of flow velocities were performed with a vessel mounted ADCP.

The author has done most of the work in this paper.

The paper is published in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, Volume 8A: Offshore Engineering*, and was presented orally by the author in San Francisco, California, USA, June 10 2014.

**PAPER II**

The tidal site of the Fold fjord was additionally investigated by deploying an ADCP for 54 days, measuring the flow characteristics. The data was analyzed in terms of characterizing metrics, and also used to develop a simple model coupling tidal height to peak velocities at the site.

The author has done most of the work in this paper.

The paper has been revised and re-submitted to the *International Journal of Marine Energy*, November 2015.

**PAPER III**

This paper explains the deployment process of a marine current energy converter in the river Dalälven, which is part of the Söderfors project at Uppsala University. Also three ADCPs where deployed to monitor the water currents upstream and downstream of the turbine, as well as horizontally across the rotor plane.

The author was participating in the reassembling of the turbine blades, preparation of ADCPs for deployment and during the deployment of the converter and the measurement instruments.

The paper is published in *Proceedings of the 10th European Wave and Tidal Energy Conference Series, EWTEC 2013.*
PAPER IV

The wake characteristics of the flow behind the marine current energy converter in Söderfors was studied in this paper. Measurements of the velocity field were planned and conducted and the results give a first indication of the extent of the wake.

The author has contributed with the section about equipment, was responsible for setting up the ADCP and was participating in the collection of data.


PAPER V

This review paper discusses the variability of the renewable resources of solar, wind, wave and tidal energy. The spatial and temporal variability was reviewed and compared between the different sources. The variability of the tidal resource is mainly due to four aspects; tidal regime, the tidal cycle, bathymetry at the site and weather effects. Consequences of including such variable sources into the existing power systems is discussed.

The author is responsible for the tidal resource parts.

The paper is published in Renewable & Sustainable Energy Reviews, 44:356-375, April 2015.

En plats med tidvattenströmmar, belägen i en av alla fjordar längs Norges kust, har undersöks för sin resurspotential. Mätningar har utförts för att kartlägga resursens variation i både tid och rum. Resultaten visar att strömmar i storleksordningen 2 m/s återfinns i mitten av kanalen. Dessutom uppvisas flödet i den variation från huvudriktningen för både inkommande (flod) och utgående (ebb) flöden. Platsen har således potential för energiomvandling av fritt strömmande vatten. En modell föreslås som förutsätter strömmarnas maximal hastighet från information om höjdskillnaden mellan ebb och flod och vice versa. En motsvarande modell kan ställas upp och användas på andra platser med liknande förhållanden som berörs av tidvatten, dvs. fjordinlopp som förbinder havet med en fjord eller en bassäng.

En älv fungerar som en plats för experiment för ett marint strömkraftverk som har utvecklats vid Uppsala universitet och sjösatts i Dalälven, Söderfors. Flödeshastigheten på platsen regleras uppströms av ett närliggande vattenkraftverk, vilket gör platsen bra för att utföra experiment på prestandan av den vertikalaxlade turbinen i dess naturliga miljö. Turbinen har körts i jämnt flöde och mätningar har utförts för att karaktärisera vakens utbredning.

En plats med havsströmmar var mål för en utredning av dess potential för att ge användbar förnybar energi. En mätningskampanj genomfördes för att kartlägga flödets variation både rumsligt och tidsmässigt. Emellertid visade sig platsen inte vara lämplig för energiomvandling utifrån användning av nuvarande teknik.
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10. References


