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This is a published version of a paper published in *Journal of Renewable and Sustainable Energy*.

Citation for the published paper:

Lalander, E., Grabbe, M., Leijon, M. (2013)

"On the velocity distribution for hydro-kinetic energy conversion from tidal currents and rivers"

Journal of Renewable and Sustainable Energy, 5: 023115

URL: <http://dx.doi.org/10.1063/1.4795398>

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Citation: *J. Renewable Sustainable Energy* **5**, 023115 (2013); doi: 10.1063/1.4795398

View online: <http://dx.doi.org/10.1063/1.4795398>

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On the velocity distribution for hydro-kinetic energy conversion from tidal currents and rivers

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(Received 19 July 2012; accepted 1 March 2013; published online 21 March 2013)

Tidal currents and rivers are promising sources of renewable energy given that suitable turbines for kinetic energy conversion are developed. To be economically and technically feasible, a velocity distribution that can give a high degree of utilization (or capacity factor) while the ratio of maximum to rated velocity is low would be preferable. The rated velocity is defined as the velocity at which rated power is achieved. Despite many attempts to estimate the resource, however, reports on the possible degree of utilisation from tidal currents and rivers are scarce. In this paper, the velocity distribution from a number of regulated rivers, unregulated rivers, and tidal currents have been analysed regarding the degree of utilisation, the fraction of converted energy, and the ratio of maximum to rated velocity. Two methods have been used for choosing the rated velocity; one aiming at a high fraction of converted energy and one aiming at a high degree of utilisation. Using the first method, with a rated velocity close to the maximum velocity, it is unlikely that the turbine will reach the cut-out velocity. This results in, on average, a degree of utilisation of 23% for regulated rivers, 19% for unregulated rivers, and 17% for tidal currents while converting roughly 30%–40% of the kinetic energy. Choosing a rated velocity closer to the mean velocity resulted in, on average, a degree of utilisation of 57% for regulated rivers, 52% for unregulated rivers, and 45% for tidal currents. The ratio of maximum to rated velocity would still be no higher than 2.0 for regulated rivers, 1.2 for unregulated rivers, and 1.6 for tidal currents. This implies that the velocity distribution of both rivers and tidal currents is promising for kinetic energy conversion. These results, however, do not include weather related effects or extreme velocities such as the 50-year velocity. A velocity factor is introduced to describe what degree of utilisation can be expected at a site. The velocity factor is defined as the ratio U_{max}/U_{rate} at the desired degree of utilisation, and serves as an early indicator of the suitability of a site. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4795398>]

I. INTRODUCTION

Much has been written about marine current energy over the years and the extractable resource has been estimated to be in the range of 40–50 TWh in European waters alone.^{1,2} However, each site may present a different set of constraints and design criteria for a turbine developer, and less has been published regarding how to characterise these sites in a meaningful way. Marine current energy sites may be characterised based on the nature of the current and the driving forces behind it, be it a river (head), ocean currents (thermal or salinity), or tidal currents. Tidal current sites, for instance, have been classified in five different groups.³ Such an account could of course be very helpful while describing and modelling the resource. However, it will be of little help while designing the actual energy converter (turbine, generator, and foundation).

Other characteristics of the resource that have been discussed more recently include (but is not limited to) depth, seabed material, velocity profile, distance to nearest grid connection, and wave-current interaction, to name a few.^{3–6} The depth and seabed material are likely to be a

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deciding factor when choosing type of foundation and method of deployment. It is also important to have a good description of the velocity profile in order to know what flow the turbine will experience.⁴ Turbulence and, perhaps more importantly at some sites, the wave-current interaction are likely to be important factors determining the fatigue load on the turbine blades. In all of the above mentioned cases, however, it would be important to know the velocity distribution together with the maximum velocity (and how often it would occur) in order to choose a suitable rated power and to maintain structural integrity of the system during a worst case scenario.

In this paper, the intention is to present the velocity distribution for a number of river sections and tidal sites and to highlight what consequences this may have pertaining to suitable rated power, degree of utilisation, and the ratio of maximum velocity to rated velocity.

A. Degree of utilisation

The degree of utilisation, also referred to as the capacity factor, is defined as the ratio of annually delivered energy to the electric grid to the rated power of the device times the number of hours in a year. It is thus a viable tool to estimate the competitiveness of different renewable energy sources and the possible revenue from utilising them. The (economic) importance of the degree of utilisation for renewable energy technologies has been highlighted previously.^{7,8} Tidal power has been estimated to generate a degree of utilisation of 30%–45%, which is comparable to land-based wind farms (30%) and off-shore wind farms (40%).⁹ Even river-based in-stream power plants are estimated to have a degree of utilisation of 30%–50%.¹⁰

For in-stream technologies, only a few developers have published the achieved degree of utilisation. For the Seagen device, with a rated power of 1.2 MW and a yearly production of 3800 MWh, the degree of utilisation is 36% according to the International Energy Agency (IEA).⁹ However, in other reports the degree of utilisation for the Seagen device has been claimed to reach 48% (Ref. 11) and even 66%.^{12,13} These differences might lie in how the degree of utilisation has been calculated. It is inherently difficult to calculate the degree of utilisation based on data from a (prototype) device that has recently been deployed and only been operated for a short period of time. The device at hand might have been operated intermittently, and it is also quite likely that the device has undergone a number of different tests that requires operation that differs from its intended point of operation. A more generic approach, as suggested here, could then be to look at the velocity distribution alone and consider what possible degree of utilisation that would correspond to.

Over the years, there have been many attempts to estimate the tidal resource, see for instance two recent reviews.^{14,15} There are, however, not so many in-depth reports available on the possible degree of utilisation from tidal currents based on tidal stream data or models. One recent addition is the study by Blanchard *et al.*¹⁶ of the Minas Channel in the Bay of Fundy. Simulation results show that a degree of utilisation of 50%–60% could be achievable and that choosing a lower rated velocity for the turbine would result in an even higher degree of utilisation (83% for a rated velocity of 1 m/s).¹⁶

Walkington and Burrows¹⁷ have modelled four sites along the UK west coast and looked at the degree of utilisation (called the utilisation rate) for four possible tidal farms. Two of the farms perform quite well, achieving a degree of utilisation of 44% and 55%, respectively. The two other locations only reached 5% and 16%, respectively. This, however, says little about the velocity distribution as such, it is rather an indication that a turbine with a lower rated velocity would likely have been more suitable for those particular sites. Clarke *et al.*¹⁸ note that by limiting the rated power to 36% of the available power at spring tide, a degree of utilisation of 32.5% will be achieved and that the turbine will still deliver 80% of the energy compared to the non-limited case.

Walkinton and Burrows have made a similar analysis for tidal barrages,¹⁹ showing a degree of utilisation in the range of 10%–21% and converting 20%–38% of the available energy at sites along the UK west coast. As a comparison, the tidal barrage in France, La Rance, with a rated power of 240 MW, has a yearly production of 540 GWh (Ref. 20) on average. With these numbers, the degree of utilisation becomes 26%.

Kinetic energy conversion from rivers using in-stream turbines has been discussed as an environmentally friendly renewable energy resource, often as an alternative for rural electrification in developing countries. Similar to the situation with tidal currents, however, little has been published regarding the velocity distribution and the possible degree of utilisation. One of few authors to study river current turbines is Khan *et al.*,^{21–25} but the focus seems to be more on the technology rather than on the resource. In one of the articles,²³ Khan asks the question what the definition of a resourceful site would be. No clear answer seems to be given, other than that available river databases are not really suited for answering the question and hence it is necessary to develop new methods to analyse the available data. One might assume that Khan alludes to the abundant data on river discharge and the fact that the relationship between discharge and velocity is seldom known.

The Electric Power Research Institute (EPRI) has, with the help of the U.S. Geological Survey (USGS) and the Alaska Energy Authority, performed a characterisation survey of six river sites in Alaska.²⁶ An important part of their analysis was to establish a relationship between the USGS station discharge data and velocity, which will be used in this study.

Other recent contributions regarding kinetic energy conversion from rivers include a study of the Tanana river in Alaska by Toniolo *et al.*²⁷ A bathymetric survey was conducted and the velocity was measured at different cross-sections with an acoustic Doppler current profiler (ADCP). Results concluded that a turbine can be deployed in a site along the cross-section with a stable thalweg. An unstable thalweg can reduce the percentage of the total available power for the turbine, due to lateral migration of the maximum velocity. Another recent article studies the resource characteristics in a Swedish river including the generator-turbine performance under those conditions.²⁸

To summarise, there is as yet no consensus for a standard for development of marine turbines similar to those regarding wind power. There, agreed methods for resource assessments and design loads are established. Often, a Weibull distribution²⁹ is used to describe the wind velocity distribution which makes it more or less straightforward to choose a suitable rated velocity and to calculate the degree of utilisation. In tidal energy, the situation is a bit more complex as a farm of turbines will to a certain extent block the flow and reduce the velocity, see e.g., Refs. 30 and 31. In this study, the undisturbed velocity is used, assuming the turbine is small compared to the cross section of each site.

A standard method for the assessment of the tidal energy resource has been suggested.³² The standard is not yet easily utilised, perhaps owing to the fact that there are still no standard methods of how to measure and describe all aspects of the resource, for instance turbulence. Important contributions have been made recently,^{33–36} but more work is still needed. The scope of this paper, however, is limited to the velocity distribution and the degree of utilisation for tidal currents and rivers.

II. METHODS AND DATA

The degree of utilisation is, as previously mentioned, defined as the ratio of annually delivered energy to the electric grid to the rated power of the device times the number of hours in a year. It is thus required to have at least a one-year-series of data for a proper analysis of the degree of utilisation for a certain site. In this section, we present the data used and the method of constructing a one year-series of velocity data for rivers and tidal currents. The statistical analysis used for describing the different distributions and the steps taken for calculating the degree of utilisation are also presented.

A. Velocity data

1. Regulated rivers

For rivers, a separation has been made between regulated and unregulated rivers. Regulated rivers are here defined as rivers having a reservoir downstream governing the water level in the river. Discharge data for regulated rivers were collected for rivers in Sweden in which the

discharge was larger than $100 \text{ m}^3/\text{s}$ (see Fig. 1). The data were obtained from the Swedish Meteorological and Hydrological Office (SMHI). For most sites, there were 12 years of data (1995–2007). The data were measured at daily intervals. For one site, however, discharge data measured at hourly intervals were obtained (the site Söderfors in Dalälven) for the years 2003–2008 from Vattenfall AB. Velocity measurements with a bottom-mounted 600 kHz ADCP have been conducted at this site for 26 days in April–May 2010. The ADCP was deployed at a

FIG. 1. Geographical overview of the regulated river sites.

FIG. 2. Histogram of measured velocity (black) and calculated velocity from discharge (grey) with a correlation coefficient of 0.94. The Y-axis shows the number of hours.

depth of 7 m in the middle of the river, and the measurements were set to 3 min intervals with a depth resolution of 1 m.

Assuming only small changes in the water level of the reservoir, the velocity will be linearly dependent on the discharge, Q . Since actual velocity data are lacking for all sites except one, a normalised value for the velocity, U_{Rn} , has been used according to

$$U_{Rn} = \frac{Q_R}{\bar{Q}_R}, \quad (1)$$

where the $\bar{Q}_R$ is the total mean of the data. Index R indicates that the data are from regulated rivers and index n that the data are normalised. The velocity measurements in Söderfors were used to confirm this theory. At that site, a reservoir regulated by a hydropower station is situated immediately downstream. The velocity was found to be linearly dependent on the discharge, and the correlation coefficient (R) was 0.94, see Fig. 2.

The assumption of a linear relation between velocity and discharge was used for all regulated river sites. A histogram of two selected rivers is seen in Fig. 3 based on 12 years of data.

2. Unregulated rivers

In an EPRI report from 2008,²⁶ the non-linear relationship between velocity and discharge was shown for a few sites in Alaska. Measured velocity was correlated to the discharge. In this paper, the same relationships have been used for further analysis of the data for five of the river sites presented in the EPRI report,²⁶ with permission from the authors. For the geographical overview of the unregulated river sites, see Fig. 4.

A more detailed analysis of the Kvichak river (site 4) has been published by Terrason Ltd.³⁷ and by Toniolo.³⁸ In these studies, the velocity has been measured across the channel,

FIG. 3. Histogram of the velocity ($Q_R/\bar{Q}_R$) for two selected regulated rivers. The vertical lines indicate U_{opt} (see Sec. II C) for each site.

FIG. 4. Geographical overview of the unregulated river sites.

and the correlation between discharge and velocity given in the report from Terrasond³⁷ gives small differences in the analysis performed here. Thus the analysis of all the unregulated river sites is based on the EPRI report.²⁶

Discharge data for the unregulated rivers in Alaska were acquired from the USGS. The data had a time-interval of one measurement per day. The river sections and their respective relationship between velocity and discharge are presented together with the statistical analysis of the velocity in Sec. III A. The velocity is denoted U_{UR} to distinguish that it is for unregulated rivers.

The distribution for two selected sites is presented in Fig. 5. The difference between the discharge distribution and the calculated velocity distribution due to their logarithmic relation is easily noticeable.

FIG. 5. Histogram of the discharge distribution (a and c) and the velocity distribution (b and d) for two of the unregulated rivers. The Y-axis shows percentage of time.

3. Tidal sites

The selection of tidal sites was based on the work by Hardisty.³⁹ The author highlights sites in the U.S. likely to be of interest for kinetic energy conversion. However, tidal height and velocity were only found for a few of these sites.

Tidal height data were acquired from the Center for Operational Oceanographic Products & Services (CO-OPS) at the U.S. National Oceanic and Atmospheric Administration (NOAA).⁴⁰ Velocity data were acquired in June 2011 from C-MIST at the NOAA's web-page.^{40,41} The time resolution for the tidal height data was 1 measurement per hour. Details on the collected velocity series such as length of measurement, depth at measurement site, and other information are found on page 13 in Table I.

The chosen sites are widely spread across North America to include different tidal regimes (see Fig. 6 for the geographical overview of the tidal sites). The length of the velocity measurement series for each site was rarely more than a month, and thus a one-year velocity series had to be constructed.

The obtained velocity measurements were used for correlation and calibration with the tidal height. Using this correlation, the tidal height data were then used to create a one-year velocity series. All bins from the velocity data were used, but due to interference close to the surface layer the upper 3 m were removed. Bins with bad velocity data were also removed and the data were then depth-averaged.

The tidal level, here denoted as H , was correlated with the measured velocities, $U_{T,meas}$, according to $U_{T,meas} \propto H(\phi)$, where ϕ is the phase shift in time measured in hours. Index T indicates the tidal regime data. Several values of ϕ were applied and the value giving the best correlation coefficient value (R) was used. The correlation coefficients for the tidal sites are presented in Table II. The tidal height data were then calibrated with the velocity (Fig. 7) to achieve an approximated velocity, U_T , using

$$U_T = H(\phi) \cdot A + B \approx U_{T,meas}, \quad (2)$$

where A and B were adjusted until the best fit was found. Using these calibration values together with ϕ , a one-year velocity series could be constructed from a one-year series of the tidal height data for each site. The correlation for three different sites is plotted in Fig. 7. Sites with low correlation were omitted from the later analysis of the degree of utilisation. The results of the correlation and calibration are shown in Table II.

B. Statistical analysis

1. Data characterisation

The data were characterised using several different measures such as the mean ($\bar{U}$), median (U_M), and standard deviation (std). For the river sites, the maximum value was taken for every year and then these were averaged ($\bar{U}_{max}$). For the tidal sites, the maximum value of the selected year was chosen as U_{max} , as there was only one year of data. To be able to compare the different regimes, $\bar{U}_{max}$ and U_M were divided by the mean value.

It should be noted that the length of the time series differed for most sites, and only one of the analysed rivers had a time-series longer than 50 years. The average of the yearly maximum has been chosen as a measure to show the usual conditions of the site. Data for extreme conditions such as the 50- or 100-year occurring velocity were not available for this analysis.

2. Velocity distributions

A measure of the symmetry of the data was performed with a test of the skewness. Positive skewness indicates that the right tail of the histogram of the data is long compared with the left and negative skewness indicates the opposite. Analysis of the kurtosis of the data was also performed.⁴² Positive kurtosis indicates that the data have a distinct peak near the mean whereas negative kurtosis indicates that the distribution is flat. For a normal distribution

TABLE I. Details on the collected velocity series and the corresponding tidal reference numbers used for the correlation.

Site	C-MIST ref	Start date	End date	# of days	Depth [m]	Latitude [°]	Longitude [°]	Orientation	# bins used	Bin size [m]	1 st bin [m]	Time interval [min]	Tidal ref	Year
1 Chesapeake Bay, VA	CHB9902	99/05/21, 15:00	99/07/22, 12:00	62	17.1	36.9774	−76.1242	Up	14	1	3.5	6	8 638 610	1999
2 Chesapeake Bay, VA	CHB9903	99/05/20, 15:17	99/07/29, 15:17	70	23.2	36.9943	−76.3053	Up	19	1	3.5	6	8 638 610	1999
– Buzzards Bay, MA	COD0911	09/08/01, 15:07	09/09/18, 02:12	49	7	41.5193	−70.68289	Up	18	0.5	1.65	6	8 447 930	2009
– Buzzards Bay, MA	COD0914	09/08/14, 18:59	09/09/14, 18:59	31	15.7	41.4427	−70.84825	Up	0	1	2.95	6	...	2009
– Buzzards Bay, MA	COD0915	09/07/23, 17:48	09/09/14, 17:48	52	2.8	41.424	−70.90788	Up	0	0.5	2.22	6	...	2009
3 Cook Inlet, AK	COI0303	03/07/22, 22:00	03/08/22, 22:00	31	31.1	61.2523	−149.92067	Up	19	1	10.46	6	9 455 920	2003
4 Cook Inlet, AK	COI0304	03/07/20, 04:57	03/08/20, 04:57	31	43.3	61.2642	−149.89715	Up	12	2	11.44	6	9 455 920	2003
5 Cook Inlet, AK	COI0501	05/05/29, 21:00	05/06/29, 21:00	31	33.5	60.722	−151.6469	Up	12	2	10.13	6	9 455 760	2005
– Cook Inlet, AK	COI0502	05/07/16, 18:00	05/08/16, 18:00	31	33.8	60.7207	−151.55733	Up	18	3	11.08	6	9 455 760	2005
6 Eastport, ME	EPT0003	00/08/06, 22:15	00/09/06, 22:15	31	34.1	44.8879	−66.99565	Up	18	2	2.87	6	8 410 140	2000
7 Eastport, ME	EPT0004	00/08/06, 18:30	00/09/06, 18:30	31	32	45.0763	−67.10097	Up	18	2	4.22	6	8 410 140	2000
8 Hudson River, NY	HUR0501	05/06/05, 17:05	05/07/06, 17:05	30	16.2	40.8486	−73.95032	Up	21	1	4.05	6	8 518 750	2005
– Hudson River, NY	HUR0504	05/07/23, 18:40	05/08/23, 18:40	31	30.5	41.3159	−73.98385	Up	0	1	2.71	6	...	2005
9 Chesapeake, VA	LCB9904	99/04/23, 12:30	99/07/09, 12:30	77	10.4	36.9798	−75.98085	Up	18	0.5	1.37	15	8 638 863	1999
– San Francisco Bay	s03020	05/04/05, 12:11	05/07/01, 17:11	82	10.7	37.8086	−122.3559	Up	14	1	2	6	9 414 750	2005
– San Francisco Bay	s04020	99/09/24, 20:35	99/09/25, 09:17	0.5	55.78	37.8203	−122.4621	Up	26	2	3.6	6	9 414 290	1999

FIG. 6. Geographical overview of the tidal sites.

both measures would have a value of 0. These measures are presented to characterise the data of each site in a comparable way. The results of the analysis are presented in Sec. III A.

The distribution of the data at each site was compared with a normal, a log-normal and a Weibull distribution. The purpose was to see if it is possible to generalise distributions for each regime, and to see if this had an effect on the degree of utilisation.

TABLE II. The parameter values of A and B from Eq. (2), the correlated ϕ -values and the correlation coefficients for the tidal sites. Names in *italic* were not used in the later calculations due to the low correlation or short measurement time.

Site	A [1/s]	B [m/s]	ϕ [h]	R	R^2
1 Chesapeake Bay, VA	1.3	0.1	0.0	0.91	0.83
2 Chesapeake Bay, VA	2.1	0.0	-4.8	0.97	0.94
– <i>Buzzards Bay, MA</i>	3.7	-0.1	2.3	0.83	0.68
3 Cook Inlet, AK	0.5	-0.1	3.7	0.92	0.85
4 Cook Inlet, AK	0.5	0.5	4.0	0.87	0.76
5 Cook Inlet, AK	0.7	0.0	2.2	0.93	0.87
– <i>Cook Inlet, AK</i>	0.5	0.4	1.9	0.82	0.68
6 Eastport, ME	0.4	0.0	-2.9	0.98	0.96
7 Eastport, ME	0.2	0.0	3.9	0.96	0.91
8 Hudson river, NY	1.4	-0.2	0.4	0.97	0.95
9 Chesapeake, VA	1.3	0.1	2.7	0.91	0.84
– <i>San Francisco Bay</i>	0.7	0.0	-3.2	0.85	0.73
– <i>San Francisco Bay</i>	1.7	0.4	2.3	0.98	0.95

FIG. 7. Histogram of three selected tidal sites with measured velocity in black and calculated velocity in grey.

Normality tests were done by visual inspection of histograms and box plots and also Q-Q (quantile-quantile) plots. A Kolmogorov-Smirnov test was also performed comparing the established mean (μ_d) and standard deviation (σ_d) for the site to a normal curve with the same parameters (index d is for distribution).

A log-normal curve was made with values of shape and scale parameters that visually best fitted the data for each site. A Q-Q plot was then compared for each site to establish whether the distribution of the data for each site was comparable to a log-normal distribution.

The same analysis was made for the Weibull distribution as for the log-normal distribution.

C. Calculating the degree of utilisation

The yearly converted energy was calculated through the following steps. Using the velocity distribution it was possible to calculate the kinetic energy per square meter, E_w/A_t , for each site using

$$E_{w,i}/A_t = \frac{1}{2} \rho U_i^3 N_i 8760 \quad [\text{Wh/m}^2], \quad (3)$$

where N_i is the annual incidence of each velocity segment, i is the index of each velocity segment, and A_t is the device cross sectional area. For river data, the whole series was used in this step, i.e., several years. The velocity giving the highest value of E_w is the optimal velocity, U_{opr} .

Equation (3) describes the kinetic energy in the flowing water, and not the available energy for a hydro-kinetic turbine to convert as only approximately 60% is theoretically available.²⁹

The converted energy was estimated in the next step using

$$E_c/A_t = \sum E_{w,i}/A_t C_{P,i} \quad [\text{Wh/m}^2], \quad (4)$$

where C_P is the power coefficient vector of the assumed turbine. This is further described below. The degree of utilisation, α , is then defined as

$$\alpha = \frac{E_c/A_t}{P_{rate}/A_t \cdot 8760} \times 100, \quad (5)$$

where P_{rate} is the rated power of the turbine. Here, internal losses of the device, such as generator losses, have not been taken into account since that will vary with the chosen device. The focus has instead been on defining the C_P -value of the turbine.

Two different C_P -curves were used corresponding to two turbines with different rated power. These are described as Method I and II below:

- Method I: A proposed turbine assumed to have its maximum efficiency occurring at the optimal velocity of the site.
- Method II: A proposed turbine assumed to have its rated velocity, U_{rate} , coinciding with the optimal velocity of the site. The maximum efficiency thus occurs at a lower velocity than for Method I.

A wind-turbine C_P -curve, $C_{P,wind}$, has been used in both methods but was scaled differently. The C_P -curve was taken from an Enercon turbine⁴³ multiplied with a factor of 0.8 so that the maximum C_P was 40%, which, at this early stage of development, might be a reasonable value for a marine current turbine. The C_P -curve has been scaled to fit the distribution at each site. Method I scales the C_P -curve by $C_{P,wind} \times U_{opt}/8$. Method II scales the C_P -curve with $C_{P,wind} \times U_{opt}/13$. The curve for both methods is shown in Fig. 8.

For the analysis of the results, a few different measures were used. First, U_{rate} has been compared with the mean value according to $\frac{U_{rate}}{U}$. This measure was used as an estimate of the distribution of the data. Also, the fraction of converted energy to available energy was used according to $E_c/E_w \times 100$. The last measure is the difference between rated velocity and maximum velocity using U_{max}/U_{rate} .

As an example of how the results can look for an assumed tidal current, two very simple annual series were analysed: one assuming a tidal variation that is purely sinusoidal, and one assuming the tides vary in monthly cycles, a method that was proposed by Fraenkel,⁴⁴ see Fig. 9. The value of the constants K_0 and K_1 used in Ref. 44 was set to 2 m/s and 0.5 m/s, respectively.

For these two tidal current regimes, the degree of utilisation varies greatly between Method I and II (see Table III), especially for the “Fraenkel” regime, in which the degree of utilisation is increased with 170%. The actual amount of extracted energy is in the meantime decreased with 40%.

III. RESULTS AND DISCUSSION

The results from the statistical analysis are presented in Tables IV–VI and the resulting degree of utilisation is presented in Table VII. First of all, however, it should be made clear that the sites have not been chosen because they were thought to be particularly suitable for deployment of kinetic energy conversion devices, pertaining to, e.g., location, depth, or velocity.

FIG. 8. The C_P -curves for Method I (a) and Method II (b) that were used in the calculations. The vertical line is showing the rated velocity. U_{opt} is 1.5 m/s in both figures.

FIG. 9. The velocity distribution for two theoretical velocity series: a simple sinusoidal (a) and a tidal series according to Ref. 44 (b).

The intention was to study the resource characteristics as such and the various velocity distributions that tidal currents and rivers may present, rather than characterising a certain site or a certain technology.

The results for tidal currents could, however, be considered rather general as both diurnal, semi-diurnal, and mixed tidal regimes were included. The results for rivers should, on the other hand, not be taken as representative for rivers in general as differences in precipitation and run-off might be large between different parts of the world.

The results indicate that the degree of utilisation could be in the same range for tidal currents and rivers. There are, however, several factors that could in practice limit the degree of utilisation for rivers. Here, the water level and depth were not taken into consideration. This is especially important for the unregulated rivers as the turbine might be exposed during certain times of the year due to low water levels. Furthermore, floating debris and ice breakup in rivers may be an issue if it leads to interrupted operation or damage on the equipment. Some methods of dealing with the debris problem have been suggested,⁴⁵ but ice breakup might hinder development at certain sites.

The velocity in the regulated rivers was calculated assuming a linear dependence on the discharge data. This is an assumption and is only applicable to the sections in each river where there are small variations in the water level compared with the depth of the site. Velocity measurements would be required at all sites to check this assumption.

The results for rivers in Table VII show that the degree of utilisation and the converted energy might vary from year to year. The 100-year and 1000-year discharge for the rivers have not been included in the data, but should, of course, be analysed before developing a site. For the tidal sites, it should be noted that weather related effects have not been included, but variations from year to year could still be expected to be small. According to Legrand,³² both the maximum 1-year, 10-year, and 50-year currents as well as the 50 and 100-year storm waves should be included in a thorough resource assessment and site description. Such an analysis is, however, considered to be outside the scope for this article.

It was not possible to take into account other effects, such as the influence of wind and waves and the effect of river discharges close to the tidal sites in this analysis. This is a limitation of the study.

TABLE III. Example results using a sinusoidally varying tidal velocity and a tidal velocity variation according to a method proposed by Fraenkel, 2002.⁴⁴

	Method I				Method II			
	$\frac{U_{rate}}{U}$	$\frac{U_{max}}{U_{rate}}$	α	$\frac{E_c}{E_w}$	$\frac{U_{rate}}{U}$	$\frac{U_{max}}{U_{rate}}$	α	$\frac{E_c}{E_w}$
Simple sin	2.0	0.8	34	38	1.3	1.3	66	17
Fraenkel	2.5	0.8	19	39	1.6	1.3	52	24

TABLE IV. Regulated river characteristics based on discharge data normalised by the mean of the discharge for 12 years of data. For the last site (no. 18), discharge data from 5 years have been used, and the velocity could be correlated to the discharge. SMHI-ref is the reference for the rivers in the SMHI database.⁴⁶

River	Site	SMHI-ref	$\overline{U_{Rn}}$	$\text{std}(U_{Rn})$	$\frac{\overline{U_{Rn,max}}}{\overline{U_{Rn}}}$	$\frac{U_{Rn,M}}{\overline{U_{Rn}}}$	Skewness	Kurtosis	Distribution
1. Luleälven	Porjus	1702	1.0	0.5	2.2	1.0	0.1	-0.7	N
2. Luleälven	Boden	2131	1.0	0.3	2.0	1.0	0.7	2.0	L-N
3. Luleälven	Letsi	2039	1.0	0.6	2.9	0.9	1.8	7.5	...
4. Skellefteälven	Kvistforsen	1870	1.0	0.4	2.6	1.0	1.8	6.6	L-N
5. Umeälven	Harrsele	1733	1.0	0.5	2.4	1.0	1.9	9.6	...
6. Umeälven	Storuman	20010	1.0	0.5	2.2	1.1	0.3	1.25	...
7. Ångermana.	Nämforsen	1506	1.0	0.6	2.9	0.9	2.5	12.9	...
8. Ångermana.	Hjälta	1557	1.0	0.4	2.2	1.0	0.8	3.6	L-N
9. Ångermana.	Lasele	1736	1.0	0.7	3.5	0.9	2.6	11.9	...
10. Indalsälven	Hissmofors	1357	1.0	0.5	2.3	1.0	1.0	4.8	L-N
11. Ljungan	Skallböle	1650	1.0	0.7	3.2	0.8	3.3	21.1	L-N
12. Ljusnan	Dönje	2384	1.0	0.7	3.8	0.9	3.1	16.7	...
13. Ljusnan	Sveg	2434	1.0	0.6	4.0	0.9	4.2	32.6	L-N
14. Dalälven	Långhag	1643	1.0	0.5	2.5	0.9	2.3	6.9	L-N
15. Dalälven	Näs	1911	1.0	0.6	2.5	0.9	2.0	5.1	L-N
16. Dalälven	Gråda	1949	1.0	0.5	2.1	0.9	1.1	2.4	...
17. Dalälven	Forshuvud	2175	1.0	0.5	2.6	0.9	2.2	6.4	L-N
18. Dalälven	Söderfors	...	0.8 ^a	0.4	1.9	1.0	0.2	2.2	...
Average				0.5	2.7	1.0	1.7	8.0	

^aMeasured data.

A. Statistical analysis

The results from the statistical analysis and distribution tests are presented in Tables IV–V. Not all sites were well suited for either of the test-distributions and these sites are marked with a dash in the result tables. Note that only tidal sites with an R value of around 0.85 and above were used.

For the analysed regulated rivers, the log-normal distribution was most common among the sites. In Fig. 3, the histogram of site 2 (Luleälven) and site 14 (Dalälven) are shown. The distribution of these sites was quite representative of the sites with log-normal distribution.

For unregulated rivers, the distribution was in general difficult to assign to any test-distribution. This is due to the fact that the distribution for most sites has two peaks, as is shown in Fig. 5 (1. Yukon, Eagle and 3. Tanana, Bigdelta).

TABLE V. Unregulated river characteristics together with log-function values used in the EPRI-report,²⁶ and the statistics of the sites. USGS-ref is the reference of the site in the USGS database.⁴⁷ Q_{fi} is Q measured in ft^3/s and each log-function gives the result in ft/s and must thus be converted to m/s by multiplying the result with 0.3048.

Site	USGS-ref	# years	Log-function	$\overline{U_{UR}}$	$\text{Std}(U_{UR})$	$\frac{U_{UR,max}}{\overline{U_{UR}}}$	$\frac{U_{UR,M}}{\overline{U_{UR}}}$	Skewness	Kurtosis	Distr.
1. Yukon, Eagle	15 356 000	60	$2.0\ln(Q_{fi}) - 18.0$	1.2	0.6	1.9	0.9	0.1	-1.4	...
2. Taku, Juneau	15 041 200	21	$1.2\ln(Q_{fi}) - 8.2$	0.9	0.4	2.0	1.0	0.0	-1.4	...
3. Tanana, Bigdelta	15 478 000	9	$1.5\ln(Q_{fi}) - 10.7$	1.0	0.4	1.6	0.8	0.5	-1.3	...
4. Kvichak, Igiugig	15 300 500	20	$2.6\ln(Q_{fi}) - 20.3$	1.4	0.3	1.3	1.0	0.1	-0.5	N
5. Yukon, Pilot	15 565 447	9	$-3.8 \times 10^{-12} Q_{fi}^2 + 1.0 \times 10^{-5} Q_{fi} + 0.3$	0.7	0.4	2.3	0.7	0.6	-1.1	...
Average					0.4	1.8	0.9	0.3	-1.1	

TABLE VI. Tidal site data statistics for the nine selected sections that were analysed.

	$\overline{U_T}$	Std (U_T)	$\frac{U_{T,max}}{\overline{U_T}}$	$\frac{U_{T,M}}{\overline{U_T}}$	Skewness	Kurtosis	Distr.
1. Chesapeake, VA	0.3	0.2	2.9	1.0	0.3	-0.5	N
2. Chesapeake, VA	0.5	0.3	2.7	1.0	0.2	-0.7	N
3. Cook Inlet, AK	1.2	0.7	2.7	1.0	0.2	-0.7	...
4. Cook Inlet, AK	1.2	0.7	2.6	1.0	0.2	-1.0	...
5. Cook Inlet, AK	1.1	0.7	2.9	1.0	0.4	-0.6	...
6. Eastport, ME	0.7	0.3	2.2	1.1	-0.2	-1.0	...
7. Eastport, ME	0.3	0.1	2.2	1.1	-0.2	-1.0	N
8. Hudson river, NY	0.6	0.4	3.0	0.9	0.4	-0.7	...
9. Chesapeake, VA	0.3	0.2	2.8	1.0	0.2	-0.6	N
Average		0.4	2.7	1.0	0.2	-0.7	

For the tidal data, the velocity distribution of the sites could best be compared with a normal distribution. Looking at the histograms from the three sites in Fig. 7, sites 2 and 8 both had positive skewness (the right tail longer than the left) whereas site 6 has negative skewness (the left tail longer than the right). The sites differ in their tidal regimes; whereas site 6 lies in an fairly open water, both sites 2 and 8 are situated at sites with freshwater outflow, i.e., a river estuary. This might affect the distribution of the data.

B. Data distribution and degree of utilisation

The results for the degree of utilisation are presented in Table VII. The distributions analysed in Sec. III A were compared with the degree of utilisation and the value of E_c/E_w for each site. A t-test using an α of 0.05 was used to check if a difference existed. The results showed that there was a difference in E_c/E_w between a normally distributed site and a log-normally distributed one. The average value of E_c/E_w was 38% for the ones considered normally distributed and 30% for the log-normally distributions. However, there was no difference in the degree of utilisation for the two distributions.

Even though one would expect that a peaked velocity distribution (high kurtosis) would lead to a high degree of utilisation, this could not be seen. Due to the limited number of sites that could be used in the analysis, the results of this cannot be generalised.

C. Difference in degree of utilisation between methods I and II

The degree of utilisation is presented in Table VII for the two methods used. The difference between the methods is due to a decrease of the rated velocity from Method I to Method II. For river data, the average degree of utilisation is presented, which is an average of all the years for which it was calculated. The standard deviation is thus a measure of how large the variations could be between the years. This was not calculated for tidal sites, as only a one year series has been used.

As expected, a lower rated velocity leads to a greater degree of utilisation at the cost of a decrease in converted energy. For unregulated rivers, the degree of utilisation is more than doubled by using Method II, whereas the ratio of E_c/E_w is only decreased by around one third. Thus one might consider choosing a lower rated velocity for the turbine (and therefore decreasing the turbine cost), allowing a small reduction in annually converted energy while achieving better utilisation of the equipment.

In Fig. 10 (top two), the degree of utilisation and E_c/E_w have been plotted as a function of $U_{rate}/\overline{U}$ for both Method I and II. It is clear that the degree of utilisation decreases with increasing rated velocity, and there is an almost linear dependence on the two. However, the fraction of extractable energy increases. In Fig. 10 (bottom two), similar figures are presented, but as a function of the ratio U_{max}/U_{rate} . There is no linear dependence between the velocity

TABLE VII. Results for the calculation of the degree of utilisation using the two methods proposed in Sec. II C.

	Method I						Method II					
	$\frac{U_{rate}}{U}$ $\frac{\overline{U}_{max}}{U_{rate}}$		α [%]		$\frac{E_c}{E_w} \cdot 100$ [%]		$\frac{U_{rate}}{U}$ $\frac{\overline{U}_{max}}{U_{rate}}$		α [%]		$\frac{E_c}{E_w} \cdot 100$ [%]	
			Mean	Std	Mean	Std			Mean	Std	Mean	Std
Regulated rivers												
1. Luleälven	2.4	0.9	20	6	38	1	1.5	1.5	53	12	24	3
2. Luleälven	2.0	1.0	26	8	36	3	1.2	1.6	70	13	24	5
3. Luleälven	2.6	1.1	16	8	31	8	1.6	1.8	45	14	23	11
4. Skellefteälven	2.1	1.3	25	12	31	6	1.3	2.0	64	20	22	9
5. Umeälven	1.9	1.2	30	13	32	9	1.2	2.0	70	18	20	9
6. Umeälven	2.5	0.9	20	8	36	4	1.5	1.5	55	16	24	6
7. Ångermanälven	2.2	1.3	21	11	30	10	1.4	2.1	54	17	21	11
8. Ångermanälven	2.1	1.0	25	11	35	5	1.3	1.7	65	21	23	7
9. Ångermanälven	2.1	1.6	24	12	25	10	1.3	2.7	54	17	16	10
10. Indalsälven	2.1	1.1	28	9	34	7	1.3	1.8	63	14	19	6
11. Ljungan	2.8	1.1	14	11	29	9	1.7	1.9	35	19	24	12
12. Ljusnan	1.9	1.9	27	13	23	12	1.2	3.2	60	14	15	10
13. Ljusnan	2.2	1.8	20	10	26	11	1.4	2.9	53	15	19	11
14. Dalälven	2.0	1.2	25	13	29	9	1.2	2.0	61	17	20	10
15. Dalälven	2.0	1.3	27	14	28	9	1.2	2.1	62	18	19	10
16. Dalälven	2.3	0.9	22	13	34	7	1.4	1.5	54	17	23	10
17. Dalälven	2.0	1.3	25	13	29	9	1.3	2.1	60	17	20	10
18. Dalälven	2.7	0.7	15	7	38	1	1.7	1.2	46	15	29	6
Average	2.2	1.2	23	11	31	7	1.4	2.0	57	16	21	9
Unregulated rivers												
1. Yukon, Eagle	2.6	0.7	17	3	39	0	1.6	1.2	48	4	25	3
2. Taku, Juneau	2.6	0.8	18	2	39	0	1.6	1.2	50	4	25	2
3. Tanana, Bigdelta	2.4	0.7	16	6	38	2	1.5	1.1	44	16	26	5
4. Kvichak, Igiugig	1.9	0.7	31	10	39	1	1.1	1.1	81	10	26	5
5. Yukon, Pilot	3.1	0.7	15	4	38	1	1.9	1.2	38	5	24	4
Average	2.5	0.7	19	5	39	1	1.5	1.2	52	8	25	4
Tidal sites												
1. Chesapeake, VA	2.9	1.0	15		37		1.8	1.7	41		24	
2. Chesapeake, VA	2.6	1.0	18		37		1.6	1.7	48		23	
3. Cook Inlet, AK	2.6	1.0	18		37		1.6	1.7	48		23	
4. Cook Inlet, AK	2.8	0.9	16		38		1.7	1.5	44		24	
5. Cook Inlet, AK	2.8	1.0	16		37		1.7	1.7	42		22	
6. Eastport, ME	2.6	0.8	18		39		1.6	1.4	52		26	
7. Eastport, ME	2.6	0.8	18		39		1.6	1.4	52		26	
8. Hudson river, NY	2.9	1.0	16		37		1.8	1.7	41		23	
9. Chesapeake, ME	2.8	1.0	16		37		1.7	1.7	44		24	
Average	2.7	1.0	17		37		1.7	1.6	45		24	

ratio and the degree of utilisation, but a strong dependence on the fraction of extractable energy to the velocity ratio.

When choosing the rated velocity, there will have to be a compromise between degree of utilisation and converted energy. The choice of a suitable rated velocity is likely to be found

FIG. 10. Degree of utilisation (a and c) and fraction of converted energy (b and d) compared with ratio of rated velocity to mean velocity (top) and to maximum velocity (bottom) using Method I and II for all sites in Table VII. The square of the correlation factor (R^2) is presented in each figure.

somewhere in between the two methods presented here. An example of how the degree of utilisation will vary depending on the rated velocity is presented for two sites: tidal site No. 6, Eastport and the regulated river site No. 2, Luleälven in Fig. 11. The variation of the degree of utilisation and the quotient E_c/E_w are shown as functions of $U_{\text{max}}/U_{\text{rate}}$. Note that all 12 years have been displayed for the river site and the asterisk and the circle signify the average value for the results from the two methods. As shown in the left figure, using Method I (*), the rated velocity will be such that the maximum value of E_c/E_w (39%) will be gained at the cost of having a low degree

FIG. 11. The variation of the degree of utilisation and E_c/E_w with different quotients of $U_{\text{max}}/U_{\text{rate}}$ for the tidal site in Eastport (tidal site No. 6) (a) and the regulated river site Luleälven (regulated river site No. 2) (b). The asterisks show the rated velocity for Method I and the circles show the rated velocity for Method II.

of utilisation (18%). A more suitable rated velocity could be chosen so that the degree of utilisation would be close to 40% while the fraction of the converted energy would decrease to 35%. The figure to the right shows similar results, but with annual variations.

Despite the choice of rated velocity, the turbine would still have to be built to withstand the maximum velocities in a given river or tidal site. The ratio of maximum to rated velocity for Method II is on average 2.0 for regulated rivers, 1.6 for the tidal sites and even lower for the unregulated rivers (see Table VII). In comparison with wind power, the typical cut-out speed is set to approximately 2 times the rated velocity (12 m/s rated velocity and 25 m/s cut-out velocity) and the extreme 50-year gust can be several times higher. If the same rule is applied for hydrokinetic energy converters, the turbine could be operating at all times since the cut-out speed would be higher than the maximum velocity, especially for tidal sites. As mentioned previously though, the data used here are not sufficient to estimate the 10-, 50-, or 100-year velocities.

The maximum velocity (or cut-out velocity) is important for the reliability and survivability of the turbine,⁴⁸ and it is desirable that the ratio U_{max}/U_{rate} remains low. On the other hand, the degree of utilisation is important for the economic viability of the installation, and is desired to be as high as possible. We thus propose the use of a velocity factor to describe the suitability of a site. The velocity factor, β_α , is defined as the ratio U_{max}/U_{rate} at the desired degree of utilisation (α) at a particular site,

$$\beta_\alpha = \frac{U_{max}}{U_{rate}}. \quad (6)$$

Here, the yearly sustained maximum^{32,33} is used as U_{max} , so that extreme velocities can be handled separately. The velocity factor would give an early indication if the desired degree of utilisation can be reasonably achieved at a particular site. If for instance $\beta_{40} = 1.3$, this would mean that the desired 40% degree of utilisation is achieved at a U_{max}/U_{rate} ratio of 1.3. With such a low velocity factor, this would seem to be a promising site. On the contrary, if $\beta_{40} = 2.7$, the suitability of the site would be questionable.

As was seen in Fig. 10(c), there is no clear correlation between the degree of utilisation and the quotient U_{max}/U_{rate} . In other words, a simple design rule (such as setting the rated velocity to 75% of the maximum velocity) could yield very different utilisation at different sites. The velocity factor could thus be a simple and clear way to characterise individual sites.

IV. CONCLUSIONS

The velocity distribution of a number of tidal currents and rivers has been analysed with regards to the type of distribution, the degree of utilisation, the fraction of converted energy, and the ratio of maximum to rated velocity.

The degree of utilisation and the fraction of extractable energy could not be related to the type of distribution of the sites. However, a high degree of utilisation could be reached for all sites given that a suitable rated velocity was chosen. With a rated velocity close to the maximum velocity, the degree of utilisation was found to be in the range of 20% for both tidal currents and rivers with roughly 30%–40% of the kinetic energy converted. With a rated velocity closer to the mean velocity, the degree of utilisation increased as expected. The interesting result is that the ratio of maximum to rated velocity was still quite low. For tidal currents, an average degree of utilisation of 45% was achieved while the ratio of maximum to rated velocity was 1.6. Unregulated and regulated rivers gave an average degree of utilisation of 52% and 57% with a ratio of maximum to rated velocity of 1.2 and 2.0, respectively.

A suitable rated velocity will likely be found in between the two methods presented in this paper. Nevertheless, it can be concluded that both the tidal currents and the rivers studied in this paper offer velocity distributions that can give a relatively high degree of utilisation while the ratio of maximum to rated velocity remains low.

Since it is desirable to remain at a low ratio of U_{max}/U_{rate} when choosing a site, the velocity factor, which gives U_{max}/U_{rate} at the desired degree of utilisation, is suggested as a measure of the suitability of the site.

ACKNOWLEDGMENTS

The work reported was financially supported by the Swedish Centre for Renewable Electric Energy Conversion, STandUP for Energy, CF's Environmental Fund and the Swedish Research Council (Grant No. 621-2009-4946). The author's would also like to thank Vattenfall AB for providing discharge data.

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