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TECHNICAL SPECIFICATION

Marine energy – Wave, tidal and other water current converters –
Part 301: River energy resource assessment

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Marine energy – Wave, tidal and other water current converters – Part 301: River energy resource assessment

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MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 301: River energy resource assessment

FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62600-301, which is a technical specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
114/285/DTS	114/301/RVDTS

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy - Wave, tidal and other water current converters*, can be found on the IEC website.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be:

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

The extraction of energy from flowing water in rivers and canals is gaining acceptance around the world as a means of generating electricity without the use of conventional hydropower dams. The purpose of this document is to provide a uniform methodology that will ensure consistency and accuracy in the estimation, measurement, characterisation, and analysis of the river-velocity resource at sites that could be suitable for the installation of an individual or array of River Energy Converters (RECs), together with defining a standardised methodology with which this resource can be described and reported. Application of the estimation, measurement, and analysis techniques recommended in this document will ensure that resource assessment is undertaken in a consistent and equitable manner. This document presents techniques that are expected to provide fair and suitably accurate results that can be replicated by others. This document is intended to be updated as understanding of the resource and its response to power extraction improves.

The overall goal of the methodology is to enable calculation of the Annual Energy Production (AEP) for the proposed individual or array of river energy converters either as part of a feasibility study (generic river energy converter) or a full study. For the full study, this methodology is employed in conjunction with IEC TS 62600-300 applied at each river energy converter location. Consistency is also maintained with IEC TS 62600-201 wherever possible.

In this document, the river energy resource (undisturbed or disturbed by power extraction) is defined by the velocity duration curve. This document describes only the aspects of the resource required to calculate the velocity duration curve and it does not describe aspects of the resource required to evaluate design loads or to satisfy environmental regulations. Furthermore, this document is not intended to cover every eventuality that may be relevant for a particular project. Therefore, this document assumes that the user has access to, and reviews, other relevant IEC documentation before undertaking work (e.g., surveys and modelling), which could also satisfy other requirements.

MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 301: River energy resource assessment

1 Scope

This part of IEC 62600 provides:

- Methodologies that ensure consistency and accuracy in the determination of the theoretical river energy resource at sites that may be suitable for the installation of River Energy Converters (RECs);
- Methodologies for producing a standard current speed distribution based on measured, historical, or numerical data, or a combination thereof, to be used in conjunction with an appropriate river energy power performance assessment;
- Allowable data collection methods and/or modelling techniques; and
- A framework for reporting results.

The document explicitly excludes:

- Technical or practical resource assessments;
- Resource characterisation;
- Power performance assessment of river energy converters; and
- Environmental impact studies, assessments, or similar.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1: Terminology*

IEC TS 62600-201, *Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization*

IEC TS 62600-300, *Marine energy – Wave, tidal and other water current converters – Part 300: Electricity producing river energy converters – Power performance assessment*

ISO 1100-2:2010, *Hydrometry – Measurement of liquid flow in open channels – Part 2: Determination of the stage-discharge relationship*

ISO 9825:2005, *Hydrometry – Field measurement of discharge in large rivers and rivers in flood*

ISO 15769:2010, *Hydrometry – Guidelines for the application of acoustic velocity meters using the Doppler and echo correlation methods*

ISO 18365:2013, *Hydrometry – Selection, establishment and operation of a gauging station*

ISO TS 19130-2:2014, *Geographic information – Imagery sensor models for geopositioning – Part 2: SAR, InSAR, lidar and sonar*

ISO TR 24578:2012 *Hydrometry – Acoustic Doppler profiler – Method and application for measurement of flow in open channels*

ISO/IEC 98-1;2009, *Uncertainty of measurement – Part 1: Introduction to the expression of uncertainty in measurement*

ISO/IEC 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM: 1995)*

IHO (International Hydrographic Organisation), 2008, *Standards for Hydrographic Surveys. Special Publication No. 44. 5th Edition*

ICES, 2006, *Guidelines for Multibeam Echosounder Data*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
equivalent diameter
<of a river energy converter> diameter of a circle with area equal to the device **projected capture area**

3.2
power-weighted speed
<of a river energy converter> mean current speed derived with the weighted function of the cube of the speed across the **projected capture area**

3.3
principal flow direction
<of a river current> primary orientation or heading of the **river current**

3.4
project blockage ratio
<of a river energy converter> ratio of the sum total of the flow-facing area of the moving and non-moving parts of all **river energy converters** divided by the average channel cross-sectional area

Note 1 to entry: The average cross-sectional area is calculated by dividing the volume of the fluid in the river energy converter site, determined from bathymetry subject to the lowest operational flow, by the length of the project site along the direction of flow.

3.5
project site
<of a river energy converter> portion of the river within which **river energy converters** and their entire supporting infrastructure are located

3.6
projected capture area
<of a river energy converter> frontal area perpendicular to the **principal flow direction** of **river energy converter** components hydrodynamically utilised in energy conversion

4 Symbols, units and abbreviated terms

4.1 Symbols and units

a, b	Linear fit coefficients for index rating (–)
A	Projected capture area of the REC (m^2)
$A_{i,k}$	Area of current speed bin *i*,*k* (m^2)
$A(h)$	Cross-sectional area of the river as a function of water level, *h* (m^2)
B	Number of current speed bins (–)
B_i	Width of the i^{th} bin for the VDC (–)
d	River depth (m)
D_E	Equivalent diameter (m)
EP	Energy production (kW)
F	Exceedance probability (%)
Fr	Froude number (−)
h	River water level (stage) (m)
i	Rank (–)
I	Turbulence intensity (–)
k	Index number across the vertical dimension of current speed bins (–)
n	Number of discharge (or velocity) measurements (–)
N_B	Number of velocity bins for the VDC (–)
N_h	Number of hours in the month or year of interest (–)
$P_i(U_i)$	Power according to the REC power curve (kW)
Q	Discharge (m^3/s)
S	Total number of current speed bins (–)
U_i	Speed of the i^{th} bin from the VDC (m/s)
$\hat{V}$	REC power-weighted speed
V_{avg}	Average velocity for a river cross section (m/s)
V_i	Index velocity (m/s)
$V_{i,k}$	Speed of the river velocity at current speed bin *i*,*k* (m/s)

4.2 Abbreviated terms

ADV	Acoustic Doppler velocimeter
AEP	Annual energy production
CP	Current profiler
EP	Energy production
FDC	Flow duration curve
GPS	Global positioning system
IEC	International Electrotechnical Commission

IHO International Hydrographic Organization

ISO International Organization for Standardization

MEP Monthly energy production

MV Moving vessel

NTP Network time protocol

PST Phase space thresholding

REC River energy converter

RTK Real time kinetic

TS Technical specification

VDC Velocity duration curve

5 Methodology overview

5.1 Study classification

Two types of studies are covered in this document: a full study and a feasibility study. The distinction between the two is based on the amount of information available for the RECs to be employed (i.e., whether it is a generic REC or has been extensively characterised with regard to its performance). To complete the analysis, the following details of the REC shall be available:

- REC dimensions including position in the water column and swept area;
- REC power curve with specified freestream measurement location;
- REC operational range; and
- REC thrust coefficient (for projects that include modelling energy extraction by the REC).

For the full study, REC data are supplied by the manufacturer following IEC TS 62600-300. For the feasibility study, a generic REC is chosen and all supporting device data shall be presented with justification in the report. The power and thrust coefficient shall be defined as a range and therefore the feasibility study will result in an AEP range.

5.2 Project location identification

There is no required methodology for identifying particular project locations. This document assumes that a project location has already been identified; however, some or all of the methods outlined herein may be used to assist with project-location identification.

In this document, projects are considered small when the project blockage ratio is less than 5 %. Projects with blockage ratios greater than 5 % are considered large.

5.3 Resource definition

This document describes the methodology for the resource assessment, which consists of the determination of the VDCs required for computing the AEP for individual or arrays of RECs.

5.4 Methodology

5.4.1 General

The resource assessment requirements are defined depending on the scale of the project relative to the scale of the resource at the project location as well as the availability of measurement data of sufficient quality and duration relative to the annual hydraulic cycle. The resource assessment may be undertaken based upon exclusive use of site data or upon numerical-model simulations used in conjunction with direct measurements for model calibration and validation. A combination of measurements and numerical models may be used to generate the required data for different parts of the resource assessment.

The following assumptions are made:

- The turbines are operating, therefore excluding impact of maintenance or technical issues on the resource assessment;
- The turbines are operating in steady flow. Transient flow conditions due to flooding or due to human impact such as filling or draining of a reservoir are excluded; and
- The turbines are operating in subcritical flow, i.e. with a Froude number smaller than 1:

$$Fr = \frac{V_{avg}}{\sqrt{gd}} < 1 \quad (1)$$

where

V_{avg} is the average velocity,

g is the gravitational acceleration, and

d is the water depth.

NOTE While installation in supercritical flow, such as at rapids may be feasible, this type of installation would most likely be small scale due to the nature (shallow, highly localised, high-velocity flow) of such flow systems. Further, a turbine-triggered hydraulic jump is likely, however, capturing this effect in a model is challenging, and could lead to significant error in the resource assessment.

The flowchart in Figure 1 outlines the methodology for performing the resource assessment. The flowchart maps the multiple viable pathways through the methodology (centre of flowchart) and includes all requirements (left and right sides of the flowchart). The rectangles represent the required goals of the resource assessment, the ovals represent the different paths to achieve these goals, and the rounded rectangles represent the measurements required to support each step of the process. Table 1 outlines the various measurements, their purpose, the minimum quantity, and the standardised collection method.

5.4.2 Flow duration curves

A flow duration curve (FDC) quantifies the percentage of time that the discharge in a river exceeds a particular magnitude typically compiled on a monthly or annual basis. To produce the FDC, at least 10 out of the previous 15 years of discharge and water-level field data for the project site shall be used. If the specified minimum duration of field data is not available, regional hydrological modelling shall be performed to develop at least 10 years of data, validated with at least one year of discharge measurements. This document describes the acceptable methodology for collecting the necessary field data, performing the model simulations, and creating the FDC based on measured (6.2) or modelled (6.3) data.

5.4.3 Velocity duration curves

5.4.3.1 General

A VDC quantifies the percentage of time that REC power-weighted speed at a REC location exceeds a particular value. The relationship between the river discharge and the corresponding speed at each REC location needs to be ascertained to develop the VDC. For small projects (project blockage ratio less than 5 %) where each REC has at least 10 D_E downstream spacing, and where no flow modification for enhancing the power is incorporated, the VDC may be estimated from direct hydrodynamic measurements as described in 7.2.

For all other projects, the VDC shall be assessed by hydrodynamic modelling including the effect of energy extraction with appropriate verification by measurements. Of course, even small projects may implement the hydrodynamic modelling required for larger projects. If the resource assessment reveals that RECs should be deployed in different locations where field data have not been collected, then a combined data-collection and modelling effort focused on the new REC locations shall be implemented.

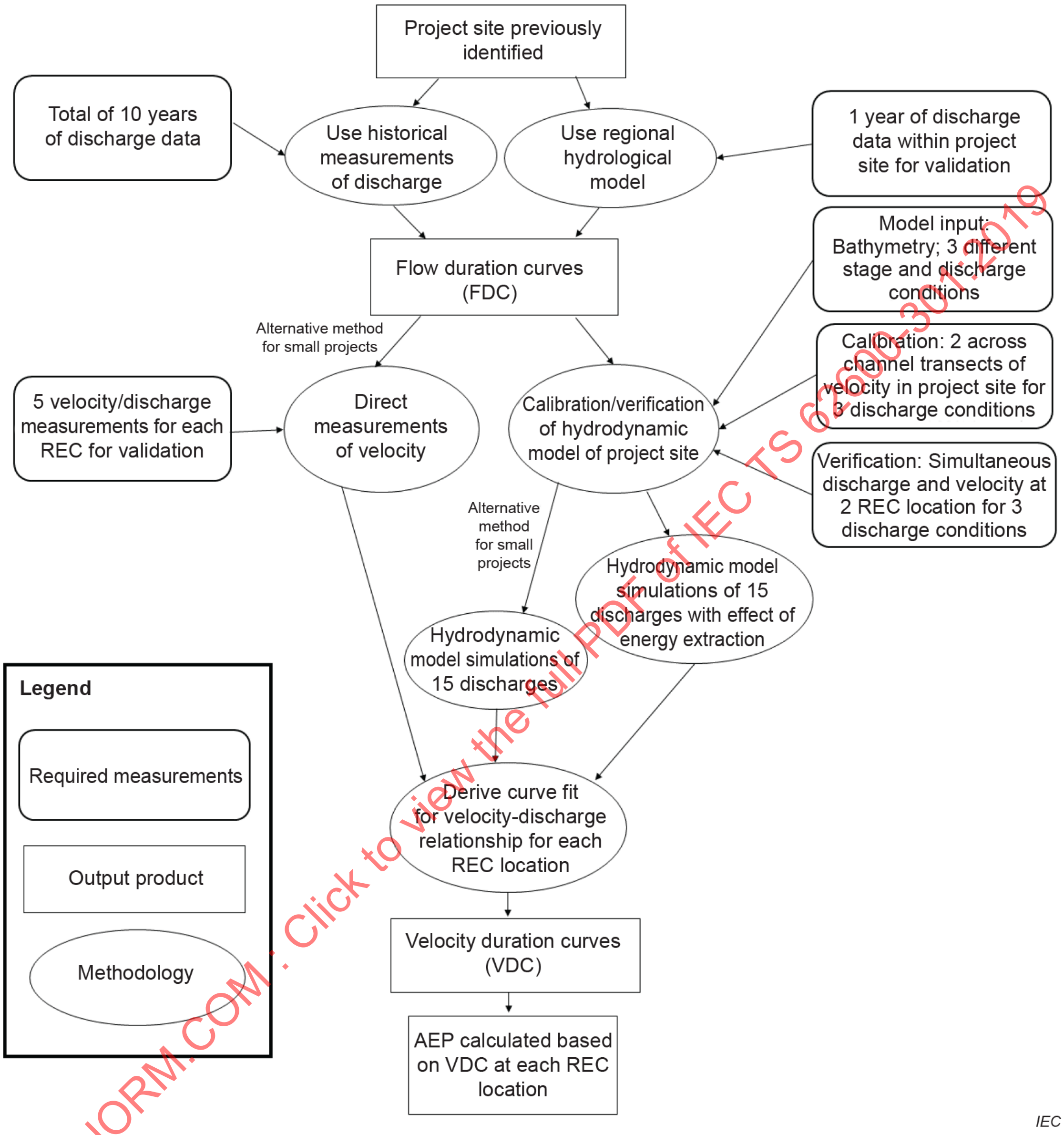


Figure 1 – Flowchart outlining the methodology for a resource assessment

Table 1 – Outline of measurements

Types of measurements	Purpose	Number of measurements	Method	Clause
Discharge	Measurement FDC	10 years of daily field data	ISO 1100-2, ISO 18365	A.3
	Hydrology model FDC	1 year of daily field data for validation		
	Boundary conditions for hydrodynamic model validation	3 different discharges for each calibration (i.e., high-flow, median-flow, and low-flow calibrations)		
*Water level	Boundary condition and calibration of the hydrodynamic model	Upstream and downstream boundaries and within the project site during discharge measurements	ISO 18365: 2013	A.2
Bathymetry	Cross-sectional data Field data for the hydrodynamic model	At least 1 set (more if river morphology is seasonal and multiple model grids are used)	IHO, S-44: 2008	A.1
*Cross-section velocity contour *Cross-channel transects of flow velocity	Calibration of the hydrodynamic model	4 transects for each river cross-section, for each discharge used in the calibration	Vessel or in situ, ISO 15769	A.4.2
Vertical distribution of velocity at REC location	*Validation of hydrodynamic model	2 REC locations for each of the 3 discharge conditions	Vessel or *in situ*	A.4.1
	Computation of VDC from measurements	5 velocity/discharge measurements from each REC location		
*Turbulence	Optional for the hydrodynamic model	Each discharge	Vessel or *in situ*	A.5
*Only needed for projects using hydrodynamic models to compute the VDC as defined in 7.3.				

5.4.3.2 Direct measurement method

This document describes the acceptable methodology for collecting velocity and water-level data in 7.2. Velocity data shall be collected at each REC location, but the water-level data (stage) may be obtained anywhere within the project site. Total-discharge data shall be collected simultaneously with the water-level and velocity field data to determine the relationship between the current speed, water level, and discharge, which is then used to develop the VDC.

5.4.3.3 Numerical modelling method

This document describes the acceptable methodology for determining the current speed/discharge relationship based on numerical-model simulations in 7.3. First, the required hydrodynamic model features are described, then the model inputs and required field data are stipulated. The model shall have sufficient grid resolution to resolve individual REC locations. Calibration field data consist of water-level measurements within the project region and cross-channel transect measurements of current velocities. The model may have separate calibration parameters (e.g., horizontal and vertical momentum diffusivities, eddy viscosities, etc.) for different flow conditions; however, the model shall be validated for each set of calibrated parameters with independent direct measurements of the vertical profile of velocity at an individual REC location for three different discharges. Verification field data consists of velocity data at two or more REC locations for three different discharges. The validated hydrodynamic model shall be run for at least 15 different discharge conditions spanning the FDC to develop the corresponding VDC at each REC location. If required, the effects of REC emplacement and operation shall be included in the model simulations used to develop the VDC.

5.4.4 Energy production

The methodologies for computing the expected energy production (EP) for each month along with the expected AEP are described in Annex B.

6 Flow Duration Curves

6.1 General

To estimate the hydrokinetic resource of a river segment with adequate reliability, a significant quantity of measured or model-generated discharge data shall be compiled. Although an FDC can be developed for any period of time, at least 10 years of data are required to ensure a stationary curve because hydrologic and climatic variability can lead to substantially different flow regimes over the course of just a few decades. Stationarity means that hydrological variables fluctuate randomly and have time-invariant probability density functions, whose properties can be estimated from an available record. For example, 10 years of data would take into account the impact of large-scale atmospheric circulation phenomena, for example the El Niño Southern Oscillation (ENSO), on basin-scale hydrology. If consecutive field data are not available, 10 out of the last 15 years are acceptable, but all available field data shall be used. Shorter than 10 years of field data sets can be augmented using outputs from a hydrologic model.

NOTE In all FDCs, low flows are exceeded most of the time while high flows are infrequently exceeded. The x axis (abscissa) indicates the percentage of time (or probability/frequency of occurrence) that a particular discharge exceeds the corresponding discharge on the y axis (ordinate). On the FDC, the highest discharge in the record (i.e., the period-of-record flood) is found close to 0 on the x axis and the lowest recorded discharge, which may be zero, is found closer to 100 %.

Nonstationarity of the hydrologic regime, such as climate change and human intervention in the river basin, is a complicating factor. Existing climate models and trend analysis from short hydrological records are often not reliable and detailed enough to project changes in flows. It is difficult to predict how the climate change will affect the watershed and such changes cannot be estimated with a sufficient accuracy from short hydrologic records.

6.2 Measurement-based Flow Duration Curve

Continuous daily stage-discharge measurements for at least 10 years (for each month of the year) shall have been collected over the most recent 15 years. Intermittencies (sporadic outages) are acceptable so long as these omissions do not exceed 5 % of the data set; measurement years are not required to coincide with calendar years. These stage-discharge data shall be available on a daily basis. Higher frequency (e.g., 15 min) data can be used, but they should be converted to daily-average stage-discharge data.

Any modifications to the river near the project site (e.g., diversions, reservoirs, vegetation removal, land-cover or land-use changes, pumping, etc.) including natural modifications (e.g., landslides, forest fires, etc.) need to be taken into account when reviewing the suitability of available field data. Data collected prior to permanent (e.g., dams) or during temporary significant changes (e.g., landslide) in the river shall be excluded.

In general, obtaining direct continuous measurements at the project site is the preferred approach because this facilitates the most accurate analysis. In some cases, long-term field data may be available at the project site. However, if long-term field data are available at a nearby (surrogate) site, they may be used if the FDC derived from the project site (so long as it is composed of at least one year of data) is within 10 % of the FDC at the surrogate site.

This implies that the flow at the two sites is not altered by dams/weirs or through merging/forking of tributaries.

Long-term data will usually be in the form of stage-discharge data (i.e., water-level measurements and corresponding discharge). For these data to be viable for resource assessment, an accurate stage-discharge relationship needs to be established (see Clause A.4).

6.3 Hydrologic modelling

6.3.1 General

When only limited measurement data are available at a project site, hydrologic modelling can be used to develop the FDC. Hydrologic modelling can help avoid expensive long-term field data collection campaigns. However, to validate the hydrologic model, a minimum of one year of discharge data will need to be collected at the project site.

There are two general categories of hydrologic models: deterministic and stochastic as conceptualised in Figure 2. Recently, hybrid models that combine elements of both types of modelling approaches have also been suggested [Corzo Perez, 2010]. Any type of hydrologic model that satisfies the specified accuracy requirements may be used for simulating flows and then computing the corresponding FDC and VDC. The following subclause details the desired requirements and accuracies when applying models in this context.

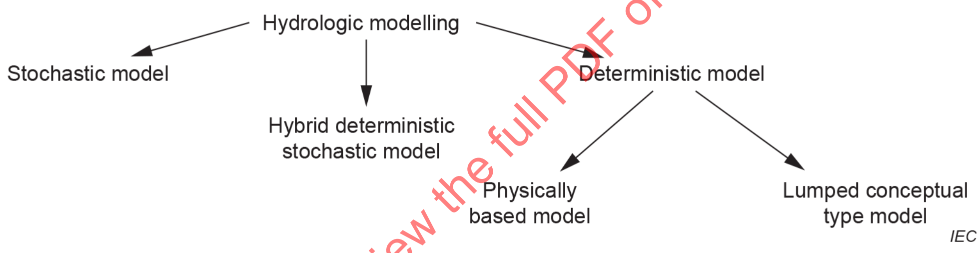


Figure 2 – Types of hydrologic models for simulating discharge

6.3.2 Stochastic modelling

Statistical regionalisation approaches are sometimes used to estimate FDCs at sites where limited or no discharge measurements are available. Compared to regional flood-frequency analyses commonly used in hydrology, regionalisation of FDCs is performed less often. Despite numerous advantages to the regionalisation approach, appropriate validation of estimated FDCs at ungauged sites remains a challenge. The selected modelling approach and associated field data shall be justified.

When estimating FDCs for ungauged watersheds, the following steps should be considered:

a) Identify gauged watersheds similar to the target, ungauged watershed within the surrounding large geographic/hydrologic/climatic region and/or within the attribute space. In hydrology, this process is called neighbourhood selection (i.e., identification of a homogeneous region). A neighbourhood shall be selected from within the same geographic/hydrologic/climatic region where the ungauged site is located. There are several ways of accomplishing this task such as using the region-of-influence approach, canonical correlation analysis, cluster analysis, or variants of these approaches [Burn, 1990; GREHY, 1996; Hosking and Wallis, 1997; Zrinji and Burn, 1994].

b) Develop regional relationships of FDC characteristics and watershed attributes from locations with available field data and transfer those relationships to ungauged locations. Some of the techniques used for this purpose include the index-flood method, drainage-area-ratio methods, parametric characterisation of FDCs, statistical characterisation of FDCs, graphical characterisation of FDCs, nonlinear spatial-interpolation techniques, regression-based logarithmic interpolation, multiple linear/nonlinear regression methods, etc.

c) Select representative FDCs (i.e., 50 % exceedance probability) for the site. The selected FDCs shall be justified and validated with a minimum of one year of site discharge field data.

In general, any suitable stochastic modelling approach that satisfies study objectives can be selected. However, approaches differ with respect to input data requirements. Therefore, it is important to explore all available data sources (e.g., physiographic, climatic, soil, land-cover type, and geological attributes) and their reliability before making a final choice. It is also important to make a detailed comparison of the underlying modelling assumptions in light of available field data sources.

It is recommended that several techniques (e.g., those mentioned above under item b) be selected to estimate the FDC at ungauged sites. If these estimates differ significantly, justification for the selected technique is required – typically based on the results of cross-validation assessments. Cross-validation (also called the jackknife approach) is currently the best way to evaluate reliability of a selected method in this context [Efron, 1983; Hirsch, 1991; Stone, 1974]. With respect to the choice of a method, combinations of the above-mentioned approaches that result in reduced uncertainty based on cross-validation testing are preferred.

6.3.3 Deterministic modelling

Deterministic models simulate flows by modelling various physical processes in a watershed. These models are classified as:

- Physically based models (sometimes referred to as distributed models): These models describe the process of runoff generation within a watershed based upon topographic, vegetation, soil type, land cover, relief, and other related physical features of the watershed, with meteorological data as forcing functions. Parameterisation typically varies across watershed models. Hence, physical models of the watershed are often referred to as distributed models.
- The data sets required as inputs for physical modelling include:
  - Meteorological inputs (precipitation, solar radiation, wind speed and direction, humidity, atmospheric pressure, temperature, etc.);
  - Land use, soil type, vegetation (all at a minimum of 1 km resolution); and
  - Topography based on a digital elevation model (DEM) (e.g., surface slope, aspect, channel slope, etc.). The resolution of the required DEM depends upon the location of the watershed. For example, for a relatively flat basin, 500 m resolution may be appropriate while for a mountainous region, 30 m resolution is better. Given the varied resolutions of DEM data, the modeller shall justify their selection of resolution.

When employing physically based models, observed discharge rates are primarily used for validation. However, if some parameters of the model require calibration, then a part of the observed records can be used for calibration purposes.

- Lumped-conceptual-type models: These models conceptualise the entire catchment as a single, homogeneous unit and characterise the various physical processes occurring in that catchment (e.g., surface runoff, interflow, groundwater flow, routing, etc.) using a single set of parameters and following a conceptual framework that rigorously applies continuity and water-balance constraints. Although lumped models are simple to develop, parameter calibration (e.g., the proportion of rainfall less evaporation that contributes to surface runoff and the proportion that infiltrates and then, in turn, contributes to interflow and groundwater flow) is required to improve quality of simulated discharge rates [Singh and Frevert, 2002; Viessman Jr. et al., 1977].

The required output from the deterministic model is the average daily discharge (the model is run with no larger than one-day time steps), which is then used to compute the FDC. One of the important requirements when using a deterministic model to generate an FDC based on simulations is that the model needs to be validated against no less than one year of recorded field data from the project site. Other factors important in model selection include data demands, computing requirements, scale of application, and ease of model setup.

NOTE 1 The time and effort to setup a physically based model is often 5-10 times greater than that required for a lumped-conceptual-type model.

NOTE 2 In addition to modelling an entire watershed, deterministic models can also be set up for partial watersheds or separately for each sub-reach of a larger watershed. This is generally done to improve local model accuracy.

NOTE 3 Common deterministic hydrologic models include: VIC, DHVSM, RORB (Australia), Xinanjiang (China), Tank (Japan), ARNO (Italy), TOPMODEL (UK), UBCWM (Canada), HBV (Scandinavia), HBV-EC (Canada), MOHID Land (Portugal), GSSHA (USA), Vflo (USA), SWAT (USA), PRMS (USA), SWIM (USA), HEC-HMS (USA), WATFLOOD (Canada), MIKE-SHE (Denmark), and HSPF (USA), to name a few.

The hydrology model shall be validated by at least one year of measured discharge data within the project site. This validation data may coincide with the time period simulated for generating the full FDC. The FDC for the one-year period of measurements shall be determined using both the measurements and model following the method outlined in 6.4. The mean square difference between the model and measurements should be less than 10 %.

6.4 Computing Flow Duration Curves

Using 10 years or more of discharge data from some combination of direct measurements and hydrologic models within the project site, an FDC is developed as follows:

- Sort and rank-order the discharge data (i.e., assign 1 to the highest discharge and n to the lowest discharge assuming n observations in the record);
- Calculate the exceedance probability for each discharge as $F = 100 \times i/(n + 1)$, where i is the rank; and
- Plot F on the y axis and discharge on the x axis.

An example of an FDC is shown in Figure 3.

To characterise the seasonal variability of EP, the intra-annual variability of the flow is quantified by developing an FDC for each month. The same procedure to develop the annual FDC should be followed by restricting data to the month of interest (e.g., including all January data from the 10-year data set). The interannual variability is quantified by computing a FDC for each year.

NOTE One reason to quantify seasonal variability of EP is open-water season months for rivers in Arctic and sub-Arctic environments, that is when the river is not ice-covered. For example, in interior Alaska this may correspond to the months of May to October.

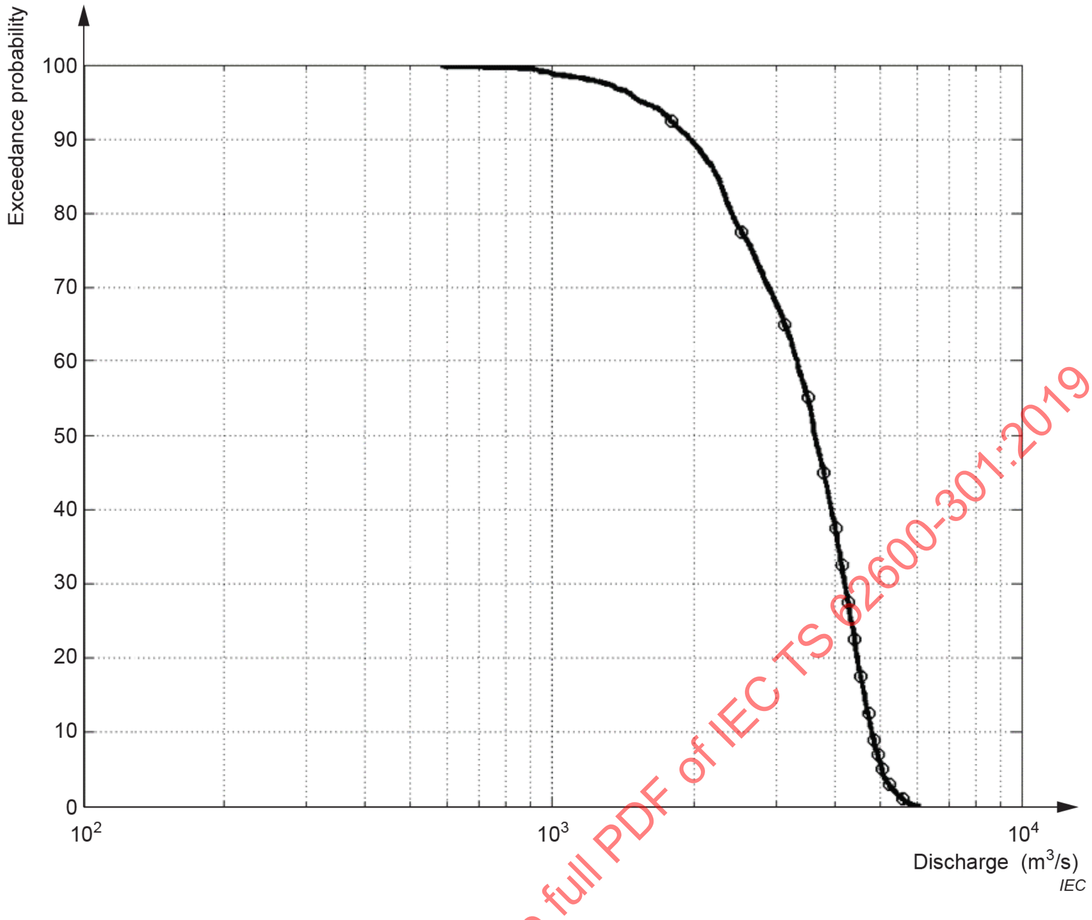


Figure 3 – Example FDC (curve) and assumed non-uniform discretisation (circles)

This document focuses on theoretical resource assessments. Downtime is often related to either a device, a river characteristic, or both. Downtime conditions are often related to the actual flow conditions, which will result in downtime regardless of the characteristics of the REC device (e.g., ice either floating in the river or covering it, low water levels, heavy bedload and/or floating debris at high-flow conditions, etc.). Downtime conditions occur when either the REC is non-operational or the REC performance is significantly influenced (potential EP decreased by more than 10 %) because of river conditions.

Downtime conditions are defined as either:

- A fixed annual period (e.g., November to April); or
- A threshold condition for one of the flow-describing parameters (e.g., discharge, velocity, water level, etc.)

The FDC can be corrected for non-productivity during downtime as follows:

- If downtime occurs during a consistently fixed annual period, this period shall be entirely excluded from each year of the 10-year dataset;
- All other observations with downtime conditions are included and shall be considered as zero-discharge conditions in the FDC;
- All further calculations (VDC, AEP, etc.) shall be handled likewise; and
- For threshold conditions, the correlation between the threshold and downtime shall be described.

7 Velocity Duration Curves

7.1 General

For small projects, if 10 years of measured velocity data are available for the REC location, then the same procedure used to develop the FDC in Figure 3 can be used to develop the VDC. For small projects were fewer field data are available, there are two acceptable approaches for transforming an FDC to a VDC at each REC location based on:

a) measurement data, or

b) hydrodynamic model data.

In general, reliability and confidence will be better with direct measurements of velocity. Either way, what results is a transfer function relating the discharge to the current speed for a given exceedance probability. Large projects are required to use a hydrodynamic model with the effect of energy extraction included.

For the direct-measurement method, the FDC shall be discretised into at least five representative current speed/discharge pairs whereas for the model method, the FDC shall be discretised into at least 15 representative pairs. These values should not be equally spaced; instead they should have increased resolution (smaller ranges) toward higher discharges (where more REC energy is generated). The discretised points shall span the full operating range of the REC from cut-in to cut-out speeds. An example is shown in Figure 4. The current speeds corresponding to these discretised discharges are determined through direct measurement or hydrodynamic modelling.

7.2 Measurement-based Velocity Duration Curve

The measurements-only technique is derived from the index-velocity method, which is commonly used when collecting discharge measurements. The traditional index-velocity method is based on the assumption that there is a relation between the cross-sectional-averaged velocity (V_{avg}) and the local velocity (i.e., the index velocity) at individual locations (V_{i}) in the cross-section and this relationship is used to determine discharge directly from single velocity measurements. The rating is established by simultaneously measuring the river discharge at a (temporary) control section and the local velocity and water level at the gauging station across a sufficiently broad range of discharge conditions. If not already in place, a semi-permanent gauging station should be established at the project site. The water level is measured to compute the cross-sectional area from the stage-area rating (i.e., $A(h)$, which can be derived from the cross-sectional bathymetric profile). From the measured discharge and the cross-sectional area, the average velocity in the cross-section can be calculated. Finally, the index rating is assigned through linear regression. Once the rating is established, only a local velocity and water level need be measured to compute the rivers discharge as:

$$Q(V_i, h) \ = V_{avg}(V_i)A(h) \qquad (2)$$

The basic form of the index rating is a linear relation. Common variations are a compound linear relation (two or more linear branches) or a multi-linear relation (velocity depends on more parameters, of which water level is the most common). For computing the VDC from the FDC, the index rating has to be inverted to calculate a local velocity from the discharge, a multi-linear relation will not work (the purpose is to convert the FDC into a VDC, but the FDC does not relate the discharge to any other parameter). Before choosing the index-velocity method, it is important to check for conditions that are likely to cause dependencies on other parameters. After the data have been collected it should be shown that there are no significant correlations with other parameters (e.g., water level), which is generally demonstrated with a regression analysis.

Because the method is not limited to a single location, it can be used to derive velocity ratings for multiple planned REC locations (e.g., by mounting a velocity meter and GPS to a boat or by placing a velocity meter at each planned REC location). The technique can be used to directly calculate the VDC from the FDC without resorting to computational modelling.

The FDC is representative for a river reach with steady-state condition. The VDC is location-specific. For a REC array, one FDC is sufficient for all RECs if the reach is short enough such that discharge does not change by more than 5 % along its length. The VDC, however, is location-specific and should be calculated at each planned REC emplacement based on individual index-velocity ratings.

The measurements-only technique can be applied when:

- The impact of the REC(s) on the velocity field can be neglected because the project blockage ratio is less than 5 %, each REC has at least 10 D_E downstream spacing, and no flow modification for increasing the power is incorporated, refer to 5.4.2;
- The index-velocity rating is independent of any parameter other than the discharge and is stable over time (stationary); and
- The stage-discharge rating is independent of any parameter other than the discharge and does not change over time (stationary).

To derive index-velocity and stage-discharge ratings, the following data are required: simultaneous measurements of water level, river discharge, and local velocity at the REC location(s), and for five different flow conditions if a stage-discharge rating is already available. The local velocity should be time-averaged over a sufficient duration to minimise velocity variations caused by large-scale eddies, but also short enough to ensure that the velocity during the time window is quasi-stationary [Gunawan et al., 2014b]. Analysing the velocity can be done by averaging the velocity data over different temporal averaging windows and plotting the averaging windows on the *x* axis and velocity magnitude on the *y* axis. The averaging window at which the velocity magnitude converges (within 5 %) corresponds to the required sampling time to achieve a stable mean velocity. Averaging windows that range from 3 to 15 min are appropriate for rivers and tidal channels [Barua and Rahman, 1998; Gunawan et al., 2014a; Muste et al., 2004; Petrie et al., 2013; Szupiany et al., 2007]. For consistency, all other quantities will also need to be averaged over the same temporal window used for velocity averaging.

NOTE 1 For building a stage-discharge rating many discharge measurements are used. These measurements can easily be combined with local velocity measurements at the REC location(s) to improve the index-velocity rating.

The temporally averaged velocity profile shall be used to compute the REC power-weighted speed to be used as the index velocity.

The measurements should span the full range of discharge within the FDC that produces speeds within the operational range of the REC. The operational range can be determined either by the characteristics of the REC, the river, or both. On the high-speed end it is not necessary to record extreme flow conditions that occur less than 5 % of time. In the VDC, the speeds shall be maximised to the level of the maximum observed current speed. Although it is not strictly necessary to capture extreme flood events, it may give useful additional information, especially when the cross-sectional area during these events is subject to significant changes due to increased sediment transport.

The rating should be validated with at least three additional measurements at significantly different flow conditions. Validation measurements should be taken at least six months before or after the measurements used for deriving the index rating, but no more than two years before AEP is calculated. The absolute error between the predicted and measured current speed should be less than 10 % of the measured current speed.

A cross-sectional profile of the bathymetry at the REC location(s) should be validated according to the local bed activity (sediment dynamics that change the morphology). If the bathymetry changes significantly between measurements (average cross-sectional depth changes by more than 5 %) then the cross-sectional profile should be remeasured. Using the measured cross-sectional profile, the area is computed as a function of water level and the average velocity is found from the discharge:

$$V_{avg} = \frac{Q(h)}{A(h)} \qquad (3)$$

Both the index-velocity rating and the stage-discharge rating should be established following the directions of ISO 18365:2013.

Gauging stations frequently apply the index-velocity method when the stage-discharge method is not feasible (e.g., if there is no stable rating). This means that one should be cautious when using data from velocity-discharge gauging stations and ensure that there is a stable stage-discharge rating.

For specification of the VDC, the inverse rating is used to calculate the local velocity at the REC location from river discharge. Because discharge at the gauging station is calculated from both water level and velocity when developing the VDC from the FDC, a stage-discharge rating is also needed. For a linear index-rating:

$$V_{avg} = aV_i + b \qquad (4)$$

the inverted rating is:

$$V_i = \frac{1}{a}\left(V_{avg} - b\right) = \frac{1}{a}\left[\frac{Q}{A(h(Q))} - b\right] \qquad (5)$$

NOTE 2 An extensive description on building an index-velocity rating is available [Levesque and Oberg, 2012] that provides specific directions for planning and executing the field measurements and for performing the regression analysis for building the rating curve.

7.3 Hydrodynamic-model-based Velocity Duration Curve

7.3.1 General

A numerical hydrodynamic model may be used to produce the required relationship between discharge and current speed at each REC location. The numerical model shall be calibrated and validated (as discussed in 7.3.10) using direct measurements of discharge, velocity and water levels. If regular seasonal changes in the river morphology are directly linked to specific discharge rates, multiple grid and bathymetry combinations may be established, provided each one is independently calibrated and validated. Once the model has been established, the discharges needed to populate the discretised FDC are simulated to provide the necessary data for computing the discharge and current speed relationship for each REC location.

7.3.2 Model selection

Because discharge characteristics of a river subject to REC operation will be discretised according to the FDC, only steady-state calculations for various quantiles of discharge are required (although transient models are acceptable). Because acceptance of the model by regulators and stakeholders is an important consideration, the software code shall be well established, released in a stable version, and have a demonstrated track record of success through peer-reviewed citations. The model can be based upon either a structured (i.e., rectangular or curvilinear orthogonal) or an unstructured/flexible grid/mesh depending upon the software selection and domain complexity. The model should solve the Reynolds-averaged Navier-Stokes equations with the shallow water equation for the free surface or something comparable (e.g., full Navier-Stokes solution with the volume-of-fluid approach to track the free surface). The model shall include some form of a turbulence closure scheme (e.g., k-ℓ, k-ε, k-ω, large eddy simulation, or the like). It is important to consider turbulence even in riverine systems as Blackmore et al. [2014] demonstrated the importance of turbulence intensity on wake recovery. The higher the turbulence intensity, the faster the wake dissipates downstream of the REC device. The model should be parameterised to include bottom roughness, appropriate horizontal and vertical momentum diffusivities/eddy viscosities, turbulence parameters, etc. If required due to the project blockage ratio (project size) or if power generation estimates are to be made, there shall also be appropriate representation of REC devices as momentum (energy) sinks and also as sources of turbulence and its length scale or dissipation rate.

The model shall provide a fully three-dimensional representation of the river, although selection of the model is at the discretion of the modeller.

NOTE At the time of this writing, models that can simulate large domains (typically not CFD models where, for example, rotating turbine blades are explicitly simulated) known to admit hydrokinetic turbines as momentum sinks include CCHE3D, Delft3D, EFDC, FVCOM, MIKE3D, ROMS, and Telemac-3D (although others may be available).

7.3.3 Model domain

The upstream and downstream boundaries need not be symmetric because REC effects are primarily manifest as an increase in upstream water level and because most models will specify a downstream water-level boundary condition. Downstream of the REC devices, it is important to capture the wake characteristics, but wake effects dissipate after approximately 25 D_E [Polagye, 2009].

For a small project, the three-dimensional river domain should extend upward from the upstream project-site boundary by at least 1 500 m (or to an upstream flow-control structure if closer) and downstream from the project-site downstream boundary by no fewer than 500 m (or to a downstream flow-control structure if closer). For a large project, the river domain should extend upward from the upstream site boundary by at least 5 000 m (or to an upstream flow-control structure if closer) and downstream from the downstream boundary by no fewer than 1 000 m (or to a downstream flow-control structure if closer). The overarching requirement is that the water-surface elevation and velocity profiles are fully developed within the project site and that boundaries are remote from any changes due to effects from RECs when they are included.

7.3.4 Grid resolution

a) General: Model resolution shall be detailed and justified. Also, model refinement should occur as more data become available, such as improved bathymetric resolution, riverbed characterisation, and validation data (e.g., water levels and velocity profiles).

b) Grid resolution: Grid resolution may be variable with higher resolution required within the footprint of the project site. In the domain of interest, grid cells should not be sized more than approximately twice the D_E of the REC device. Near the model boundaries, grid resolution may be coarsened to up to 25 D_E of the REC device. Vertical resolution shall be established such that accurate vertical velocity profiles are captured. Vertical velocity profiles are defined as the variation of the horizontal velocity as a function of water depth. This should be no less than five layers (defined as the vertical resolution of the numerical mesh) although some models may require more. Model layers shall be specified such that the vertical dimension of the REC device is no less than three model layers in the project area.

c) Grid convergence: A grid-convergence study shall be conducted to ensure that the numerical grid is sufficiently refined such that numerical truncation errors and numerical dispersion are small. Specifically, for the grid that is ultimately used for production modelling, it should be refined such that it has a Grid Convergence Index (GCI) of less than 6 % for both water level and depth-averaged current speed at a location of a REC device. Roache [1994] carefully outlined the development of the GCI and a target of less than 6 % should be achievable for all first-order models when going from a coarse to a fine grid and doubling the resolution. If doubling the grid refinement is not possible for a large model, a fine grid may be coarsened, and a GCI of less than 3 % would be required upon halving the resolution. To ensure sufficient vertical resolution, vertical refinement (often layers) should be added until the current speed at the water surface changes by less than 5 % upon adding refinement (or a layer). The positions in the model where grid convergence is verified should correspond to potential REC deployment locations.

When modelling the system without REC devices, the maximum grid resolution within the project site should be approximated twice the D_E of the device intended for emplacement. If the project requires that the REC devices be explicitly included in the model, it should span an odd number of cells: at least one, preferably three, or even up to five or more. This ensures that the characteristics of the wake at the centreline are symmetric. Avoid using an even number of cells to define a single device in the direction perpendicular to flow so that the wake can be optimally interrogated.

7.3.5 Model inputs

7.3.5.1 Bathymetry

Bathymetry field data should be collected according to the specifications outlined in the Clause A.1. Bathymetry data shall be interpolated onto the model grid. The bathymetry and grid should be visualised in reference to a satellite image of the site to ensure consistency with regards to the river course and riverbanks. As bathymetric data improve over the course of the project (e.g., using a multibeam echosounder), updated bathymetries should be applied to the model grid. The model grid should not be refined below the minimum resolution of the bathymetric data.

NOTE A standard inverse distance to a power-weighting scheme is appropriate to interpolate bathymetric data onto the model grid. Other approaches such as Kriging [Isaacs and Srivastava, 1989; Kitanidis, 1996] are acceptable.

If measurements indicate a significant seasonal variation in the channel morphology (e.g., widening, shifting, deepening, or shallowing), then multiple bathymetric surveys should be conducted and multiple grids based on the distinct bathymetries should be developed. Each model using a distinct grid should be independently calibrated and validated.

It is not necessary to create additional grids to simulate conditions for which the REC will not be operating such as current speeds below the cut-in speed or when too much debris is in the river.

7.3.5.2 Tides

Because this specification is for riverine hydrokinetic energy sites and a valid stage/discharge relationship needs to be developed, tides are not considered. The importance of the tidal influence may be determined by evaluating the water level under maximum (spring) tide conditions during an average discharge condition. If tidal flows are important, such that the maximum tidal amplitude is greater than approximately 5 cm, then the influence of tides should be considered using IEC TS 62600-201.

NOTE Probability distributions for current speeds will not be a simple superposition of the tidal and riverine flows because this would neglect the important nonlinear interactions between the tides and steady flows.

7.3.5.3 Meteorological impacts

With minimal fetch length (distance over which wind shear acts to alter currents, waves, and discharge) and specified discharge (upstream) and water level (downstream) boundary conditions, there is little chance that wind or atmospheric pressure changes will significantly impact the site. Unless compelling reasons exist to include meteorological forcing at the site, this may be omitted from the simulations.

7.3.5.4 Turbulence

The model shall be able to represent turbulence (e.g., k-ℓ, k-ε, k-ω, large eddy simulation, or the like). If it is possible to specify the inlet turbulence intensity, then the modeller should do so in accordance with measured turbulence data. If turbulence data are not available, then typical values of turbulence intensity in rivers (i.e., ~0,05 to ~0,2) may be used as an initial value for running the model. Neary et al. [2013] have measured turbulence data in rivers and flumes including their variations over the flow depth. Stationary acoustic Doppler velocimeter (ADV) measurements, for example bed-mounted using a frame [Gunawan et al., 2014b; Thomson et al., 2012], are the preferred method for turbulence data collection. Frame deployment helps to minimise/eliminate ADV movements during measurements, hence ensuring that measurements are conducted at the same location at all times. Turbulence measurement at the planned rotor hub-height centreline is recommended. Moving ADV measurements, for example a cable-deployed from a boat [Holmes Jr and Garcia, 2008], can also be used. However, errors due to ADV movements shall be corrected prior to deriving turbulence information from the velocity data. Correcting moving ADV data is an ongoing research field [Durgesh et al., 2014; Kilcher et al., 2016].

7.3.5.5 Sediment

If significant suspended sediment load is observed at the project site, then the impact on the fluid density/viscosity used in the model should be considered, including the resulting changes in bed shear stress and turbulence. Because sediment transport is a highly nonlinear function of discharge, it may be important to consider how emplacement of the REC devices could impact sediment dynamics [Amoudry et al., 2009; Martin-Short et al., 2015; Neill et al., 2009; Robins et al., 2014; Thiébot et al., 2015]. Many models have coupled sediment-dynamics capabilities (e.g., Delft3D, EFDC, ROMS, and FVCOM); however, sediment-dynamics models are notoriously challenging to implement and require a significant effort to collect the field data required to establish the initial conditions and sediment characteristics for the site. For example, most sediment-dynamics models will require specification of multiple sediment size classes, the median particle size of each class, the critical shear stress for erosion for each size class, the critical shear stress for suspension of each size class, and the settling speed of each size class. This shall be done throughout the model domain with consideration of the spatial variability. Sediment beds are highly heterogeneous and a significant field data collection effort would need to precede any modelling effort. Flood events tend to purge the river of mobile sediments and would need to be given special consideration. If included, the procedures used to model suspended sediments in the numerical model shall be reported and justified.

NOTE A typical approach would be to conceptualise how sediment transport behaves in the system (a qualitative approach) and identify relevant source, sink, and transport links, which are then represented in the model to gain further insight into behaviour.

7.3.6 Boundary conditions and forcing

Model boundary conditions are typically specified as upstream discharge rates (inflow) and a downstream hydrograph (water level as a function of discharge). When modelling, perhaps the most important governing parameter is the specified incoming discharge to the model domain. In the transverse direction (across the river), inflow should be distributed according to the depth. That is, sum the depth of all wet model cells across the river and distribute the discharge in each column of cells using a multiplier of the local depth divided by the sum of depth across all columns of cells. If convenient (e.g., when using the logarithmic velocity profile in Delft3D), specify the vertical flow structure in the column of cells due to the boundary layer. This is not a requirement because the upstream boundary is sufficiently far from the project site to allow the model to restructure the flow profile due to bed roughness.

If there are other sources of inflow (e.g., tributaries) between the upstream and downstream boundary conditions with combined median inflow in excess of 5 % of the median river discharge, they shall be included as additional inflow sources. Intermittent discharge shall be considered (e.g., rainfall runoff) if their maximum inflows exceed 5 % of the median discharge in the river. If a downstream hydrograph is not available, standard techniques to estimate this relationship shall be used and documented [ISO 1100-2:2010, 2010; Vogel and Fennessey, 1994].

7.3.7 Field-data requirements

Observational data are required for calibrating and verifying the model. Once the model has been calibrated and validated, additional model runs will be used to generate current-speed distributions. Field data-collection campaigns shall be conducted at no less than three different river discharges that fall within the operating range of the REC with a broader range of discharges better.

7.3.8 Velocity measurements

Current-speed contours (e.g., obtained from current profiler (CP) moving-vessel (MV) measurements) shall be collected at a minimum of two channel cross sections selected to maximise coverage across the project site passing through as many potential REC locations as possible, following the specifications outlined in A.4.2. Current-speed contours are to be used for model calibration. Current-speed contours obtained from CP MV measurements typically contain a significant number of spikes due to ambiguity lane jumps along one or more beams, or bottom locks onto suspended-sediment pulses. CP operators are recommended to consult the instrument's manual to troubleshoot and attempt to reduce spikes in the data. In addition, further data post-processing to reduce spikes (e.g., spatio-temporal averaging of the velocity using inverse distance weighting or Kriging methods) is recommended prior to using the data for model calibration. The use of spatio-temporal averaging on CP data has been well documented [Dinehart and Burau, 2005; Gunawan et al., 2010; Gunawan et al., 2017; Szupiany et al., 2007].

Fixed-location velocity profile measurements are to be conducted at a minimum of two proposed REC locations for each discharge condition, to measure vertical variation of the current speed profile to be used for model validation. The CP can be bottom-mounted or otherwise fixed. For each location, the measurement should be conducted for an extended period of time, typically not less than 5 min, until a stable mean velocity is obtained. Stable mean velocity in rivers has been achieved for averaging windows ranging from 100 s to 15 min [Barua and Rahman, 1998; Gunawan et al., 2010; Muste et al., 2004; Stone and Hotchkiss, 2007]. Simultaneous with the discharge and velocity measurements, stage should be measured at one location within the project site. Measurements at the upstream and downstream boundaries are also encouraged.

7.3.9 Calibration

Calibration exercises shall be undertaken to demonstrate that the model accurately simulates the velocities in the river without turbines when compared to available water levels and current-speed profiles. Specifically, an automated calibration code like PEST [Doherty, 2016a; b], DREAM [Vrugt, 2015], DAKOTA [Eldred et al., 2006], or the like shall be applied. The automated calibration code should ensure that system parameters are optimised, that the uncertainty is quantified, and that the entirety of the calibration field data set (including expert judgment) has been considered to guarantee that uncertainty is mathematically minimised.

Given that at least 15 different discharge levels are to be modelled to generate the VDC, calibration shall be conducted for at least three of these discharges with corresponding current speeds that span the operating envelope of the REC device. For each discharge to which the model is calibrated, corresponding field data (water level, Clause A.2, and current-speed profiles, Clause A.5) shall be used in the calibration effort. At a minimum, water levels from at least one location within project site shall be used. Moreover, velocity data from within the project site domain shall be used for calibration. Care shall be taken to ensure that calibration velocities correspond to the specified discharge (i.e., velocity and discharge should be measured at the same time). For most models, bottom roughness, horizontal momentum diffusivity, and vertical eddy viscosity will need to be adjusted to achieve an acceptable match between simulations and field data. If the calibrated bottom roughness differs by more than a factor of two (or less than a factor of one-half) between the three calibrations, then additional calibrations at other discharges shall be documented and parameter trends identified and discussed. While bottom roughnesses are expected to be fairly independent of discharge, horizontal momentum diffusivity and vertical eddy viscosity may change, typically with trends of increasing values with increasing discharge. Any trends should be noted. Techniques such as regularised inversion may assist in identifying unique parameter combinations that calibrate the model [Aster et al., 2011; Moore et al., 2010; Tonkin and Doherty, 2005; 2009] .

The degree to which measurements and simulations agree is reflected in the weighting scheme applied to each calibration data set (observation group) when formulating the objective function. The modeller shall justify their selection of weighting scheme. Simulated water levels should agree to within 10 cm or 1 % of measured water levels, whichever is greater, for all three discharge rates used for calibration.

Cross-channel and vertical velocity measurements shall be processed to provide estimates of depth-averaged current speeds at locations corresponding to REC devices. Modelled depth-averaged current speeds should agree to within 5 % of measured depth-averaged current speeds at the REC location. Vertical current-speed profiles shall be computed using a spatial/temporal average of measurement data where the averaging scale shall be justified based on the speed of the vessel and the relative scale of the river. The constituents of vertical current-speed profiles (speeds at specific depths) from the model should be computed using the same spatial averaging scale and should agree to within ±20 cm/s of their measured counterparts. If these standards are not met, the model should be adjusted and refined to meet these criteria. Any notable discrepancies that are unable to be resolved shall be analysed and documented and an assessment of the overall accuracy of the modelling at the site and an explanation of how the model accuracy will impact the estimated river resource shall be undertaken.

Because turbulence is important to wake recovery behind RECs [Blackmore et al., 2014], if turbulence has been measured, it may be useful to compare model output to the measured turbulence intensity or turbulent kinetic energy data from the project area or even to include this in the calibration effort.

7.3.10 Validation

The model shall be validated by implementing calibrated parameter values into model simulations for at least three discharge rates (the calibrated discharge conditions are allowable provided the validation field data are independent from the data used in the calibration). Specifically, new field data (or data withheld from the calibration exercise) consisting of vertical current speed profile measurements at no less than one proposed REC location shall be replicated with sufficient accuracy. This shall be defined as the predicted depth-averaged current speed being within 10 % of the validation data as well as no component of the vertical variation of the current speed profile exceeding 25 % of the difference between the measured validation current-speed profile data. Any deviations from these limits should be discussed and justified. This validation exercise will build confidence in the model capabilities and support use of model results for decision-making.

7.3.11 Energy extraction

7.3.11.1 General

The basis of the resource assessment is the calibrated, validated numerical model without the REC array (i.e., the “base case” or existing natural river hydrodynamic system). Repeating the base-case model with the addition of the energy-extraction components (i.e., specification of REC characteristics and array layout) yields the “future-case” scenario. This allows quantification and reporting of:

- The amount of energy extracted (or removed) from the river system, estimated through the energy-extraction terms in the model, which is a function of the REC characteristics;
- The amount of useful energy harvested (i.e., electricity) from the river system using the power curves from either IEC TS 62600-300 (full study) or a generic REC (feasibility study) together with the method outlined in Annex A of this specification; and
- Alterations to the river including local and far-field changes to velocities, flows, and water levels (by direct comparison between the “base case” and “future case” models).

NOTE Alterations to the far-field response of the river system will have various levels of importance depending upon the legislative and regulatory requirements imposed on the project. Presenting these results could use various methods of parsing the far-field-response data comparisons. From an operational perspective, all projects will benefit from consideration of alteration to local velocities.

Energy extraction modelling shall be included in the resource-characterisation activity when the project blockage ratio exceeds 5 % because the act of extracting energy from this resource will disturb the river. This has implications locally in terms of altered flow fields in the immediate vicinity of the REC (e.g., the downstream wake generated by the device, changes in eddy patterns) and potentially far-field impacts (e.g., increased water-surface elevations upstream, flow diversions within the project site). A parametric equation is required, embedded in the numerical model, that captures the essential operational characteristics of the proposed technology and acts as an appropriate energy sink.

Further developments in understanding the impact of REC operation and energy extraction are likely to arise. Solutions proposed in the latest peer-reviewed literature should be carefully considered as the scientific understanding evolves. In particular, enhanced understanding of REC-to-REC interactions informed by observations of operation of REC arrays and high-resolution CFD modelling may facilitate improved parameterisation of these processes within hydrodynamic models.

One of the current challenges in modelling REC devices is in parameterising the model appropriately for the specific device to be deployed. Certainly, the device thrust coefficient is critical to both the performance of the device and the impact on the flow field and the technology developer should provide this parameter as a function of inflow current speed (thrust curve). More challenging is to identify the turbulence parameters for a device. For example, in the k-ℓ or k-ε turbulence modelling of Delft3D, EFDC, FVCOM, ROMS, or Telemac-3D, each device acts as a source or sink in the momentum, turbulent kinetic energy, and turbulent kinetic energy dissipation rate (or length scale) conservation equations.

Challenges notwithstanding, if RECs are to be modelled, the manufacturer should supply thrust and power curves to the model-development team. For the full study, the REC data shall follow IEC TS 62600-300, noting that the details of the development of these curves (i.e., blockage ratio of test and sampling point for free-stream conditions) shall be reported and taken into consideration for modelling the energy extraction as well as AEP.

7.3.11.2 Methodology for incorporating energy extraction

Models simulate extraction of energy by turbines through a reduction in momentum in the model cell(s) where the devices are situated and according to device performance metrics. A density-normalised momentum sink will most likely be implemented [Batten et al., 2013]. Energy is extracted from the river resource according to the prescribed momentum sink; however, a model is not able to provide the free-stream condition – that is precisely what is absent in a model that simulates device operation. This challenge can be overcome through use of an axial induction factor [Burton et al., 2011]. Although dependent upon the turbulence-closure scheme implemented in the model, sources of turbulence intensity and its dissipation rate (or length scale) should be included [James et al., 2017]. Selection of empirical turbulence parameters shall be justified or based on literature values [Katul et al., 2004; Poggi et al., 2004; Réthoré, 2009]. It is incumbent upon the modeller to select turbulence parameter values that yield simulations with a sufficiently close match to the wake characteristics of a single device.

7.3.12 Computation of model-based velocities

To compute required velocities, model simulations with discharge boundary conditions based on each value from the discretised FDC shall be run. If required, these model simulations shall include the effect of energy extraction as described in 7.3.11. The velocity between two and five D_E upstream of each REC location will be extracted from the model for each of the discharge conditions.

A separate VDC shall be constructed for each REC location using the REC power-weighted speed.

7.3.13 Calculating the Velocity Duration Curve

The REC power-weighted speed corresponding to each discretised discharge is plotted in Figure 4. A curve fit to find the transfer function between current speed and discharge shall be developed. The method for performing the curve fit shall be justified.

NOTE Many different types of curve fits may be used, higher-order curve fits such as the cubic shown in Figure 4 work well.

The VDC is constructed using the probability for each discharge from the full FDC along with the computed current speed curve-fit coefficients. An example of the computed VDC is shown in Figure 5.

An individual VDC for every REC location shall be computed for each FDC including the 10-year, monthly, and yearly FDCs. A minimum of five data points are required for each REC location.

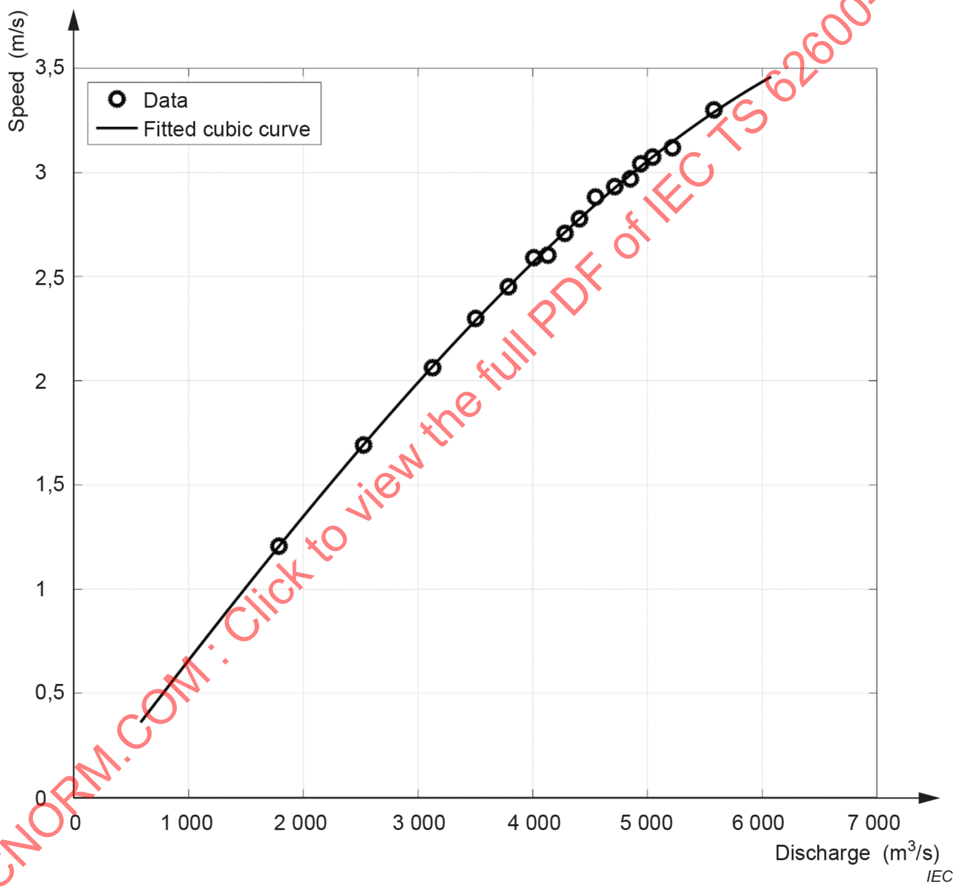


Figure 4 – Example REC power-weighted speed versus discharge relationship using discretised discharge values (circles) in Figure 3

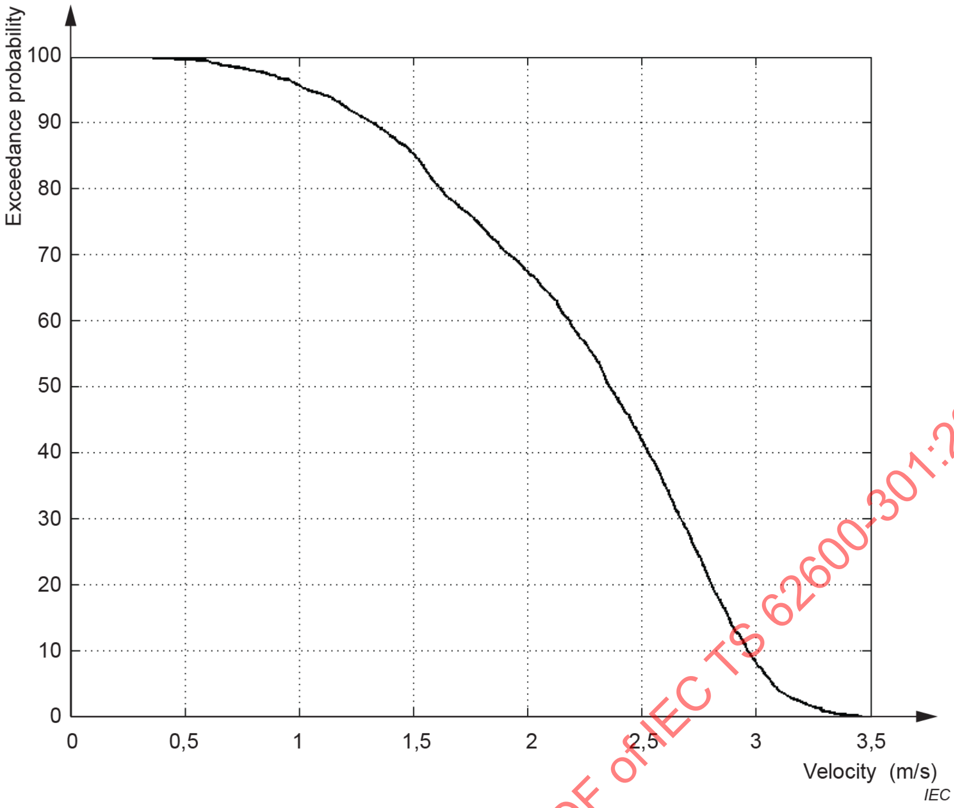


Figure 5 – Example VDC using the transfer function derived from the curve fit shown in Figure 4 and the full FDC shown in Figure 3

8 Reporting requirements

8.1 General

Reporting requirements are described below. All work performed should adhere to the requirements in this document and any deviations should be documented as described in 8.6. A technical report shall be prepared to document the methodologies used in the study to summarise the main results. Information on the site, flow and velocity duration curves, modelling, and AEP shall be reported. The reporting format described below is recommended to facilitate comparison with other resource-assessment studies. The study results shall also be archived in a digital database to ensure that they are available for future studies and projects.

8.2 offers an outline for the technical report and what should be included. Subclauses describe how to present derivations of the FDC, VDC, and AEP as well as additional reporting suggestions.

8.3 outlines the requirements for the digital database.

8.4 describes the test equipment reporting requirements and 8.5 the measurement procedure reporting requirements.

8.6 summarises the requirement for documenting any deviations from the procedures outlined in this document.

8.2 Technical report

8.2.1 General

A written technical report shall be prepared to document the methodologies used in the resource assessment and to summarise the results. The REC project site should be well defined by including hydrographical/navigational charts of the project site that are of suitable scale to illustrate the:

- Extent of the project footprint;
- Proposed REC locations and blockage area (in a projectable coordinate system);
- Bank-full river profile;
- Project area bathymetry;
- Water depth or water-surface elevation including a reference elevation (water level / stage);
- Any nearby hydrographic or environmental-monitoring stations;
- Any other notable features or infrastructure in proximity to the device(s); and
- Identification of the cross-channel transect and CP measurement locations used during the river resource assessment.

A short description of the REC device(s) to be installed at the site should be provided. Importantly, the physical dimensions of the device (including mounting and support-structure equipment) shall be included. This information is necessary to assess the project blockage ratio because if it exceeds 5 %, the project is considered large with the commensurate additional modelling requirements. The report shall include information about the coefficient of power, C_P, and the thrust coefficient, C_T, if used, as well as the methodology used to determine these, which is specified in IEC TS 62600-300. For a feasibility study, a generic REC shall be described, with dimensions and a range of power and thrust curves, all of which shall be justified appropriately.

The report shall document at least one detailed bathymetric survey including clear identification of any unique features. The general flow characteristics at the site should be described including the principal flow direction. A detailed description of the source or the measurements used to collect bathymetry, 10 years of daily discharge field data, corresponding water-level measurements, current-speed contour measurements for the distinct discharge rates at no less than two cross-section locations, and vertical current-speed profiles at no less than two proposed REC locations. Cross-channel transect locations and CP positions shall be indicated on a figure.

8.2.2 Development of the Flow Duration Curve

FDCs shall be developed as exemplified in Figure 3. Whether developed through direct measurements or a hydrologic model, all FDCs shall be clearly presented in figures as described in 6.4.

If a hydrologic model is used to develop the FDC, then it shall be thoroughly documented as outlined in 6.3. Model selection shall be justified. The required one year of discharge data collected at the REC site used to calibrate the model shall be clearly described and presented as a time series and FDC. Development of the hydrologic model and input data shall be thoroughly described in the report. The hydrologic model shall be calibrated to the year of site field data and this process shall be appropriately described in the report. The calibrated model shall report the input data and average daily discharge for 10 years to develop the FDC. Discharge data should be made available digitally and they should be used to develop the FDC.

8.2.3 Development of the Velocity Duration Curve

The VDC shall be developed as exemplified in Figure 5 and detailed in Clause 7 using one of the two acceptable approaches either through direct measurements (7.2) or through development of a hydrodynamic model (7.3). The index velocity corresponding to each discretised discharge from the FDC (Figure 4) shall be developed and described. The curve fit that describes the transfer function from current speed to discharge, the velocity index, shall be presented and justified. Finally, using the methodology in 7.3.13, both the VDC as developed from the transfer function and the FDC shall be presented in a figure and discussed in the report. Discharge, velocity, and stage data should be made available digitally and they should be used to develop the VDC.

If the index velocity is not calculated from 10 years of field data, it shall be calculated through hydrodynamic modelling. Model selection shall be justified in the report. The model domain shall be indicated in a figure that also indicates locations of the upstream inflow and downstream water-level boundary conditions. Water-level contour plots shall be included. A full description of the hydrodynamic model calibration and validation as described in 7.3.9 and 7.3.10, respectively, shall be fully documented in the report. Calibrated model parameters shall be indicated and discussed. If energy extraction is modelled, its development in the model and corresponding results shall be presented and discussed. Model outputs used to develop the VDC should be made available digitally along with an archive of the model itself.

8.2.4 AEP calculation

The AEP shall be calculated as described in Annex B and fully documented in the report. Both intra-annual and interannual AEP variability shall be assessed and discussed. The report shall describe calculation of the monthly or annual EP for each REC in the proposed array. This should include a plot of power exceedance probabilities. The performance assessment power curve for each REC shall also be presented graphically. A detailed model-development section shall be documented including a description of the conceptual model, model physics, input data, and the minimum of one year of field data used to validate the model. Model outputs used to develop the FDCs should be made available digitally along with an archive of the model itself.

8.2.5 Additional reporting

The written technical report shall include information on the following topics:

- Class and purpose of the resource assessment;
- Any underlying assumptions not already discussed;
- Assessment of uncertainty; and
- Discussion of limitations including factors not taken into account.

Information on other topics relevant to the resource assessment and necessary to gain a full understanding of the methodology and results should be included.

It is recommended that a short (2- to 4-page) summary of the key findings of the resource assessment be produced, converting some of the more technical language into information that is readily understood by a non-technical reader.

8.3 Digital database

The main results/outputs of the resource assessment shall be stored in a georeferenced, digital database. The purpose of the database is to preserve the outputs of the resource assessment for future use. The database shall include information on river discharge, water level, and velocities (both cross-section transects and current-speed profiles). Each data-collection location shall be clearly identified in its horizontal coordinate system and vertical datum. The database shall include full time histories when applicable. Where a numerical model is used to develop FDCs and VDCs, boundary conditions used to drive the model shall also be archived in the digital database. Measurements used to validate the numerical model should also be archived in the database. Most importantly, the database shall be made accessible and available to the certifying body for the life of the project.

8.4 Test equipment report

A description of all test equipment used during field data collection including sensors, data acquisition system, current profiler, and boat-based methods used to collect discharge, stage, and velocity data shall be documented. For each component, this should include:

- Name, model number, and general description;
- Specification sheet demonstrating ability to meet requirements defined in Annex A;
- Reporting of all user-defined settings;
- Calibration documentation or certificate of conformance, as well as documentation of compliance to manufacturer-recommended procedures; and
- CP information as prescribed in Annex A.

The method and results of data acquisition system end-to-end testing in accordance with Annex A should be reported.

8.5 Measurement procedure report

A description of the demonstrated performance-measurement procedure in accordance with Annex A should be provided including:

- Reporting of the time used for data acquisition (UTC ± T hours), procedural steps, test conditions, sampling rate, time-drift considerations as per Annex A, and averaging time for each data set; and
- A log book containing details as prescribed in Annex A should be appended to the report.

8.6 Deviations from the procedure

Any deviations from the requirements in this document should be clearly documented. Each deviation should be supported with the technical rationale and an estimate of its effects on test results.

Annex A
(normative)

Guidelines for field data measurements

A.1 Bathymetry

If a bathymetric survey is required to complement and expand the existing field data in the region of interest, the survey should be conducted in accordance with the IHO Standards for Hydrographic Surveys [IHO, 2008]. The appropriate guideline for the technique employed should be followed (e.g., if a multibeam echosounder is employed, the reporting of the survey activities should be completed to the standard established in the ICES Guidelines for Multibeam Echosounder Data [ICES, 2006]).

High-resolution bathymetric data shall be used to define the bottom of the model domain. Topographic data of the banks and flood plains may be required if RECs are expected to be operating during flood events. Software such as the GIS-based River Bathymetry Toolkit [ESSA, 2016] allows the user to describe and measure river channels using high-resolution digital elevation models derived from airborne remote sensing [ISO TS 19130-2:2014,], such as LiDAR, or from ground-based topographic surveys.

A.2 Water level

Stream gauges are used to monitor river water levels (river stage). It is recommended that the stream gauge be routinely inspected to ensure that the water level is being measured above a constant reference elevation (datum). Recorded water-surface elevations should provide an appropriate spatial coverage of the domain and be selected to provide the best overall description of discharge dynamics. Guidelines for establishing and operating a gauging station are provided in ISO 18365: 2013.

A.3 Discharge

A.3.1 General

Discharge gauging stations typically measure the discharge at a river cross section continuously. Instruments used for measuring or deriving discharge at these stations include electromagnetic gauges, ultrasonic gauges, or acoustic instruments, such as a horizontal CP. Discharge can also be derived from water level measurements if the stage-discharge relationship is known. The stage-discharge relationship of a gauging station is typically determined by the owner of the station using a standard such as ISO 1100-2:2010 and ISO 9825:2005.

NOTE Government-operated gauging stations in the US and UK typically record discharge at intervals of every 15 min to one day, which is sufficient for assessing the temporal variability of the riverine hydrokinetic energy resource. The historical records from these stations are often shared through the public website of the agency that manages the station. Long historical records ensure that a broad range of discharge conditions including extreme events such as periods of drought or flood is taken into account in the resource assessment.

For stationary CP measurements, standard guidelines for collecting these data should be followed [ISO 15769:2010; ISO TR 24578:2012]. For sites where continuous discharge measurements from the nearby stations are not available, discrete (snapshot) discharge measurements shall be collected. The recommended method for collecting snapshot discharge measurements is through CP MV measurements. The CP MV measurement method for measuring discharge, as well as the corresponding data quality control, are well described by Mueller et al. [2013].

A.3.2 Stage-discharge relationship

Guidelines for developing the stage-discharge relationship are available [ISO 1100-2, 2010]. To ensure a high-quality stage-discharge relationship and to avoid scatter in the resulting plots, the measurement location should be carefully selected. Guidelines for site selection are available in ISO 18365: 2013.

The stage-discharge relationship should be derived with water level and discharge observed concurrently and for discharge values that span the range of discharges appropriate for the REC operating envelope. Fitting these data yields the rating curve. Effects such as bed erosion, presence of aquatic vegetation, ice cover, backwater effects, and overflows all contribute to uncertainty in the resulting relationship. Measurement locations near such features or processes should be avoided. If it is not possible to avoid such features or processes, their impacts should be assessed and considered in the uncertainty assessment of the stage-discharge relationship.

A.4 Current profiler measurements

A.4.1 General

This clause outlines protocols and practices for CP measurements of velocity.

A.4.2 Fixed-location velocity profile

A fixed-location velocity survey provides current-speed profile measurements at a specific (stationary) location for a given discharge. Fixed-location velocity profile measurements are used in calibration and/or validation of the hydrodynamic model, and/or used to directly calculate the VDC for individual turbines in combination with the turbine's power curve and stage-discharge relationship. The survey shall record water-level data simultaneously with velocities to correlate with the stage-discharge relationship.

CPs should be mounted and operated by competent operators with experience using such devices. Poorly mounted and/or configured system can severely degrade the quality of the survey.

A sample record of velocity and water level shall be used to confirm stable mean values for a given discharge at the project site. Mean-value stability can be analysed by plotting the averaging windows (a function of the number of samples used to calculate the mean) versus their corresponding mean values.

NOTE Refer to the work of Barua and Rahman [1998], Muste et al. [2004], and Szupiany et al. [2007] for examples of analysing mean-value stability.

Field data collection should occur when there is a fairly steady water level in the river (avoid rapid changes or transient flow). Corrections to the velocity measurements shall be implemented and justified for rapidly changes in water level and for the effects of channel storage.

For a vessel-mounted CP, the vessel's position shall maintain a fixed position by anchoring or by carefully manoeuvring the vessel against the river current. Variation in vessel motion shall be measured during the collection of velocity data and shall be accounted for accordingly in the survey. Comparison of the distance made good from the CP bottom-tracking pings and distance made good from the GPS can be used to verify if a moving bed is present. The use of a real time kinematic (RTK) GPS system with a properly calibrated compass is recommended for measuring the vessel motion during data collection if a moving bed is present. Movement of the CP to locations with different flow characteristics should be avoided.

Arrays of CPs can also provide the required mean flow information if care is taken to prevent interference from the moorings (e.g., vortex shedding or flow alteration within the sample volume).

NOTE See the report by Mueller et al. [2013] for details on fixed-location velocity profile measurements and their corrections. Refer to the work of Petrie et al. [2013] for selecting and evaluating adequate sample-record lengths, evaluating motion of the CP and vessel, and processing of the velocity measurements.

A.4.3 Discharge and velocity transect survey

A discharge survey measures discharge in the river for development of the stage-discharge relationship and provides cross-sectional velocity data for calibration and/or validation of the hydrodynamic model. The survey shall simultaneously record water-level data to develop the stage-discharge relationship.

NOTE Helpful guidelines are outlined by Mueller et al. [2013].

The most practical method for conducting such surveys is by using vessel-mounted acoustic CPs. The method used to compute discharge shall be justified. A minimum of two reciprocal transects having a total exposure time of 720 s shall be collected under approximately steady-flow condition. The measured discharge will be the average of the discharges from these transects [Mueller et al., 2013]. Exposure time refers to the total sampling time only and does not include time between transects. A transect with a critical data-quality problem as specified by Mueller et al. [2013] should be replaced with another transect collected in the same direction. Field data from a nearby water-level or discharge gauging station may be used to confirm the steady-flow condition. Alternatively, a temporary water-level logger, which is relatively inexpensive, can be deployed during the CP measurement campaign [U.S. Department of Energy, 2017]. The collected data can be used to verify flow steadiness.

For a vessel-mounted CP, variation in vessel motion shall be measured during the collection of velocity data and shall be accounted for accordingly. The use of a RTK GPS system is recommended for measuring the vessel motion during data collection.

NOTE Refer to ISO/TR 24578:2012 [2012] for details on vessel-mounted CPs and refer to the work of Morlock et al [2002] for details on structure-mounted side CPs. Details of CP setup are available [Mueller et al., 2013].

A.4.4 Instrument configuration

CPs shall include heading, pitch, and roll sensors to convert measurements from instrument coordinates to Earth coordinates. For stationary deployments, time series of these quantities should be inspected to verify that the platform did not move over the course of deployment. This should also be verified by noting, with best possible accuracy, the deployment and recovery locations.

In accordance with IEC TS 62600-300, instruments should be configured to obtain a vertical spacing across the device's projected capture area according to one of the following:

- For devices where the relevant dimension is smaller than 2 m, the maximum bin-spacing should be 0,2 m;
- For devices larger than 2 m, the maximum bin-spacing should be the smaller of one-tenth the relevant device dimension, or 0,5 m.

The extent of the projected capture area should be within the measurement range of the current profiler (e.g., profiles extending only to hub height are discouraged). CPs designed for water resources applications are generally able to measure velocity along the river depth, with the exception of the small region near the CP transducer, due to blanking distance, and the small region near a boundary (river bed if the CP is surface deployed, or water surface if the CP is bottom mounted), due to side-lobe interference. The characteristic distance corresponding to the contaminated area is a function of the river depth and typically has a value of 6 % of the depth for a CP with 20° slant angle [Mueller et al., 2013].

NOTE When two or more active acoustic instruments are deployed in close proximity or on the same mooring, there is potential for mutual interference (cross-talk). This can occur for two instruments operating at the same frequency or at integer multiples of a common frequency (e.g., a 50 kHz depth sounder will cause interference for a 300 kHz current profiler). In addition, side bands adjacent to the primary instrument frequency may contain enough acoustic energy to induce mutual interference.

A.4.5 Correcting for clock drift

Internal clocks for different instruments may drift over the course of deployment. This complicates the process of data assimilation as two measurements with the same time stamp may not be sampling the same event and this shall be considered when processing the field data. Clock drift may be neglected if its effect is relatively minor on analysis of the phenomena of interest. If so, the rationale shall be presented and justified.

A.4.6 Depth quality control

Most CPs include a pressure sensor that simultaneously measures water depth during velocity measurements. Quality control to remove erroneous depths is performed by correcting for any abrupt changes in depth. Differences in depths for consecutive measurements should be calculated, and if differences are greater than a specified threshold value, which depends on survey characteristics such as acquisition frequency, they should be replaced with the average depth from the previous and next measurements. The threshold value used shall be reported and justified.

A.4.7 Velocity quality control

Spikes in velocity measurements are unavoidable and they should be removed or replaced with representative values. For this purpose, the differences between the velocities from consecutive measurements in a velocity burst for all bins showing the burst should be calculated. If these differences exceed a specified threshold value, they should be removed/replaced. This threshold value shall be reported and justified. Note that despiking is not required for acoustic CPs.

NOTE Methods that are often used include the phase-space thresholding (PST) technique [Goring and Nikora, 2002], the modified PST method [Parsheh et al., 2010], and spectral noise filtering [Chanson et al., 2007; García et al., 2005; Nikora and Goring, 1998; Thomson et al., 2010] for turbulence intensity. Details on quality-assurance and quality-control protocols including those for the PST method are described by Gunawan and Neary [2011].

A.5 Turbulence

The level of ambient turbulence can have a significant impact on the wake recovery behind RECs [Mycek et al., 2014a; b] and hence the total power reported based on simulation data from a hydrodynamic model. When hydrodynamic modelling is performed to establish the AEP for an array of RECs, it is beneficial to assess the ambient turbulence, i.e., the gross properties of the mean and fluctuating flow measured with the CP [Gunawan et al., 2014a; Thompson and Beasley, 2012].

The parameters typically considered are:

- turbulence intensity (I);
- turbulent kinetic energy (k); and
- turbulent kinetic energy dissipation (ε).

These may be used as input parameter for the hydrodynamic model depending on the selected turbulence model.

NOTE It is anticipated that some sites will have deployed a REC and have measured wake characteristics. Gunawan et al. [2014b] provide an example of a data-collection test plan in a canal. In addition, a description of how to collect both the characteristics of the wake structure downstream from a single device and changes to upstream water levels are described.

Annex B
(informative)

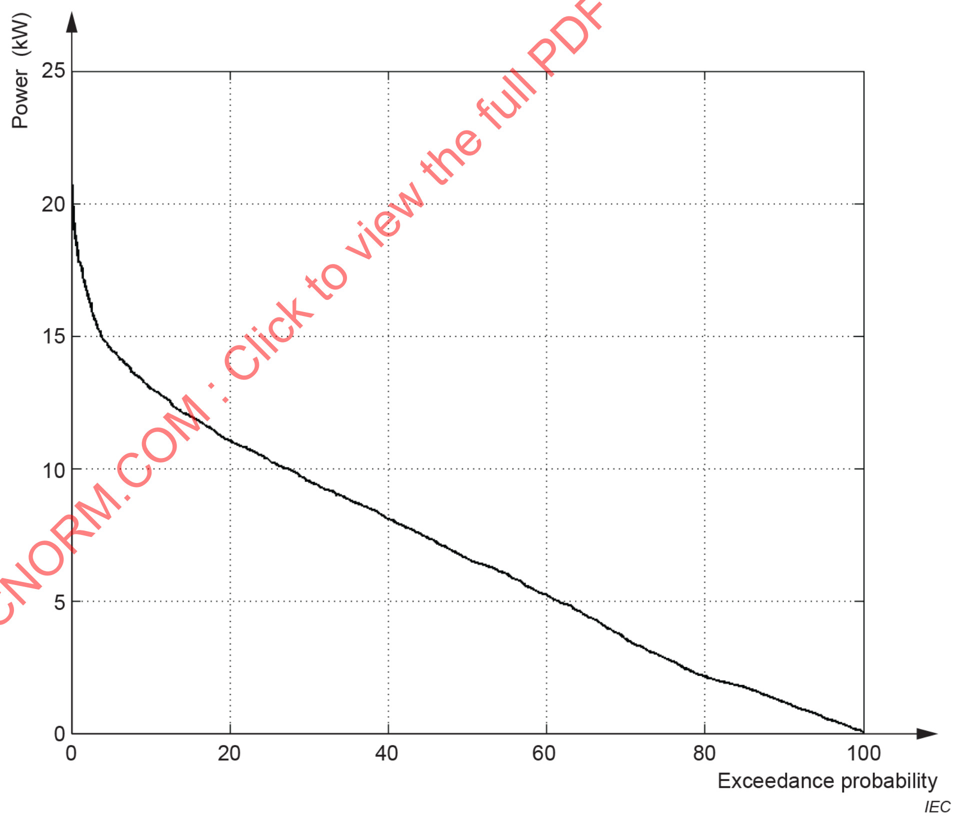
Calculation of energy production

B.1 General

This Annex describes the recommended method for calculating the AEP and estimating the intra-annual and interannual variability for each REC within an array. This is achieved by combining the VDC outputs from this document (IEC TS 62600-301) with REC performance-assessment power curves. Any deviations from this method shall be justified and documented.

B.2 Energy production

The EP for individual REC locations is estimated by combining an appropriate REC power curve, with the VDC corresponding to the relative power curve for the intended REC deployment location (see 7.2 and 7.3.8). The power curve determines the power, P_i, produced by the REC for the current speed, U_i, associated with the ith bin. The width of each bin for the VDC represents the proportion of time each speed bin occurs for the particular month or year of interest. An example of a power duration curve is shown in Figure B.1.



Power corresponding to the speeds in Figure 5 are plotted on the same exceedance probability scale (x axis).

Figure B.1 –Power exceedance probabilities

The EP of each REC is estimated as:

$$EP = N_\mathrm{h} \sum_{i=1}^{N_\mathrm{B}} P_i(U_i) B_i$$

where

N_h is the number of hours for the month or year of interest,

N_B is the total number of speed bins in the VDC,

$P_\mathrm{i}(U_\mathrm{i})$ is the power in from the REC power curve associated with the i^{th} speed bin of the VDC,

U_i is the speed of the i^{th} bin of the VDC, and

B_i is the width of the i^{th} bin for the VDC given as a decimal probability.

NOTE 1 The calculated AEP is the technical resource based on turbine characteristics and does not include many factors that may influence the practical resource. For example, the availability of the turbine would have a direct effect on the practical resource.

NOTE 2 Water-level measurements along with the discharge-stage relationship may also be useful to determine when there is sufficient depth for REC operations.

The EP based on the VDC computed from the 10-year FDC is the AEP for that REC location. A measure of the interannual variability at each REC location is derived by computing the standard deviation of the EP derived from the 10-year VDC. Intra-annual variability is derived by computing the EP corresponding to the monthly VDC.

When estimating AEP based on the power curve generated from both demonstrated and tested performance data as described in IEC TS 62600-300, the fraction of energy computed from tested data should be indicated.