MERSEY TIDAL POWER

FEASIBILITY STUDY: STAGE 3

Development of Tidal Barrage Scheme Options

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Project Sponsors:

www.merseytidalpower.co.uk

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Project Background

In the face of current and anticipated issues of security of supply and climate change, the need to find local sources of renewable energy has never been more urgent.

The Mersey Estuary has one of the largest tidal ranges in the UK, making it one of the best locations for a tidal power generation scheme. It has the potential to make a significant contribution to the Government's target to secure 15% of UK energy from renewable sources by 2020.

A large scheme could deliver enough renewable electricity to meet the needs of a significant proportion of the homes within the Liverpool City Region, as well as beyond. Any scheme put forward will need to take into account the ecological diversity of the Estuary, which supports internationally important bird habitats.

Phase 1 Pre-Feasibility Study - 'Power from the Mersey'

Peel, in partnership with the NWDA set out to explore the potential, the impacts and the implications of utilising the Mersey Estuary's renewable energy potential for the benefit of the Northwest region.

The Mersey Basin Campaign gave its full backing to the work and a consortium of consultants led by Buro Happold was commissioned in July 2006 to undertake a 'pre-feasibility' Phase 1 Study.

The primary objective of the Phase 1 Study was to undertake a full and open assessment of the options available for the generation of renewable energy and to undertake a preliminary assessment of viability.

A number of potentially viable schemes were identified. The continued development of marine power technology means that others may also need to be considered as the project moves into the next phase.

Meeting 2020 Renewable Energy Targets

An overall timetable was defined to ensure the project supports the policy objective of contributing to 2020 renewable energy targets. The key milestones of the project include submission of applications for planning or other statutory consents by 2012 and commissioning of the scheme by 2020.

Phase 2 Feasibility Study

Peel Energy and the Northwest Development Agency are progressing the project in line with the principles for sustainable development. A feasibility study has been commissioned to assess the options and identify a preferred scheme to take forward for submission of a planning application.

The feasibility study has been led by URS Scott Wilson, EDF and Drivers Jonas Deloitte, and supported by RSK, APEM, HR Wallingford, Regeneris, Turner and Townsend, University of Liverpool, Proudman and Global Maritime.

The feasibility study has been undertaken in three stages as follows:

- Stage 1: Definition of project strategies, data gathering and gap analysis, and selection of long list of suitable technologies
- Stage 2: Appraisal of the long list of technologies and formulation and appraisal of scheme options to identify a shortlist
- Stage 3: Further refinement and appraisal of the short list of scheme options and selection of the preferred scheme.

The project has been pursued in an open and transparent manner, building on the consultation and stakeholder engagement started in the Phase 1 study. An extensive programme of stakeholder engagement has taken place through project advisory groups, consultation with statutory and non-statutory consultees and public consultation targeted during appropriate stages of the project.

Mersey Tidal Power Scheme Objectives

The objectives of the Mersey Tidal Power scheme are:

(a) To deliver the maximum amount of affordable energy (and maximum contribution to Carbon reduction targets) from the tidal resource in the Mersey Estuary with acceptable impacts on environment, shipping, business and the community either by limiting direct impact in the Mersey Estuary or providing acceptable mitigation and/or compensation;

and in doing so,

(b) To maximise social, economic and environmental benefits from the development and operation of a renewable energy scheme, including where appropriate:

    (i) the development of internationally significant facilities and skills to support the advancement of renewable energy technologies and their supply chains,
    (ii) improvements to local utility and transport infrastructure,
    (iii) improvements to green infrastructure and environmental assets,
    (iv) the development of a leisure opportunity and tourist attraction.

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Glossary and Abbreviations

0-D Modelling	‘Flat estuary’ or ‘two-tank’ computer modelling of tidal range energy extraction, using flow equations containing no spatial coordinates.
2-D Modelling	Computer modelling of tidal energy extraction using flow equations with two spatial dimensions. The values calculated are taken to represent the vertical average. Considered suitable for exploring flow hydrodynamics, but not for sediment transport studies.
BU	Bulb Unit
CSH	Constant Starting Head
E	Ebb
F	Flood
DoEn	Department of Energy. Also used to refer to the 1980s studies, and the configurations of turbines and sluices found in these studies to give the most cost-effective energy in ebb mode. A DoEn (or 1xDoEn) installation is here taken as one with installed turbine capacity (and complementary sluicing) consistent with the outcomes of the UK Department of Energy’s 1980s studies, with the characteristics of extracting about half the available ebb phase energy, in a scheme where the basin in ebb mode operation drains only to near mean tide (sea) level. This arrangement was found from these early studies to yield electricity at minimum unit cost.
DT	Direct Turbining
DTE	Direct Turbine in Ebb
HCO	Head Control Operation
mCD	metre Chart Datum
NOC	National Oceanography Centre, Liverpool, UK
OM	Orifice Mode
OSH	Optimised Starting Head
RBU	Reversible Bulb Unit
RT	Reverse Turbining
RTF	Reverse Turbine in Flood
SG	Sluice Gate
UoL	University of Liverpool, UK

Note on Terminology

This technical report uses a different naming system to the Stage 3 Feasibility Report to refer to schemes variants, as follows:

- IBv2a = A1.02a;
- IBv2b = A1.02b;
- VLHBv2a = A2.01a; and
- VLHBv3a = A2.02a.

If a lower case letter is not used, this is because the operating regime (denoted by the lower case letter) is not relevant.

1 Introduction

1.1.1 This report presents the results of an advanced case study referring to a Tidal Barrage in the Mersey Estuary equipped with large diameter turbines (assumed for the moment to be of Bulb type) and a series of large sluice gates.

1.1.2 The aim of this study is to provide elements helping decision in determining the best scheme for the tidal energy extraction in the advantageous location of the Mersey River estuary. The best or preferred scheme is the one which provides the maximum energy with acceptability in respect to environment. The latter means that environment is to be rigorously considered in terms of estuary basin water level range, rates of change of in and out discharges, intertidal exposure, standing periods, water level difference between tidal sea level and estuary basin level.

1.1.3 Thus several options have been selected at the beginning of the Stage 3 in order to explore any possible operation by using the units as well as the sluice gates. By doing so, the main design characteristics of the units have not been optimised though it normally should in an overall and refined optimisation. The turbine type and pre-sizing stated since the previous Mersey studies of the 90's and then during the Mersey Project Stage 2 have been maintained all along this Stage 3. This means that the turbine design is still to be optimised in a further study in order to better fit to the preferred operation scheme concluded at the end of this Stage 3 study. Similar discussion applies to the design of the sluice gates but with lower significance.

1.1.4 The study has been carried out by using both EdF and University of Liverpool 0-D model computer programs and results have been compared and cross-checked by the University of Liverpool. Such 0-D modelling software is convenient enough to make operation and energy comparisons between the various schemes. In particular, a significant effort has been deployed in order to embed confident turbine operating paths in both direct, reverse turbine and pumping mode as well as to take into account many various control modes of the units and sluice gates. But using a 0-D modelling implies many assumptions made about the real hydraulics effects which might affect the correct energy extraction by the plant. These have been appreciated all along the Stage 3 by using Mike-21 2-D software to have a better feedback of the behaviour of the plant.

1.1.5 This technical report presents details about the global methodology, reminds the particularities of the scheme options studied in order to fit environmental constraints and then presents the detailed results of a series of simulation cases corresponding to the Stage 3 options.

2 Methodology

2.1.1 Firstly, the theory and background issues are reviewed in **Annex A,** leading to estimate of the energy extractable from the tidal resource in the Mersey estuary. This **Annex A** presents the tidal characteristics of the site. Year 2010 tides are analysed in order to extract the range frequency diagram, then 5 typical ranges which help in plotting details about the plant operation. The full time series of sea levels is also used to simulate the whole year and thus obtain the annual energy capture as well as full statistics about operational behaviour.

2.1.2 The energy production study is based on 0-D modelling by using the year 2010 tides at Alfred Dock for the impounding barrage set in Line A. The detailed presentation of the 0-D modelling is given in **Annex B**. The year 2010 was selected to provide a consistent base line with the ecological surveys conducted during the same period. The year 2010 is also broadly representative of a mid point in the 18.6 year nodal cycle.

2.1.3 The estuary basin is taken into account by using its capacity curve obtained from the bathymetry. A comparison between 0-D and 2-D modelling is presented in **Annex C**.

2.1.4 Sluice gates equations are discussed in **Annex B** in the 0-D modelling section. The turbine topic is discussed in **Annexes D**, **E** and **F**. The latter introduces cost estimates of Electro-Mechanical equipment.

2.1.5 Stage 3 Schemes and Options are given in Table 1. Operation parameters for the sluice gates and the turbines guide the simulations according to the schemes requested in this Stage 3 Options table.

2.1.6 Simulations provide results which are of graphical or tabular forms. Graphics present details on each typical tide and then the whole year time series, the latter is analysed through a series of frequency histograms and the occurrence of the average output per daily hour. The results are grouped in 2 main annexes:

- **Annex G** Case Study: Ebb tide only power generation
- **Annex H** Case Study: Ebb and Flood tide power generation

2.1.7 Pumping is introduced in both annexes.

Table 1: Stage 3 working table of option simulation cases

Internal Option Designation	Details: Structure	Details: Operation	Details: Generating Plant	Project Stage	Comment
A 1.01a	28 turbine and 18 sluice gate barrage. PC units on piles. Single navigation locks on Wirral and Liverpool shore.	a) Impound all ebb tide for power generation. Flood tide through sluice gates and orifice mode turbines.	Conventional bulb turbines.	2A	Commercially marginal. Reduced impact on inter tidal zone required.
A1.02a	As A1.01 but with double lock on Wirral shore and barrage approximately 300 m further downstream to avoid Devils Bank and improve geological conditions.	a) Ebb tide only generation with starting head optimised for maximum energy. No ebb tide releases through sluices. Flood tide through sluice gates and orifice mode turbines.	Conventional bulb turbines	3	To provide a best energy base case for assessment of alternative operating strategies.
A1.02b		b) Ebb tide only generation with low tide sluicing and hold period at the end of the ebb generation phase to improve inter tidal exposure. Flood tide through sluice gates and orifice mode turbines.		3	Selected for 2D hydrodynamic modelling and ecological assessment.
A1.02c		c) Ebb tide only generation with head control and use of sluices on ebb tide to limit gross head across barrage to generally less than 3m. Flood tide through sluice gates and orifice mode turbines.		3	For commercial comparison with Option A2.01a. Turbine setting level may require adjustment. (See Option A1.04)
A1.02d		d) Operated as A1.02a for 8 months of the year as A1.02c for 2 months of the year and in transition for 2 months of the year		3	To investigate a potential balance between commercial and ecological requirements.
A1.02e		e) Operated as A1.02a but with high tide pumping to increase energy output from ebb tide generation.	Bulb pump turbines	3	To examine impact on energy yield. Environmental implications not assessed.
A1.03a	As A1.02 but with 24 sluice gates	a) Ebb tide only generation with low tide sluicing and hold period at the end of the ebb generation phase to improve inter tidal exposure as A1.02b. Flood tide through sluice gates and orifice mode turbines.	Conventional bulb turbines	3	To provide an initial indication of the improvement in high tide level and energy yield that can be achieved by increasing the number of sluice gates. Using the 2D model for Spring tide only.

Internal Option Designation	Details			Project Stage	Comment
	Structure	Operation	Generating Plant		
A1.04a	Layout as A1.02 but with A2.01 turbine caissons.	a) Ebb and flood tide power generation without head control. Sluice gates are operated to partially restore high and low tide levels.	Reversible bulb turbines	3	To investigate the impact of ebb & flood operation.
A1.04b		b) Ebb only generation on the Spring - Mean tide range, ebb only with restricted head or ebb & flood on the Mean – Neap tide range and ebb only on the lower Neap tide range.		3	To investigate dual requirements of high energy yield and improved ecological performance.
A1.04c		c) Ebb and flood generation as A1.04a but with high tide pumping to restore high tide levels	Reversible pump turbines	3	To indicate potential for high tide pumping to restore high basin level and improve energy output of ebb and flood operation.
A2.01a	44 turbine and 18 sluice gate barrage with lower turbine setting. Revised stability requirements result in extended geometry on basin side that additionally suits flood generation.	a) Ebb tide only generation with head control to limit gross head across barrage to generally less than 3m. No ebb tide releases through sluices. Flood tide through sluice gates and orifice mode turbines.	Conventional bulb turbines	3	Selected for 2D hydrodynamic modelling and ecological assessment.
A2.02a		a) Ebb and flood tide power generation with head control to limit gross head across barrage to generally less than 3m. Sluice gates are operated to partially restore high and low tide levels.	Reversible bulb turbines	3	Selected for 2D hydrodynamic modelling and ecological assessment.

3 Lessons Learnt from Stage 2

3.1.1 Stage 2 previous studies have informed the Stage 3 work on the following:

- It is confirmed that a tidal barrage is able to extract a lot of energy amount compared to any other type of plant.
- The site is similar to the La Rance Tidal Power Plant e.g. an estuary with a narrow entrance allowing a short dike, by using the mean tidal range and the volume comparison; the rule of thumb ratio is of magnitude 2.2.
- Compared to the results provided by the previous Mersey Barrage Company studies, the average annual amount of energy is lower: this point has focused attention all along Stage 3 in particular to understand the hypotheses assumed previously in terms of estuary basin capacity curves as well as tidal ranges.
- As a consequence, if it is confirmed that the available volume of water is less than expected, the 28 turbines plant could be slightly oversized in terms of large diameter low head number of turbines.

3.1.2 Concerning turbine units, Stage 2 has confirmed the advantage of large diameter units close to bulb type technology which really have high discharge capacities and make possible the reverse turbining as well as the pumping. Such a choice contributes to decrease the total cost of Electro-mechanical equipment compared to high number of smaller turbines. Also, this type of turbine is at an industrially advanced state. Nevertheless, new concepts might be considered and encouraged as for instance the Rolls Royce symmetric double propeller technology proposed for a Tidal Power Plant which is at the intermediate between conventional hydro turbine and tidal stream turbine.

3.1.3 Lastly, recognising that the energy production is sensitive to the rules of operation of the devices (turbines and sluice gates), the Stage 3 study has aimed to provide complementary information towards the implication of incorporating a number of environmentally sympathetic constraints as part of the operational controls.

4 Influence of Environmental Constraints

4.1 Tidal Operation Possible Impacts on Estuarine Environment

4.1.1 In addition to safety and navigation, the environment topic covers sediment, erosion, and waves, animals and fish habitat. In the plant operation point of view, the list of possible environmental constraints consists of:

- Shape of the trajectory of the estuary basin level during operation: water levels difference (also mentioned as head control).
- Standing period (low or high water) – especially for settling of sediment.
- Intertidal exposure.
- Low and high estuary basin levels.
- Low and high water hold periods in the estuary basin.
- Constraints on the rates of change of water level (dh/dt) and (mainly) on the total discharge (dQ/dt), and consequently surge transients, waves, sudden increase of water levels, unacceptable velocity fields, etc.

4.1.2 For example, in La Rance case, the maximum total discharge rate of change has been stated not to exceed 180 m^3/s per minute. This involves precautions during starting / opening phases and maybe also on stopping / closing. Remind also the exceptional case of the units load rejection which may cause severe wave transients.

4.1.3 During the engineering development of the studies, it is then necessary to pay attention to the 2-D model results to bring back directives to be used in the 0-D model (dQ/dt).

4.2 Schemes of Operation in Stage 3

4.2.1 At the beginning of Stage 3, the environmental constraints mainly concerned the estuary basin level amplitude and the water level difference (head control). A water level difference of 3 m limitation has been proposed as a target for consideration. Now in Tidal Barrage application, head limitation has significant consequence on the amount of energy even though the turbine is especially designed.

4.2.2 The acceptable rates of change have not been expressed but they were to be deduced from 2-D observations by using Mike 21 software.

4.2.3 On the other hand, the energy production amount, the generation time, the occurrence of generation with high tariff periods, had to be equally considered with the environmental constraints. Both are difficult to reconcile and requires the best use and design of the industrial existing technology of turbines.

4.2.4 Thus, to help decision a series of numerical outputs are provided for each simulation case.

5 Data and Results

5.1 Estuary Basin Data

All simulations use the estuary basin area versus water level curve of

5.1.1 Figure 1 which also presents the volume or capacity curve from Line A to upstream end of the estuary.

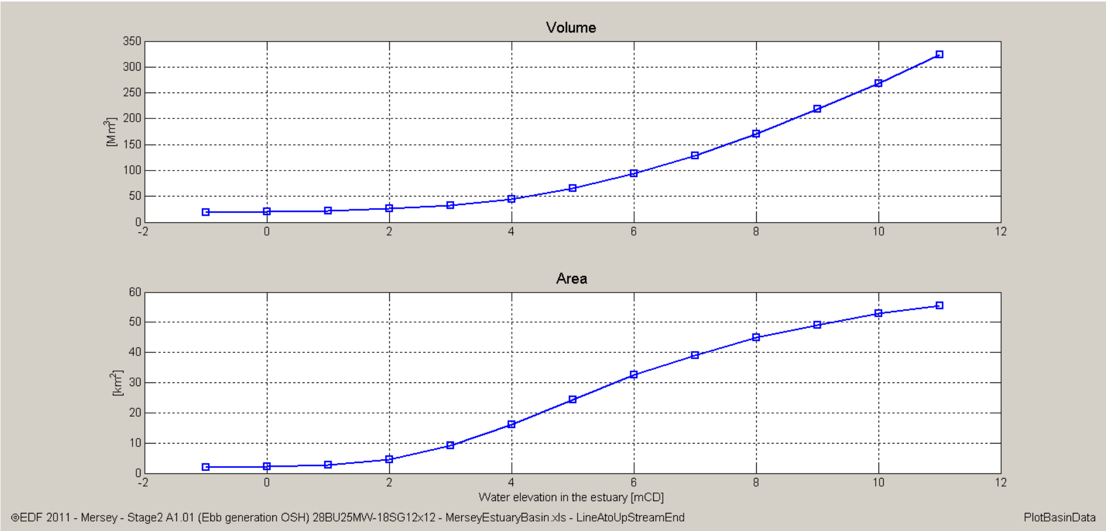

Figure 1: Mersey Estuary basin capacity curve (bathymetry data) from Line A to upstream end

5.2 Tides

5.2.1 The tides topic is discussed in a general point of view in **Annex A**.

5.2.2 All simulations involved in Stage 2 and 3 energy production and operation studies are carried out by using the whole year 2010 series of tides at Alfred Dock (Liverpool, UK) whose characteristics are presented in the next Figure 2.

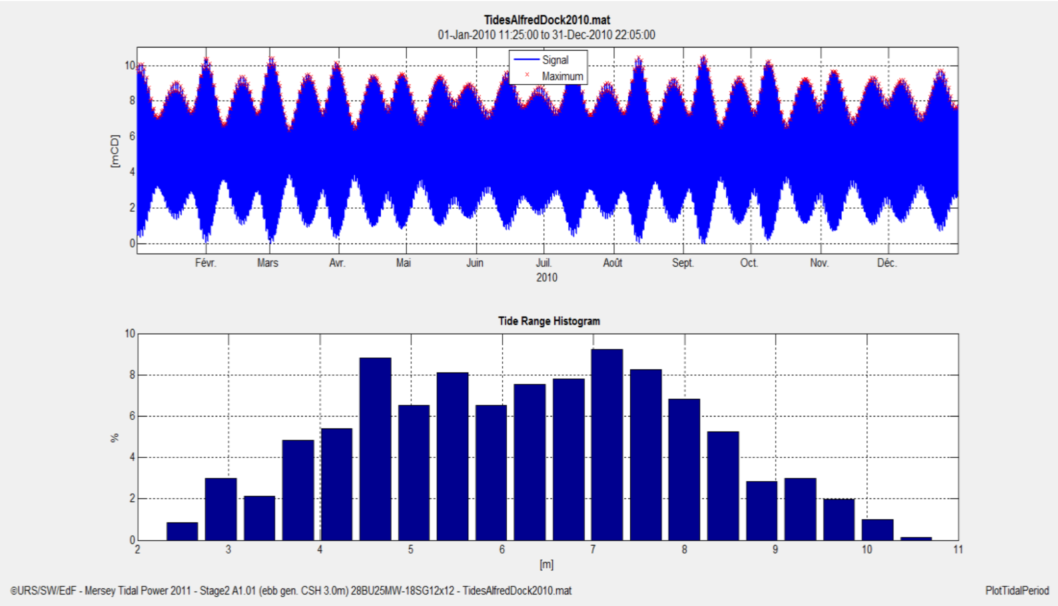

Figure 2: Year 2010 tides characteristics at Alfred Dock

5.2.3 Optimised Starting Head (OSH) routine uses a series of 20 tidal cycles (Figure 3 – Series of 20 tides extracted from the Year 2010 at Alfred Dock). This procedure is explained in section 5.5.4.

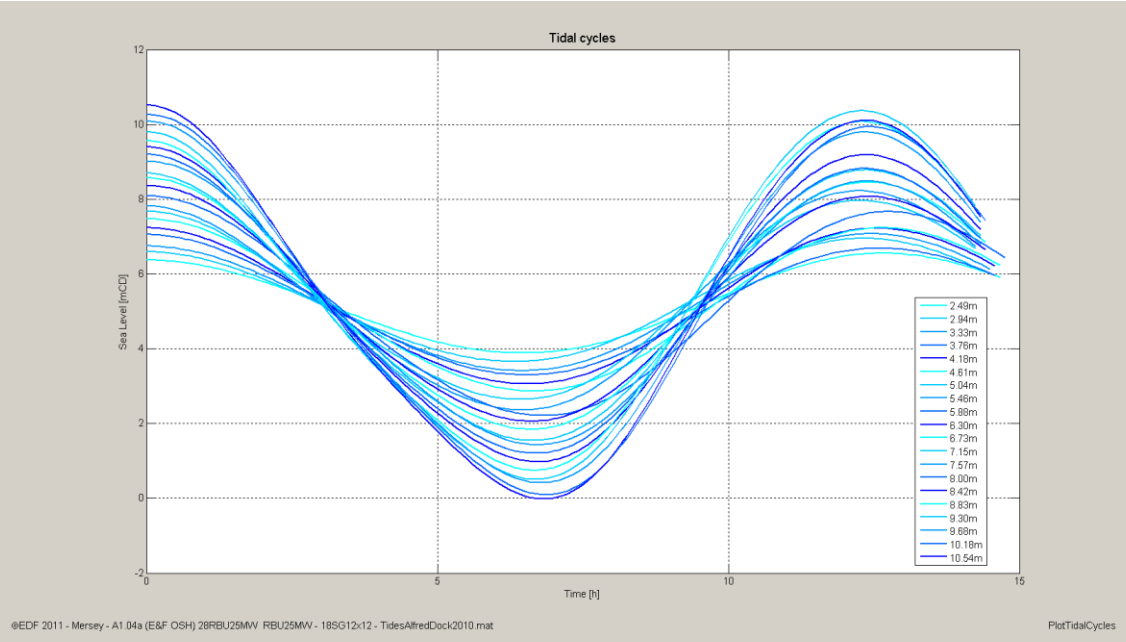

Figure 3: Series of 20 tides extracted from the Year 2010 at Alfred Dock

5.2.4 Lastly explanations are given in **Annex A** about the occurrence of tides all throughout a year according the daily hour timeframe. In effect, this aspect which is of great interest when considering the concomitance of generation and energy tariff peak hours shall be discussed later.

5.3 Plant and Barrage Data

5.3.1 In Stage 3 the baseline plant equipment is 28 conventional bulb type units. In order to improve their performances in some schemes and reduce their total number, their runner diameter is fixed about 8 m and their rated output is roughly 25 MW. In some options, an increased number of turbines are considered aiming to manage the head control limitation. In this case, the rated output is reduced to 15 MW. Lastly, when turbines are considered as pump reversible turbines, the rated consumption power is assumed to be of $1/5^{th}$ of the rated turbining output.

5.3.2 The number of sluice gates is fixed to 18. A larger number of sluice gates has also been considered.

5.4 Devices Manoeuvring Times

5.4.1 In the 0-D modelling, the turbine starting delay which is of magnitude 5 minutes is not taken into account due to the calculation time-step which is of 300 sec. According the sluice gates, the manoeuvring time is taken into account and assumed to be of 15 minutes.

5.5 Control

5.5.1 The control curves topic has been a major one aiming to adapt the plant operation to the expected goals of each scheme. Control options have been developed which mainly concern the units then the sluice gates.

5.5.2 **Head Control by the Sluice Gates:** the sluice gates are controlled in order to limit the head or water level difference between sea and estuary basin during generation operation. In this respect, a proportional gain pilots the sufficient number of opened sluice gates.

5.5.3 **Sluice Gates discharge rate of change:** The sluice gates are controlled to moderate the discharge rate of change when the head is high. In order to avoid brisk and large discharging in the medium (channel or estuary medium ?), a control curve adjust the number of opened sluice gates according the head in such a way that at high head values, the number of operating gates is limited and at low head values, the maximum of available units are fully used.

5.5.4 **Optimised Starting Heads (Ebb only):** When energy is to be maximised, the simultaneous control of the turbine units follows the so named Optimised Starting Heads curve. The “OSH.m” Matlab routine is applied on a given scheme configuration which is defined by the tides, the estuary basin capacity curve, the number of units and their operating path assumed to be unique. The energy then depends on the tidal cycle range and on the initial estuary basin level which is unknown and depends on the previous filling performances. In general, the latter is much less influential than the former when the variation range is reduced thanks to largely dimensioned sluice gates equipment. Thus the "OSH.m" routine consists of a calculation loop which determines the highest energy starting head in a head range starting from the turbine minimum operating head till a maximum value. The program provides 2-D curves visualizing four surfaces gathered in a same figure, presenting the optimal energy, the corresponding generation time, the volume turbined to sea and the estuary basin range (see Figure 4) and the corresponding 2-D starting head curve as a function of the tidal range and the initial condition of the basin level (Figure 5).

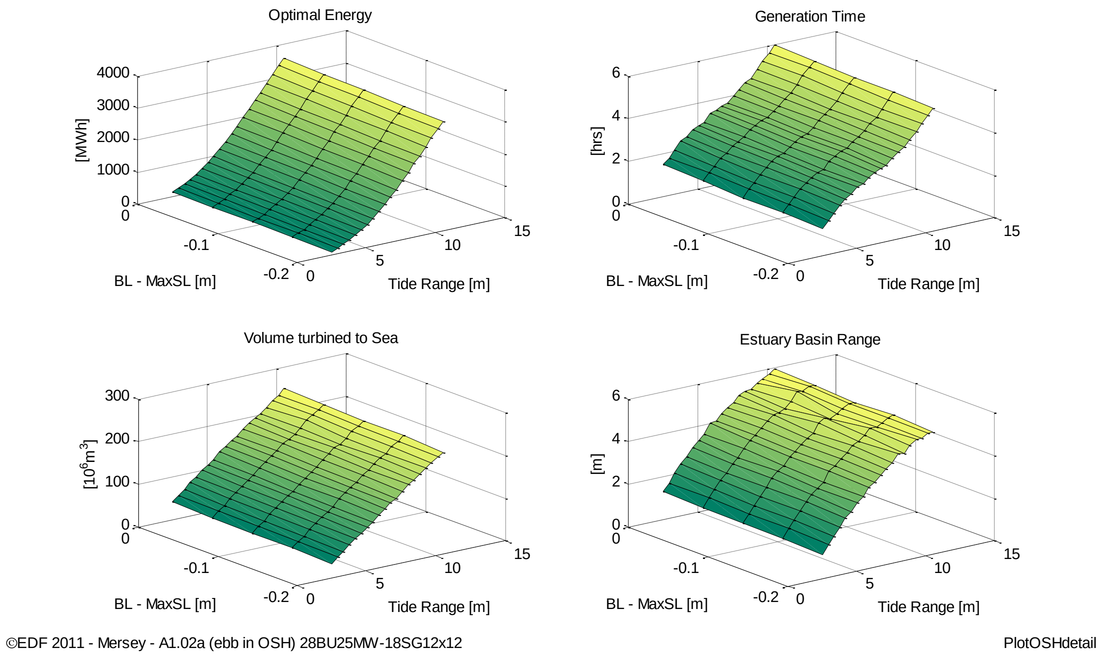

Figure 4: Maximisation of the ebb energy production by means of the optimised starting heads method

5.5.5

5.5.6 Figure 5 here after presents the 2-D and 1-D curves of the optimised starting heads for the A1.02a scheme. This illustrates that if sluice gates discharge capacity is sufficient to ensure a full filling of the estuary basin, then the gap range between the maximum tidal sea level and the initial estuary basin level before generation is tight. And if so, the 2-D curve can be averaged into a 1-D curve only function of the tidal range. This curve is then ready to use in simulation.

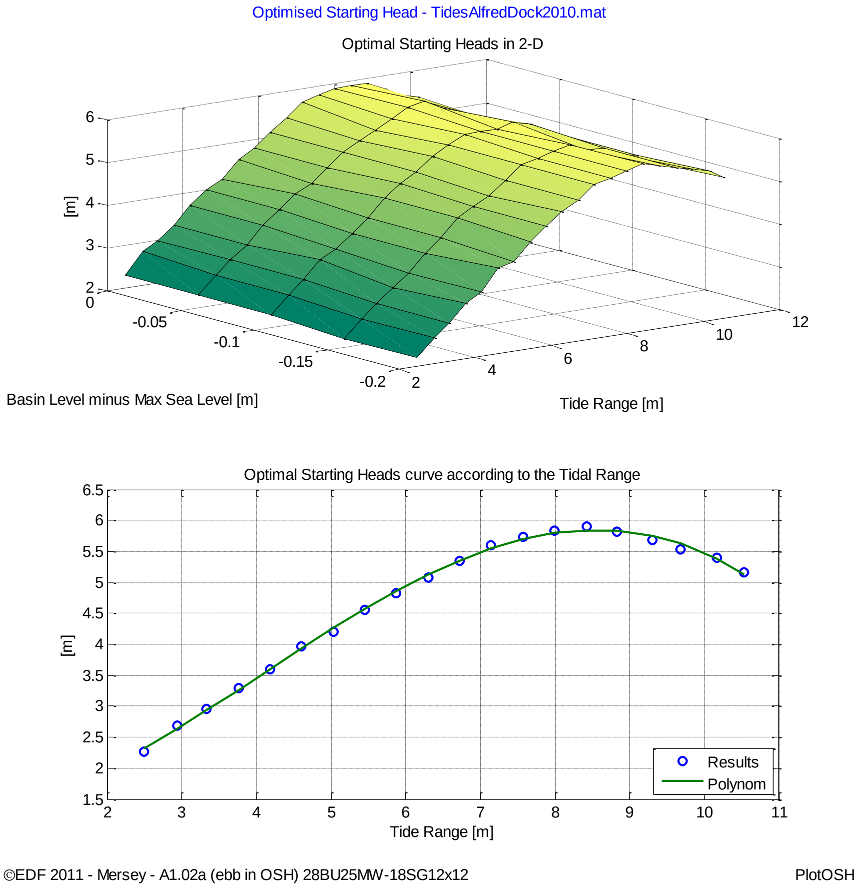

Figure 5: Optimised Starting Heads (OSH) as a 2-D function of Tide Range and the initial estuary basin level (top) and as a 1-D curve function of Tide Range only (bottom)

5.5.7 **Optimised Starting Heads (Dual):** When operation conditions change e.g. ebb and flood (dual) generation for instance, the "OSH" procedure is to be run to adapt the curve. The next figures show the same values as before in the A1.04a case which refers to an optimised (best energy figure) ebb and flood operation by using 28 reversible bulb turbines of rated output 25 MW. The OSH 1-D curve shows differences with the one obtained on the A1.02a ebb only case.

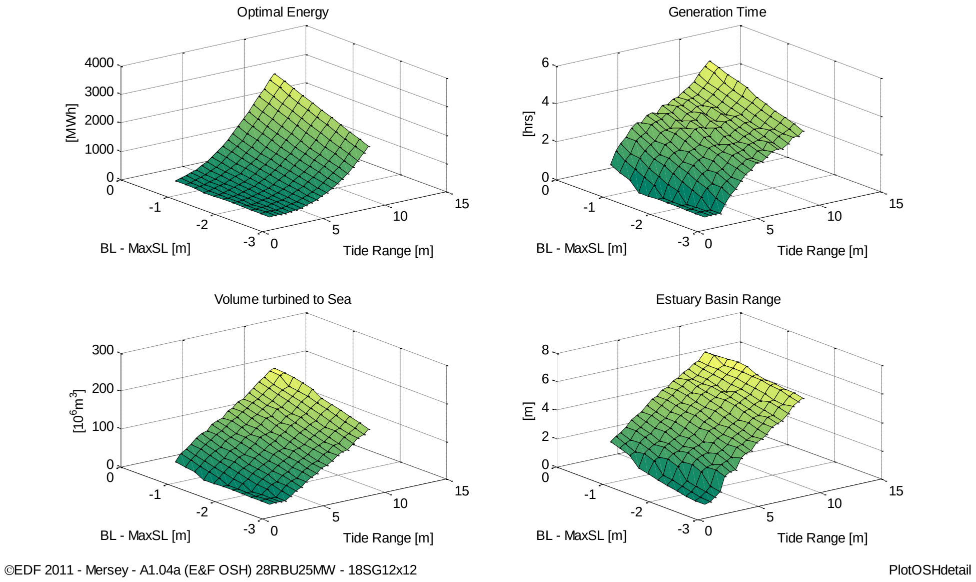

Figure 6: A1.04a. Maximisation of the energy production in ebb generation only by means of the optimised starting heads method

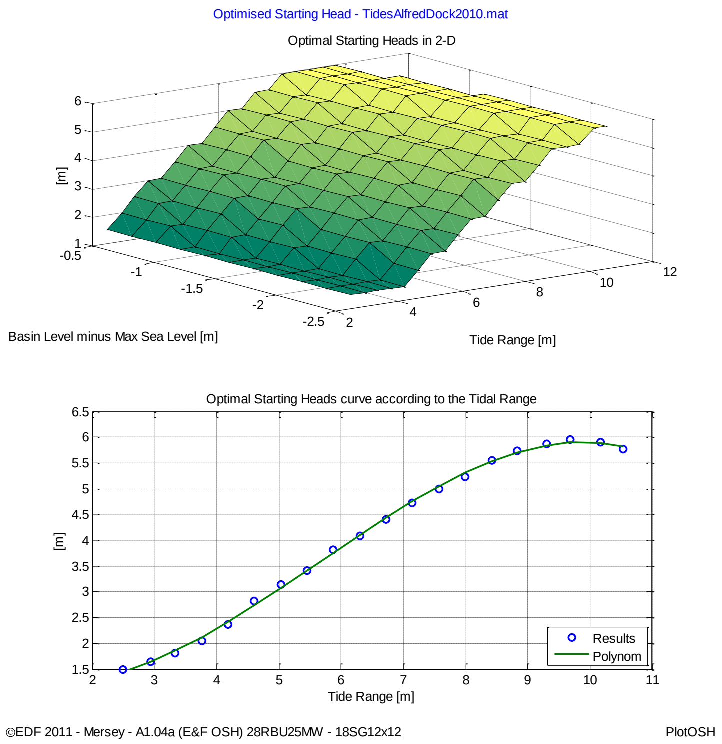

Figure 7: A1.04a Ebb Optimised Starting Heads (OSH) as a 2-D function of Tide Range and the initial estuary basin level (top) and as a 1-D curve function of Tide Range only (bottom)

5.5.8 Lastly, the head limitation (e.g. ≈ 3 m) control by the turbine units is made by adapting the number of generating ones according the head. This kind of control is managed by considering a larger number of units (Figure 8). Note that this curve is not smoothly linear because the turbines are operated in groups of 4 units.

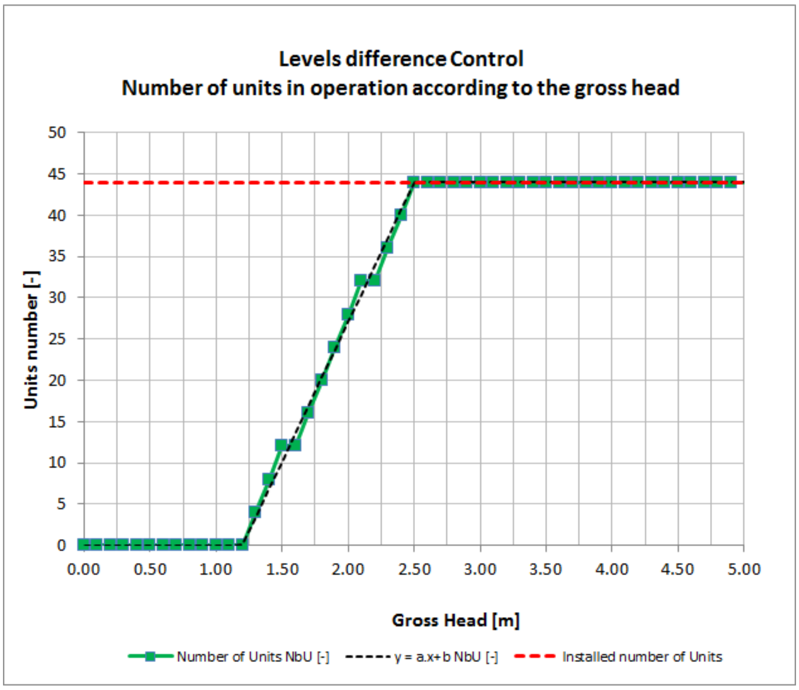

Figure 8: Head Control Operation: number of units versus gross head

5.5.9 Now, the turbine units control means have to be considered in both generating ways e.g. ebb / direct quadrant direction and flood / reverse quadrant direction. Finally, a total of 5 control curves are parameterised into the simulation software (see example of Figure 9). Such a set of control curves is shown for each simulation case whose results are displayed in **Annexes H** and **G**.

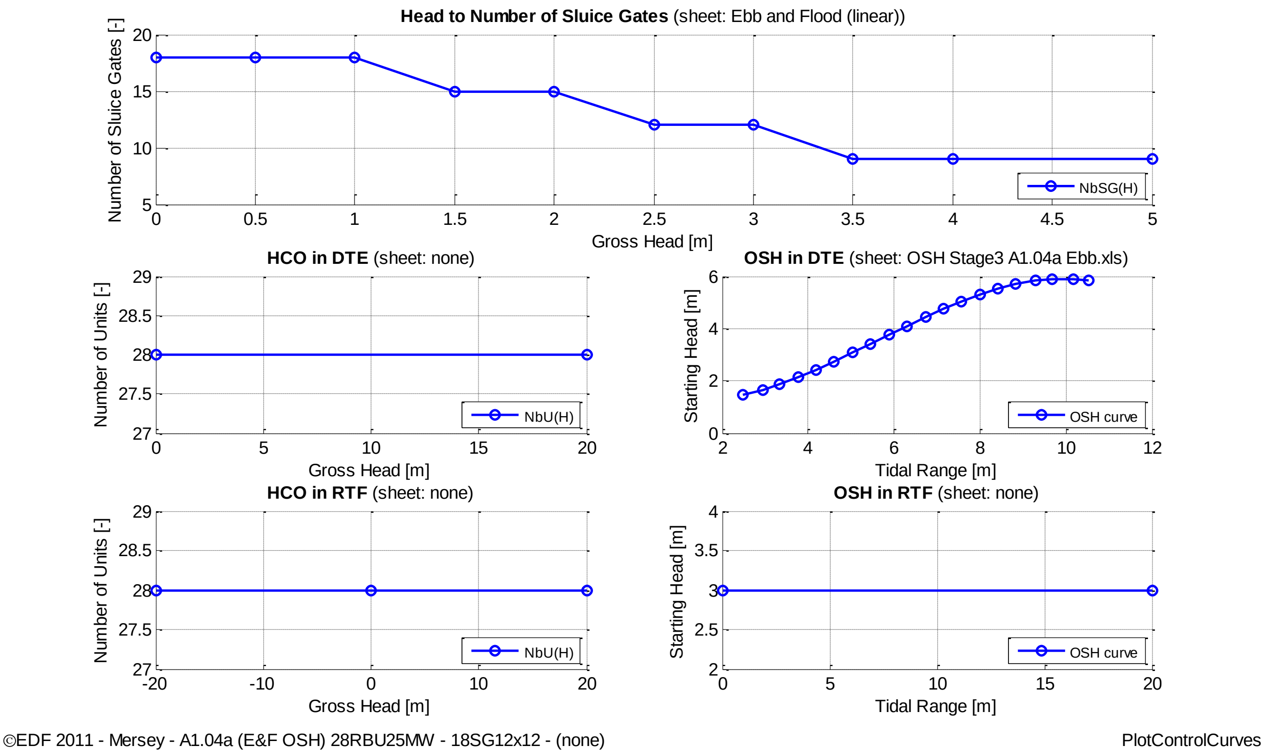

Figure 9: Control curves example corresponding to the A1.04a simulation case

5.5.10 When respecting some given environmental constraints, the optimisation or maximisation of the energy relies to a significant number of parameters including the previous control curves. Among them, the starting heads, the stop heads (with a minor effect), the turbine operating path choice, the opening times of the sluice gates, the use of them during emptying / filling operation, etc.

5.6 Ebb Only and Ebb and Flood Simulation Cases

5.6.1 The **ebb** only and **ebb and flood** generation modes corresponding to the Stage 3 Options (see Table 1) are discussed in the section 6 and the results are collected in 2 separate **Annexes G** and **H**. This is mainly due to a major change in the turbine performances data which are assumed to be of bulb type: direct only or reverse. Reverse bulb turbines do not have same direct quadrant than direct only ones. This topic is explained in **Annex D**.

5.7 Results Provided in Annexes G and H

5.7.1 The next section discusses each Option and provides explanations about the data used, in particular the control rules which apply to the turbines and the sluice gates.

5.7.2 For each Option correspond a simulation case and all available results are given in **Annex G** for **Ebb** generation only and in **Annex H** for **Ebb and Flood** operation.

5.7.3 **5 typical tidal cycles** extracted from year 2010 and corresponding to the 5 typical tidal ranges which are high spring, mean spring, mean, mean neap and low neap tides are simulated providing detailed figures presenting the levels, heads; discharges, outputs, according to time. These curves help in discussing the environmental impacts of the plant operation.

5.7.4 Then, the **whole year 2010** simulation results are presented through a series of graphical outputs including the general view of levels, discharges, powers evolution in time. This general view indicates statistical values of each kind of physical values.

5.7.5 More interesting are the **histograms** summarising the behaviour of the tidal plant and its effect on the estuary: water levels frequency diagrams, sluice gates and turbines in orifice mode histograms, units and plant with all the available units in operation.

5.7.6 Finally, the average power sent out in each hour of the day is extracted for each year 2010 simulation. This hourly average output is plotted in bar diagrams with associated power values. According section 5.2.4 (and Annex A section 1.1), the result is strongly focussed on two periods in the day. The current evening load peak on the UK system sits within the second period of high average output which is a convenient result. In effect this aspect contributes to improve the value of energy from the project by maximising coincidence with the high tariff time of day.

5.7.7 One question among others is which scheme is preferable in this respect, for instance between pure ebb and ebb and flood generation. Although the frequency of coincidence will clearly be increased by ebb & flood operation, the magnitude of each energy dispatch will be reduced and the net result in terms of value needs to be investigated.

6 Stage 3 Scheme Assessment

6.1 Ebb Tide Only Generation

6.1.1 All the results of the options discussed in this section are presented in Annex G.

Foreword

6.1.2 The ebb generation scheme without any constraints is potentially the one which provide the maximum energy if the sluice gates present a sufficient discharge capacity able to fill up the basin permitting to operate by exploiting the upper layers of the estuary basin which supply the maximum available volume of water (Figure 1). Any reshaping of the best energetic operating mode of the pure ebb is open to be less efficient.

A1.01a (Stage 2A)

6.1.3 A1.01a studied during Stage 2A is an impounding Barrage equipped with 28 conventional bulb turbines and 18 sluice gates which impounds all ebb tides for power generation. The flood tide is managed through sluice gates and orifice mode turbines which are to be sufficiently sized to fill up at most possible the estuary basin.

6.1.4 During the previous Stage 2, the annual energy productions were estimated by using the simplified constant starting head approach. The energy is highly sensitive to the choice of this value. The annual energy is of **900 GWh** (year 2010) for a constant starting head (CSH) of 3.90 m (830 GWh by using a 3.00 m CSH). But, this type of operation involves a significant amount of production interruptions and zoomed

6.1.5 Figure 10 shows low tidal range cycles missing.

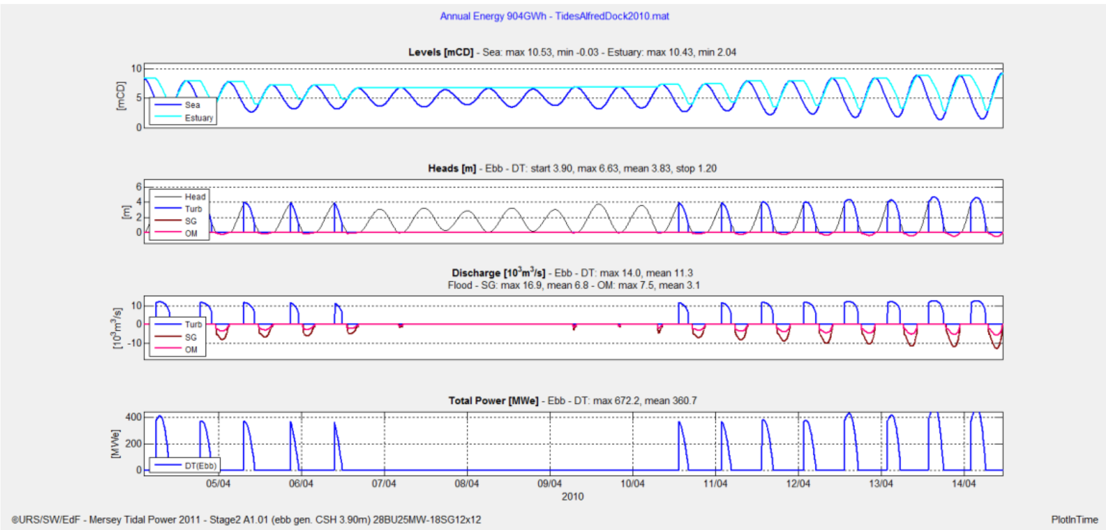

Figure 10: Stage 2A Option A1.01 – CSH 3.90m. Low tide generation missed cycles.

6.1.6 Regarding environment, a reduced impact on inter tidal zone is required. Nevertheless, the estuary basin level range covers the major part of the baseline tidal range, except the lowest layers of the basin (the minimum estuary basin level value is 2.00 mCD). The covering is better seen by the mean of a frequency histogram comparison between sea water level and estuary basin water level Figure 11.

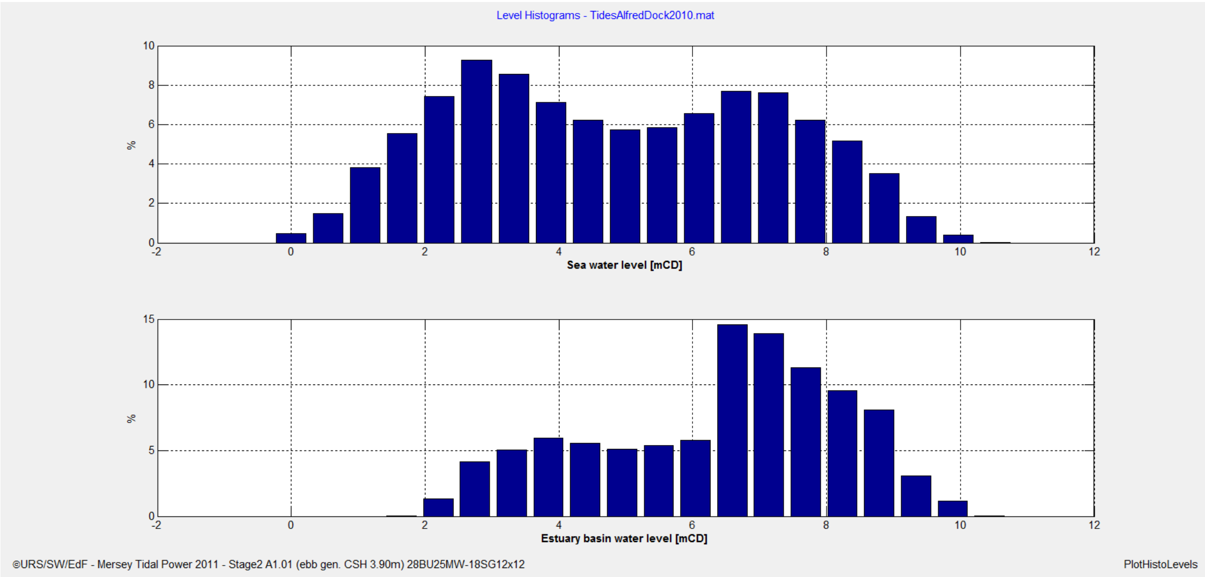

Figure 11: Stage 2A Option A1.01 – water level histograms

A1.02a – Maximising Ebb Tide Energy Production

6.1.7 A1.02a refers to pure ebb generation in so-called OSH (Optimised Starting Head) operation aiming to maximise the energy production at any tidal cycle. No environmental constraints are taken into account. All the available turbines are operating simultaneously. They start at the time when the starting head value corresponding to the tidal range in progress is reached. This value is interpolated in a pre-calculated curve (refer to section 5.5.5). They all stop when the stopping head corresponding to the minimum operating head is reached.

6.1.8 The difference with the previous A1.01 is that every ebb tidal cycle is generated by the means of an appropriate starting head. Thus, the energy amount is to be compared to the A1.01's to underline the gain involved by this optimisation.

6.1.9 The filling of the estuary basin is simultaneously carried out by all the sluice gates fully open and all the available turbines in reverse orifice mode. The main impacts on the medium are, firstly, the minimum estuary basin water level and the loss of the low layers of the impounded area of the estuary, secondly the brisk discharge rate of change at the plant starting time and in a minor sense, the stopping time. This is due to simultaneous operation of the units. Obviously, particular starting and stopping sequences can be investigated as well as load ramping but anything done in that aim alters the energy production in some per cents.

6.1.10 The 0-D model does not take into account any of these particular operating adjustments. Consequently the energy value of **1050 GWh** (year 2010) can be considered as a maximum.

A1.02b – Low Tide Sluicing and Hold Period Before Basin Filling

6.1.11 A1.02b refers to same pure ebb generation approach as A1.02a.

6.1.12 The constraints taken into account are the low tide level restoring and a hold period for intertidal exposure before the filling. An anticipated opening of the sluice gates in ebb (reverse) flow direction contributes to restore the low tide levels as much as possible. The turbines do not switch into orifice mode at generation end.

6.1.13 All the available turbines are operating simultaneously. They start according the same OSH procedure as the one stated for A1.02a. They all stop when the stopping head corresponding to the minimum operating head is reached.

6.1.14 The hold period is maintained till a 1.5 m head is reached (normally corresponding to 1 hour). At this time, the sluice gates are sequentially opened according a control curve (see **Annex G**) according the instantaneous head in order to control the discharge rate of change in the estuary basin side. In parallel, all the turbines open in reverse orifice mode.

6.1.15 The main impacts on the medium are, firstly, the minimum estuary basin water level and the loss of the low layers of the impounded area of the estuary, secondly the brisk discharge rate of change at the plant starting time and in a minor sense, the stopping time. This is due to simultaneous operation of the units. Obviously, particular starting and stopping sequences can be investigated as well as load ramping but anything done in that sense alters the energy production in some percents.

6.1.16 Depending on the effort applied to low tide sluicing and on the moderation of the sluice gate opening during filling after hold, more or less energy is lost. A sensitivity analysis has led to energy production value of **950 GWh**. This value corresponds to a sluice gate opening at the time when the turbines stop but in that case the low tide levels may be insufficiently restored. On the other hand, delay applied to the flood sluice gate opening leads to a reduction of the estuary basin filling which involves energy loss at the next ebb tide generation.

A1.02c – Head Control by the Sluice Gates

6.1.17 A1.02c is dedicated to limit the water levels difference to approximately 3 m. Two ways have been explored, firstly (the present A1.02c) by using the sluice gates proportionally when the head sill value exceeds 2.90 m in parallel to turbine generation, secondly by increasing the number of units in order to increase the plant discharge capacity in order to control the head as much as possible close the 3 m set-point. The latter is described further (option A2.01a).

6.1.18 In order to facilitate comparison on energy results within the series of simulation cases of this Study and also because the search of a well-adapted turbine needs some iterations, the same bulb type turbine characteristics have been maintained.

6.1.19 The respect of the 3 m limitation is satisfying. This limitation involves two negative consequences on the energy production which are a shorter generation period (moreover in ebb only) and a significant loss of energy due to the weak operating heads. The annual energy is **530 GWh** (year 2010).

A1.02d – Operation Mitigation within A1.02a and A1.02c

6.1.20 This case has not been modelled but it considers a mitigated operation as follows: A1.02a for 8 months of the year, then A1.02c for 2 months of the year and in transition for 2 months of the year. Mitigation of these two options leads to an estimated energy amount according the period durations of approximately **920 GWh**.

A1.02e – Maximising Ebb Tide Energy Production with Pumping

6.1.21 The same characteristics as A1.02a have been considered in that first trial with pumping. The bulb type turbines have been assumed to pump according a consuming power of 1/5 of the rated 25 MW turbine e.g. 5 MW. Unit discharge - head – efficiency operating path has been roughly transposed from La Rance reversible pump turbine hill chart. The stop head in pump has been set to a 1.60 m constant value at any tide.

6.1.22 The major consequence is a reshaping of the tidal signal especially with significantly increased maximum estuary basin levels. This is noticeable especially by comparing the neap tide cycle between A1.02a and this A1.02e case (see **Annex G**).

6.1.23 The annual energy is increased from 1050 to approximately **1340 GWh** (see **Annex G**, section 6).

A1.03a – A1.02b with 24 Sluice Gates Instead of 18

6.1.24 This case has been simulated showing very negligible differences with A1.02b thus this case is not discussed here. The similar energy values between A1.03a compared to A1.02b having 18 sluice gates are because the sluice gates equation and coefficient assumptions supply an efficient filling of the estuary in the 0-D model. The annual energy output is **1010 GWh.**

A2.01a – Head Control by Using up to 44 Units

6.1.25 Several sensitivity analyses have led to the conclusion that 44 units were sufficient to control the water level difference between sea and impounded estuary. In effect, the method consists of operating an adaptive number of turbines according the gross head. A curve is parameterised into the model and different shapes (linear or non-linear) have been studied.

6.1.26 Note that in that case, the rated output has been decreased to 15 MW (instead 25 MW) leading to a total installed capacity of 660 MW. The unit power histogram in **Annex G** confirms that the unit maximum output rarely reaches the 14/15 MW range.

6.1.27 The result is close to the A1.02c option with an energy value of **560 GWh** (year 2010).

6.2 Ebb and Flood Generation

6.2.1 All the results of the options discussed in this section are gathered in Annex H.

6.2.2 The purpose of this section is to present the A1.04a scheme which is permanent Ebb and Flood tide power generation without head control (water level difference limitation) or any particular constraints. In the A1.04a option, the plant is equipped with 28 reversible Bulb turbines able to operate in orifice mode and the barrage includes 18 sluice gates of 12 m x 12 m.

6.2.3 Then the A2.02a scheme is presented aiming to limit the water level difference at approximately 3 m. The sluice gates are operated to partially restore high and low tide levels.

6.2.4 Lastly, high tide pumping is introduced in the A1.04c scheme which obeys to the same conditions as A1.04a.

A1.04a - Maximising Ebb and Flood Tide Energy Production

6.2.5 Scheme A1.04a is an ebb and flood (dual generation) tidal generating plant equipped with 28 reversible bulb turbine units of 8m runner diameter and rated output of approximately 25MW (see **Annex D**). The tidal barrage is equipped with 18 large sluice gates. Pumping mode is not considered.

6.2.6 The generating operation of the turbines in this scheme assumes a simultaneous operation of all the units operated altogether. Direct Turbining (DT) is operated in the ebb direction. The generation period extends from the variable starting head to the stop end of the turbines. A unique specific operating path is established in the direct turbine quadrant which corresponds to two operating curves e.g. QDT(H) and PeDT(H). Reverse Turbining (RT) is achieved in the flood direction. The generation period extends in the same way as before. A unique specific operating path is established in the reverse turbine quadrant which corresponds to two operating curves e.g. QRT(H) and PeRT(H) (see **Annex D**).

6.2.7 Ebb and flood (dual) generation necessitates complementary emptying and filling of the estuary basin aiming to **increase** the energy of each next tidal generating cycle. All the Sluice gates are provided to fill (flood) or empty (ebb) the estuary basin. On another hand, all the turbines will operate in reverse (flood) or direct (ebb) orifice mode to assist with the flooding or emptying (ebb) of the basin. Obviously, this orifice mode operation is limited to the not generating period, more precisely, when the stop head is reached, the turbines are switched from synchronised mode to free rotating blades mode with an adjustment of the blades opening.

6.2.8 Particular attention refers to the sluice gates' manoeuvring which is anticipated while the turbines generate. By doing so, the beginning of opening occurs while the head is significant (magnitude of a meter) with a risk of sudden high discharges (even if the full opening time is about 15 minutes) involving inacceptable transients.

6.2.9 In order to moderate this impact, all the sluice gates are not to be opened at the same time and a particular manoeuvring sequence is applied by the mean of a 1-D control curve which gives the number of opened gates according the instantaneous gross head. The shape of this curve indicates that more the head is high, lower is the number of sluice gates to be opened in operation. This is a mean permitting to increase the discharge capacity when the head gets lower and on the contrary to limit it when the head is high.

6.2.10 The energy maximisation is carried out by the mean of the starting heads optimisation approach (see section 5.5.7 and **Error! Reference source not found.**) and also by using the sluice gates (and the turbines in orifice mode just after generation end) in both directions in order to respectively increase and diminish the estuary basin water levels. By doing so, the generation periods benefit of an increased turbine operating head as well as a gain of water volume. Even if it seems contradictory to waste non energetic water through the impounding barrage, the balance reflects a real energy gain.

6.2.11 The sluice gates anticipated operation can be managed according either the opening time either by using an opening head value. The time zero reference is for instance the extreme (minimum or maximum) sea water level. Then a delay is parameterised starting from this time zero reference. For example, in ebb generation, the sluice gates shall be opened at or beyond the minimum sea water level time.

6.2.12 The tuning of this sluice gates manoeuvring curve in regards to the energy production as well the opening time or head is highly sensitive and a series of trials have been carried out by using the 0-D model. As a result, with no particular optimisation, A1.04a annual energy is in the range of 600 / 700 GWh and with the previously discussed optimisation is improved to **800 GWh** (**Annex H**).

A2.02a – Head Control by Using up to 44 Units

6.2.13 This scheme is based on head control by an increased number of turbines. The estuary basin water level operating range is too low missing the high volume layers (see **Annex H**). Supplementary research should be applied to this scheme in order to optimise the turbine type, characteristics, operating path, sluice gates manoeuvring. Nevertheless this scheme is not commercially viable and diverges to too many units and to weak energy production. The annual energy output is **520 GWh.**

A1.04c – Bulb Reversible Pump-Turbines

6.2.14 The more relevant baseline scheme which has been chosen to introduce the pumping in ebb and flood operation is A1.04a. The same assumptions as in A1.02e have been considered in that first trial with pumping as well as a constant stop head which might be reconsidered in the future to maximise the net energy figure.

6.2.15 In that case, the pumping could help in restoring the high tidal sinusoidal shape.

6.2.16 The annual energy is increased from 800 to **930 GWh** with the following split:
Energy production in Ebb .... 780 GWh
Energy production in Flood .... 190 GWh
Power Consumption .... -40 GWh
(see **Annex H**, section 3).
Note that in that case and according these preliminary assumptions, the advantage of pumping is a win of +130 GWh for a -40 GWh expense (gain ratio of 3).

7 Assumptions, Limitations and Reservations

7.1.1 This section aims to memorise some further actions which might improve the technical issues of the Mersey Tidal Project in particular the energy prediction precision improvement and better adapted turbine equipment.

Estuary Basin Capacity

7.1.2 The disparity in basin volume (bathymetry) figures still needs resolving. For the moment, it seems that the bathymetry considered in this study might be under-estimated inducing a possible under-estimation of the energy production. Identification of the capacity curve by using 2-D modelling results has been studied at a feasibility stage and this promising approach is to be completed. On the other hand, the 0-D modelling might provide too optimistic energy results because hydraulic transients are not visible as they are by using a 2-D model.

Tides

7.1.3 0-D modelling should be repeated with modified tidal characteristics from 2-D modelling.

Turbine Unit Pre-Sizing

7.1.4 The number of units might be revised in further studies according the estuary basin capacity.

7.1.5 Considering Bulb unit design, questions remain about the choice of the rated output, the gearbox technology or other means able to operate under low and variable rotation speed, the runner diameter.

7.1.6 Dual mode under restricted head is additional issues again. For permanent operation under restricted head (≈ 3 m) conventional 8m 25MW bulb turbine appears potentially ill-conditioned for ebb or ebb and flood operation. According the frequency of these operating conditions, the sizing of the units is to be re-considered with a decrease of runner diameter, synchronous speed, rated output.

Sluice Gates

7.1.7 If necessary, 0-D modelling should be repeated for “channel-sluicing” rather than assumed submerged Venturi sluice. Sluice coefficients / sluice equation to be used needs clarifying; this has a large impact on the effective sluicing area and on basin filling / emptying (especially for ebb mode). If the sluices are not fully submerged, then the sluice equation to be used will change to that for a submerged weir and number of devices re-adjusted. But, this assumption can also be managed by introducing a similar sluice gate discharge capacity by comparison with what is observed in 2-D modelling which constitutes a better reference on that topic.

8 Summary and Conclusion

8.1.1 The aim of the Mersey Tidal Project - Stage 3 was to develop the preferred scheme for the tidal energy extraction in the location of the Mersey River estuary. Starting from the previous study conclusions, the ebb generation only scheme has been firstly considered then the ebb and flood generating (or dual) scheme, lastly, pumping mode has been introduced to both ebb and ebb and flood schemes.

8.1.2 The best or preferred scheme is the one which provides the maximum energy with acceptability in respect to environment. The latter means that environment is to be rigorously considered in terms of estuary basin water level range, rates of change of in and out discharges, intertidal exposure, standing periods, water level difference between tidal sea level and estuary basin level.

8.1.3 Ecologically, the plant operation can be managed differently some of the time periods (seasons, hours of the day). Adapted different operation strategies can help in managing the discharge rates of change, the intertidal exposure, sediment deposit,.... Note also that beyond the energy gain aspect, pumping as well can participate to these objectives too.

8.1.4 In order to determine the maximum energy figure, the pure ebb generation without pumping and with an efficient filling of the estuary basin by using large sill sluice gates has been developed with the help of the optimised starting head method.

8.1.5 Environmental aspects have been studied towards low head operation and with specific manoeuvring of the sluice gates to restore low tide levels too.

8.1.6 As a conclusion, the final annual energy table is the following (**Table 2**).

Table 2: Stage 3 annual energy table (based on year 2010)

Stage 3 Options	Scheme summary	Nr turbines	Capacity turbine (MW)	Runner diameter (m)	Installed capacity (MW)	Annual energy (GWh)
A1.01a	Ebb tide generation only with a constant starting head of 3.00 m	28	25	8.0	700	900
A1.02a	Ebb tide generation only with starting heads optimised for maximum energy	28	25	8.0	700	1 050
A1.02b	As A1.02a but with low tide sluicing and holding period to improve inter tidal exposure	28	25	8.0	700	950
A1.02c	Ebb tide generation only with HCO by using the Sluice Gates. The levels difference is limited to generally less than 3m.	28	25	8.0	700	530
A1.02d	Maximum energy (A1.02a) for 8 months per year, head control (A1.02c) for 4 months per year	28	25	8.0	700	920
A1.02e	Ebb generation OSH with high tide pumping	28	25	8.0	700	1 340
A1.03a	As A1.02b with 24 sluice gates	28	25	8.0	700	1 010
A1.04a	Optimised Ebb and flood generation without head limitation	28	25	8.0	700	800
A2.01a	**Ebb tide generation only** with the head difference limited to generally less than 3 m.	44	15	8.0	660	560
A2.02a	Ebb and flood generation with the head difference limited to generally less than 3 m	44	15	8.0	660	520
A1.04c	Ebb and flood generation with high tide pumping	28	25	8.0	700	930

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Annex A: The Mersey Tidal Energy: Theory and Main Results History of the Previous Studies

1.1 The natural tidal resource in the Mersey Estuary

General characteristics

1.1.1 The natural tidal resource in the Mersey estuary is shown in the next tables which were extracted from the National Tide and Sea Level Facility web site, http://www.pol.ac.uk/ntslf/

Tidal Characteristic	Value (m)
Highest Astronomical Tide	10.37
Mean High Water Springs	9.39
Mean High Water Neaps	7.45
Mean Low Water Neaps	3.16
Mean Low Water Springs	1.12
Lowest Astronomical Tide	0.02

Table A.1 – Tidal predictions for Liverpool from 2008 to 2026, relative to Chart Datum

Highest Spring and Autumn Tides			
9.86m	7/Apr/2008	9.83m	16/Oct/2008
9.95m	11/Feb/2009	10.05m	21/Aug/2009
10.17m	2/Mar/2010	10.25m	9/Sep/2010
10.17m	20/Feb/2011	10.21m	28/Sep/2011
9.98m	10/Mar/2012	10.00m	16/Oct/2012
9.98m	13/Jan/2013	10.06m	23/Aug/2013
10.22m	2/Feb/2014	10.29m	10/Sep/2014
10.30m	21/Feb/2015	10.37m	29/Sep/2015
10.20m	11/Mar/2016	10.27m	17/Oct/2016
9.97m	28/Apr/2017	10.01m	5/Nov/2017
9.98m	2/Feb/2018	10.06m	10/Sep/2018
10.12m	21/Feb/2019	10.23m	29/Sep/2019
10.14m	11/Mar/2020	10.22m	17/Oct/2020
9.98m	30/Mar/2021	9.97m	5/Nov/2021
9.77m	3/Feb/2022	9.94m	11/Sep/2022
10.09m	22/Feb/2023	10.20m	30/Sep/2023
10.23m	12/Mar/2024	10.29m	19/Sep/2024
10.10m	31/Mar/2025	10.11m	8/Oct/2025
9.76m	21/Mar/2026	9.78m	15/Aug/2026

Lowest Spring and Autumn Tides			
0.55m	7/Apr/2008	0.57m	3/Aug/2008
0.28m	11/Feb/2009	0.20m	22/Aug/2009
0.04m	2/Mar/2010	0.16m	10/Sep/2010
0.11m	21/Mar/2011	0.36m	31/Aug/2011
0.37m	7/Apr/2012	0.68m	6/Jul/2012
0.45m	11/Feb/2013	0.31m	25/Jul/2013
0.13m	2/Mar/2014	0.16m	13/Aug/2014
0.02m	21/Mar/2015	0.23m	1/Sep/2015
0.13m	8/Apr/2016	0.48m	17/Oct/2016
0.42m	27/Apr/2017	0.50m	25/Jul/2017
0.25m	3/Mar/2018	0.26m	11/Sep/2018
0.02m	22/Mar/2019	0.18m	1/Sep/2019
0.04m	11/Mar/2020	0.31m	19/Sep/2020
0.28m	30/Mar/2021	0.66m	8/Oct/2021
0.54m	3/Mar/2022	0.45m	14/Aug/2022
0.20m	22/Feb/2023	0.19m	2/Sep/2023
0.06m	11/Mar/2024	0.29m	20/Sep/2024
0.25m	30/Mar/2025	0.64m	10/Sep/2025
0.65m	4/Mar/2026	0.48m	14/Aug/2026
Five Highest Tides			
10.37 m	29/Sep/2015	10.37 m	29/Sep/2015
10.30 m	21/Feb/2015	10.30 m	21/Feb/2015
10.30 m	28/Sep/2015	10.30 m	28/Sep/2015
10.29 m	19/Sep/2024	10.29 m	19/Sep/2024
10.29 m	10/Sep/2014	10.29 m	10/Sep/2014
Five Lowest Tides			
0.02m	22/Mar/2019	0.02m	22/Mar/2019
0.02m	21/Mar/2015	0.02m	21/Mar/2015
0.04m	2/Mar/2010	0.04m	2/Mar/2010
0.04m	11/Mar/2020	0.04m	11/Mar/2020
0.06m	11/Mar/2024	0.06m	11/Mar/2024

Table A.2 - Liverpool Highest and Lowest Predicted Tides 2008-2026 (relative to Chart Datum)

Daily hour tidal occurrences

1.1.2 The time of spring tide is fixed by time of day (since the M2 and S2 tides have to be in phase and S2 is controlled by the phase of the sun i.e. time of day). Dover and Liverpool are similar in having the maximum (spring) HW approximately at midday and midnight so the maximum flow and ebb are at 6am and 6pm. This is not the case for other locations around the UK, as the tidal wave advances around the coast, although most of the eastern Irish Sea is close in phase to Liverpool. Also on neap tide and intermediate tides the timing is less favourable, being 6 hours different at neaps.

1.1.3 Year 2010 is not particularly special in terms of this, although there are slight variations in the maximum tidal range from year to year. The maximum tides in the year will occur at equinoctial springs (close to 21 March and September) with a range of 16% higher tides than at the solstices, then there is the 18-year nodal cycle which provides a modulation of about +/-4% of the mean tidal range. There is a variation of equinoctial tidal range on a 4.5 year cycle, with a maximum when the time of lunar perigee (nearest approach of the moon to the earth) corresponds with either the March or September equinox. Some lunar tidal constituents are also affected by an 8.85 year cycle, related to the longitude of perigee. These modulations are not particularly relevant as they cannot help in planning electricity usage and are small, being related to variations in the lunar orbit. For interest, 2010 was a maximum for the equinoctial tide on the 4.5-year cycle but this only varies in height by less than 3% (http://www.pol.ac.uk/ntslf/hilo.php?port=liverpool for maximum tides from 2008-2026).

1.2 The impact of a barrage structure on the tidal resource

1.1.4 The inclusion of a barrage structure alters the external tidal regime. This has been shown in a number of papers including Proctor (1982) and Wolf et al. (2009) who show the changes numerically and Rainey (2009) who provides an analytical approach. Rainey's paper suggests that the reflected wave off of the barrage structure destructively interferes with the approaching tidal wave to reduce the effective resource.

1.1.5 The 'Joule' 2009 study (Burrows et al 2009, see also www.liv.ac.uk/engineering/tidalpower) also showed this effect in 2-D computer modelling of the effect of conjunctive operation of five barrages along the west coast of Britain, and some model output is shown in Figure A.1, showing, in particular, the far-field effects of a barrage in the Severn Estuary. From this study, for a barrage on the Mersey operated in ebb mode, the principal lunar semi-diurnal (M2) component of the tide dropped from 3.23m to 2.86m, and the principal solar semi-diurnal (S2) component of the tide dropped from 0.98m to 0.86m (both at the seaward side of the barrage structure).

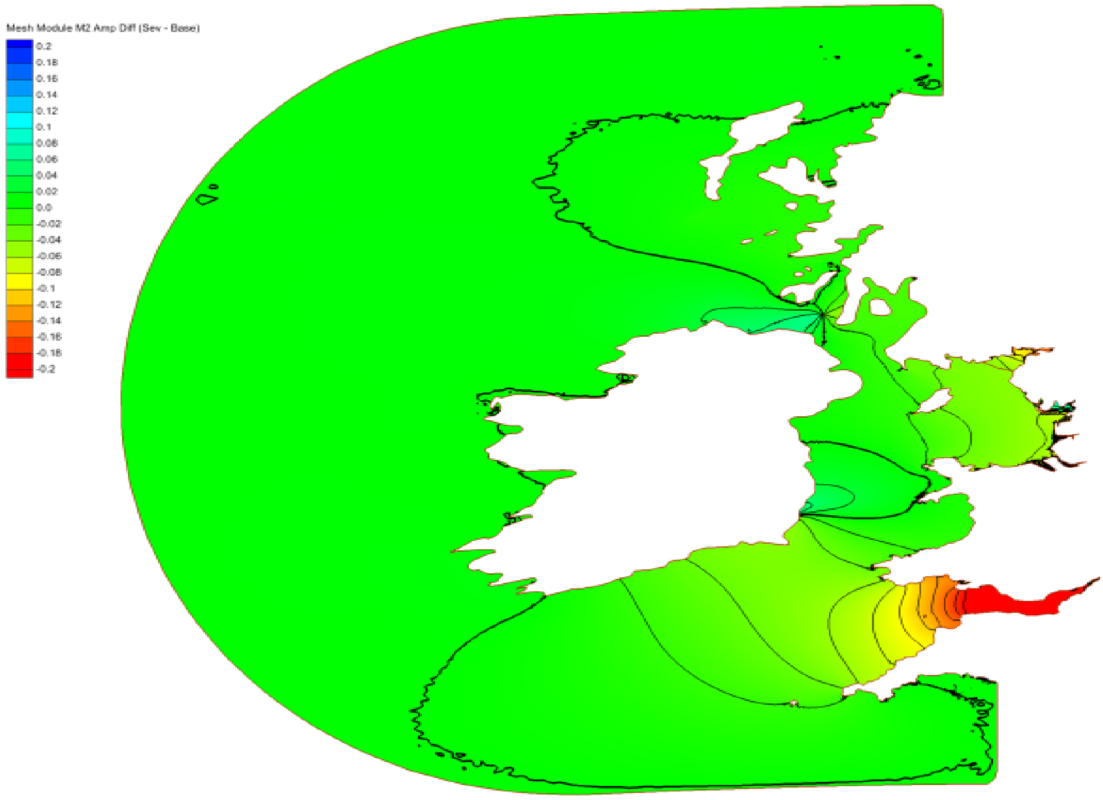

Figure A.1 - Changes in the average (M2) tidal amplitude due to the presence of a Barrage in the Severn Estuary

1.1.6 Because the presence of a barrage alters the tidal regime, there is a need for care when choosing the model boundary conditions. This is perhaps best illustrated in Fong and Heaps (1978) investigation of barrages in the Severn estuary. They demonstrated that the Bristol Channel and Severn Estuary have such extreme tides (over 14m) partly as a result of non-linear resonance effects, and they calculated changes in this resonance based on various barrage options.

1.1.7 In order to model the impacts of significant tidal energy extraction in the Severn (either tidal stream, or especially for barrages which modify the effective length of the estuary), the tidal model boundary would need to lie beyond the physical extent of the resonance effects (in this case out beyond the continental shelf to the south west of Ireland). A boundary any closer would potentially be forcing the model with (resonance amplified) pre-existing tidal values, which would no longer be valid after the modification of the tides by energy extraction. As a post-script to the ‘Joule’ study, it has been found that the southern boundary adopted, as seen in Figure A.1, needs to be extended southward to eliminate its potential effect on the modified tidal dynamics.

1.1.8 More details on tidal modification, especially the phase or the symmetry of changes in ebb or flood are still to be studied in a further stage.

1.3 Theoretical Energy from a Tidal Barrage or Lagoon

1.1.9 If the water was released from the basin instantaneously (through 100% efficient turbines) at high water to low water during the ebb phase of the tide, and the reverse on the flood phase, the maximum theoretical potential energy would be “captured”. With this theoretical **dual** mode of operation, the barrage would capture the total potential energy of the tide, giving an upper bound of energy capture of: $E_P = 2Mgh$, where M is the mass of water, g is the gravity (g = 9.81m/s^2), and h is the height of the volume’s centre of gravity above low water level. Introducing the sea water density ρ = 1025kg/m^3, S the area of the basin and A the amplitude of the (sinusoidal) tide, assuming a vertical-sided basin, the potential energy of the tide is $E_P = 2\rho(S.2A)gA = 4\rho gA^2 S$. This simplified approach is summed up in Table A.3:

M2 Amplitude (A) [m]	Area (S) [km2]	Tidal cycle potential energy [MJ]	Potential energy per tidal period [MWh]	Annual maximum potential energy (Ep) [TWh]
3.23	62	26 016 544	7 227	5.1

Table A.3 – Total annual potential energy based on the mean tide in the Mersey, assuming a vertical sided basin of area 62 km^2

1.1.10 Prandle (1984) presented a simple parametric approach for evaluating the potential energy capture from barrage schemes operated in both ebb and two-way (dual) modes approach. The approach assumes:

- constant flow rate through the turbine (not dependent on head);
- considers only tides of mean amplitude A (usually taken as M_2, the lunar semi-diurnal component) only, i.e. no explicit account for spring-neap variations;
- based upon use of fixed basin area S;
- operations simulated upon the basis of setting basin ‘start level’, ‘finish level’ and ‘minimum generating head’ as independent variables, with the energy extracted, the installed capacity and the sluicing requirements being the computed dependent variables.

1.1.11 Prandle’s simulations then suggest that the extractable ebb-phase energy per tidal cycle will be: $E \approx 0.27E_P$ and that the maximum extractable energy for dual mode operation will be: $E \approx 0.37E_P$ where E_P is the previous total potential energy. These figures do not account for turbine or generator efficiencies, outage losses or transmission losses, possible asymmetry of the turbine performances between direct and reverse mode. Moreover they assume a vertical sided estuary basin, which overestimates the available volume (in particular for ebb and flood generation) if S is taken to represent the basin area at high tidal elevation.

1.1.12 Table A.4 shows the total theoretical energy available from the Mersey, for modified and unmodified tides, and the maximum fraction predicted by Prandle's approach for ebb and dual mode. A representative area of 62 km^2 has been assumed for the basin area behind the barrage. The representative vertical sided basin area S was taken from the estuary bathymetry at a point between high water and below mean water representing an elevation at +0.35M2 above mean water level, this representing a suitable area for a basin operated in ebb mode, where water levels oscillate between high water and slightly below mean water.

M2 Amplitude (A) [m]	Area (S) [km2]	Annual maximum potential energy (Ep) [TWh]	Ebb mode maximum energy (27% of total potential energy) [TWh]	Dual mode maximum energy (37% of total potential energy) [TWh]
3.23	62	5.1	1.4	1.9
2.86	62	4.0	1.1	1.5

Table A.4 – Total annual potential energy and Prandle's maximum extractable energy (ebb and dual) for a modified / unmodified mean tide in the Mersey, assuming a vertical sided basin of area 62 km^2

1.1.13 For a basin with a varying surface area, which is the most frequent case (especially estuaries), the total potential energy is

$$E_{P(filling)} + E_{P(emptying)} = \rho g \int_0^{2A} S(z)\, z\, .\, dz + \rho g \int_0^{2A} S(z) \left(A - z\right) dz$$, which can be

solved analytically if a function for S(z) in terms of z exists or numerically by interpolating into S(z) series. This calculation is carried out by using the Mersey bathymetry which leads to the curve of the estuary basin area in terms of level z shown in Figure A.2.

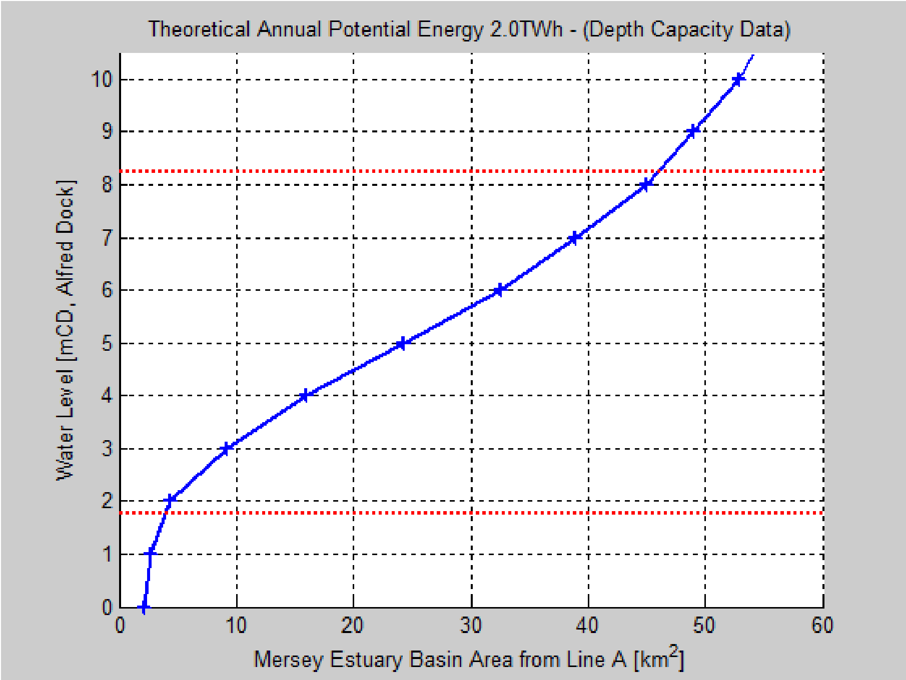

Figure A.2 – Mersey estuary basin area from Line A and corresponding theoretical annual maximal potential energy

1.1.14 Whilst Prandle's estimates of the maximum extractable energy are much quoted, recent research at the University of Liverpool (Yates NC PhD, in preparation) has shown that his approach does not generalise fully, missing a range of allowable operating solutions. In particular, Prandle's approach does not consider dual mode operation that operates beyond low water, ebb or dual mode operation for a wide enough range of start heads, or asymmetric operation in which the ebb and flood parts of dual mode operation are not the same.

1.1.15 This latest analysis has demonstrated that the maximum extractable energy for ebb mode operation is still around 30%, but that the maximum for dual mode needs to be revised upwards, indicative values being 45-50% even with "cost-effective" sluice areas. This revised theoretical analysis does not include the effects of bathymetry or turbine operating characteristics, and these are likely to be significant factors affecting the amount of energy that can be realised in the flood phase of barrage operation, the bathymetric factor especially.

1.4 Mersey Tidal Power Previous Studies

1.1.16 The Mersey Estuary has previously been considered for tidal range energy extraction in the Department of Energy Study (UK Atomic Energy Authority, 1984), the Mersey Barrage Company Study (MBC, 1992) , and the University of Liverpool / 'Joule' Centre 2009 Study (www.liv.ac.uk/engineering/tidalpower). The results from these studies are shown in Table A.5.

Study	Tidal Range	Turbines	Sluices	Energy Output (TWh/yr)
UKAEA 1984	3.23m M2 0.98m S2	27 x 7.6m 23 MW, ebb only (single regulated bulb turbine)	18 x 12 by 12m gates	1.32 (Ebb mode)
Mersey Barrage 1992	Existing tidal histogram + "consideration" of barrage effects	28 x 8m 25MW Kaplan, ebb only	46 x channel sluices	1.20 (Ebb only) 1.39 (Ebb + flood pumping)
University of Liverpool 'Joule' 2009	3.23m M2 0.98m S2	27 x 7.6m 23 MW (double regulated bulb turbine; Hill Chart from Tidal Power by Baker.) *	18 x 12 by 12m gates	1.07 (Ebb mode) 0.98 (Dual mode)

Table A.5: comparison of configuration and energy outputs of previous Mersey Barrage Studies

1.1.17 (*) In this study, the turbine characteristics for reverse mode were taken to be the same as for the forward direction, with both the power and flow rate reduced by 80% to account for machine and draft tube inefficiencies.

1.1.18 The results of the broader and less technically precise University of Liverpool study appear anomalous until it is recognised that it used different turbine characteristics, bathymetry, and sluice characteristics (sluice coefficients) to earlier studies. This "anomaly" was found to be largely due to the reductions in bathymetry and use of effective sluicing areas utilising sluice coefficients of unity. The results of this analysis are presented in Section 13.

1.1.19 It should also be noted that the previous studies used (largely) unmodified tidal information. By way of comparison, Burrows et al (2009), reported 2-D modelling results giving a reduced tidal regime in the Mersey of 2.82m (M2) and 0.86m (S2) with five barrages on the UK's North West coast operated in ebb mode.

Annex B: 0-D Model

1.1 Introduction

1.1.1 The Stage 3 studies have been made by using both EdF (Matlab-Simulink) and UoL (Matlab and Fortran) 0-D software programs. 0-D modelling is obviously less precise than either 2-D or 3-D but much quicker in simulation time and can provide suitable estimates for energy production, load factor, generation time, occurrence and frequency of generation periods, phasing with electricity tariff periods, behaviour of the estuary basin (maximum and minimum levels, water level rate of change, volumes exchanged, holding periods, etc.).

1.1.2 Notwithstanding the 0-D model's simplicity, the use of Matlab – Simulink allows detailed representation of control strategies and easy post-processing of the extensive numerical results generated.

1.1.3 Most importantly, 0-D modelling enables scenario testing and analyses to assist decision making which can subsequently guide the 2-D modelling studies, which can then highlight hydrodynamic issues including transients, surges, and wave propagation and reflection during the tidal plant operation.

1.2 General features about modelling

0-Model software description

A 0-D model used to simulate the operation of a barrage is based on the underlying equation:

$$S(z).\frac{dz}{dt} = Q(H) \qquad (1)$$

where z is the water level in the basin, t is time, S(z) is the surface area of the enclosed basin, H is the difference in water levels across the barrage and Q is the flux through the barrage. The surface area is an input parameter which is linearly interpolated to obtain exact values.

The flux values are prescribed fluxes for given head difference, dictated by operating path in the case of turbine generation, with linear interpolation used to determine exact values. When sluices are used or the turbines are operating in orifice mode (allowing free water passage) the flux is given by

$$Q = C_d.S_s\sqrt{2gH} \qquad (2)$$

where S_s is the total 'sluice' area, g is the acceleration due to gravity and C_d is the discharge coefficient.

The power produced by the turbines is prescribed by the input operating path and is used to determine the system electrical power output. The actual energy yield is determined through the following routine: Initially all generation windows are determined; within each generation window the basin water level is interpolated onto a fixed time step size. The tide level is either calculated analytically by using the tidal components or interpolated in time. The power generated by the turbines is calculated for each time step using the values of the basin and tide levels, which defines the instantaneous gross head difference. Each window is then integrated using the standard trapezium rule and the total energy is the sum of all the windows.

The simulated tide within the model is given by any sized set of tidal constituents.

The model can simulate the progressive start of blocks of turbines and the use of optimised starting head tables so that the starting head for each tide may be determined on a tide by tide basis.
The model runs approximately 500 tides per second and thus allows full year simulations to be accomplished in reasonable computational time.

Inputs: Bathymetry, Sluice characteristics, turbine characteristics including operating path, number of turbines and sluices, optimised operating head tables, operating mode.

Outputs: Water levels, power, annual energy, potential energy during sluicing, generation head stats, sluice head stats, generation window, tide amplitude stats.

1.3 Data

The 0-D model data include the following items:

- The time parameters, simulation time, time-step of solver resolution, sampling of the results
- Physical parameters and constants (gravity 9.81 m/s^2, sea water density 1025 kg/m^3)
- The tides from which are extracted 5 typical tidal cycle from low neap to high spring
- The estuary basin capacity curve in volume or area
- The sluice gates: type, number, dimensions, discharge coefficients in both directions
- The turbines: type, number, dimensions, discharge coefficients (turbine and orifice mode), performance characteristics (see below)
- Control and operation parameters

Plant

- Number of units (-)
- Operating constraints and modes (see also § 1.4)

Units main characteristics

- Type (Bulb, Eco-bulb, Propeller, Hydromatrix®, etc.)
- Runner Diameter (m)
- Speed (rpm)
- Output (MW)

- Rated point in head, discharge, efficiency or output (m)
- Setting level (mCD)
- Submergence requirement (mCD)

Turbine H-Q-P operating path

This fundamental data requires particular attention (see Annexes D and E).

Low head large sluice gates

- Number of gates (-)
- Type
- Dimensions (m)
- Sill (cill) level (mCD)

It is suggested that sluice gates should be vertical lift type in preference to radial in case reverse flow is needed under some operating conditions or other functional needs.

Sluice gates can be either of Submerged Orifice types either Non-submerged orifice e.g. Channel Sluices (see **Annex I** for detailed explanations).

The flow characteristics used throughout Stage 2 and Stage 3 studies obeys to the standard flow formula: $Q = c.S_{SG}\ \sqrt{2g.H}$ where:

- c is an average flow coefficient varying according the flow direction
- S_{SG} is the sluice gate area, m^2
- H is the head (water level difference between the sea side and the estuary side), m

Comments:
This application assumes that the gates remain submerged over their full range of operation. Revised flow modelling is required where engineering considerations may dictate operation under unconstrained free surface open-channel (‘weir’) flow.

Actually, c is a flow coefficient which may vary significantly depending upon the water levels on both sides of the barrage. This complex topic is to be improved during the next stage of the Project.

For instance, two different values of C coefficient are used according to the flow direction. This is due to the design of the hydraulic conduit which is optimised for Flood operation (La Rance and Siwha TPP experience). Values are:

c = 1.5 in Flood direction
c = 1.1 in Ebb direction

Then $Q = c.S_{SG}\ \sqrt{2g.H}$ can be simplified into $Q = C\ \sqrt{H}$ by using the dimensions of the sluice gates designed as, width 12m x height 12m:

- C = 957 in Flood direction ($\approx$ 1000 which correspond to 1000 m^3/s under H = 1 m)

- C = 702 in Ebb direction

The corresponding flow curves are plotted Figure A.3.

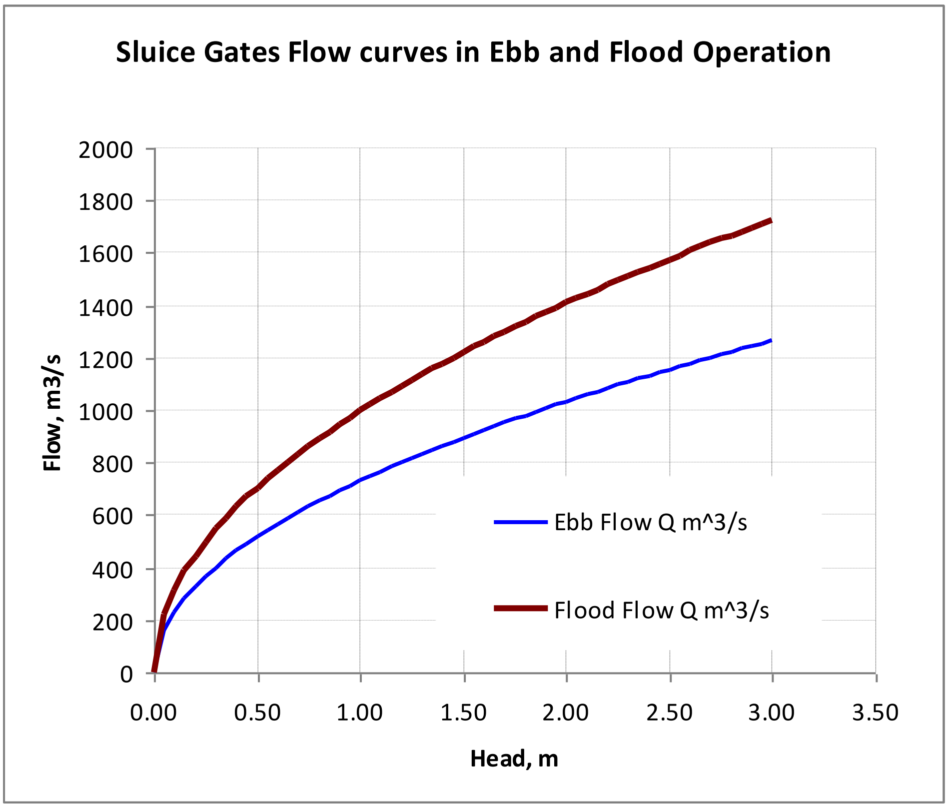

Figure A.3: 12m x 12m Sluice Gate flow curve versus head

1.4 Operating Conditions and Control

Filling and holding

Prior to the start of turbine operation in ebb mode, the estuary has been filled by using the large sluices together with the turbines 'spinning free' in orifice mode operation, whilst the sea water level stays greater than the estuary water level. Once levels equalise, sluice gates and turbine ducts are closed as the 'hold' position awaiting the development of minimum generating head as the tide level falls. Pump assisted filling by supplying electrical drive to the turbine can commence, if desired, at or close to the point at which water levels equalise.

Synchronous operation

All the available turbine units are to be simultaneously operated e.g. all machines start and stop at the same time.

Comments:

Sequencing with delayed start from one unit to the next should be a particular operation aiming to slowly increase the water movements in the channel. Note that in that case, the energy is no longer maximised. Note also that the unit Q(H) curve starts with moderate discharge values at low heads. So another way is to start the units simultaneously at low head instead of delaying for ‘optimised’ (high) starting head.

Starting head

The starting head value is an optimisation parameter aimed at energy maximisation. It can be optimised tidal cycle by tidal cycle or (less rigorously) set as an average for achievement of maximum energy over the full range of tides (spring-neap). If set constant, this value does not provide maximum energy, but may help to moderate sudden discharge rise when the units start to avoid hydraulic shocks and their impact in the estuary.

Stop head

The stop head value is set to the value provided by the turbine suppliers. In general, a safety margin is taken into account and a value of 2 metres is normally recommended for Bulb units of large diameter. In practice, the turbine stop head is lower and in the 1.20-2.00 m range.

Standing

All the operating turbine units are stopped at the stop head.
Guide vanes are closed.
No discharge passes through the turbines and the estuary water level remains constant until the beginning of the estuary filling period.

1.5 Detailed results provided by the software

Sea water (tidal) levels

- Maximum Sea Level [mCD]
- Minimum Sea Level [mCD]
- Sea Range [m]

Estuary basin levels

- Maximum Estuary Level [mCD]
- Minimum Estuary Level [mCD]
- Maximum Estuary Range [m]

Ebb, flood, turbine generation / pumping

- Energy production (or consumption in case of pumping) [MWh or GWh]
- Generation Time [hrs]
- Mean Output [MW]
- Mean Discharge [m^3/s]
- Max. Discharge [m^3/s]
- Starting Head [m]
- Mean Head [m]
- Max Head [m]
- Stopping Head [m]

Flood sluicing

- Operating Time [hrs]
- Mean Discharge [m^3/s]
- Max. Discharge [m^3/s]
- Mean Head [m]
- Max. Head [m]

Turbine sluicing

- Operating Time [hrs]
- Mean Discharge [m^3/s]
- Max Discharge [m^3/s]

Annex C: Comparison Between 0-D and 2-D Modelling

1.1.1 Comparison between 2-D and 0-D models has been carried out on a 10-day period [04 – 14 August 2010] on the A1.02b Scheme, by using the numerical results extracted from "A102b_2010_Discharges.xls / Mike 21 model".

1.1.2 This comparison concerns:

- Turbines head, total discharge, electric output
- Sluice Gates head and total discharge
- Energy provided at each generation cycle

1.1.3 The energy production calculated over the 10-day period leads to a 6.5% higher estimate from 0-D compared to 2-D, as the latter gives 31.9 GWh and the former 34.0 GWh.

1.1.4 The levels, discharges, and powers are superposed in the following series of graphical outputs.

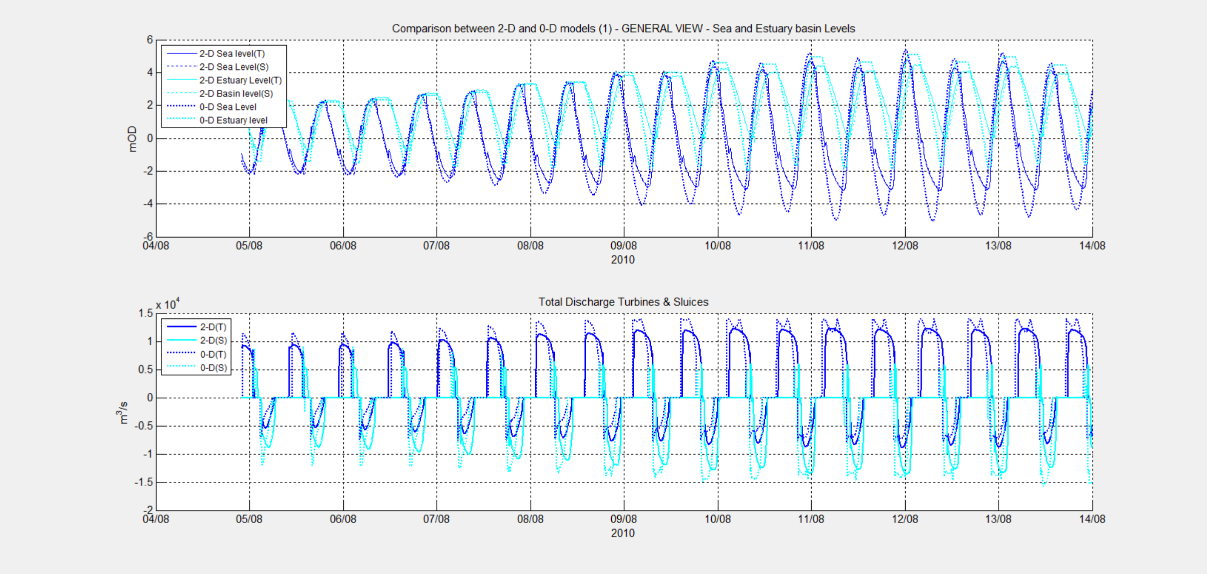

Figure C.1: General view – levels and total discharges

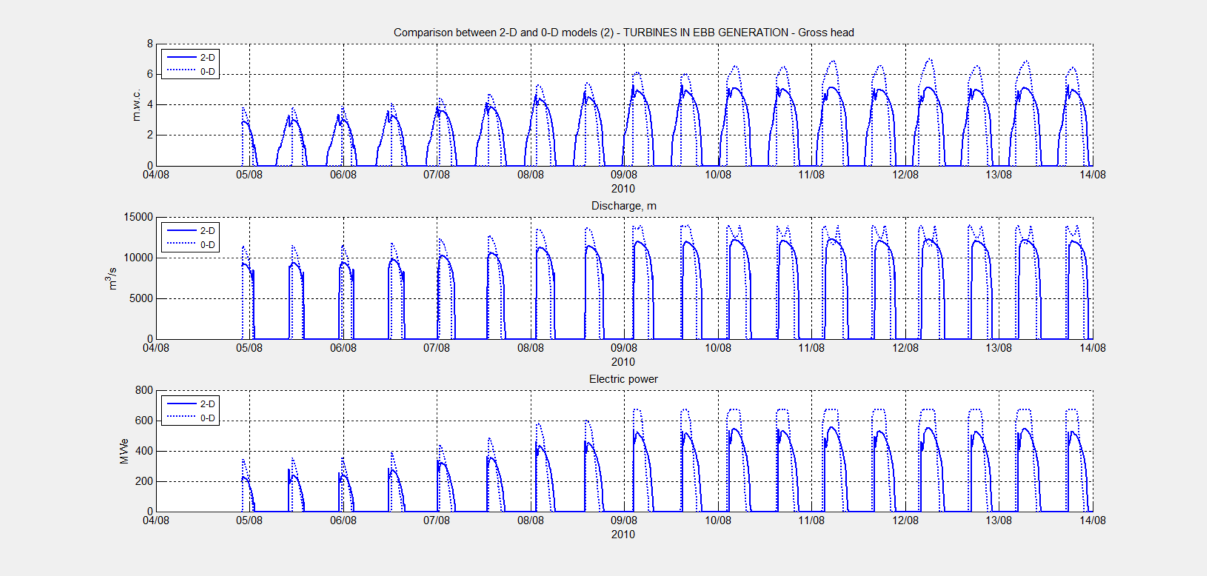

Figure C.2: Turbines in generation

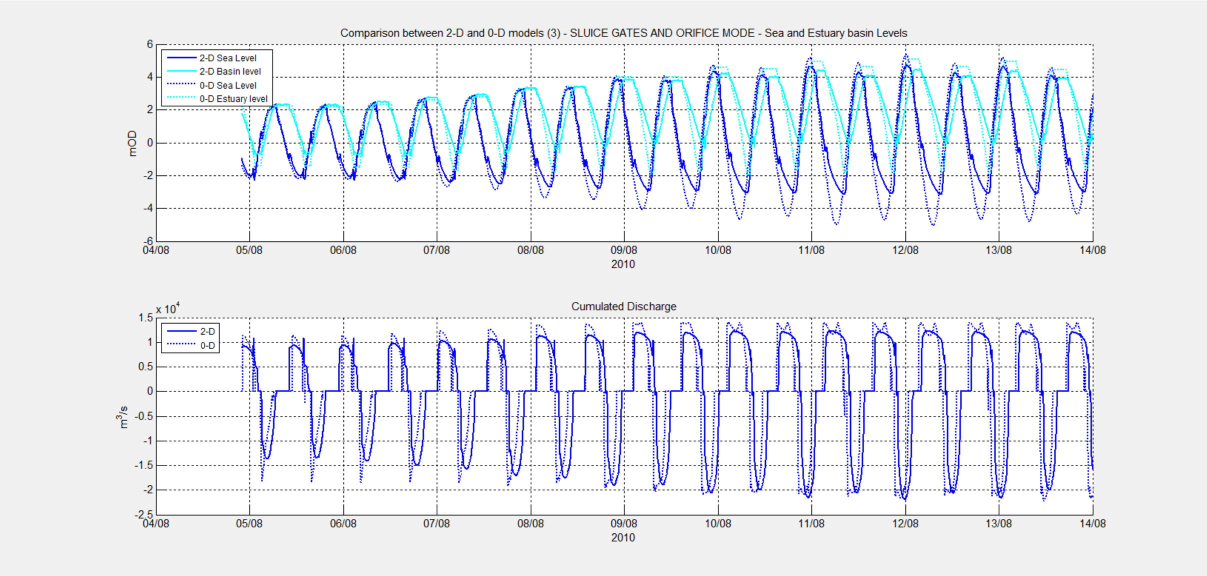

Figure C.3: Sluice gates and turbines in generation and in orifice mode

1.1.5 The key point from this comparison is the significant difference between the 2D and 0D low tide sea levels (Figure C.1 and C.3). In 2D modelling, the entrance channel hydraulics are taken into account between the open sea and the barrage. The resulting tidal modification and friction losses are not included in the 0D model, which assumes the Alfred Dock tidal sea level on the seaward side of the barrage.

1.1.6 This major difference impacts the Q(H) curves of any devices involving modified shapes of the operating discharge and power figures. In 2D compared to 0D, the operating times are longer, the operating head remains lower and consequently discharges and delivered powers are smaller.

1.1.7 This comparison is thus of great importance towards preparation for the further studies to be dedicated to optimisation of the total installed capacity of the Tidal Plant as well as the turbine unit selection; the unit rated output might not necessarily be of 25 MW but closer to 20/22 MW. As a consequence, if such hydraulic phenomena are confirmed, the revised outcome might be lower installed capacity with less annual energy production (by about 6%).

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Annex D: Bulb unit hill chart and operating path (including transposition rules)

Foreword

1.1.1 One of the main input data required for a simulation model is the turbine hill chart in a ready to use H-Q-P coordinate's frame. In order to simplify the calculations, a unique predefined turbine H-Q-P operating path may be considered. The operating path consists of two curves, discharge according the head, Q(H) and electric output according the head P(H), which are interpolated at each time-step according the instantaneous gross head. In a 0-D model, the instantaneous gross head is the difference between the water levels on both sides of the barrage e.g. sea level and estuary level.

1.1.2 Basically, a unique optimal operating path of a turbine unit is an H-Q-P trajectory which aims to maximising the tidal cycle amount of energy at any tidal range and for this objective the most high-performance trajectory is in general the one which maximises the power instead of the efficiency. But actually, the optimal turbine operating path is to be finely adjusted, according the operating conditions, the tide range and the number of available units. This level of precision is the one to be implemented in the plant's automation.

1.1.3 The most reliable way is to interpolate the turbine operating path in a turbine Hill Chart transposed to the predictive prototype patterns. Due to rarity of available hill charts because of constructor's confidentiality on their know-how, a quick approach consists of estimating an H-Q-P operating path by using simple calculation rules as explained in section 0. This approach has been used throughout the Stage 3 studies especially for all simulation cases referring to ebb tide generation only. Note that this simplified approach is only reasonably valid on direct operating only turbine.

1.1.4 For the tidal impounding barrage options referring to ebb and flood operation, a more reliable procedure has been developed in order to obtain consistent operating paths in both quadrants by knowing that a reversible turbine is a compromise which slightly alters the performances of direct and reverse turbining modes. In other words, the turbine behaviour - if it is of conventional design as bulb or propeller - is absolutely not symmetric. The transposition procedure is described in section 0 based on the use of La Rance reversible bulb turbine hill charts data.

Direct Bulb turbine operating path (simplified method)

Direct Turbine H-Q-P operating path

In a first approach, one can assume a unique operating path applicable at any tide and based on the design number of units.
The unit discharge is a function of the net head by using the following formula:

$$Q(H_n) = C.S_t \sqrt{2g}.H_n^{0.5}$$

Where:

C is an average value of the discharge coefficient

S_t is the runner area[1], m²

H or H_{gross} is the gross head, m

H_n is the net head deduced from the gross head and the head losses, $H_n = H - K.Q^2$, m

K, is the global head loss coefficient accounting for the intake and the outlet of the turbine hydraulic conduit
Consequently, this previous implicit formula is transformed in order to get a direct relationship between H and Q.

This discharge curve is limited when the corresponding rated (maximum) output is reached. When the turbine power reaches the generator capacity, the output stays at its maximum value, then the unit discharge is to be reduced according the following relationship:

$$Q = \frac{P}{\eta \ \rho \ g.H_n}$$

with η (%) the turbine efficiency varying in Q and H according the BU Hill Chart and P is the unit rated output, MW.

The unit output is a function of the head by using the classical $P = \eta \ \rho \ g.Q.H_n$ and then transformed into a direct $P(H)$ relationship or an electrical power $P_e(H)$ relationship by introducing the generator and transformer efficiencies.

The assumptions on the electric efficiencies are the following:

- Generator average efficiency is about 97%
- Transformer efficiency if 99 / 99.5%

[1] The equation has the Area as the runner area. It is tended to use the runner area less the area of the turbine hub and in that case the difference is captured in the turbine discharge coefficient.

Application to a 25 MW – 8 m runner diameter

The Bulb turbine characteristics are the following:

- mechanical output 25 MW
- runner diameter 8 m

In the context of Stage 2 starting studies, the synchronous speed had not to be defined.
The power operating path of the turbine has been stated by fixing a rated head of 6 m and a maximum discharge of 500 m^3/s.

The turbine discharge function of the net head follows the equation $Q = 0.978\, S\sqrt{2gH_n}$ and a maximum total amount of head losses through the conduct is assumed to be 0.50 m at the maximum discharge.

The efficiency curve function of the head is of exponential shape $\eta = \left(\eta_{\max} - e^{-\frac{H}{c}}\right)$. The maximum turbine efficiency has been assumed to reach 92% and the global electrical efficiency has been averaged to 96%.
Corresponding curves are presented in Figure D.1 by considering the example of a preliminary design of large diameter Bulb units which may equip the conventional Tidal Barrage in Line A:

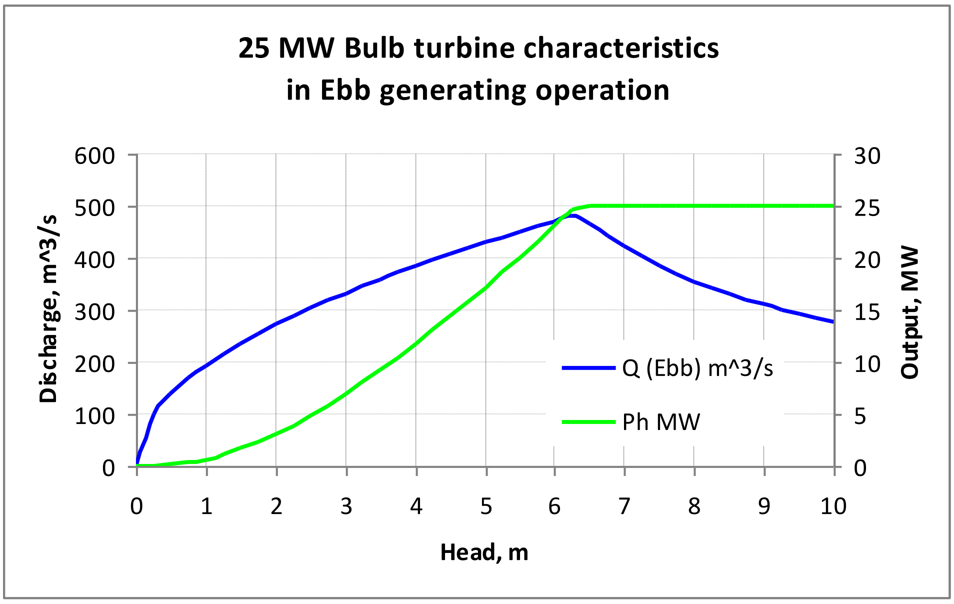

Figure D.1: Q(H) and P(H) curves example for a Bulb unit of 25 MW , diameter 8m

Minimum operating head

It is assumed a value of 1.20 m according experience. This value might be increased in reverse turbine operation according constructor's advice but is kept similar e.g. 1.20 m for the moment (see section 0).

Inlet and outlet velocities

Estimation of the inlet and outlet velocities is required to evaluate the plant impact by using a 2-D model.

- Maximum speed of the water or the maximum flux (note: the 2-D model grid needs to be able to handle the high velocities).
- Maximum flux is deduced from the Q(H) operating path.

In general, design of the outlet leads to a maximum outlet water speed in the [2.50; 3.00] m/s range.

Transposition method to determine Reverse Bulb units operating paths

The only available reference is La Rance Bulb unit hill chart designed by Alstom Neyrpic in the 1950's. Consequently, this data is used to help determining the two operating paths which are to be used for direct and reverse turbining operation in the simulations.

La Rance hill chart

La Rance hill chart defines a series of iso-curves of efficiency, power, blades and wicket gates opening in the H/Q plane, for the four possible operating modes: Direct Turbine, Inverse Turbine, Direct Pump and Inverse Pump.
This hill chart is issued from model test results transposed to La Rance characteristics: n=93.750 rpm and D=5.35m. The efficiencies correspond to the La Rance units' efficiencies, but with water per volume ratio corresponding to fresh water and not sea water, and for model scale.
The OUTPERF internal EDF-CIH software (application for hill charts transformations and visualisation) is then used to resample the La Rance base hill chart on a regular 200*200 mesh in the H/Q plane so as to be able to apply following transformations to the hill chart (for transposition to Mersey project) and in the end to interpolate on it the operating paths points.

Transposition of La Rance hill chart to Mersey project

The La Rance hill charts for direct and reverse turbine mode are then transposed to the Mersey project characteristics, using the OUTPERF internal EDF-CIH software.
The values of Head and Discharge are transposed according to the following formulas that define the homology between hydraulic machines of same specific speed:

$$H_M/H_R = (n_M / n_R)^2 * (D_M / D_R)^2$$
$$Q_M/Q_R = (n_M / n_R) * (D_M / D_R)^3$$

Where $_M$ indicates the Mersey and $_R$, La Rance, and with:

- H: net head (m)
- Q: discharge (m^3/s)
- n: rotational speed (rpm)
- D: runner diameter (m)

Transposition of the efficiency

The Efficiency values corresponding to the points in the H/Q plane are transposed from La Rance project to Mersey project using IEC 60193 scale effect formula for the direct turbining mode only.

For the reverse turbining mode, efficiencies are directly transposed from La Rance to the Mersey without scale effect as it is not a classical operating mode that is covered by the IEC scale effect formula.
The increase in runner diameter from La Rance to Mersey leads to a positive scale-effect, that means an increase of the efficiency: $\eta_M = \eta_R + \Delta\eta$.

Transposition of the power

The power associated with the transposed hill chart points of the Mersey project is calculated with the transposed efficiency, and the term ρ_M*g_M that takes into account the water per volume ratio of sea water ($\rho_M*g_M = \rho_R*g_R * 1{,}025$):

$$P_M = \rho_M*g_M*Q_M*H_M*\eta_M$$

The transposition formula for the power deducted from the previous section and neglecting efficiency effect is the following:

$$P_M/P_R = (n_M / n_R)^3 * (D_M / D_R)^5*(\rho_M*g_M/\rho_R*g_R)$$

EdF OUTPERF software

The transpositions are realised by using OUTPERF EDF-CIH software which provides the output files for direct turbine mode, and for inverse turbine mode. These files contain the predictive hill charts for a possible turbine design for the Mersey project, on which the H/Q operating paths will be interpolated.

Transposition table of results

The next Table D.1 presents the comparison and the transposition rules application previously introduced. Note that:

- The rated output is actually 23.7 MW instead of the 25 MW commonly used throughout the study.
- The synchronous speed is fixed at 62.5 rpm at this stage of the study and needs to be confirmed in a further stage.

	Reversible Bulb Turbine		
	Units	La Rance	Mersey
Gravity	m/s2	9.81	9.81
Water density (*)	kg/m3	997.73	1025
Rated output	MW	10	*23.7*
Power ratio	-	1	2.370
Grid frequency	Hz	50	50
Synchronous speed	rpm	93.750	62.500
Runner diameter	m	5.35	8.000
Synchronous speed ratio	-	1	0.667
Runner diameter ratio	-	1	1.495
Head ratio	-	1	0.994
Discharge ratio	-	1	2.229
Power ratio	-	1	2.344
Rated head	m	6.50	6.46
Rated discharge	m3/s	189.1	421.5
Efficiency increase	%	0%	3%
Efficiency at the rated point	%	83.5%	86.5%
Rated power	MW	10.0	23.7
Rated head	m	7.70	7.65
Rated discharge	m3/s	186.5	415.6
Efficiency increase	%	0%	3%
Efficiency at the rated point	%	70.1%	73.1%

(*) La Rance hill chart refers to the physical model tests by using fresh water.

Table D.1: transposition from La Rance to a Bulb turbine design for the Mersey

Interpolation of operating paths on Mersey hill chart

Convention for direct and inverse turbine modes

It has been chosen to use a positive head (and a positive discharge) for both direct and reverse turbine modes.

Operating paths calculation

A software has been developed to calculate the operating paths Q(H) from the values given in the previous section, and then to interpolate the corresponding efficiency and power values in the predictive Mersey hill chart.

The method of operating paths calculation is the same in direct and inverse turbines modes and it is the following. A rated head is defined to set the limit between the right part of the operating path at constant rated or nominal power, and the left part of the operating path is described as a third degree polynomial maximizing either the power, either the efficiency.

The part of the operating path for any value of head lower than the rated head is defined by the mean of the dQ/dH derivatives at the rated point:

- For a path maximizing the efficiency, this derivative is positive

- For a path maximizing the power this derivative is almost null

Direct Turbine Quadrant

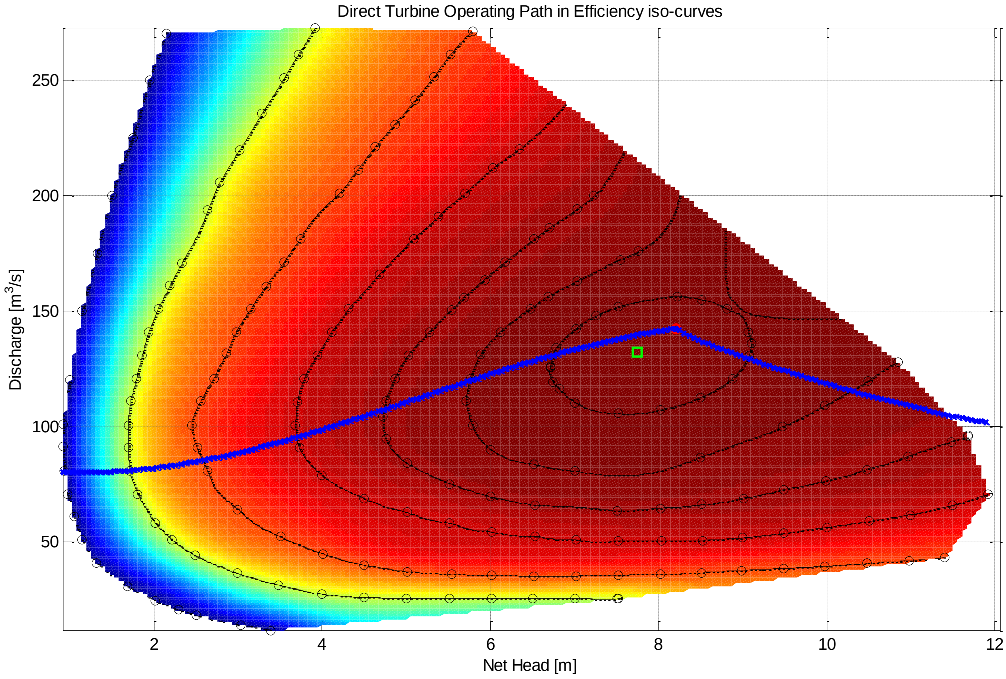

Figure D.2 : La Rance Bulb turbine – direct turbine quadrant. Best efficiency operating path. Hn min = 1.20m. Q(Hn min) = 80 m3/s. Hnom = 8.20m. dQ/dHn at rated point = 10.

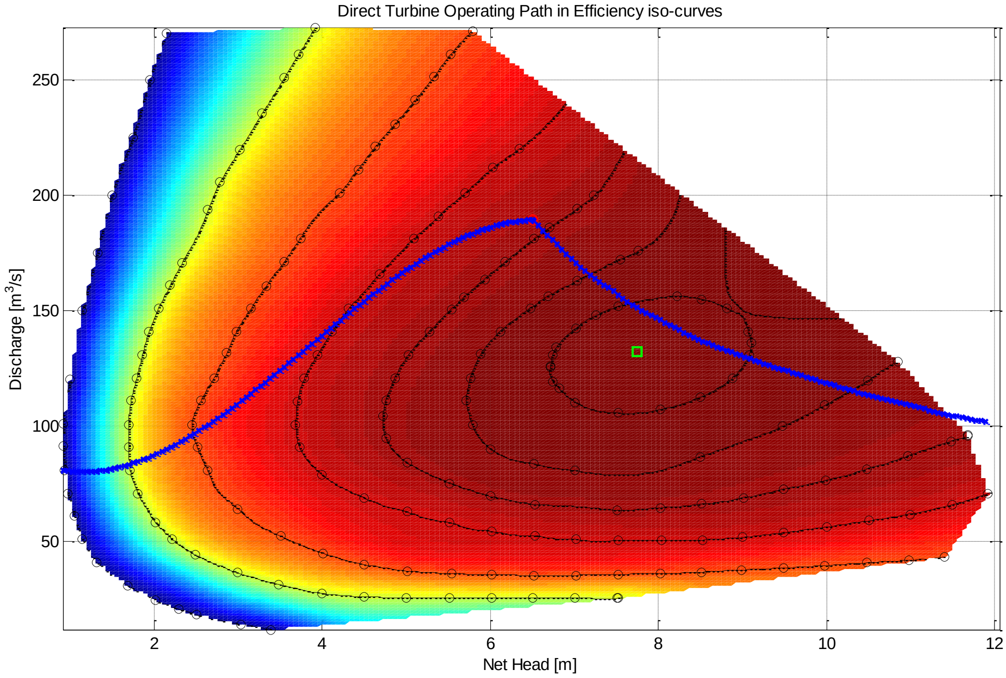

Figure D.3 : La Rance Bulb turbine – direct turbine quadrant. Best power operating path. Hn min = 1.20m. Q(Hn min) = 80 m3/s. Hnom = 6.50m.

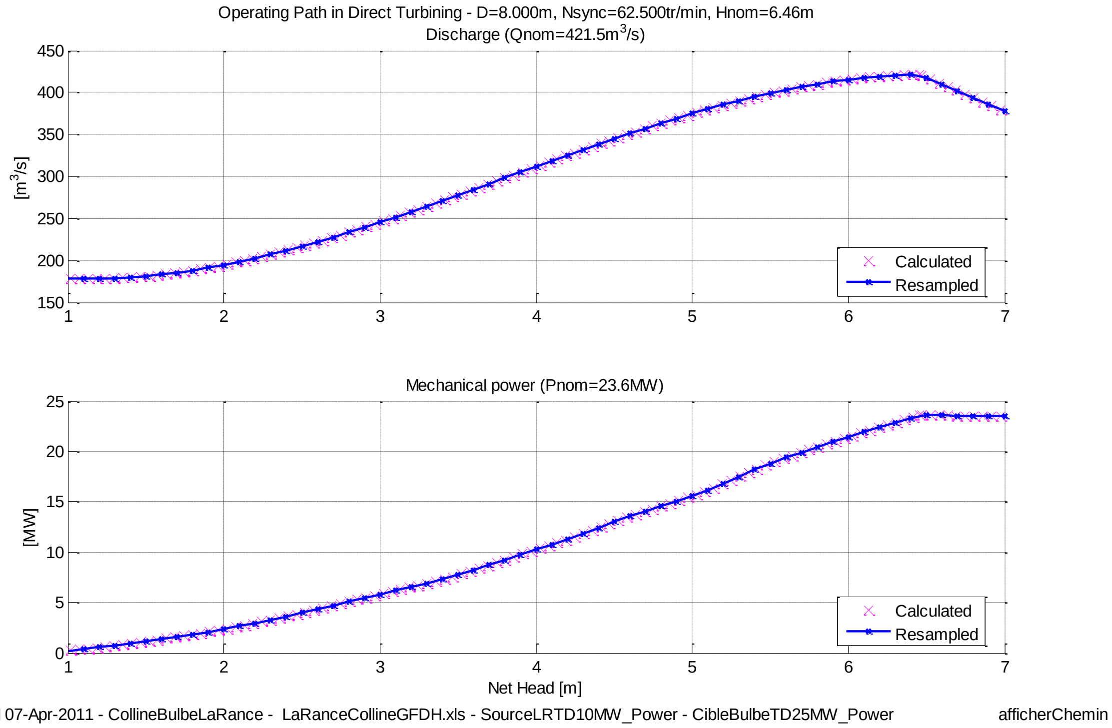

Figure D.4: 25MW 8m Bulb Turbine Power Operating Path in DIRECT Turbining

Reverse Turbine Quadrant

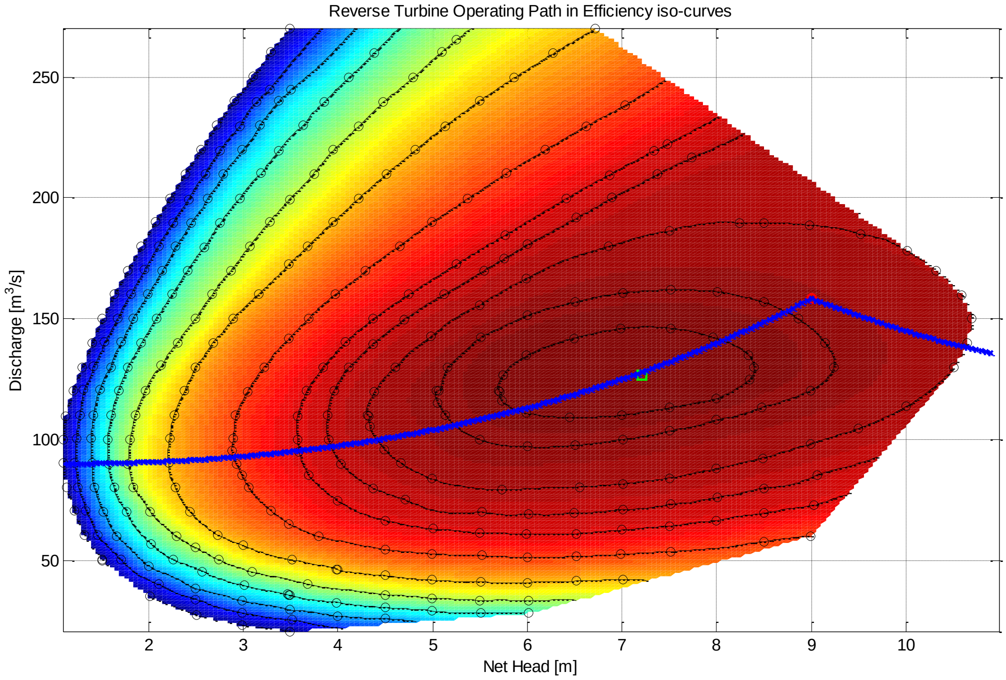

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Figure D.5 : Rance Bulb turbine – reverse turbine quadrant. Best efficiency operating path. Hn min = 1.00m. Q(Hn min) = 90 m3/s. Hnom = 9.00m.

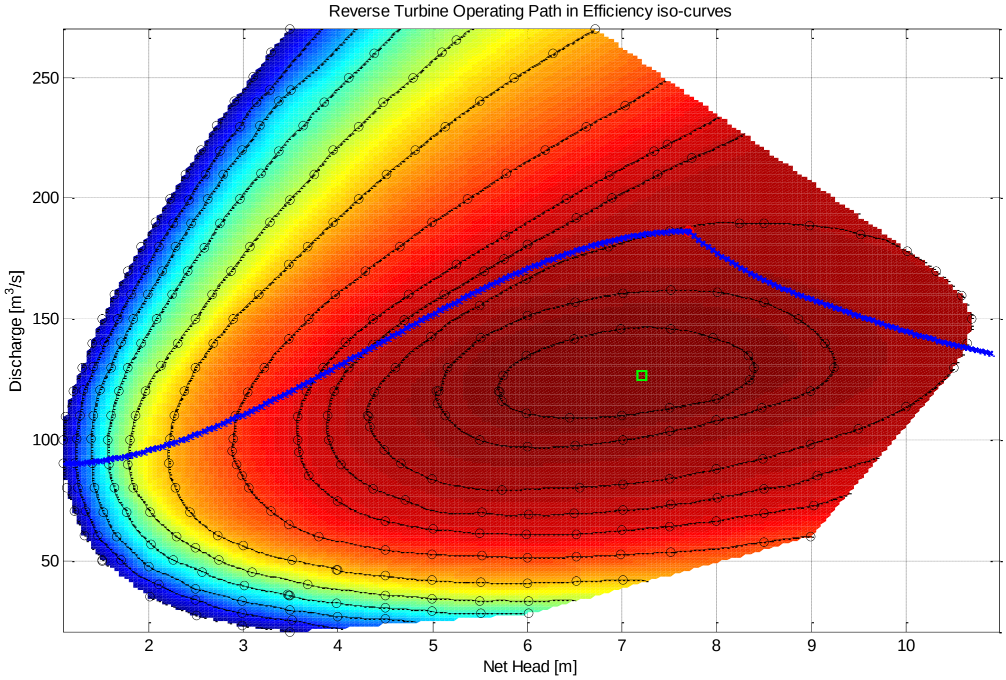

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Figure D.6 : La Rance Bulb turbine – reverse turbine quadrant. Best power operating path. Hn min = 1.00m. Q(Hn min) = 90 m3/s. Hnom = 7.70m.

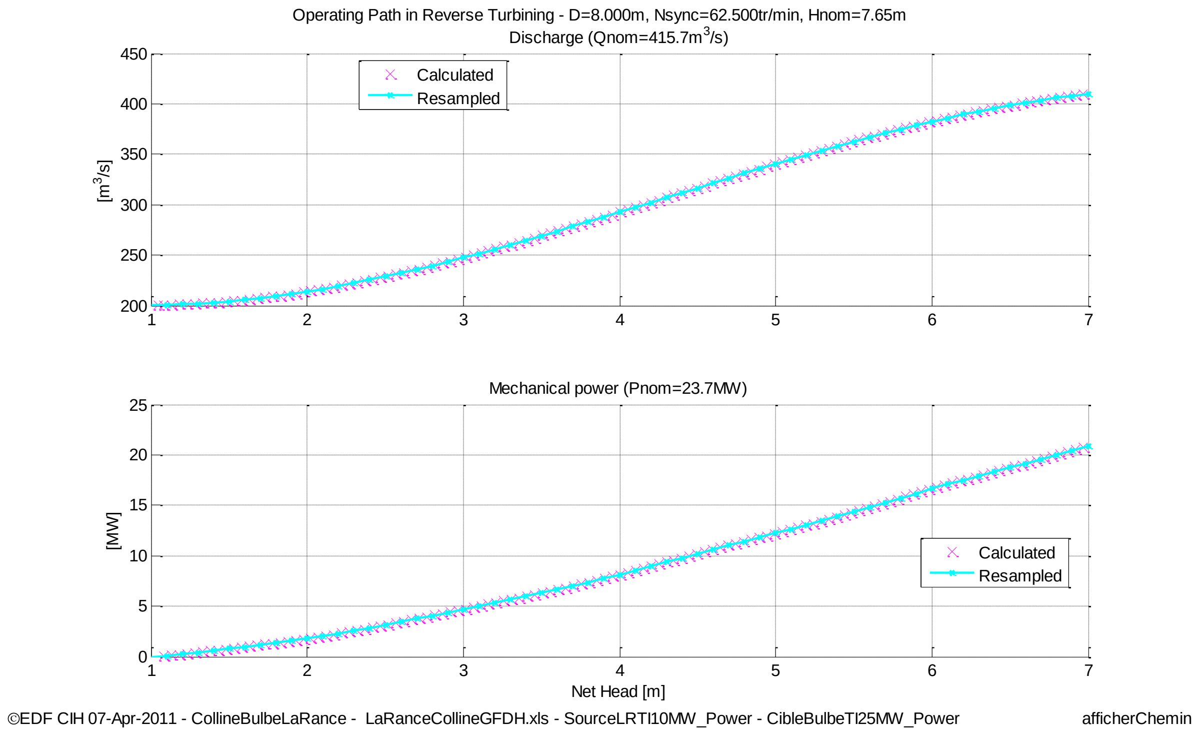

Figure D.7: 25MW 8m Bulb Turbine Efficiency Operating Path in REVERSE Turbining

Reverse Bulb units starting and stop heads

In direct (Ebb) generation, it is assumed as a first level of study that:

- The starting head is at least 2.00 m
- The stop head is the minimum operating head e.g. 1.20 m
- In reverse (Flood) generation, it is assumed as a first level of study that:
- The starting head is to be selected between 2.00 and 3.00 m
- The stop head is at most 1.80 m

Annex E: Turbine setting level calculation

This section provides the Bulb units setting level or turbine centreline axis corresponding to the 2 first options of Stage 3 with a Tidal Barrage settled in Line A, which are A1.02a and A2.01a:

- A1.02a is 28 Bulb units in Ebb generation operated in OSH (Optimised Starting Heads) mode which leads to the maximum of energy production that Ebb generation can capture in the Mersey estuary with a Barrage settled in Line A;
- A2.01a is 28 to 44 Bulb units in Ebb generation operated in HCO (Head Control Operation) mode which leads to a lower energy production and which aims to dynamically adjust the head not to exceed approximately 3 m.

The main difference to be considered between these 2 options is the minimum sea water level which is the downstream level condition to take into account in the unit setting level calculation.

Definitions

According to IEC standard n°60193, the cavitation coefficient of the plant is noted σ_{Plant} and is given by:

$$\sigma_{Plant} = \frac{NPSE}{E} \approx \frac{NPSE}{g.H_n} \approx \frac{NPSH}{H_n}$$

Where:

$NPSE$: Net Pressure Specific Energy,

E : Energy, [J.kg.m]

$NPSH$: Net Pressure Suction Head, [mwc]

H_n : Net Head, [mwc]

g : Gravity, [m.s^{-2}]

The cavitation coefficient can be calculated based on the pressure head at the tail water surface or at the outlet of the draft tube.

To simplify the calculation of the cavitation coefficient (σ) during a preliminary design of the unit, the turbine centreline axis has been selected as the reference level, and the tail water level has been used.

Including a correction factor for the variation in atmospheric pressure, the formula that defines the plant cavitation coefficient σ_{Plant} is the following:

$$\sigma_{Plant} = \frac{H_a - H_s() - t_v}{H_n()} \qquad (1)$$

With:

H_a : Atmospheric pressure, [mwc]

t_v : Vapour pressure of water, [mwc]

$H_s()$: Minimum submergence (the submergence takes a negative value when the turbine is below the tail water level), [mwc]

$H_n()$: Net head, [mwc]

According the standard convention, the minimum submergence $H_s()$ is a negative value and corresponds to:

$$H_s() = Z_{ref} - Z_{tw}() \quad (2)$$

With:

Z_{ref} : Turbine centreline axis, [mCD][2]

$Z_{tw}()$: Tailwater level, [mCD]

The cavitation coefficient can be estimated by considering the minimum tail water level e.g. the minimum sea level observed during turbine generating operation. This minimum tail water level is deduced from the 0-D model simulations for the studied Option.

To avoid damages on runner blades due to cavitation phenomena, the coefficient σ_{Plant} must be higher than the minimum coefficient value required by the turbine runner $\sigma_{Turbine}$.

$$\sigma_{Plant} \geq \sigma_{Turbine} \quad (3)$$

For a Bulb turbine, the cavitation coefficient is a function of the specific discharge Q_{11} and corresponds to:

$$\sigma_{Turbine} = f \times Q_{11}^2 \quad (4)$$

With:

f , coefficient issued from experience, [-]

Q_{11}, specific discharge, $Q_{11} = \dfrac{Q}{D^2\sqrt{H_n}}$, [m³.s⁻¹]

Furthermore, the selection of the unit setting level has to be complied with the following conditions:

- Top levels of inlet and outlet hydraulic circuit greater or equal to minimum sea or basin levels to avoid entrance of air in the circuit.
- Suitable high in the machine hall between the turbine floor and the roof of the Power House

[2] mCD: metre Chart Datum which is the altimetry reference of the Mersey Project.

Calculation method and hypothesis

In order to respect $\sigma_{Turbine} \leq \sigma_{Plant}$ and at the same time, minimise the setting of the turbine for CW cost reason, the centreline axis is deduced from $\sigma_{Turbine} = \sigma_{Plant} - \varepsilon$. By combining equations (1), (2) and (4), one obtains:

$$\frac{H_a - Z_{ref} + Z_{tw} - t_v}{H_n} = f \times \frac{Q^2}{D^4 . H_n}$$

From which it is deduced:

$$\boxed{Z_{ref} = H_a + Z_{tw} - t_v - f \times \frac{Q^2}{D^4}}$$

In order to keep some conservative approaches regarding the setting level of the units aiming to avoid any cavitation damaging, note the following assumptions of the physical constants, especially the high sea water average temperature which leads to a high vapour pressure. Note also that a low atmospheric pressure, lower than the standard value, should normally be used.

Constants	variable	units	value
Gravity	g	[m.s-2]	9.81
Sea water density	ρ	[kg.m-3]	1025
Atmospheric pressure	Patm	[Pa]	101 335
Atmospheric pressure	Hatm	[mwc]	10.08
Sea water temperature	T	[°C]	16
Vapour pressure	pv	[Pa]	1 815
Vapour pressure	tv	[mwc]	0.18

Table E.1: constants used for cavitation coefficient estimation

In the next tables here after, notations are:

$\sigma_{Plant}(Z_{ref})$: Cavitation coefficient at the turbine centreline axis.

$\sigma_{Plant}(Z_b)$: Cavitation coefficient at the highest point of the turbine blades.

Note that in the next tables, the rated specific speed is also given and it is reminded that this value is obtained from the formula:

$$N_s = N_{sync} \frac{P_{rated}^{0.5}}{H_n^{1.25}}$$

Stage 3 - A1.02a Ebb Generation in OSH operation (Annual Energy maximisation)

In the A1.02a option, year 2010 simulation provides a minimum estuary basin level of 4.08 m, thus the minimum sea water level (tail water level) is this latter value minus the stop head of the unit which is 1.20 m, e.g. 2.80 m mentioned in Table E.2 thereafter:

Stage 3 - Option A1.02a Ebb Generation in Optimised Starting Heads operation			
Turbine centreline axis	**variable**	**units**	**value**
Unit Rated Output	P	[MW]	23.7
Runner Diameter	D	[m]	8.000
Turbine discharge	Q	[m3.s-1]	500
Net Head	Hn	[mwc]	6.50
Specific discharge	Q11	[m3.s-1]	3.064
Specific discharge cavitation factor	f	[-]	0.30
Turbine cavitation coefficient	σ Turbine	[-]	2.817
Tailwater Level (e.g. minimum sea water level when unit generates)	Ztw	[mCD]	2.80
Turbine Setting Level (axis centreline)	Zref	[mCD]	**-5.66**
Submergence (standard convention of sign)	Hs	[mwc]	-8.46
Plant cavitation coefficient at the unit axis	σ plant (Zref)	[-]	2.825
Plant cavitation coefficient at the highest point of the blades	σ plant (Zb)	[-]	2.21

Table E.2: A1.02a Bulb turbine setting level

The Turbine Setting Level (axis centreline) is **-5.70 m**.

Stage 3 - A2.01a Ebb Generation in Head Control Operation (≈ 3 mwc)

In this A2.01a option, year 2010 simulation provides a minimum sea water level close to 0.00 mCD, consequently the calculation remains the same and the only changing data is the tailwater level, thus the turbine setting level (axis centreline) is to be shifted 2.80m lower leading to **-8.50 m**.

Annex F: Bulb units cost estimation

1.1.5 The assumptions for the cost estimate of the electromechanical equipment are the following :

- Despite the different operating mode of the different options studied, only two different equipment configuration cost estimates are provided :
  - 28 turbines of 8 m of diameter and 25 MW unit capacity
  - 44 turbines of 8 m of diameter limited to 15 MW unit capacity
- No contingencies are taken as all costs will be gathered and a global contingency calculation will be made.
- The general limit of supply for the options cost estimate are the following :
  - The generating plant equipment and balance of plant up to the high voltage side of the step up transformers to the export voltage.
  - For the synchronous plant this will include all equipment up to the generator transformer high voltage terminals.
  - The unit gate or stoplog if any is part of the generating plant cost estimate.
- Equipment for all substation, transmission and grid interconnection are not considered in the generating plant cost estimate.
- Cost estimates include all balance of plant in the power stations i.e. station cranes, auxiliaries, HVAC, etc.

1.1.1 The main characteristics of the equipment are the following :

- Unit type : 8m runner diameter bulb turbine
- Number of units : 28 or 44
- Unit capacity : 25 MW (for 28 units) or 15 MW (for 44 units)
- Total installed capacity : 700 MW (for 28 units) or 660 MW (for 44 units)
- Unit operation : ebb generation only or ebb and flood
- Rotation speed : 62.5 rpm or, 50 rpm for turbine 500 rpm for generator through gearbox if gearbox technology option is preferred in further studies
- Unit output voltage : 11 kV
- Step up transformer : 11kV/132kV

1.1.2 Each unit has its own gate and stoplog and associated equipment. Each group of four units has its own overhead crane.

1.1.3 Each unit has its own 11kV circuit breaker and associated equipment.

1.1.4 For the options A1.02, A1.03 and A1.04 the unit capacity is 25 MW.

1.1.5 For the options A2.01, A2.02, the unit capacity is limited to 15 MW in order to fit the head control operation mode to limit the head difference to remain under 3 m, most of the time. For the equipment point of view this means that :

- The units have the same design but the performance is reduced (generators and gearbox).
- The electrical equipment that leads the power to the grid (11kV cables, 11kV/132kV step up transformers, electrical auxiliaries and transformers, etc.) are designed to deliver a maximum of 660 MW)

1.1.6 All 11kV cables are connected to a common busbar linked to the main switchyard through a 11kV/132kV step up transformer.

1.1.7 This main generating equipment is associated with the necessary auxiliary electrical equipment and SCADA.

1.1.8 For the options A1.02, A1.03 and A1.04a the total cost of the electromechanical equipment is M£ 510.

1.1.9 For the options A2.01, A2.02, the total cost of the electromechanical equipment is M£ 750.

Annex G: Case Study – Ebb Tide Power Generation

	Variable description	Variable name	Value	Value	Value	Value	Value	Value	Dimension
Case name	Case reference name	CaseName	A1.02a (ebb in OSH)	A1.02b (ebb in OSH with low tide sluicing and hold)	A1.02c (ebb in head control 3m by the sluice gates)	A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG)	A2.01a (ebb with head control 3 m by 44 BU)	A1.02e (ebb in OSH and pumping)	
	Case description	CaseDescription	28BU25MW-18SG12x12	28BU25MW-18SG12x12	28BU25MW-18SG12x12	28BU25MW-24SG12x12	44BU15MW-18SG12x12	28BU25MW-18SG12x12	
Simulation	Simulink model name	SimulinkName	SimMersey.mdl	SimMersey.mdl	SimMersey.mdl	SimMersey.mdl	SimMersey.mdl	SimMersey.mdl	-
Tides	Sea level data file (.mat created by TidesAnalysis.m)	TidesFileName	TidesAlfredDock2010.mat	TidesAlfredDock2010.mat	TidesAlfredDock2010.mat	TidesAlfredDock2010.mat	TidesAlfredDock2010.mat	TidesAlfredDock2010.mat	-
	Level offset between mMSL and mCD	dH_MSL_CD	5.10	5.10	5.10	5.10	5.10	5.10	
Basin	Basin Area sheet name	BasinSheetName	LineAtoUpStreamEnd (2)	LineAtoUpStreamEnd (2)	LineAtoUpStreamEnd (2)	LineAtoUpStreamEnd (2)	LineAtoUpStreamEnd (2)	LineAtoUpStreamEnd (2)	-
	Estuary Basin Minimum Level	BasinMinLevel	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00	mCD
Plant equipment	Total number of units	sPlant.Nb	28	28	28	28	44	28	-
	Total installed capacity	sPlant.TIC	700	700	700	700	660	700	MW
Units	Units Xls data file name	UnitsXlsFileName	BU25MW D8m (power).xls	BU25MW D8m (power).xls	BU25MW D8m (power).xls	BU25MW D8m (power).xls	RBU15MW D8m (power).xls	BU25MW D8m (power).xls	-
Operating Mode	Direct Turbining (Ebb)	sOM.DTE	1	1	1	1	1	1	logical
	Reverse Turbining (Flood)	sOM.RTF	0	0	0	0	0	0	logical
	Direct Pumping (Flood)	sOM.DPF	0	0	0	0	0	1	logical
	Orifice Mode in Flood	sOM.OMF	1	1	1	1	1	1	logical
	Orifice Mode in Ebb	sOM.OME	0	1	0	0	0	0	logical
	Sluice Gates in Flood	sOM.SGF	1	1	1	1	1	1	logical
	Sluice Gates in Ebb	sOM.SGE	0	1	0	1	0	0	logical
	SG manoeuvring in Anticipation Mode (1) or after Generation End (0)	sOM.Delay	0	0	[illegible]	0	0	0	logical
	Flag for head limitation with SG in Ebb	sOM.HlimSGE	0	0	[illegible]	0	0	0	logical
SG & OM Control	Opening head in Flood operation	sOM.OpeningHead	0.00	1.50	[illegible]	1.50	0.00	0.00	m
	Temporisation from min sea level in Ebb	sGates.DelayEbb	0	10	[illegible]	0	0	0	mn
	Temporisation from min sea level in Flood	sGates.DelayFlood	0	0	0	0	0	0	mn
	Head limitated value controlled by the Sluice Gates in Ebb tide	sGates.HmaxSGE	0.00	0.00	2.90	0.00	0.00	0.00	m
	Regulation gain of gates number in SGE mode	sGates.Gain	0.00	0.00	2.00	0.00	0.00	0.00	-
	Number of Sluice Gates in operation Xls Filename	sGates.SheetName	Constant total number	Ebb and Flood (exp)	total number	Ebb and Flood (step) 24 SG	Constant total number	Constant total number	-
Direct Turbining	Units number in Direct Turbining Mode	sUnits.DT.Nb	28	28	28	28	44	28	-
	Head Control Mode	sUnits.DT.HeadControlChoice	2	2	1	2	3	2	-
	Optimised Starting Head Xls Filename	sUnits.DT.OSHxlsName	OSH Stage3 A1.02a (power).xls	OSH Stage3 A1.02b (power).xls	none	OSH Stage3 A1.02b (power).xls	none	OSH Stage3 A1.02a (power).xls	-
	Head Control Operation Xls Sheet Name	sUnits.DT.HCOsheetName	none	none	none	none	44BU (linear 2.80m)	none	-
	Starting Head	sUnits.DT.Hstart	0.00	0.00	2.50	0.00	1.50	0.00	m
	Stop Head	sUnits.DT.Hstop	1.20	2.50	1.20	1.70	1.20	1.20	m
Reverse Turbining	Units number in Reverse Turbining Mode	sUnits.RT.Nb	0	0	0	0	0	0	-
	Head Control Mode	sUnits.RT.HeadControlChoice	1	1	1	1	1	1	-
	Head Control Operation Xls Sheet Name	sUnits.RT.HCOsheetName	none	none	none	none	none	none	-
	Starting Head	sUnits.RT.Hstart	0.00	0.00	0.00	0.00	0.00	0.00	m
	Stop Head	sUnits.RT.Hstop	0.00	0.00	0.00	0.00	0.00	0.00	m
Direct Pumping	Units number in Direct Pumping Mode (DPM)	sUnits.DP.Nb	0	0	0	0	0	28	-
	Starting Head	sUnits.DP.Hstart	0.00	0.00	0.00	0.00	0.00	0.00	m
	Stop Head	sUnits.DP.Hstop	0.00	0.00	0.00	0.00	0.00	1.60	m
Orifice Mode	Units number in Orifice Mode	sUnits.O.Nb	28	28	28	28	44	28	-
Sluice Gates	Number of gates	sGates.Nb	18	18	18	24	18	18	-
	Manoeuvering time	sGates.Time	15	15	15	15	15	15	min
	Flow coefficient C.H^0.5 in Ebb (reverse)	sGates.CD	702	702	702	702	702	702	-
	Flow coefficient C.H^0.5 in Flood (direct)	sGates.CI	957	957	957	957	957	957	-

Antoine Libaux:
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1 A1.02a (ebb in OSH) - 28BU25MW-18SG12x12

1.1 Control curves

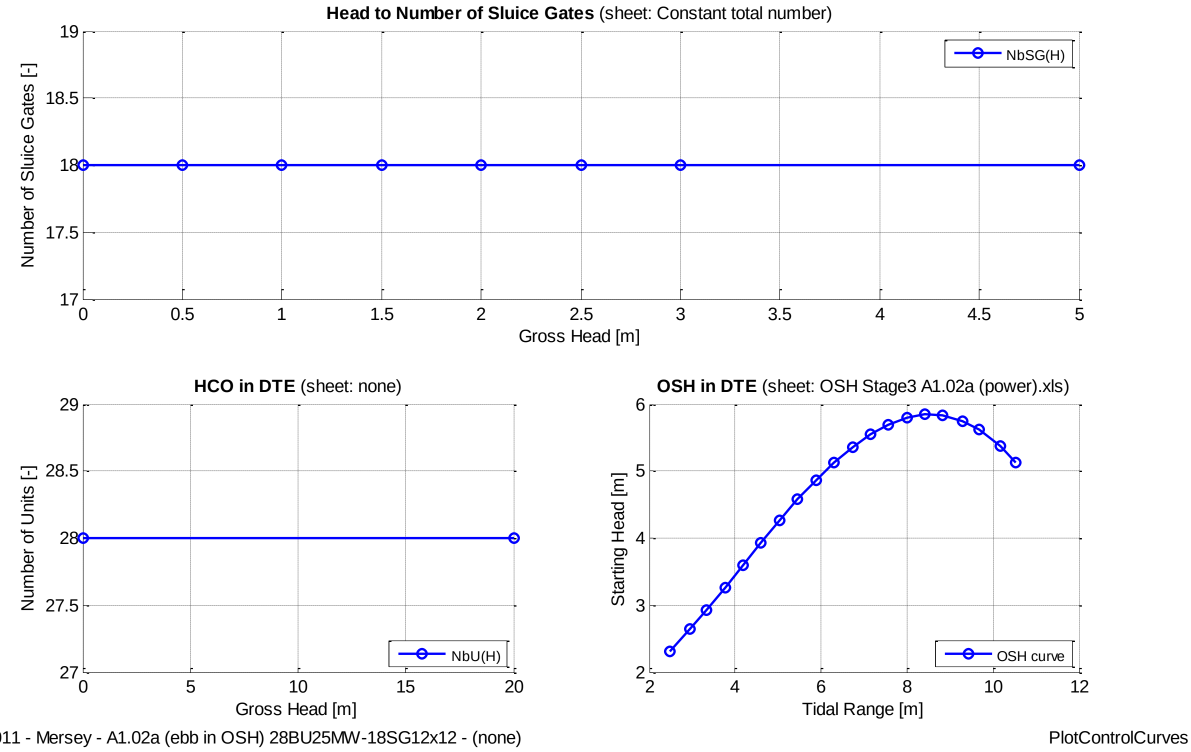


Figure G.1 - A1.02a (ebb in OSH) - Control curves

1.2 5 typical tidal range results

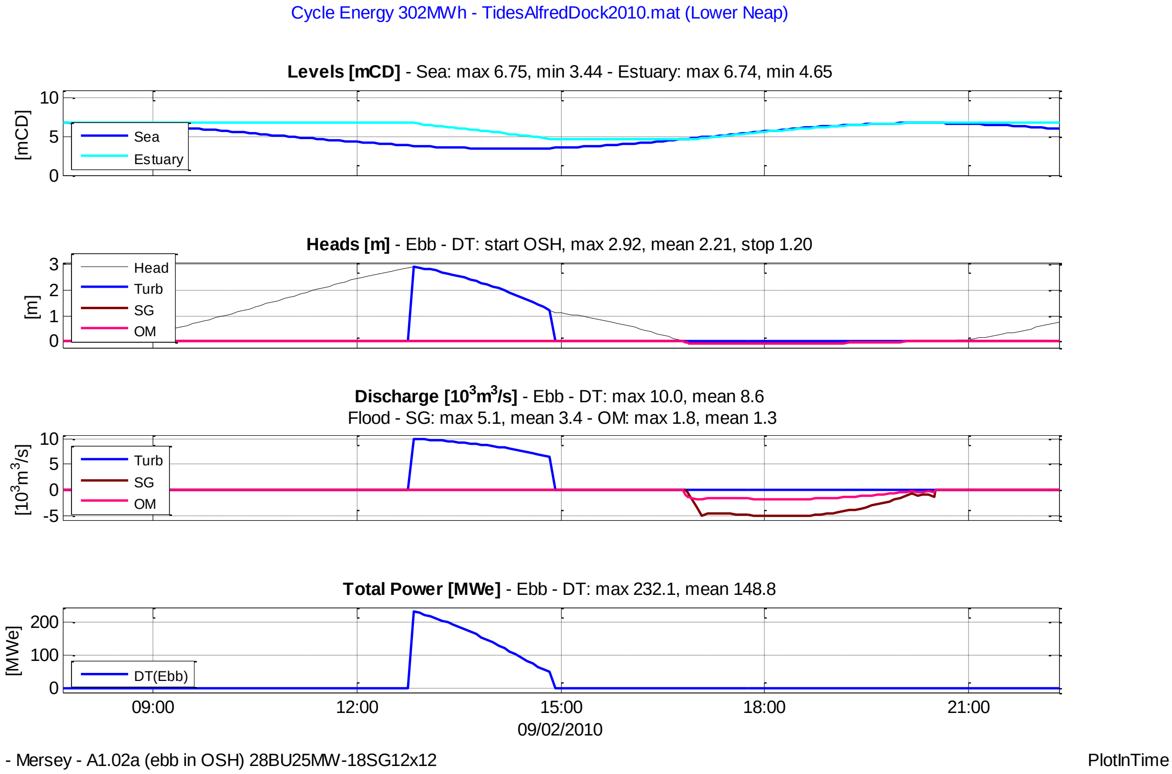


Figure G.2 - A1.02a (ebb in OSH) - Lower Neap Tide operation

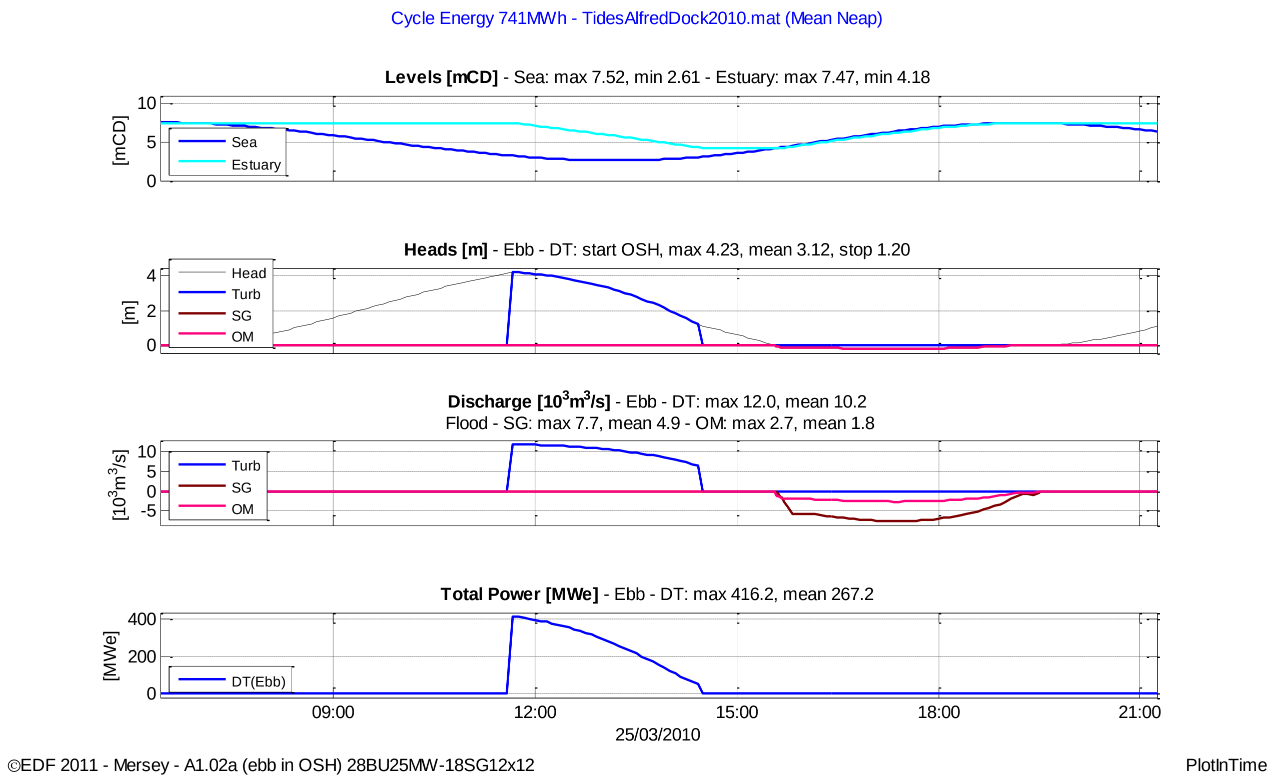


Figure G.3 - A1.02a (ebb in OSH) - Mean Neap Tide operation

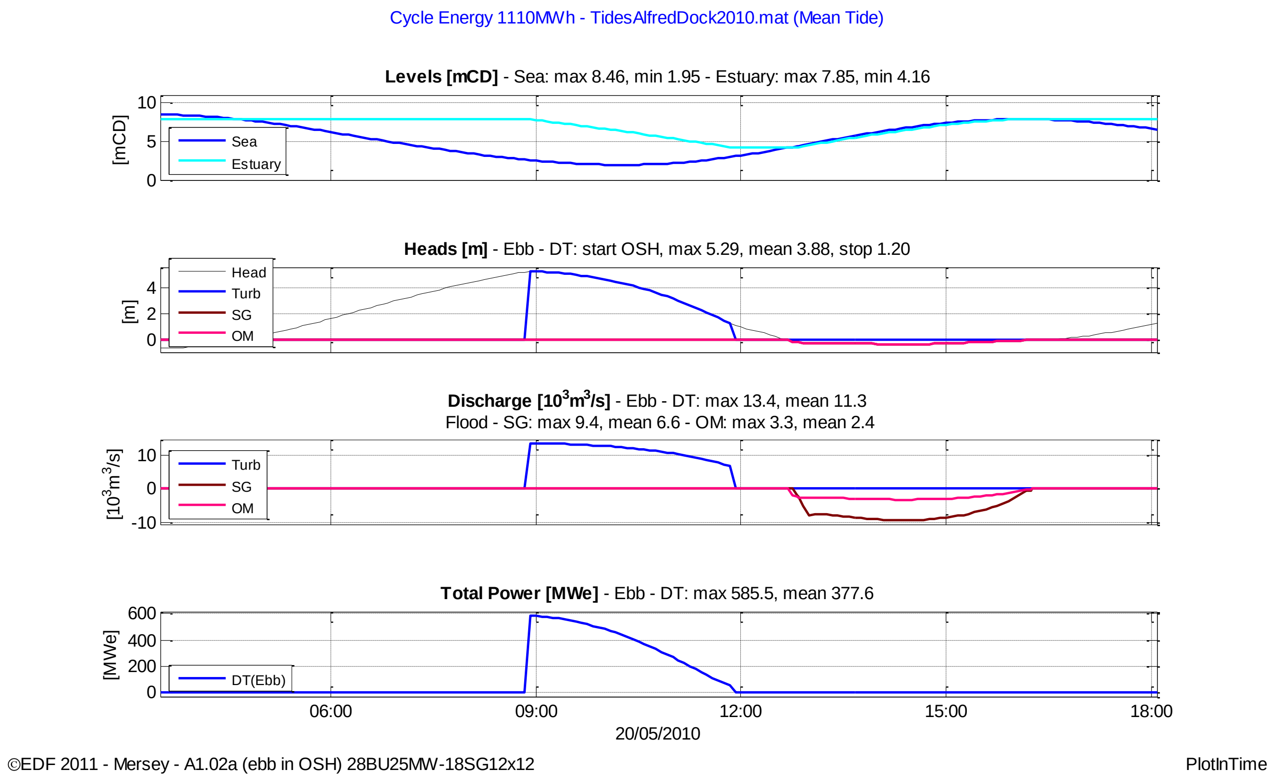


Figure G.4 - A1.02a (ebb in OSH) - Mean Tide operation

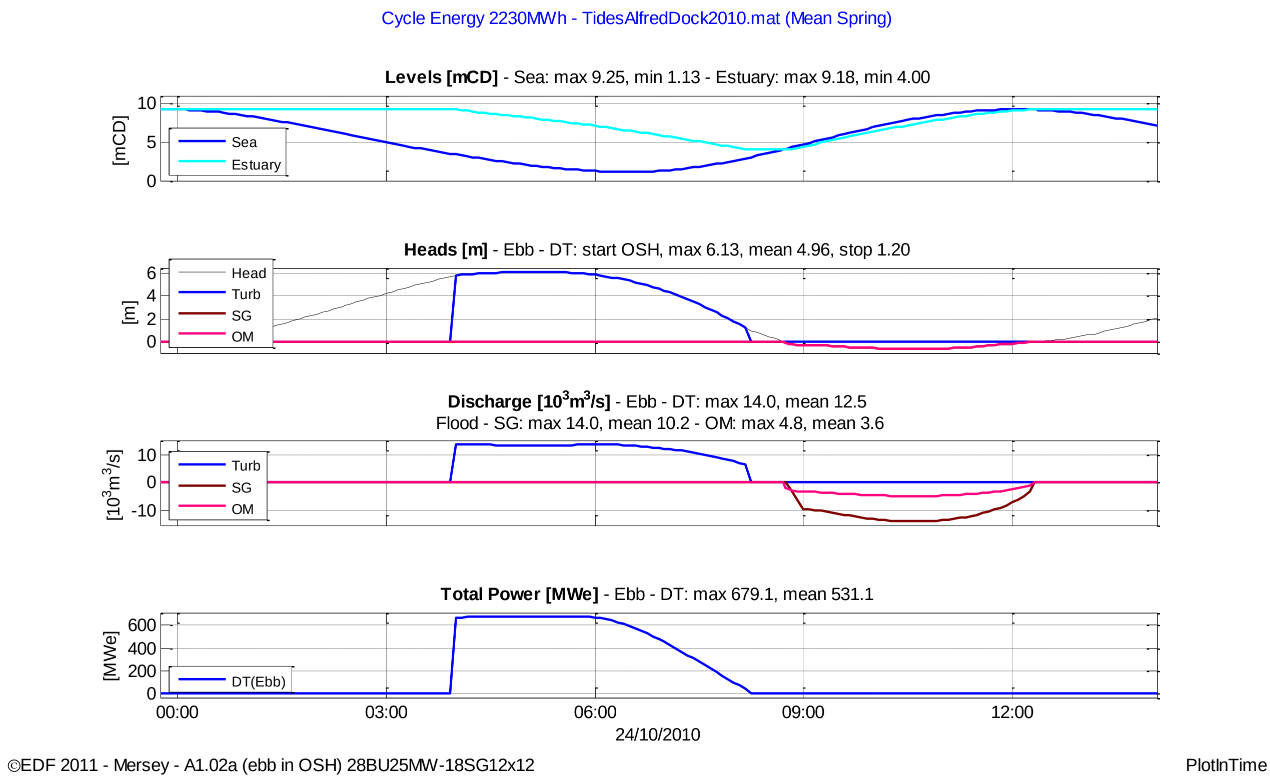


Figure G.5 - A1.02a (ebb in OSH) - Mean Spring Tide operation

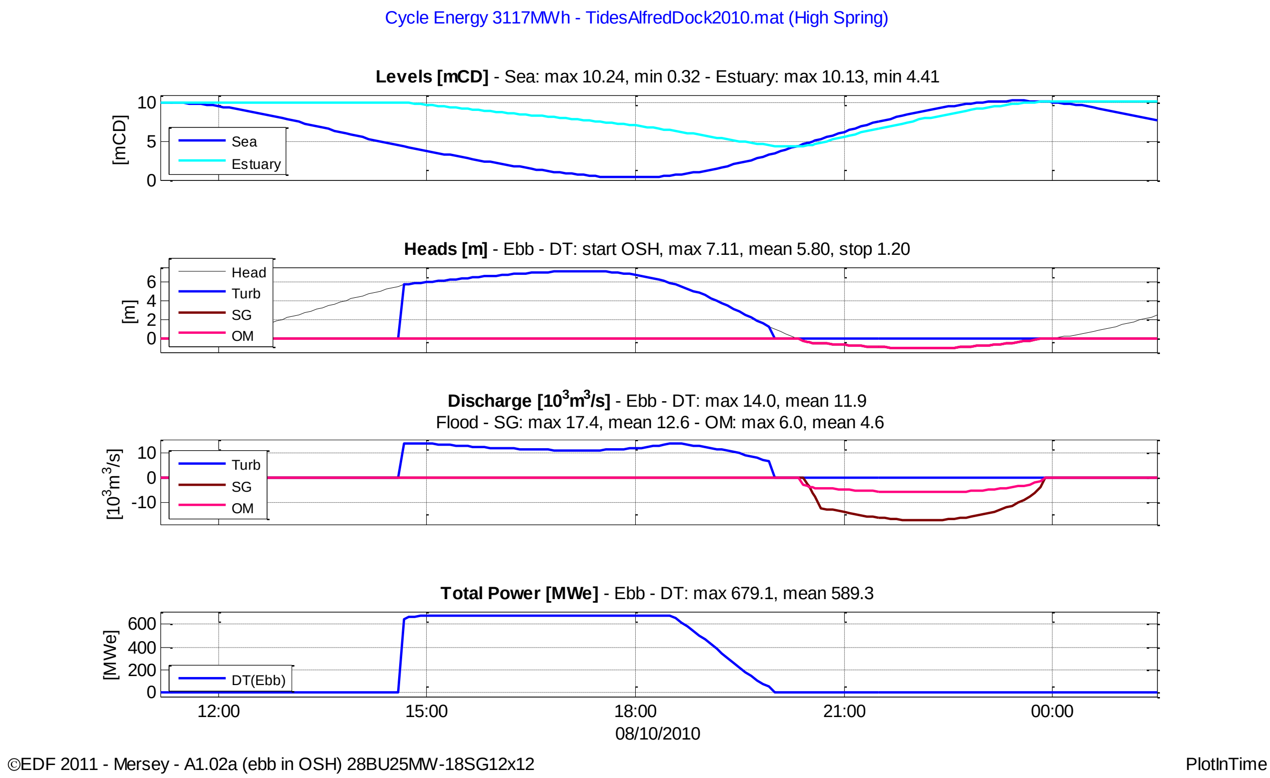


Figure G.6 - A1.02a (ebb in OSH) - High Spring Tide operation

1.3 Year 2010 simulation

Graphics

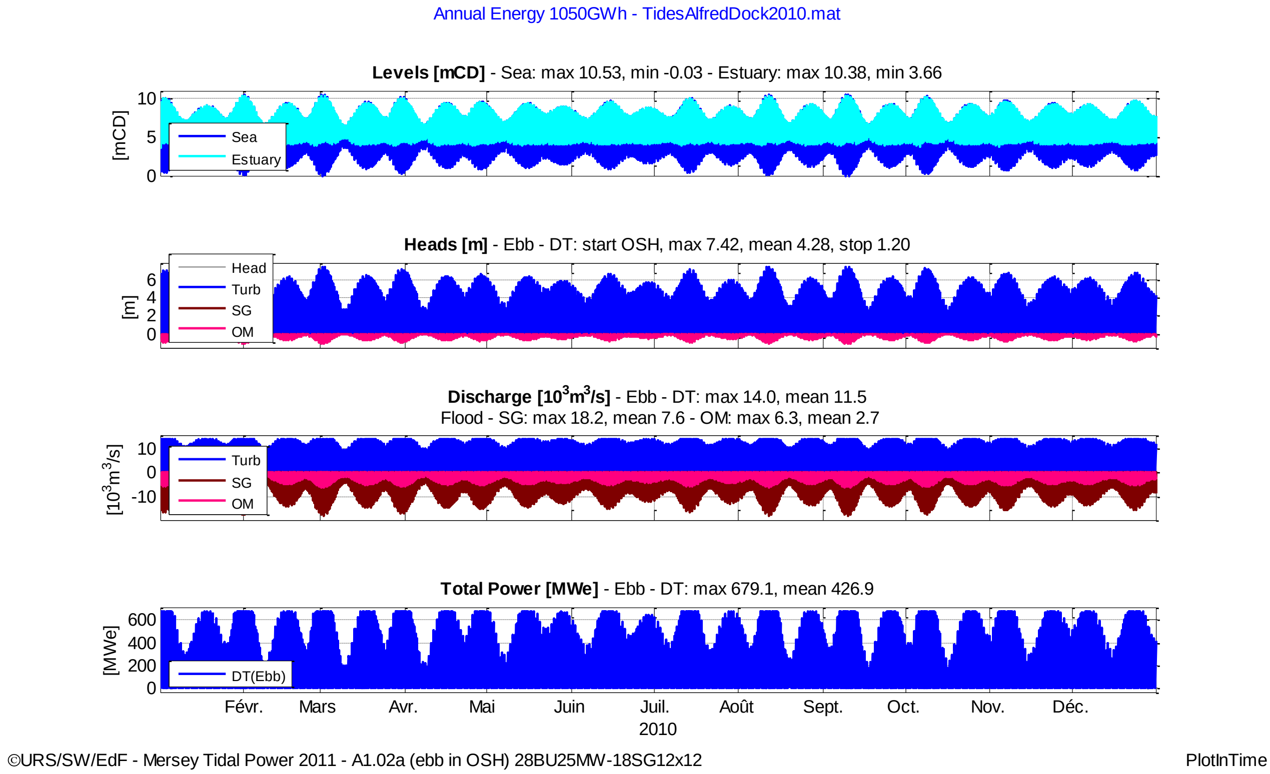


Figure G.7 - A1.02a (ebb in OSH) - year 2010 time curves

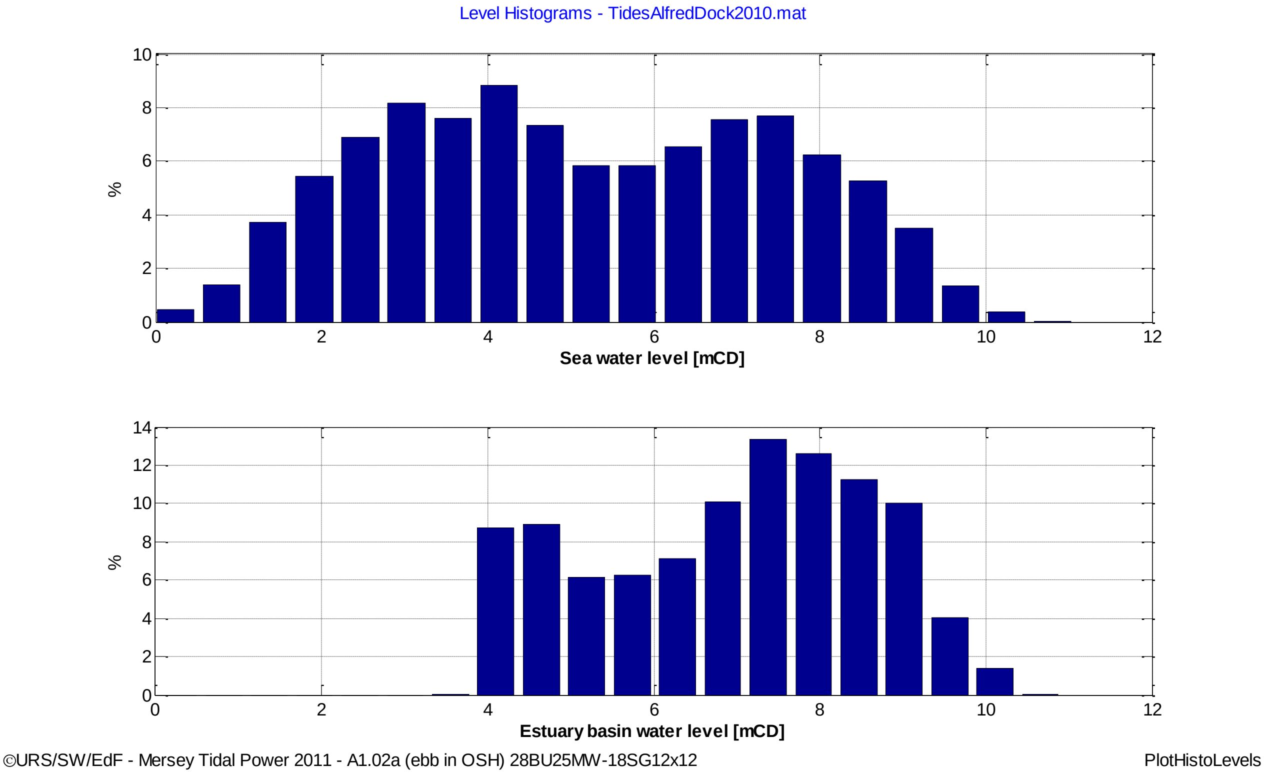


Figure G.8 - A1.02a (ebb in OSH) - water level histograms

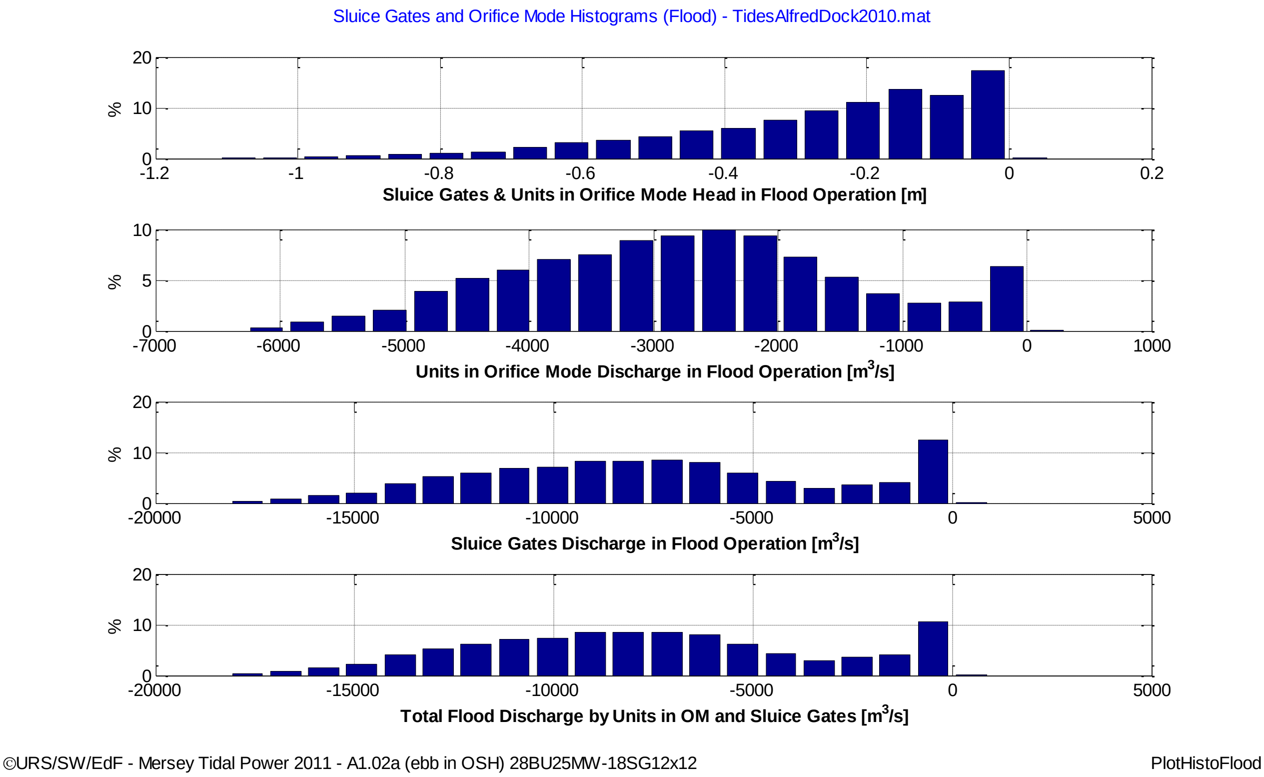


Figure G.9 - A1.02a (ebb in OSH) - sluice gates and orifice mode histograms (flood)

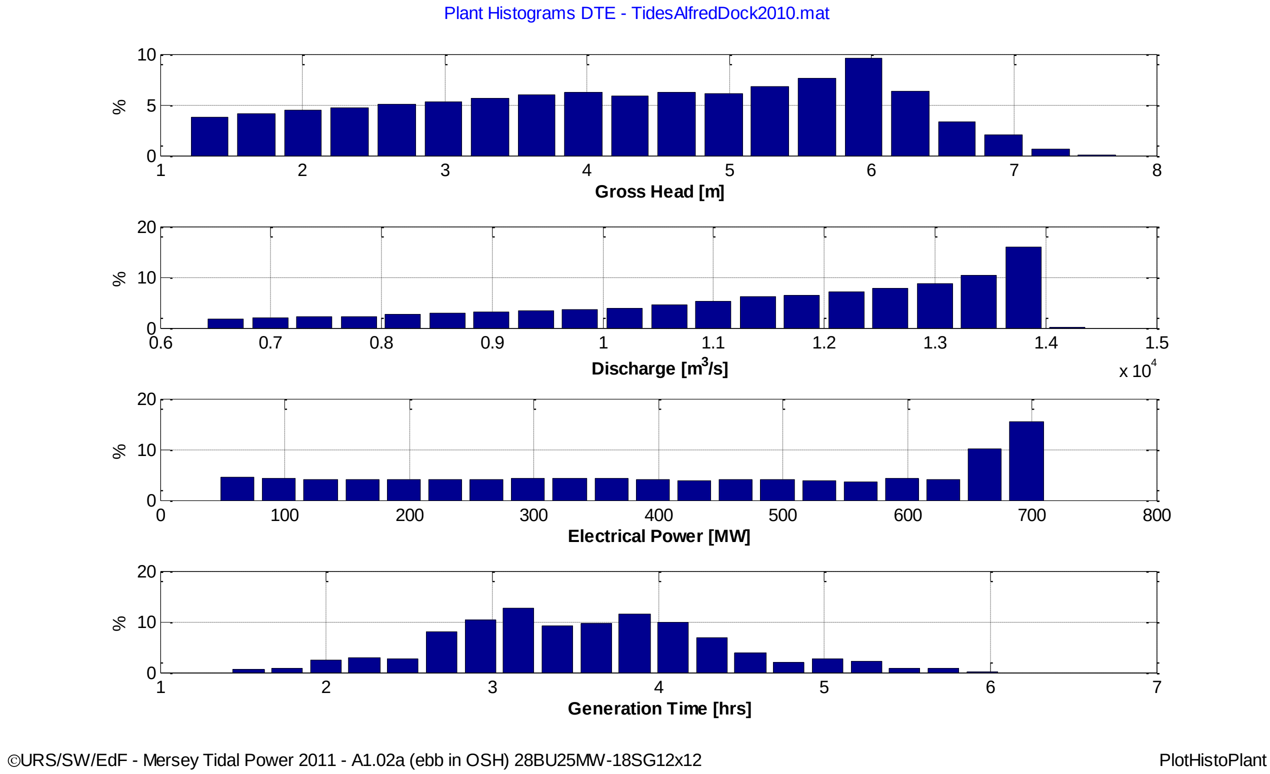


Figure G.10 - A1.02a (ebb in OSH) - plant histograms (direct turbining)

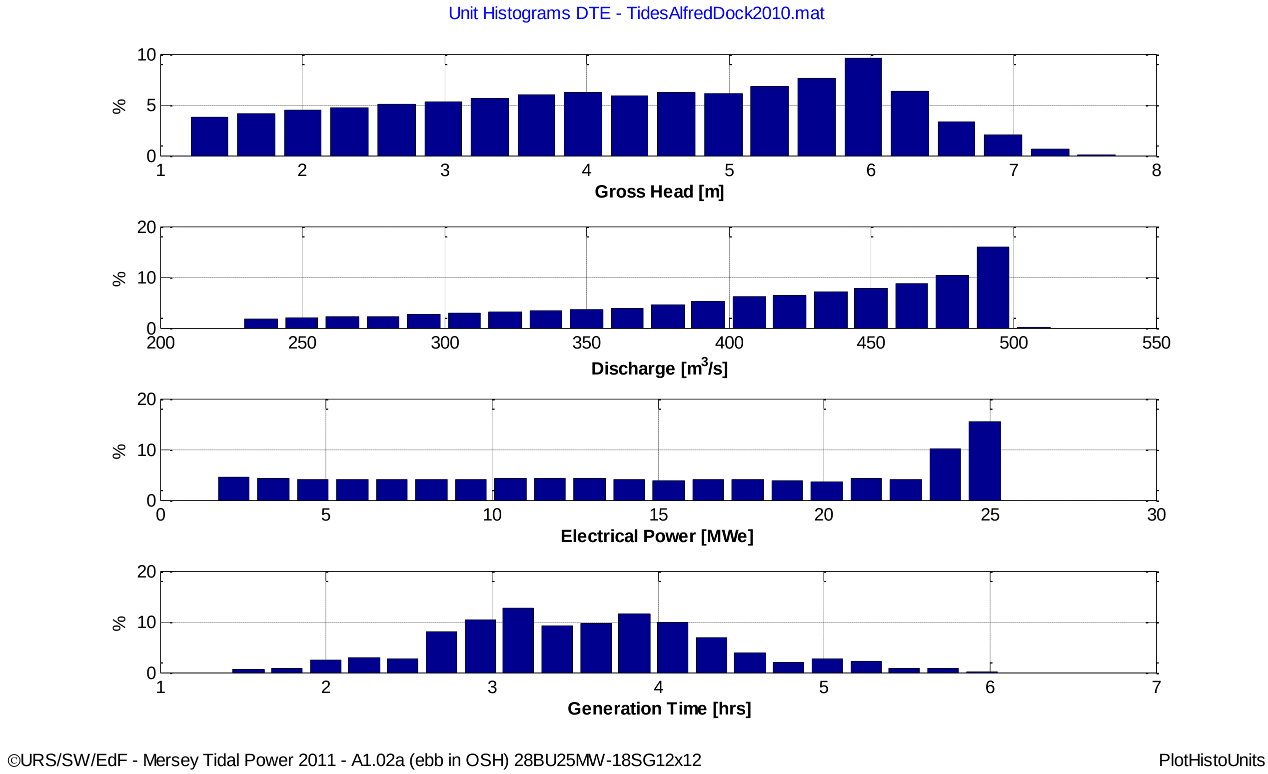


Figure G.11 - A1.02a (ebb in OSH) - unit histograms (direct turbining)

Balance Sheet Listing

```
 ---SIMULATION CASE A1.02a (ebb in OSH) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level .................. 10.38 m
Minimum Estuary Level ..................  3.66 m
Maximum Estuary Range ..................  6.73 m

 - Init Estuary Level minus Max Sea Level:
Starting value ......................... -0.60 m
Maximum ................................  0.00 m
Minimum ................................ -0.60 m

 - Ebb Generation:
Energy production in Ebb ............... 1050 GWh
Generation Time ........................ 2494.2 hrs
Mean Output ............................ 427 MW
Mean Discharge ......................... 11505 m^3/s
Max. Discharge ......................... 14000 m^3/s
Head control choice .................... in OSH operation
Starting Head .......................... optimised
Mean Head .............................. 4.28 m
Max  Head .............................. 7.42 m
Stopping Head .......................... 1.20 m

 - Flood Sluicing:
Operating Time ......................... 2578.2 hrs
Mean Discharge ......................... 7555 m^3/s
Max. Discharge ......................... 18168 m^3/s
Mean Head .............................. 0.26 m
Max. Head .............................. 1.11 m

 - Reverse Orifice Mode :
Operating Time ......................... 2578.2 hrs
Mean Discharge  ........................ 2723 m^3/s
Max Discharge .......................... 6274 m^3/s

 - Results :
Simulation Case ........................ A1.02a (ebb in OSH) 28BU25MW-18SG12x12
Average Output ......................... 427 MW
Total Installed Capacity ............... 700 MW
Load Factor ............................ 17.2%
Direct Turbining Production (Ebb)....... 1050 GWh
Reverse Turbining Production (Flood) ... 0 MWh
Net Energy ............................. 1050 GWh
DT Generation Time ..................... 2494.2 hrs (28.5%)
RT Generation Time ..................... 0.0 hrs (0.0%)
Sluice Gates Operating Time ............ 2578.2 hrs (29.5%)
Orifice Mode Operating Time ............ 2578.2 hrs (29.5%)
Standing Time .......................... 3674.3 hrs (42.0%)

Theoretical hydraulic energy lost through the Sluices Gates ... 84 GWh (8.0%)
Theoretical hydraulic energy lost in Orifice Mode ............ 30 GWh (2.8%)
```

Average output for each hour of the day

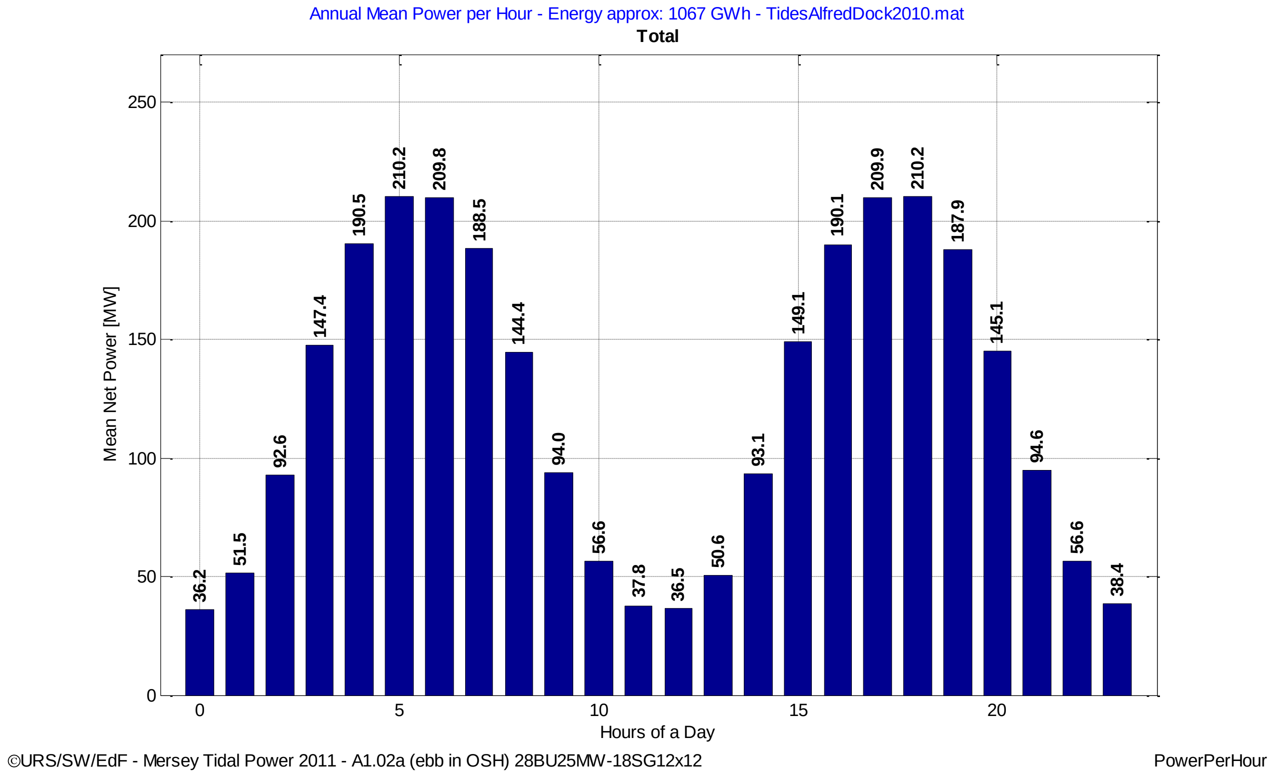


Figure G.12 - A1.02a (ebb in OSH) - mean power per hour

2 A1.02b (ebb in OSH with low tide sluicing and hold) - 28BU25MW-18SG12x12

2.1 Control curves

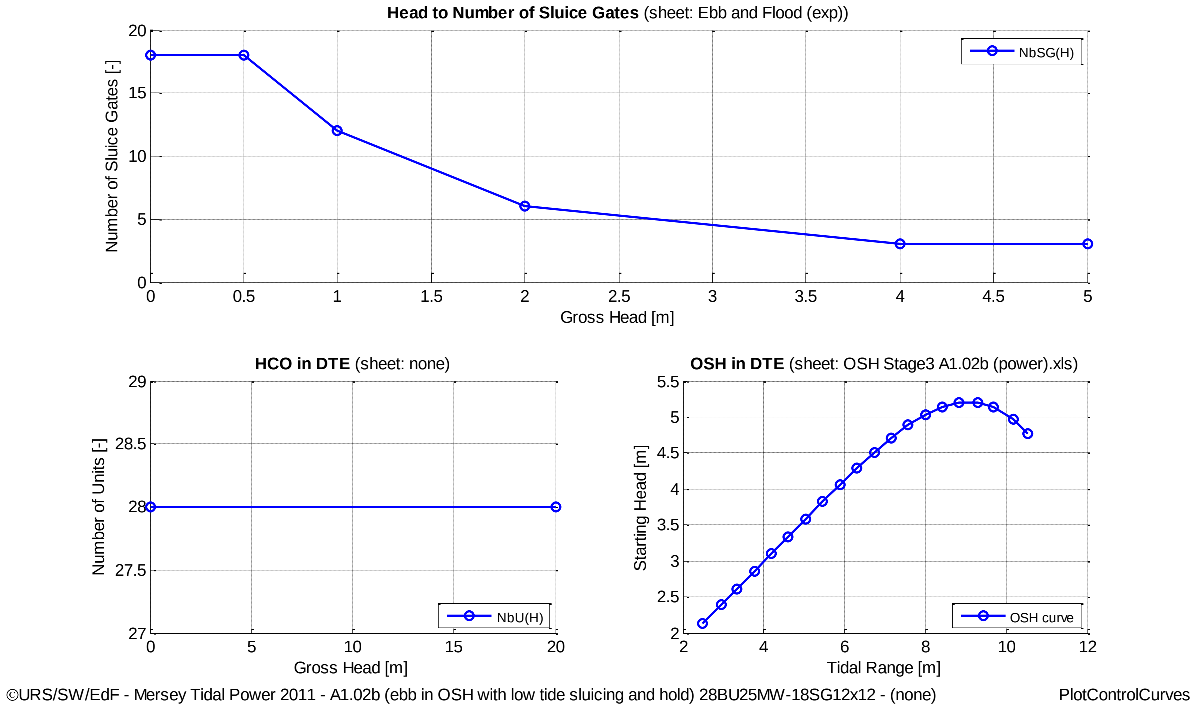


Figure G.13 - A1.02b (ebb in OSH with low tide sluicing and hold) - Control curves

2.2 5 typical tidal range results

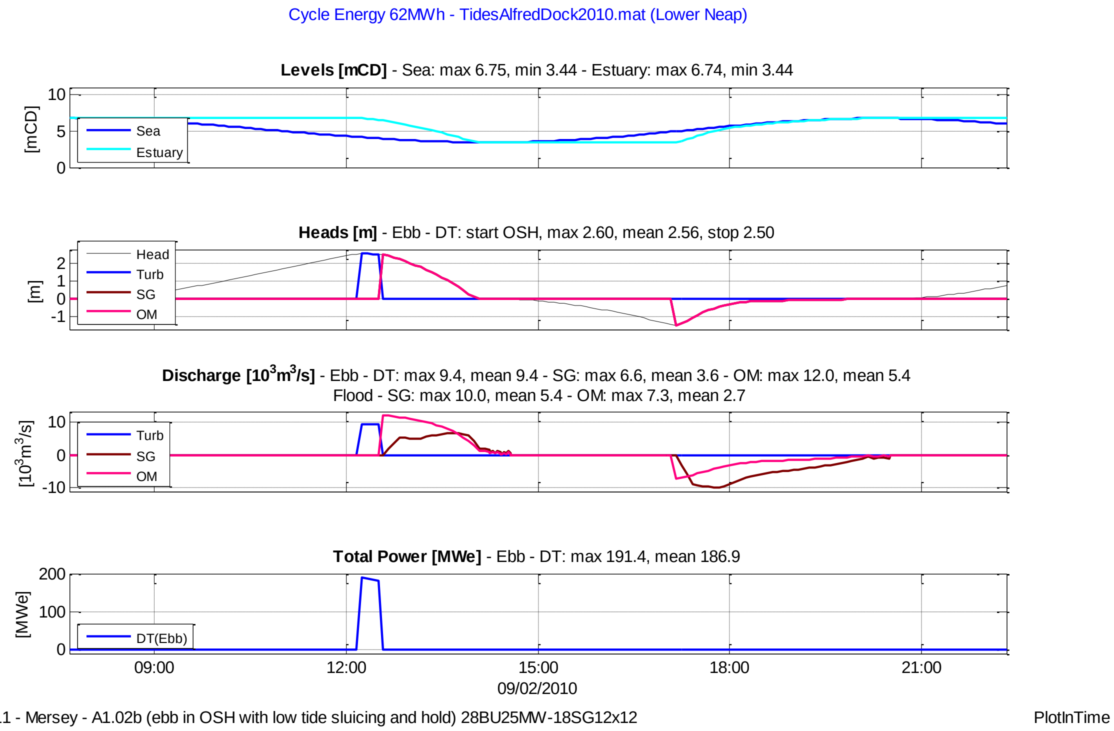


Figure G.14 - A1.02b (ebb in OSH with low tide sluicing and hold) - Lower Neap Tide operation

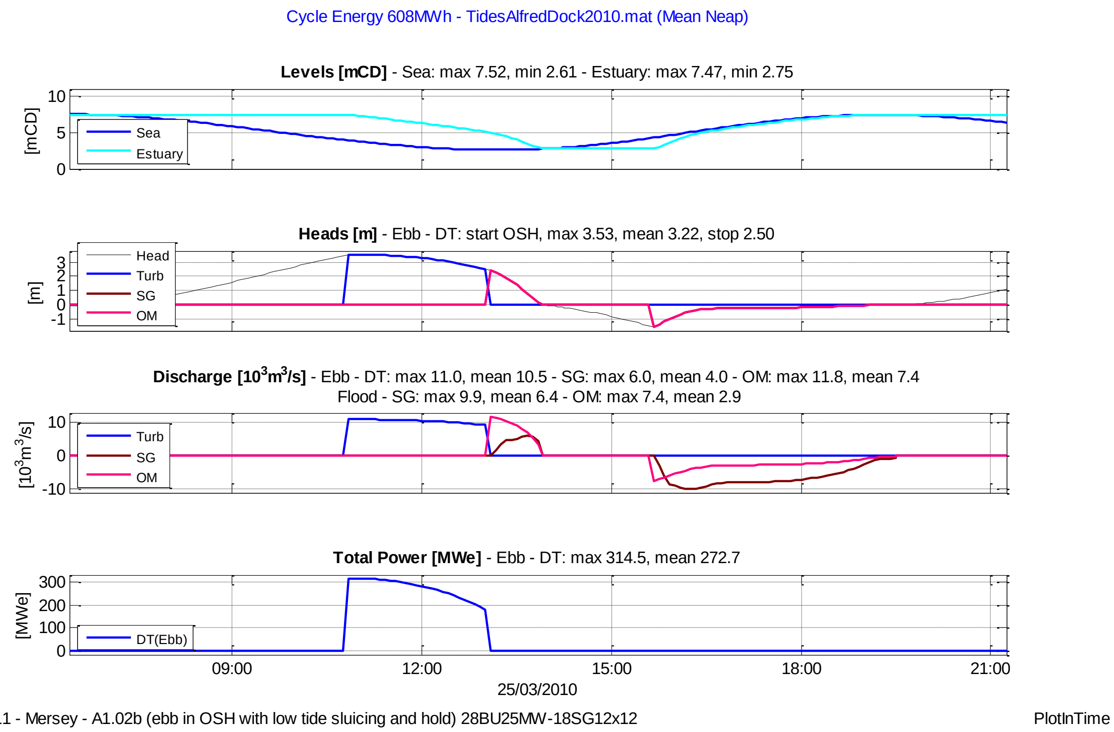


Figure G.15 - A1.02b (ebb in OSH with low tide sluicing and hold) - Mean Neap Tide operation

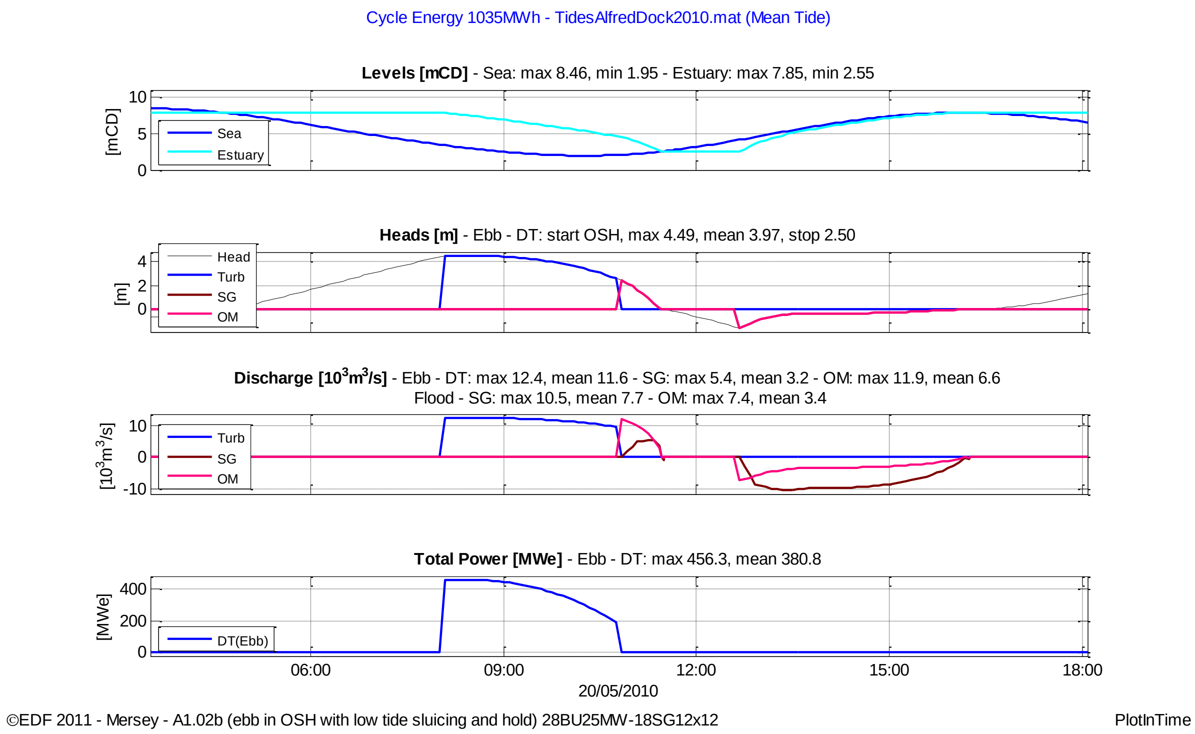


Figure G.16 - A1.02b (ebb in OSH with low tide sluicing and hold) - Mean Tide operation

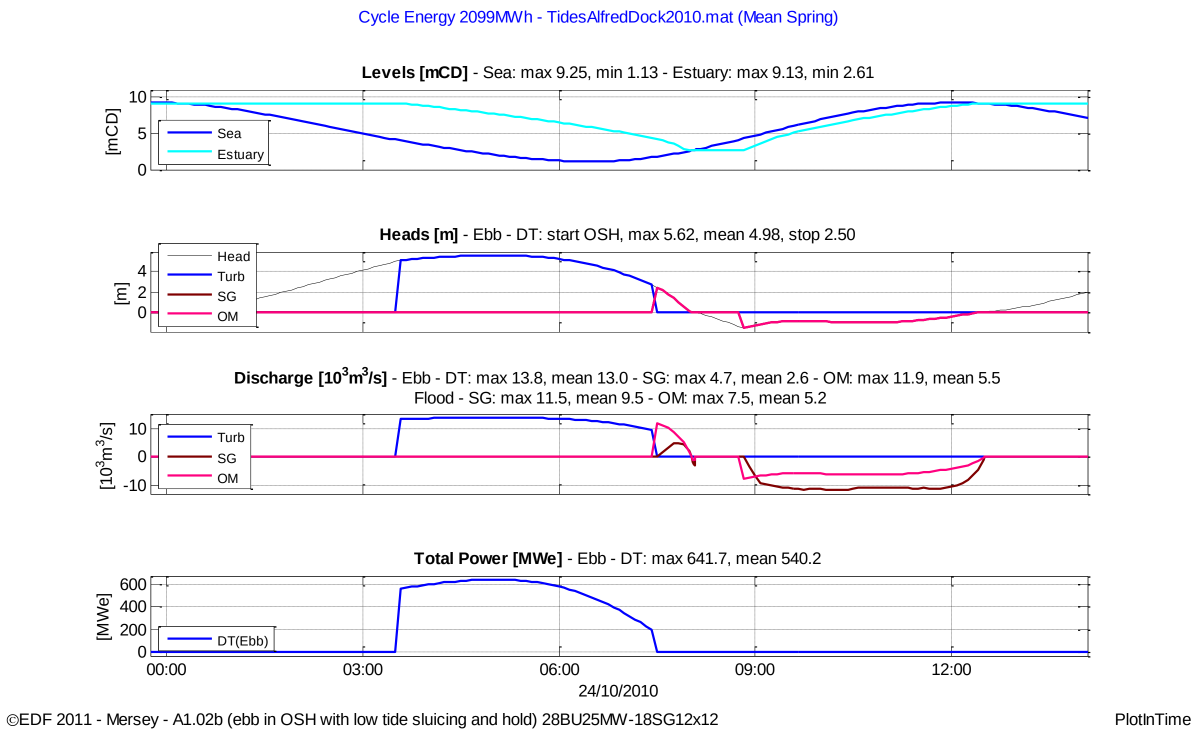


Figure G.17 - A1.02b (ebb in OSH with low tide sluicing and hold) - Mean Spring Tide operation

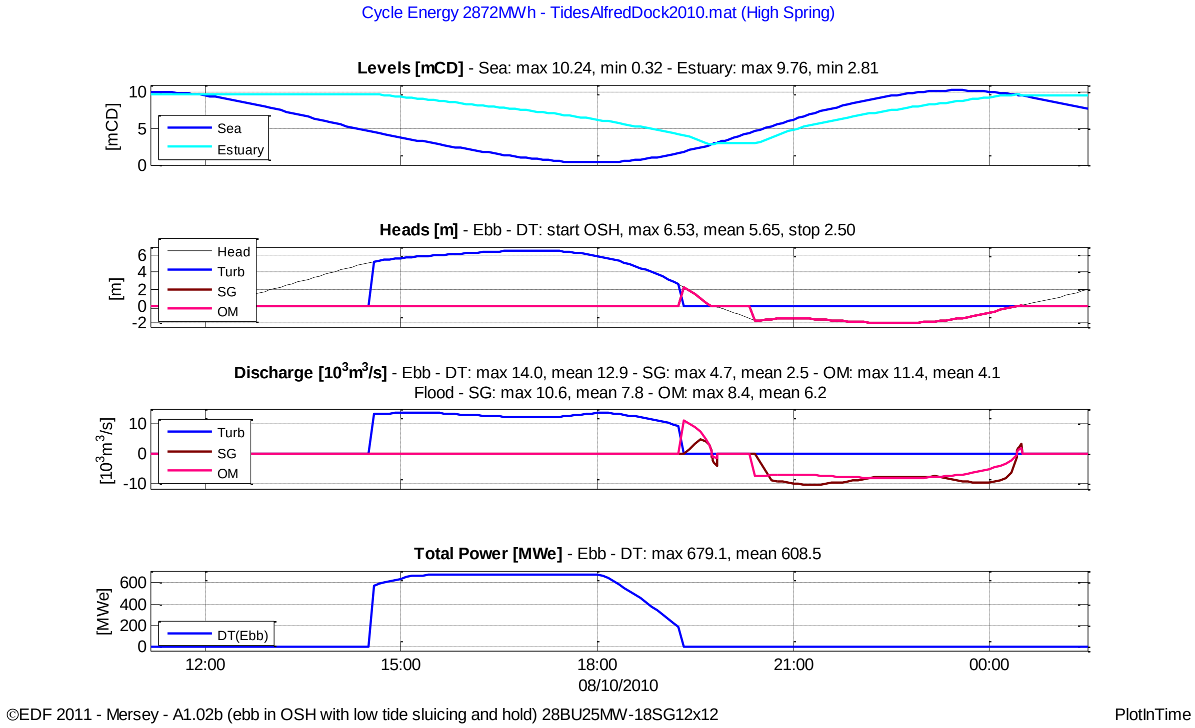


Figure G.18 - A1.02b (ebb in OSH with low tide sluicing and hold) - High Spring Tide operation

2.3 Year 2010 simulation

Graphics

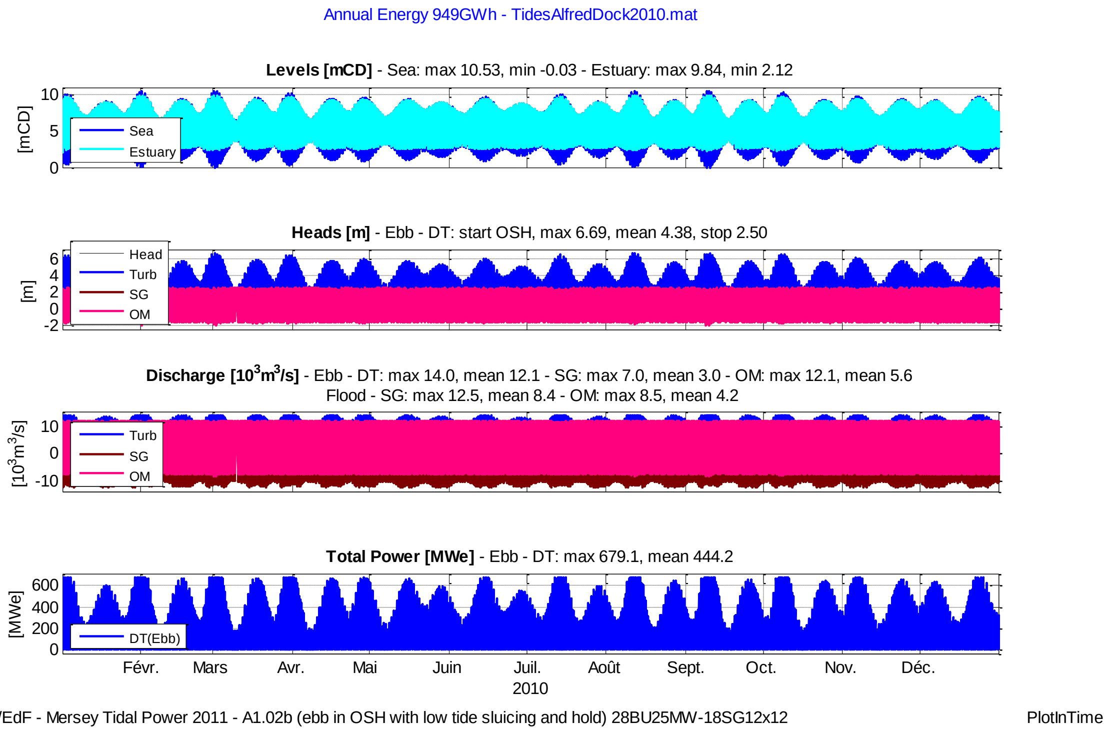


Figure G.19 - A1.02b (ebb in OSH with low tide sluicing and hold) - year 2010 time curves

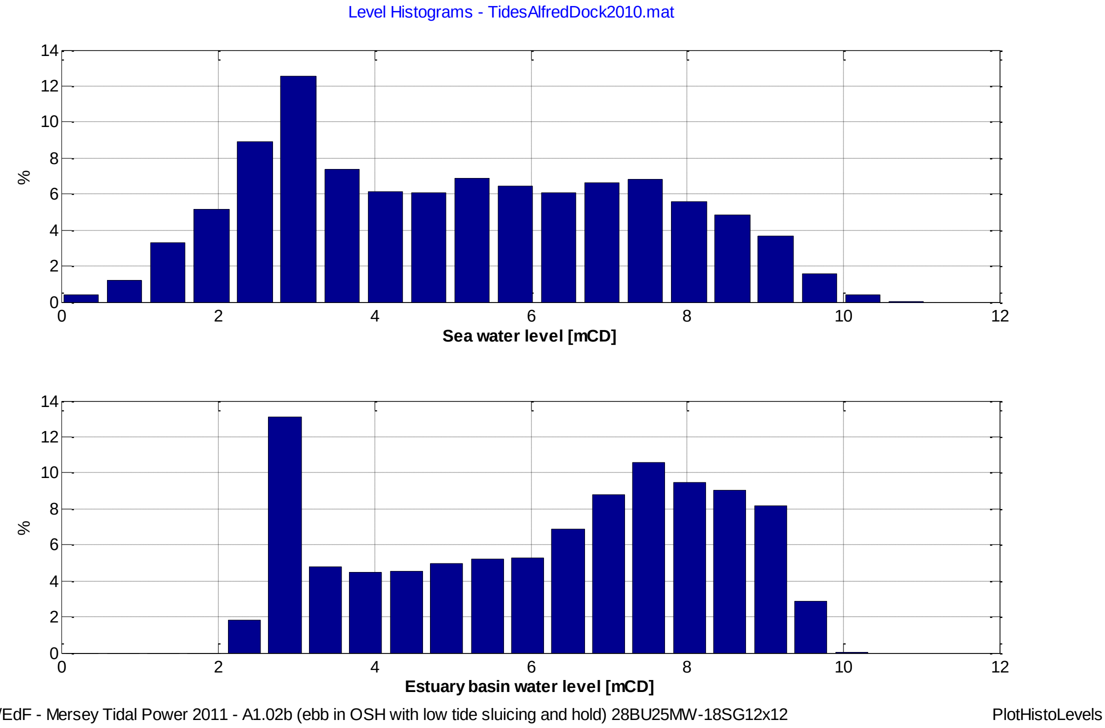
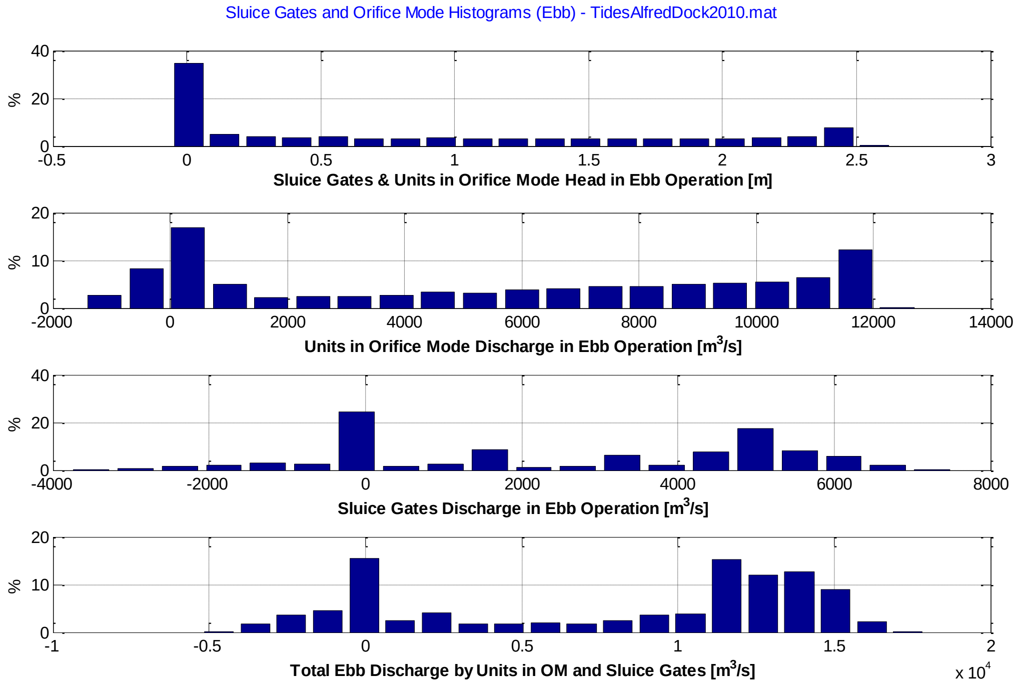
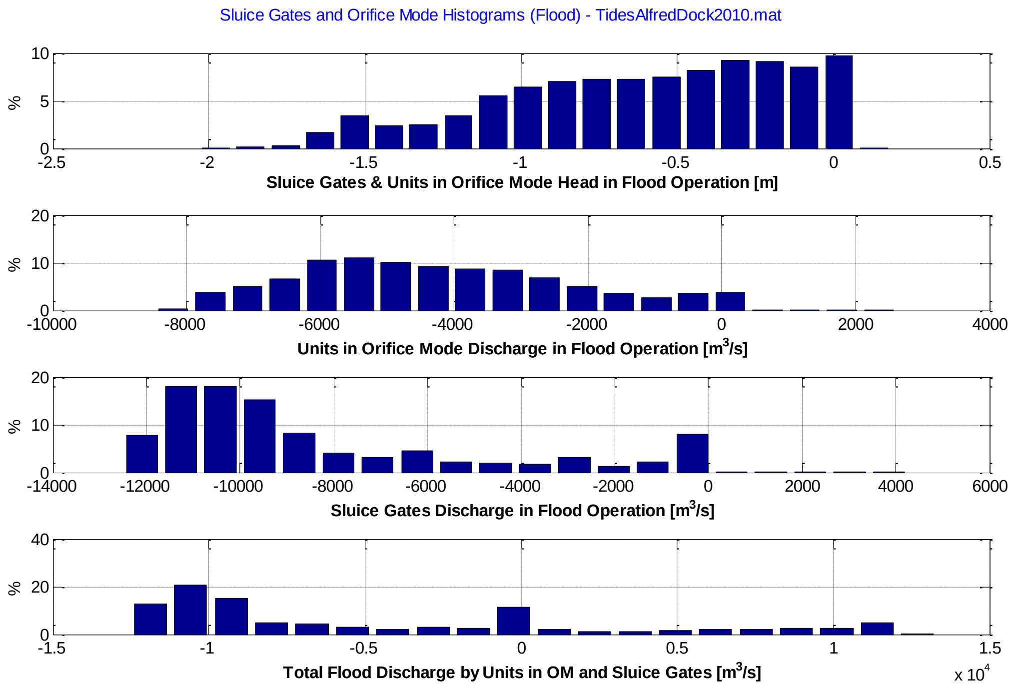


Figure G.20 - A1.02b (ebb in OSH with low tide sluicing and hold) - water level histograms



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.02b (ebb in OSH with low tide sluicing and hold) 28BU25MW-18SG12x12 PlotHistoEbb

Figure G.21 - A1.02b (ebb in OSH with low tide sluicing and hold) - sluice gates and orifice mode histograms (ebb)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.02b (ebb in OSH with low tide sluicing and hold) 28BU25MW-18SG12x12 PlotHistoFlood

Figure G.22 - A1.02b (ebb in OSH with low tide sluicing and hold) - sluice gates and orifice mode histograms (flood)

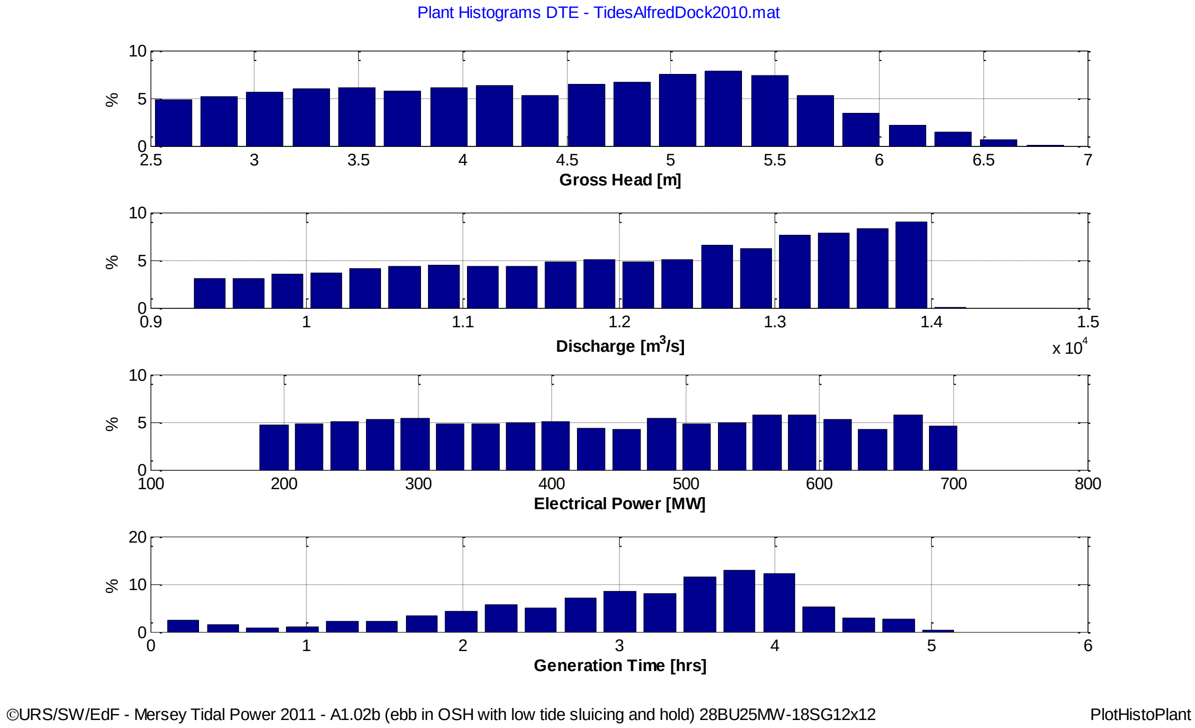


Figure G.23 - A1.02b (ebb in OSH with low tide sluicing and hold) - plant histograms (direct turbining)

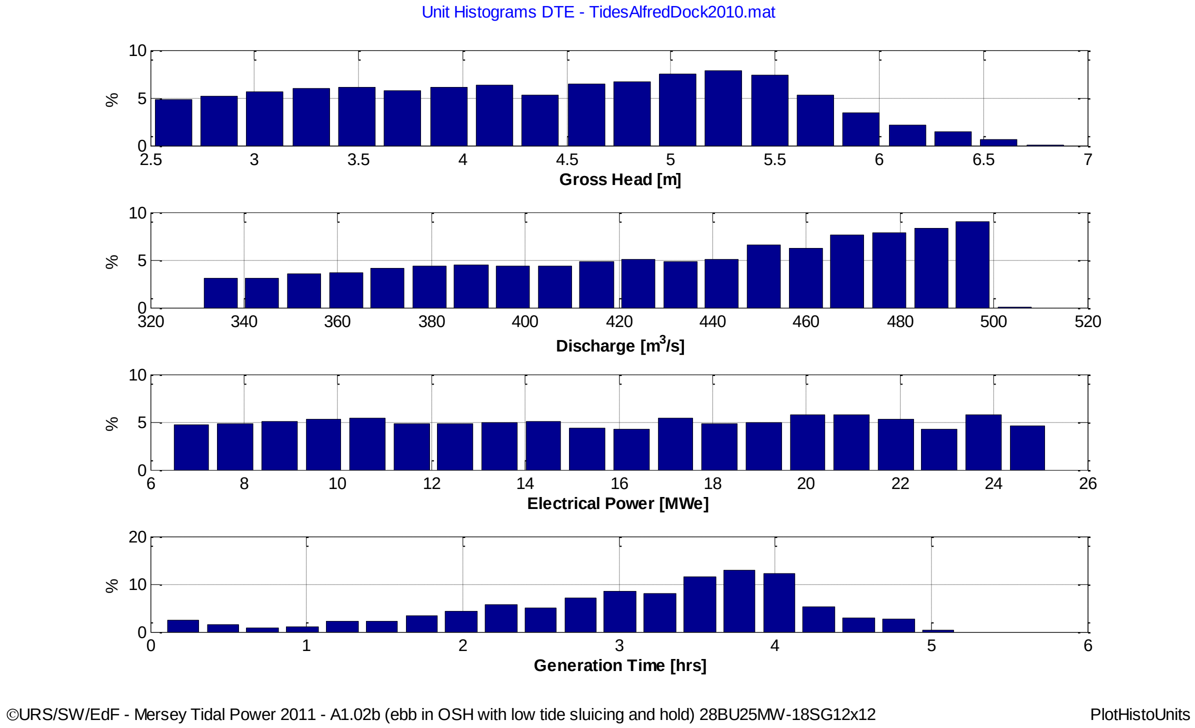


Figure G.24 - A1.02b (ebb in OSH with low tide sluicing and hold) - unit histograms (direct turbining)

Balance Sheet Listing

```
---SIMULATION CASE A1.02b (ebb in OSH with low tide sluicing and hold) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level ..................  9.84 m
Minimum Estuary Level ..................  2.12 m
Maximum Estuary Range ..................  7.73 m

 - Ebb Generation:
Energy production in Ebb ............... 949 GWh
Generation Time ........................ 2153.0 hrs
Mean Output ............................ 444 MW
Mean Discharge ......................... 12058 m^3/s
Max. Discharge ......................... 14000 m^3/s
Head control choice .................... in OSH operation
Starting Head .......................... optimised
Mean Head .............................. 4.38 m
Max  Head .............................. 6.69 m
Stopping Head .......................... 2.50 m

 - Ebb Sluicing:
Generation Time ........................ 583.8 hrs
Mean Discharge ......................... 3005 m^3/s
Max. Discharge ......................... 6973 m^3/s
Mean Head .............................. 0.87 m
Max  Head .............................. 2.50 m

 - Flood Sluicing:
Operating Time ......................... 2563.3 hrs
Mean Discharge ......................... 8444 m^3/s
Max. Discharge ......................... 12519 m^3/s
Mean Head .............................. 0.62 m
Max. Head .............................. 2.03 m

 - Orifice Mode :
Operating Time ......................... 583.8 hrs
Mean Discharge ......................... 5560 m^3/s
Max. Discharge ......................... 12052 m^3/s

 - Reverse Orifice Mode :
Operating Time ......................... 2563.3 hrs
Mean Discharge  ........................ 4212 m^3/s
Max Discharge .......................... 8477 m^3/s

 - Results :
```

```
Simulation Case ........................ A1.02b (ebb in OSH with low tide sluicing
and hold) 28BU25MW-18SG12x12
Average Output ......................... 444 MW
Total Installed Capacity ............... 700 MW
Load Factor ............................ 15.5%
Direct Turbining Production (Ebb)....... 949 GWh
Reverse Turbining Production (Flood) ... 0 MWh
Net Energy ............................. 949 GWh
DT Generation Time ..................... 2153.0 hrs (24.6%)
RT Generation Time ..................... 0.0 hrs (0.0%)
Sluice Gates Operating Time ............ 3147.2 hrs (36.0%)
Orifice Mode Operating Time ............ 3147.2 hrs (36.0%)
Standing Time .......................... 3446.5 hrs (39.4%)

Theoretical hydraulic energy lost through the Sluices Gates ... 188 GWh (19.8%)
Theoretical hydraulic energy lost in Orifice Mode ............. 119 GWh (12.5%)
```

Average output for each hour of the day

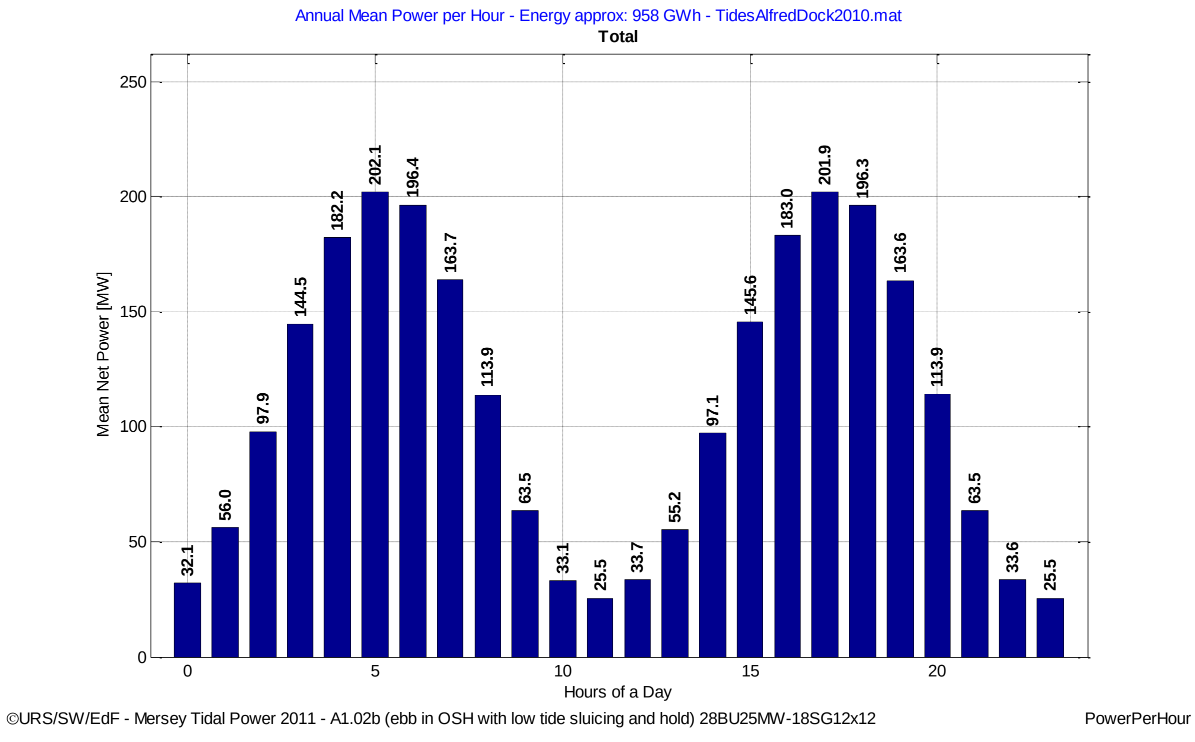


Figure G.25 - A1.02b (ebb in OSH with low tide sluicing and hold) - mean power per hour

3 A1.02c (ebb in head control 3m by the sluice gates) - 28BU25MW-18SG12x12

3.1 Control curves

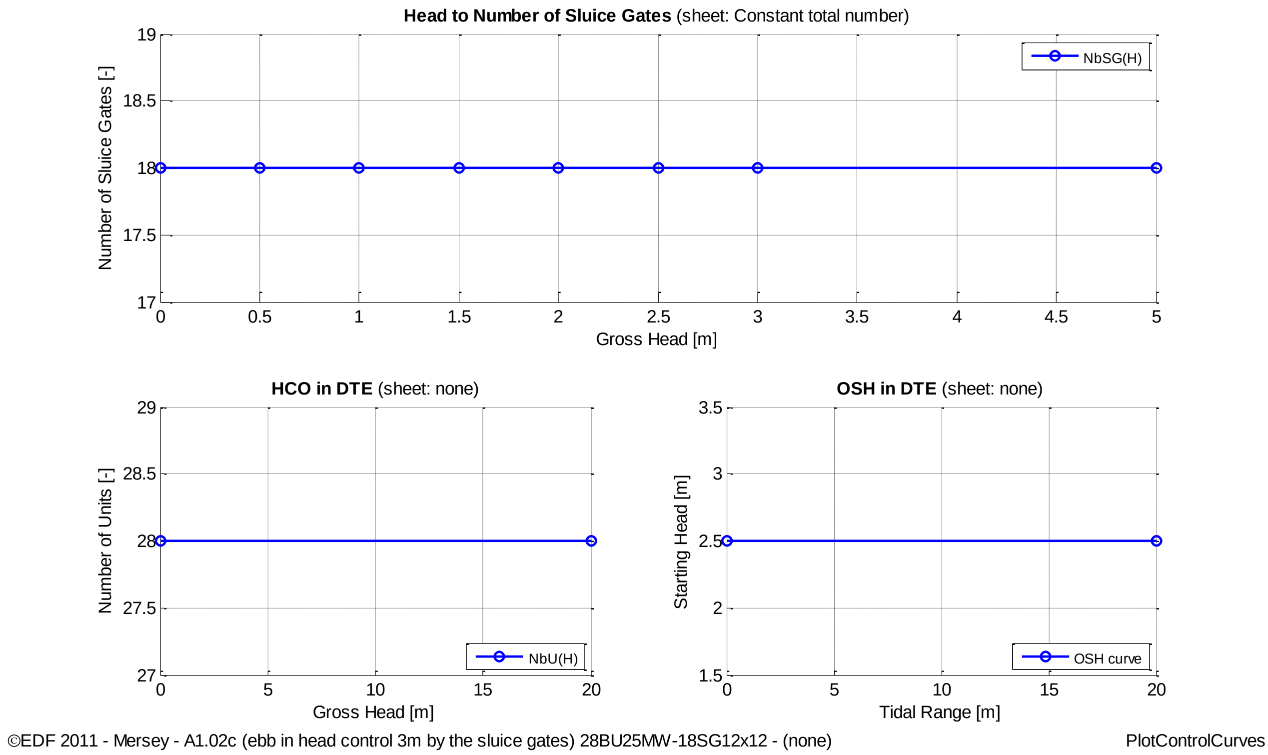


Figure G.26 - A1.02c (ebb in head control 3m by the sluice gates) - Control curves

3.2 5 typical tidal range results

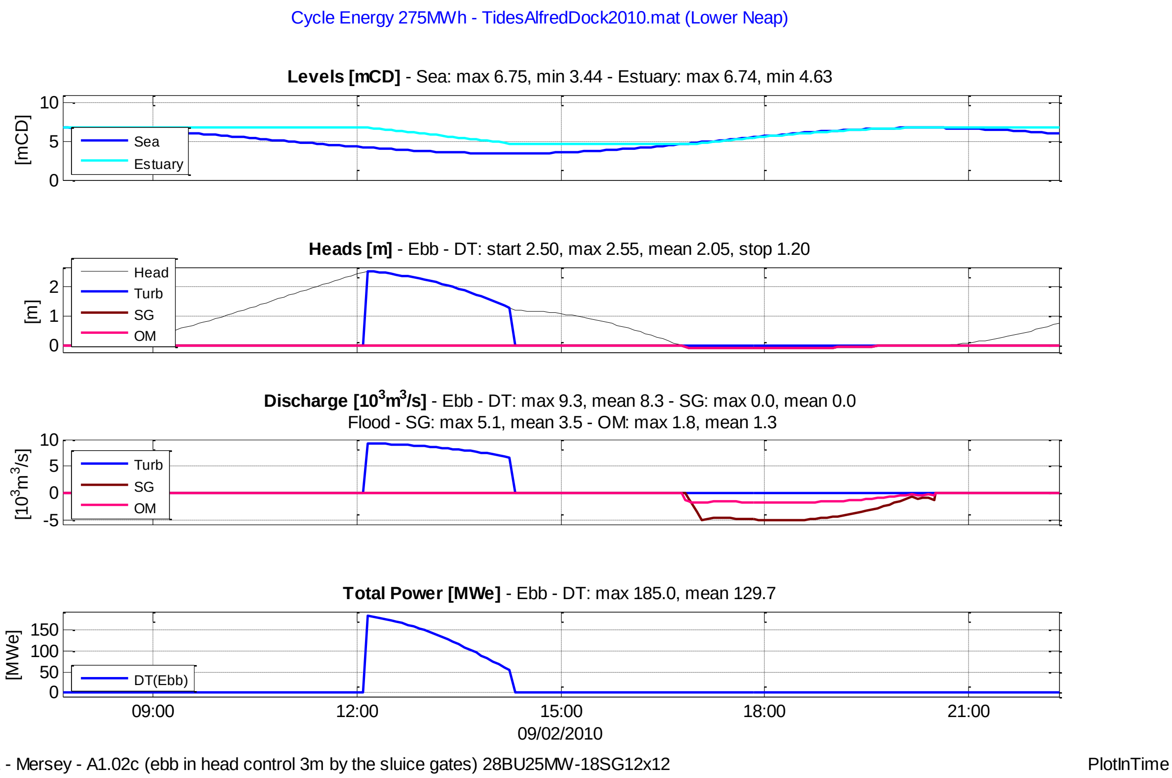


Figure G.27 - A1.02c (ebb in head control 3m by the sluice gates) - Lower Neap Tide operation

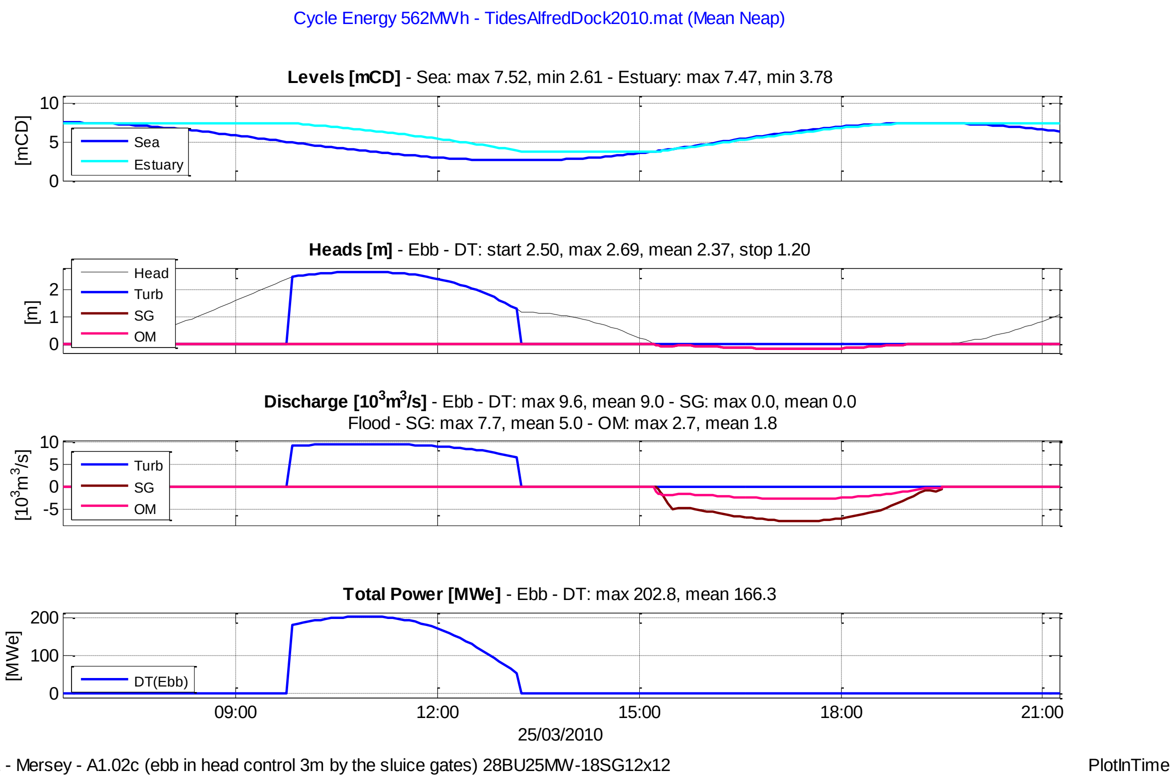


Figure G.28 - A1.02c (ebb in head control 3m by the sluice gates) - Mean Neap Tide operation

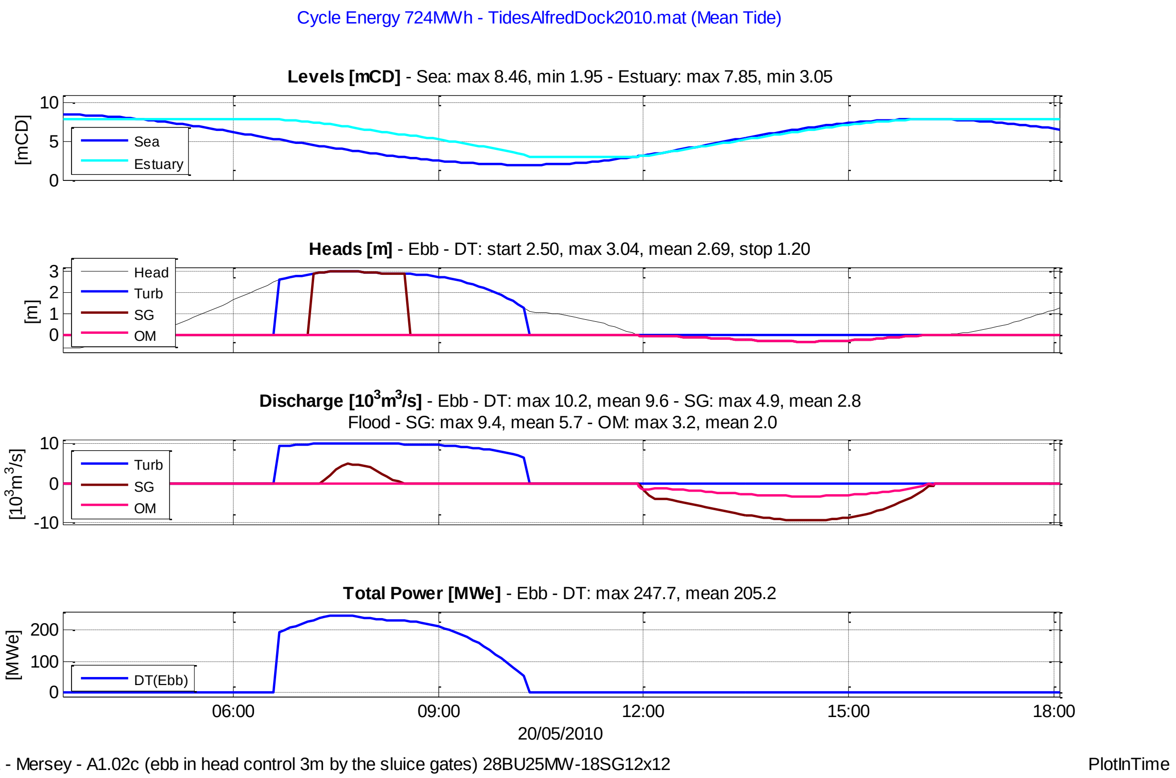


Figure G.29 - A1.02c (ebb in head control 3m by the sluice gates) - Mean Tide operation

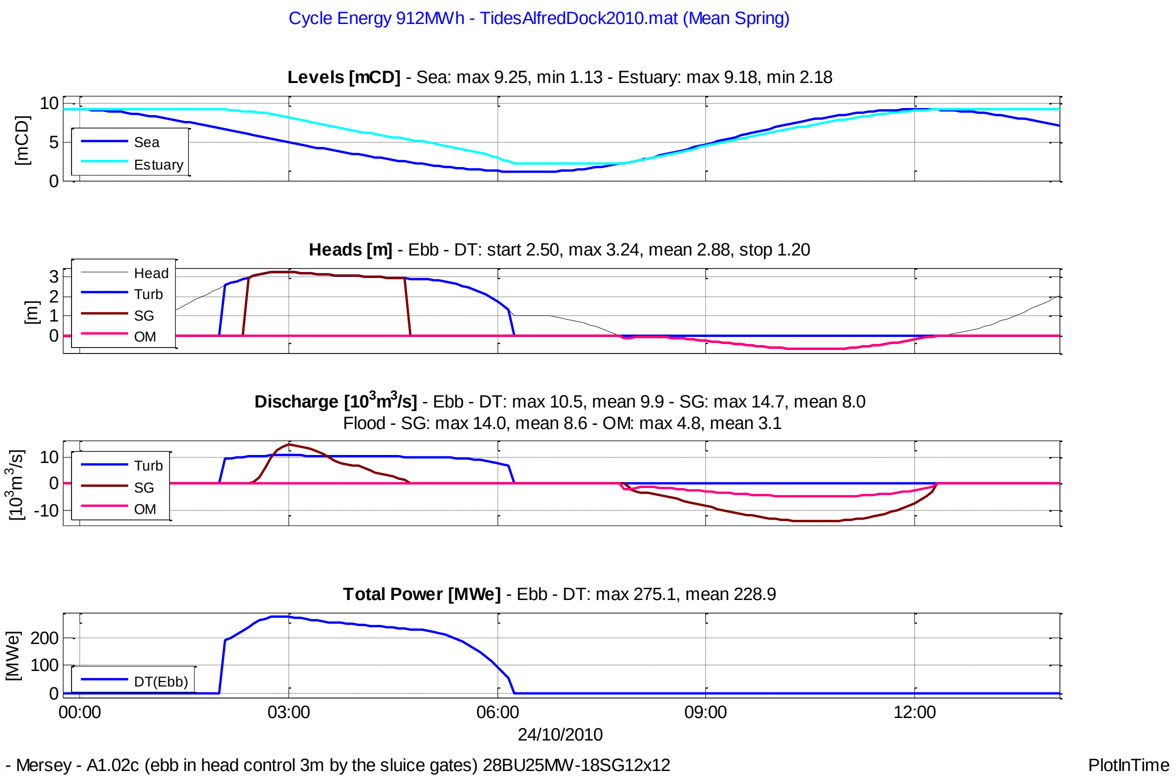


Figure G.30 - A1.02c (ebb in head control 3m by the sluice gates) - Mean Spring Tide operation

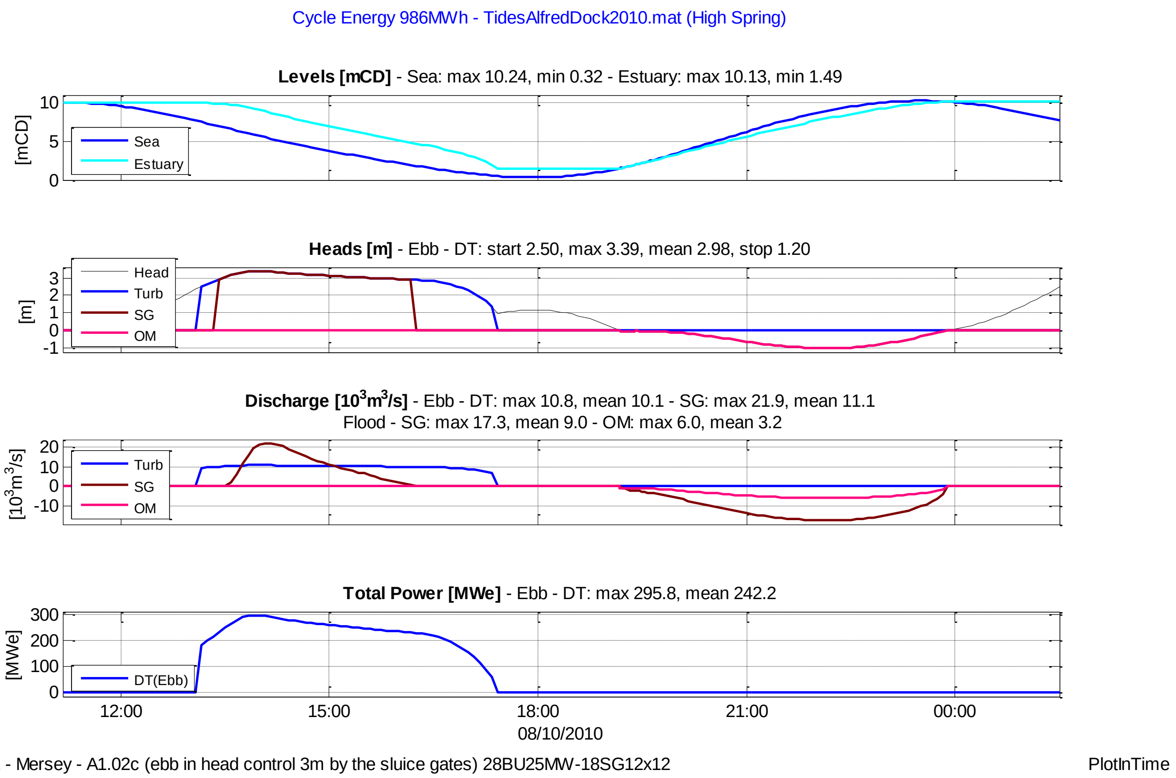


Figure G.31 - A1.02c (ebb in head control 3m by the sluice gates) - High Spring Tide operation

3.3 Year 2010 simulation

Graphics

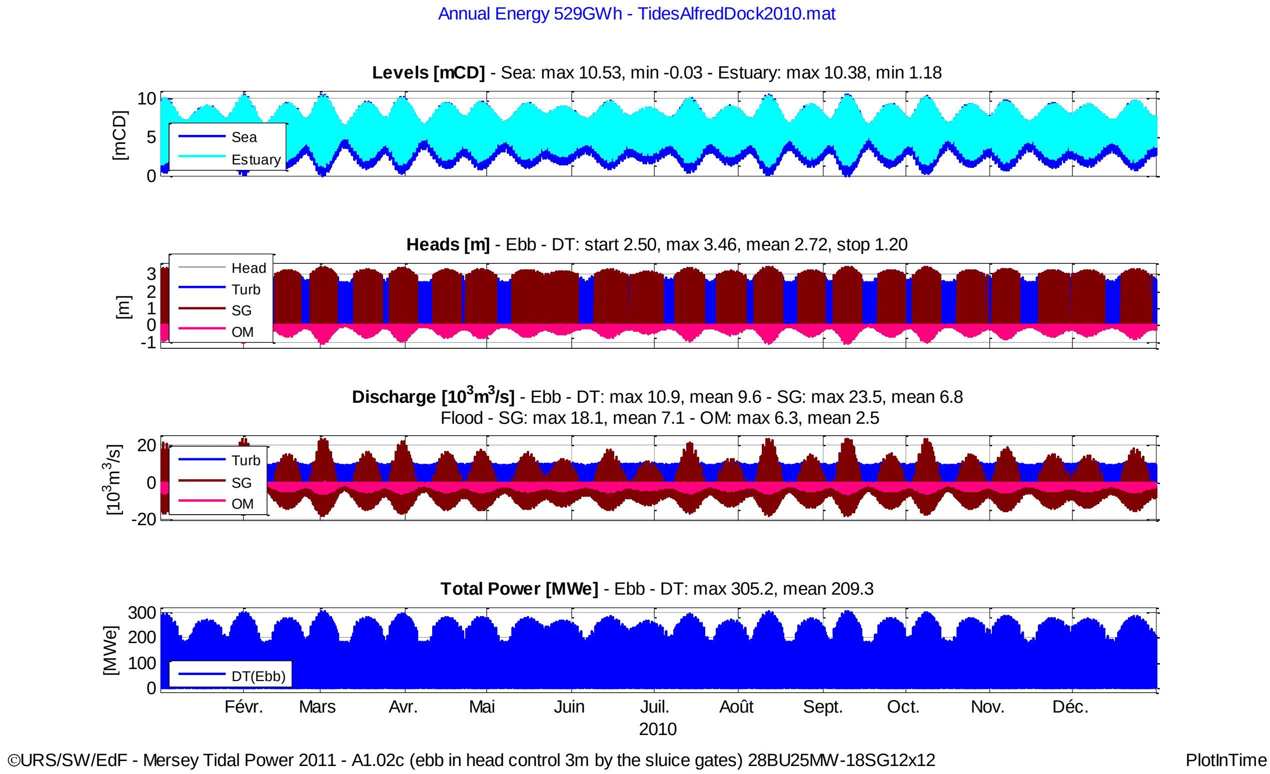
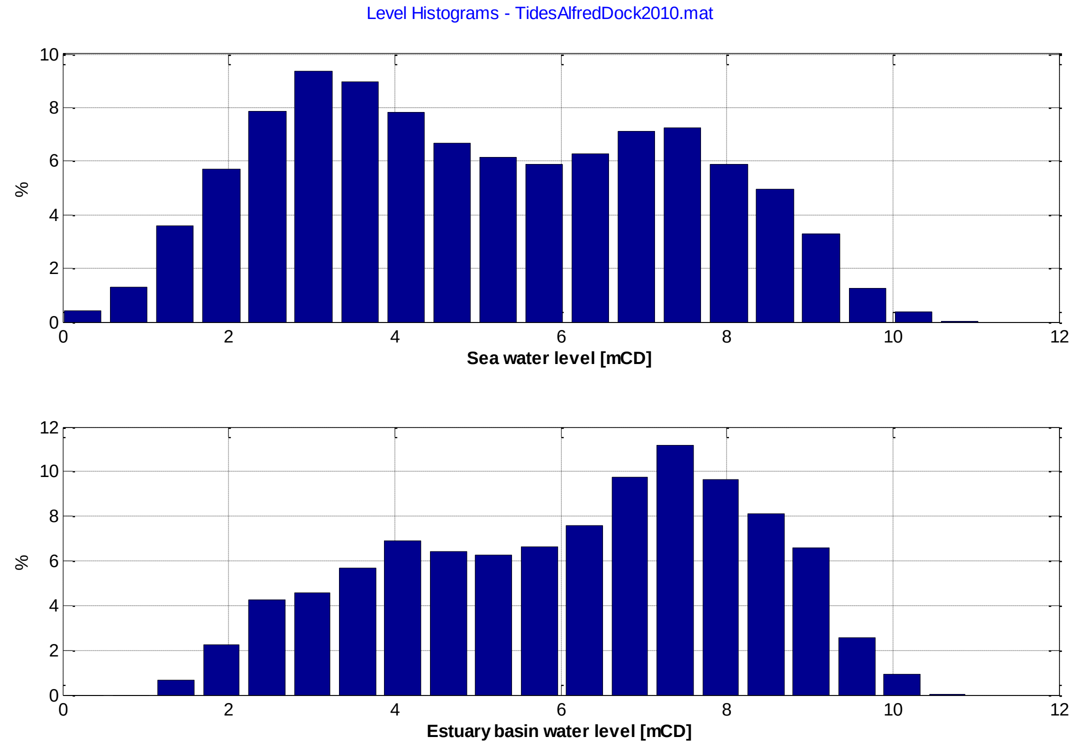
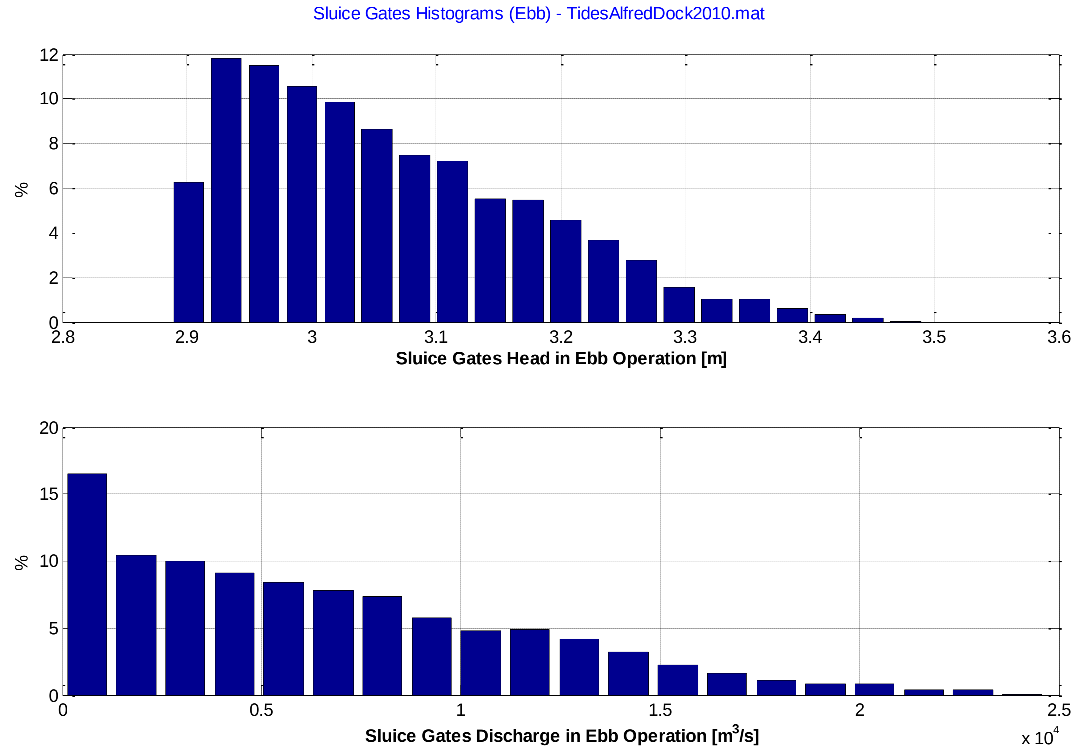


Figure G.32 - A1.02c (ebb in head control 3m by the sluice gates) - year 2010 time curves



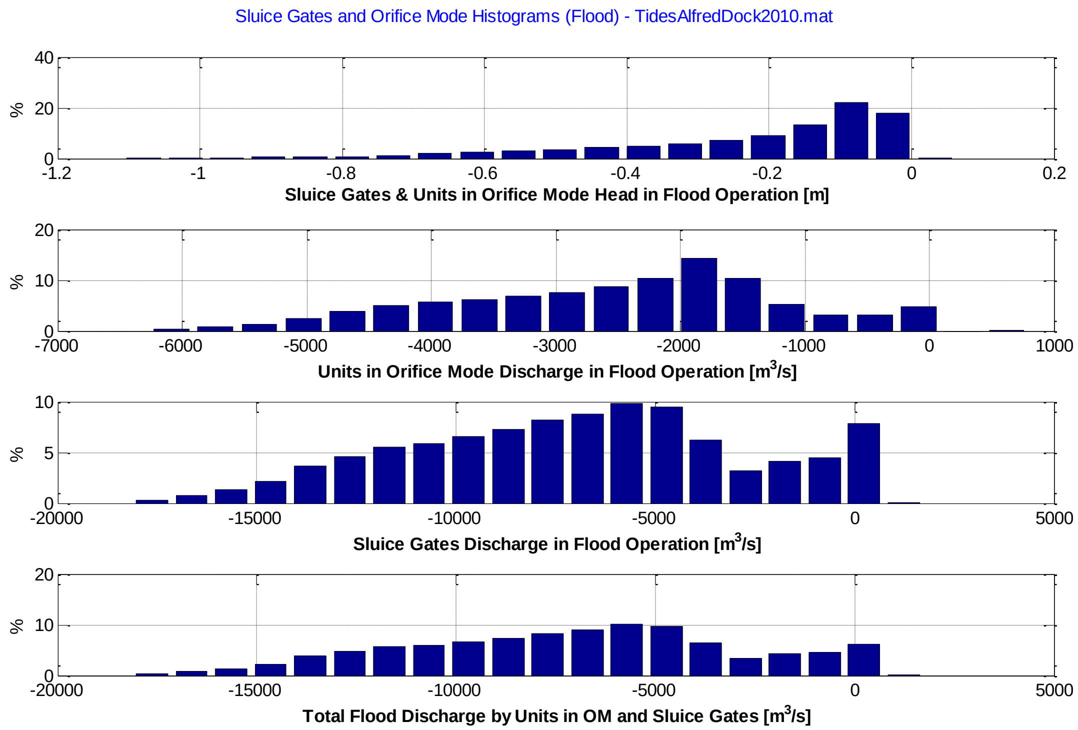
©URS/SW/EdF - Mersey Tidal Power 2011 - A1.02c (ebb in head control 3m by the sluice gates) 28BU25MW-18SG12x12 PlotHistoLevels

Figure G.33 - A1.02c (ebb in head control 3m by the sluice gates) - water level histograms



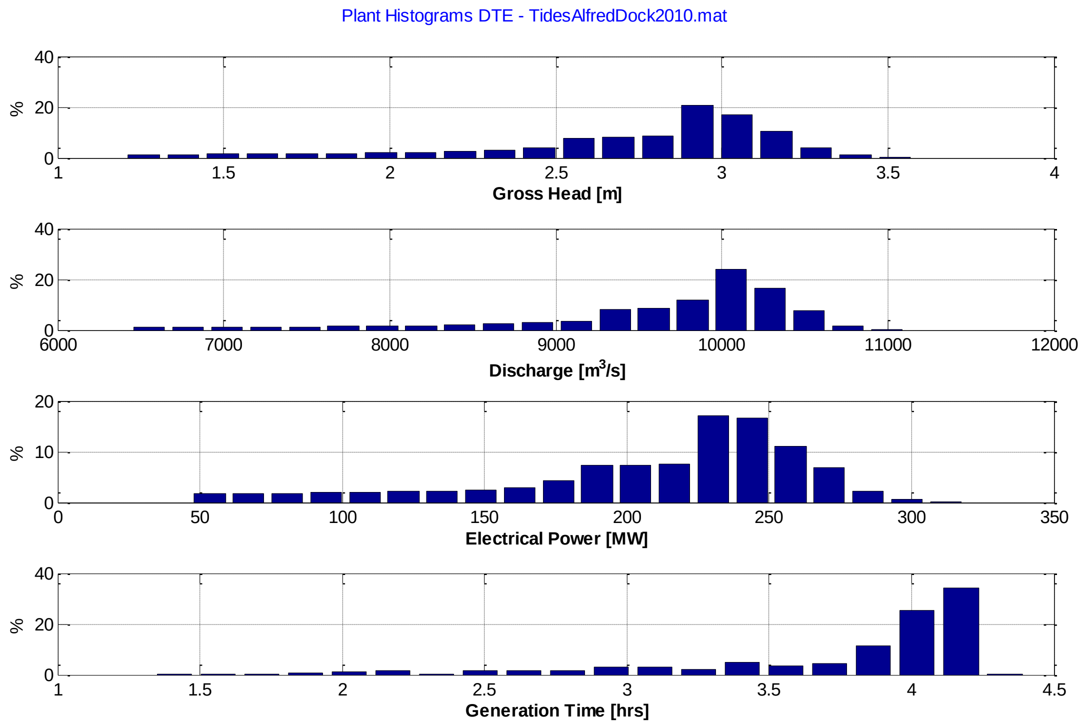
©URS/SW/EdF - Mersey Tidal Power 2011 - A1.02c (ebb in head control 3m by the sluice gates) 28BU25MW-18SG12x12 PlotHistoEbb

Figure G.34 - A1.02c (ebb in head control 3m by the sluice gates) - sluice gates and orifice mode histograms (ebb)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.02c (ebb in head control 3m by the sluice gates) 28BU25MW-18SG12x12 PlotHistoFlood

Figure G.35 - A1.02c (ebb in head control 3m by the sluice gates) - sluice gates and orifice mode histograms (flood)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.02c (ebb in head control 3m by the sluice gates) 28BU25MW-18SG12x12 PlotHistoPlant

Figure G.36 - A1.02c (ebb in head control 3m by the sluice gates) - plant histograms (direct turbining)

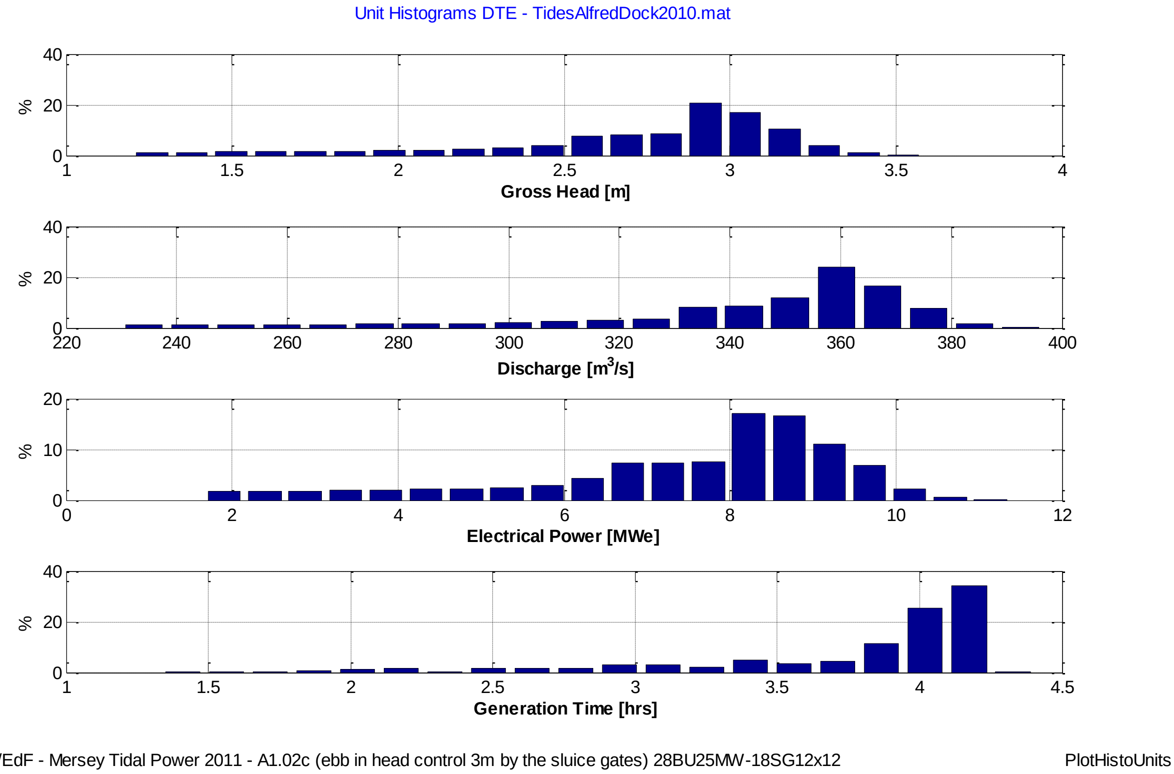


Figure G.37 - A1.02c (ebb in head control 3m by the sluice gates) - unit histograms (direct turbining)

Balance Sheet Listing

```
 ---SIMULATION CASE A1.02c (ebb in head control 3m by the sluice gates) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level .................. 10.38 m
Minimum Estuary Level ..................  1.18 m
Maximum Estuary Range ..................  9.20 m

 - Ebb Generation:
Energy production in Ebb ............... 529 GWh
Generation Time ........................ 2666.1 hrs
Mean Output ............................ 209 MW
Mean Discharge ......................... 9608 m^3/s
Max. Discharge ......................... 10876 m^3/s
Starting Head .......................... 2.50 m
Mean Head .............................. 2.72 m
Max  Head .............................. 3.46 m
Stopping Head .......................... 1.20 m

 - Ebb Sluicing:
Generation Time ........................ 987.2 hrs
Mean Discharge ......................... 6828 m^3/s
Max. Discharge ......................... 23472 m^3/s
Mean Head .............................. 3.06 m
Max  Head .............................. 3.46 m
```

```
 - Flood Sluicing:
Operating Time ......................... 3051.4 hrs
Mean Discharge ......................... 7084 m^3/s
Max. Discharge ......................... 18130 m^3/s
Mean Head .............................. 0.23 m
Max. Head .............................. 1.11 m

 - Reverse Orifice Mode :
Operating Time ......................... 3051.4 hrs
Mean Discharge  ........................ 2519 m^3/s
Max Discharge .......................... 6261 m^3/s

 - Results :
Simulation Case ........................ A1.02c (ebb in head control 3m by the
sluice gates) 28BU25MW-18SG12x12
Average Output ......................... 209 MW
Total Installed Capacity ............... 700 MW
Load Factor ............................ 8.6%
Direct Turbining Production (Ebb)....... 529 GWh
Reverse Turbining Production (Flood) ... 0 MWh
Net Energy ............................. 529 GWh
DT Generation Time ..................... 2666.1 hrs (30.5%)
RT Generation Time ..................... 0.0 hrs (0.0%)
Sluice Gates Operating Time ............ 4038.6 hrs (46.2%)
Orifice Mode Operating Time ............ 3051.4 hrs (34.9%)
Standing Time .......................... 3029.2 hrs (34.6%)

Theoretical hydraulic energy lost through the Sluices Gates ... 83 GWh (15.8%)
Theoretical hydraulic energy lost in Orifice Mode ............. 29 GWh (5.5%)
```

Average output for each hour of the day

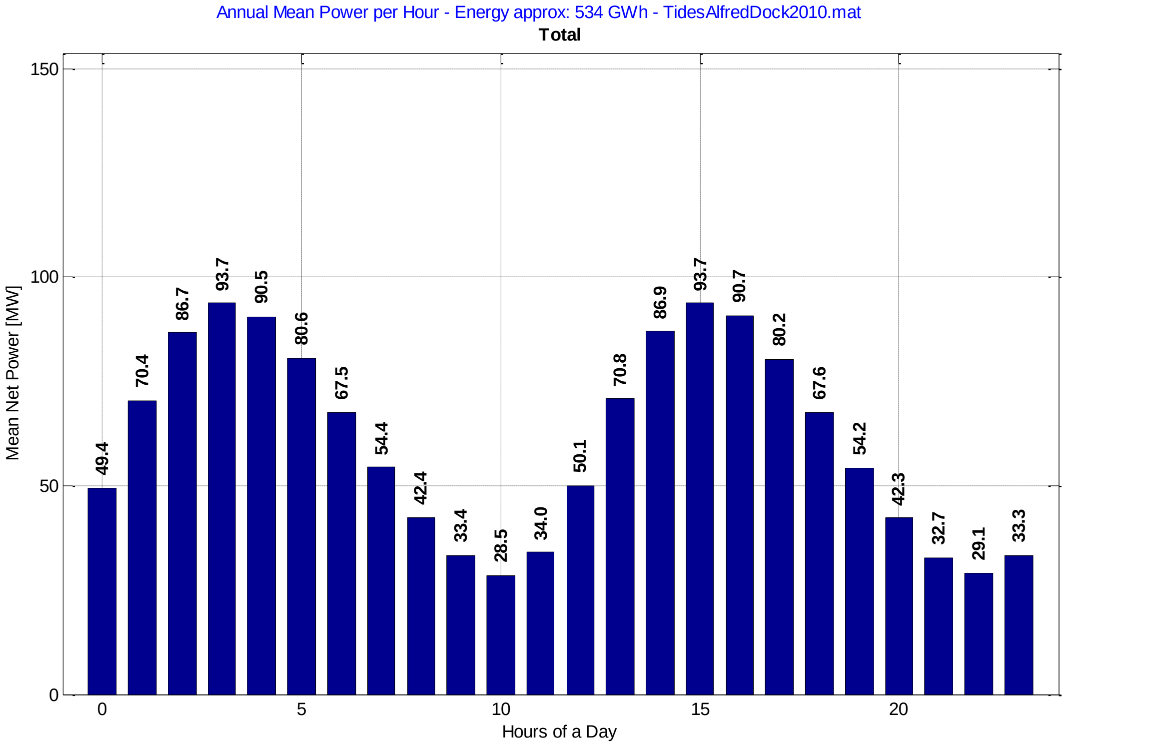


Figure G.38 - A1.02c (ebb in head control 3m by the sluice gates) - mean power per hour

4 A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - 28BU25MW-24SG12x12

4.1 Control curves

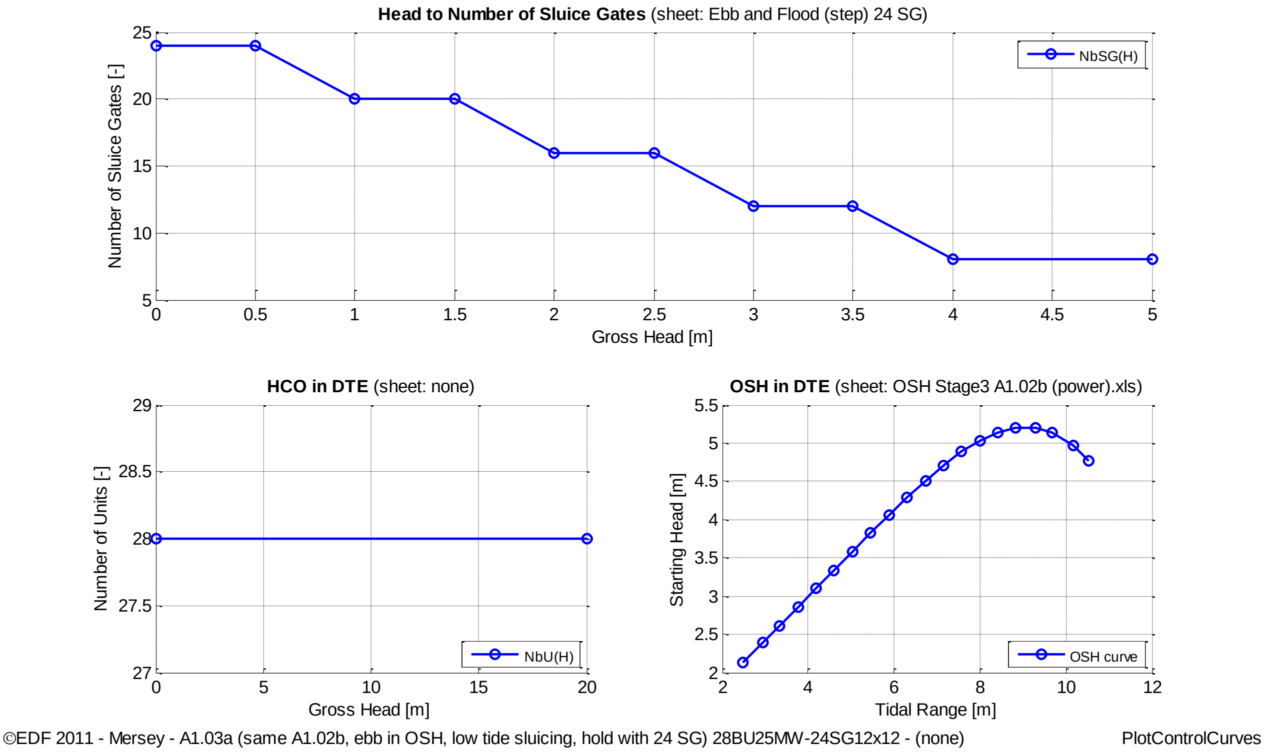


Figure G.39 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - Control curves

4.2 5 typical tidal range results

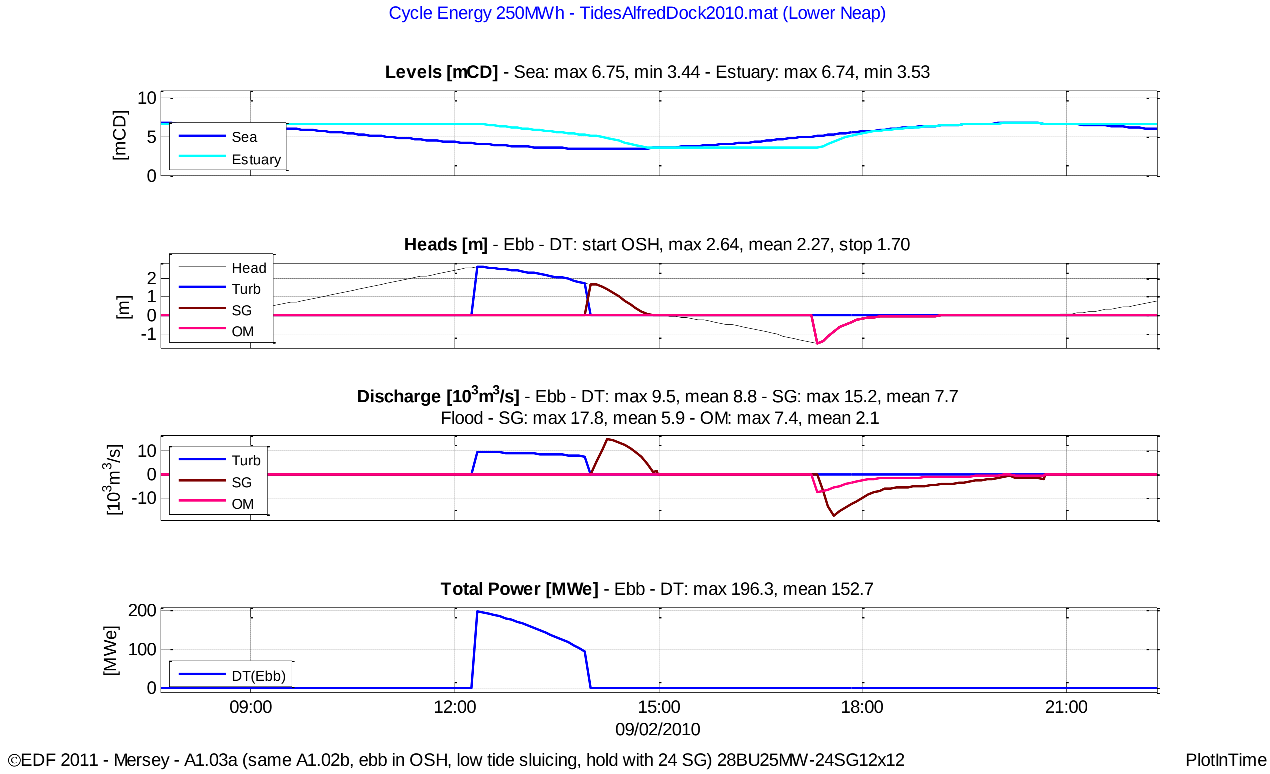


Figure G.40 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - Lower Neap Tide operation

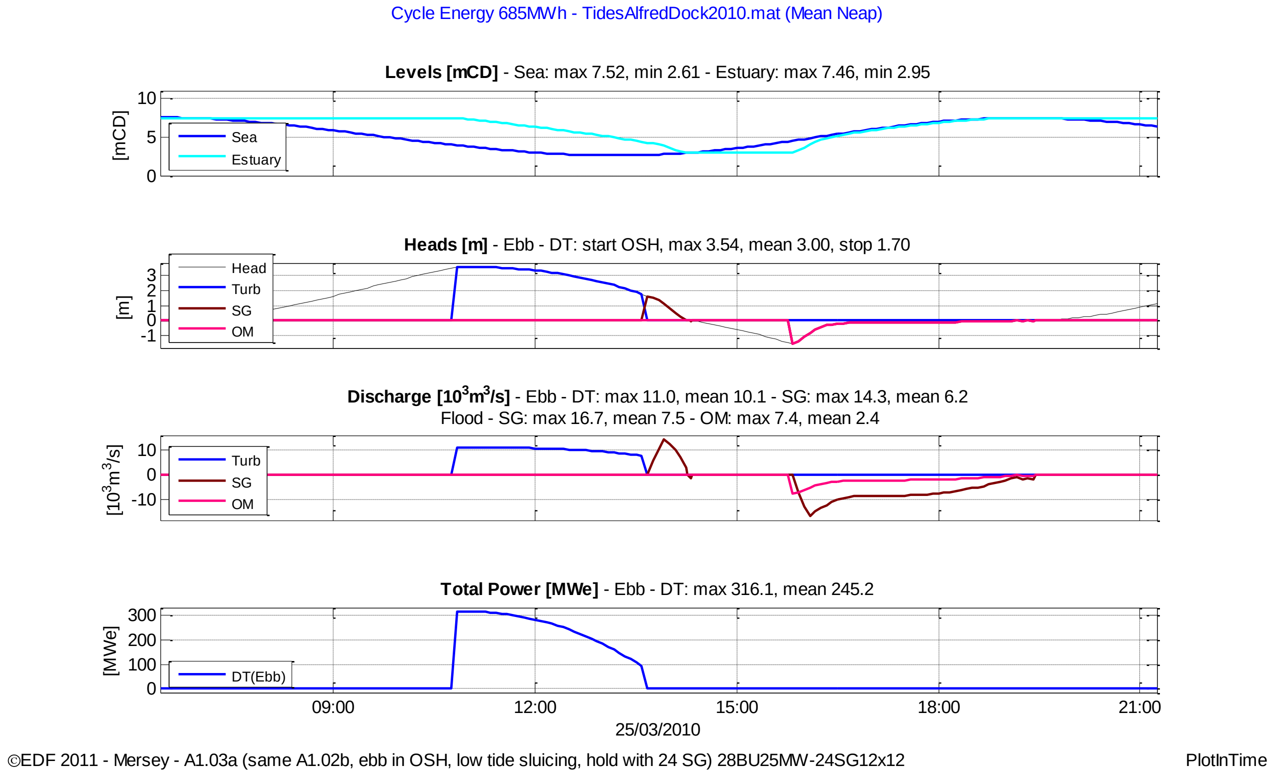


Figure G.41 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - Mean Neap Tide operation

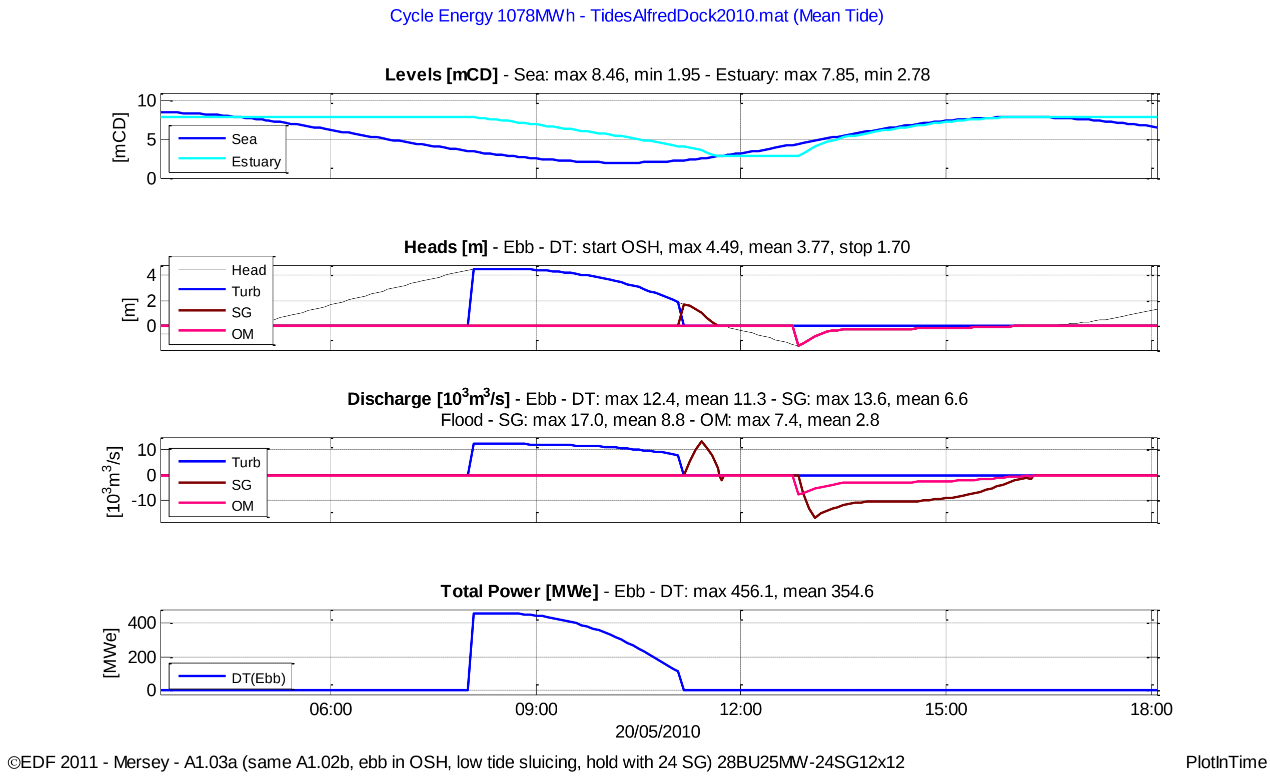


Figure G.42 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - Mean Tide operation

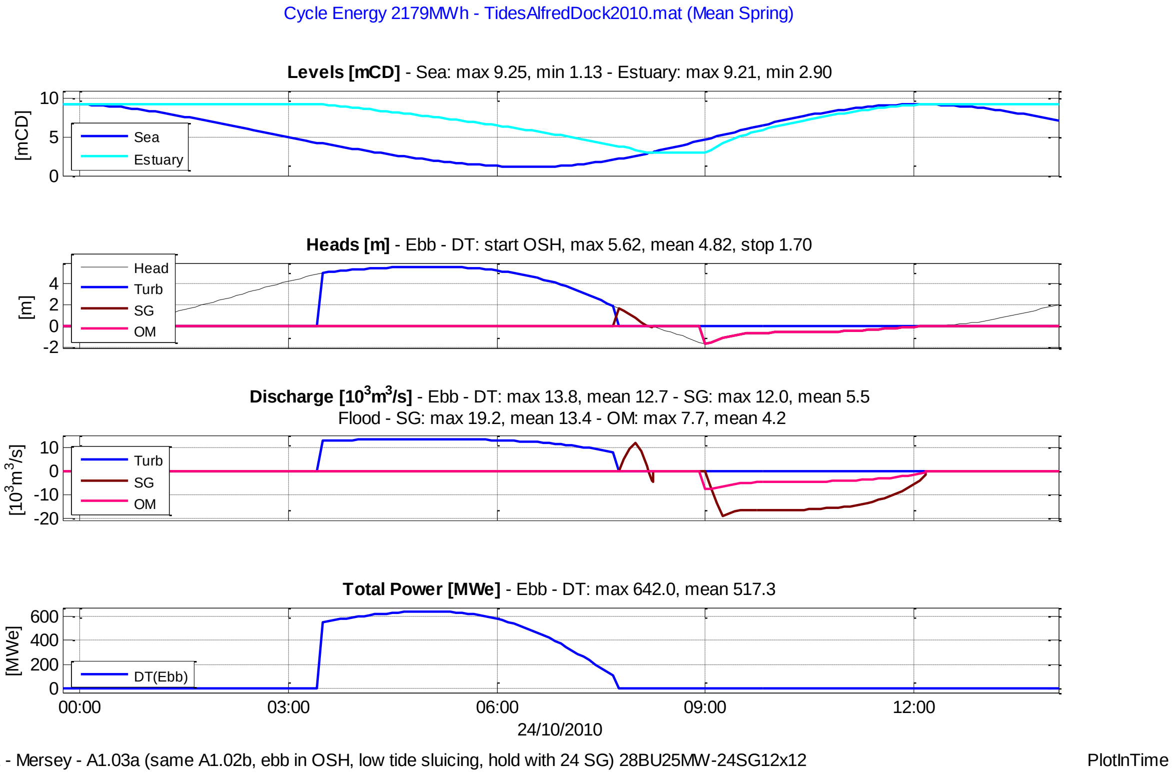


Figure G.43 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - Mean Spring Tide operation

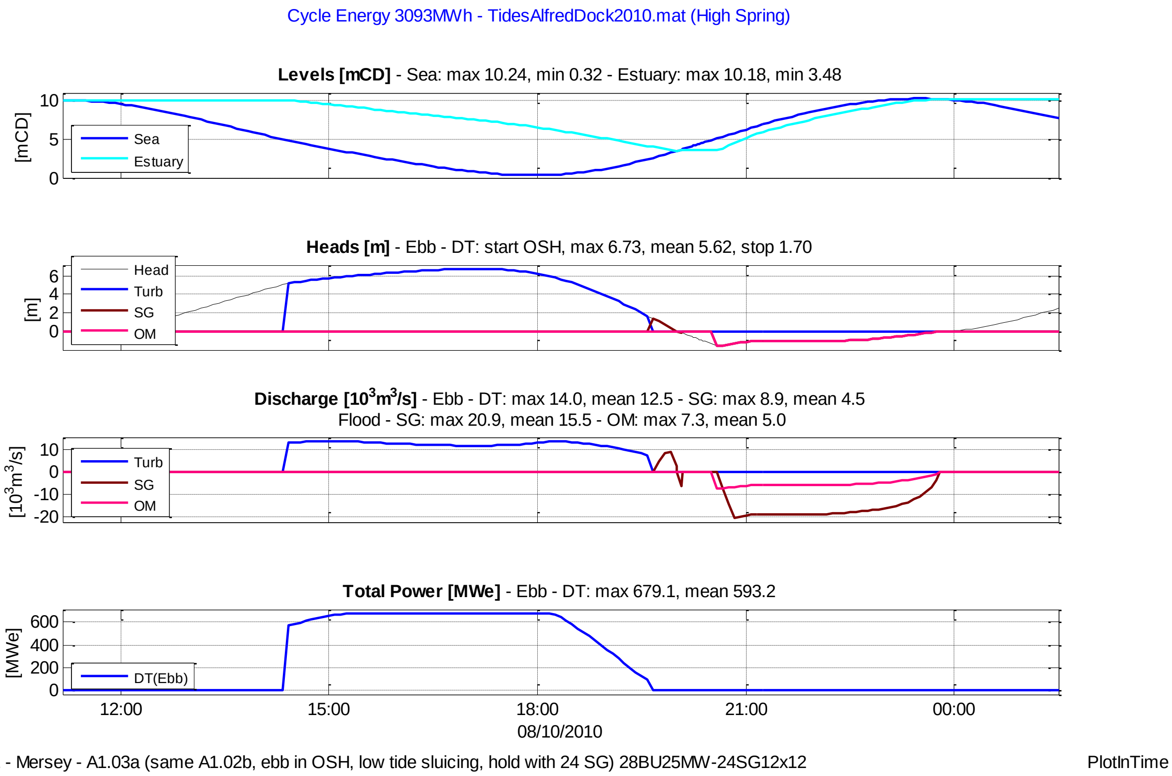


Figure G.44 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - High Spring Tide operation

4.3 Year 2010 simulation

Graphics

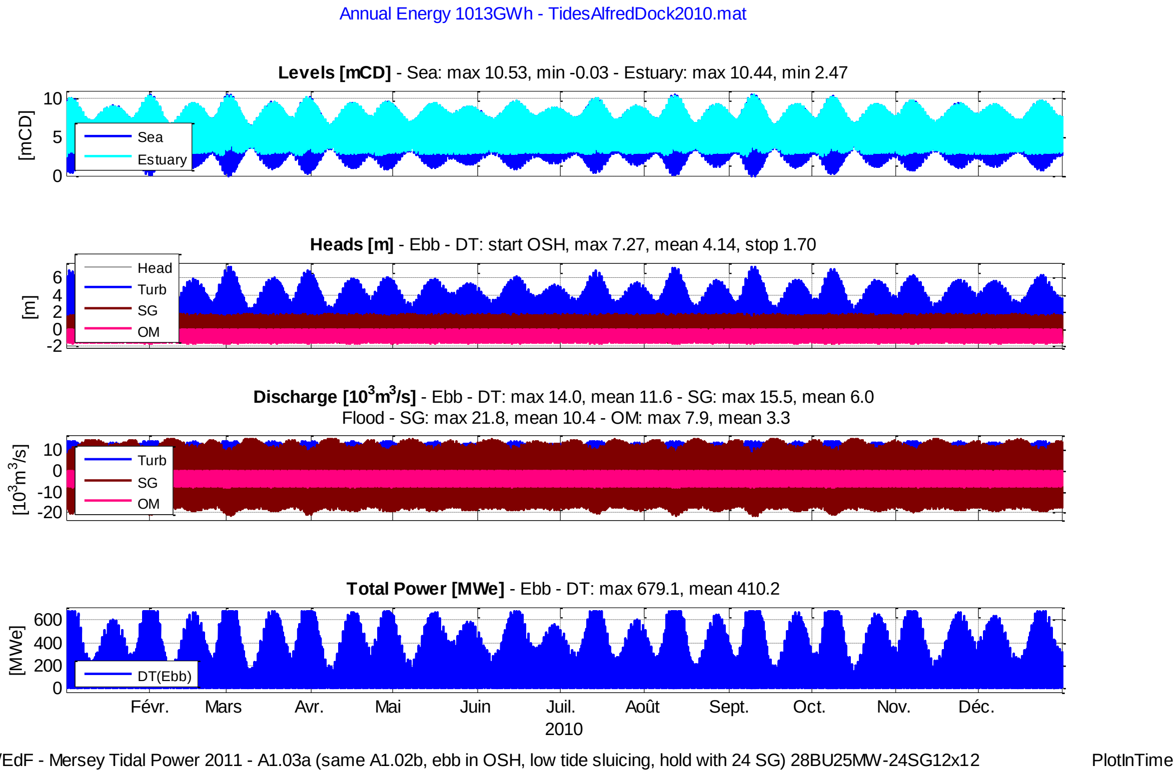


Figure G.45 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - year 2010 time curves

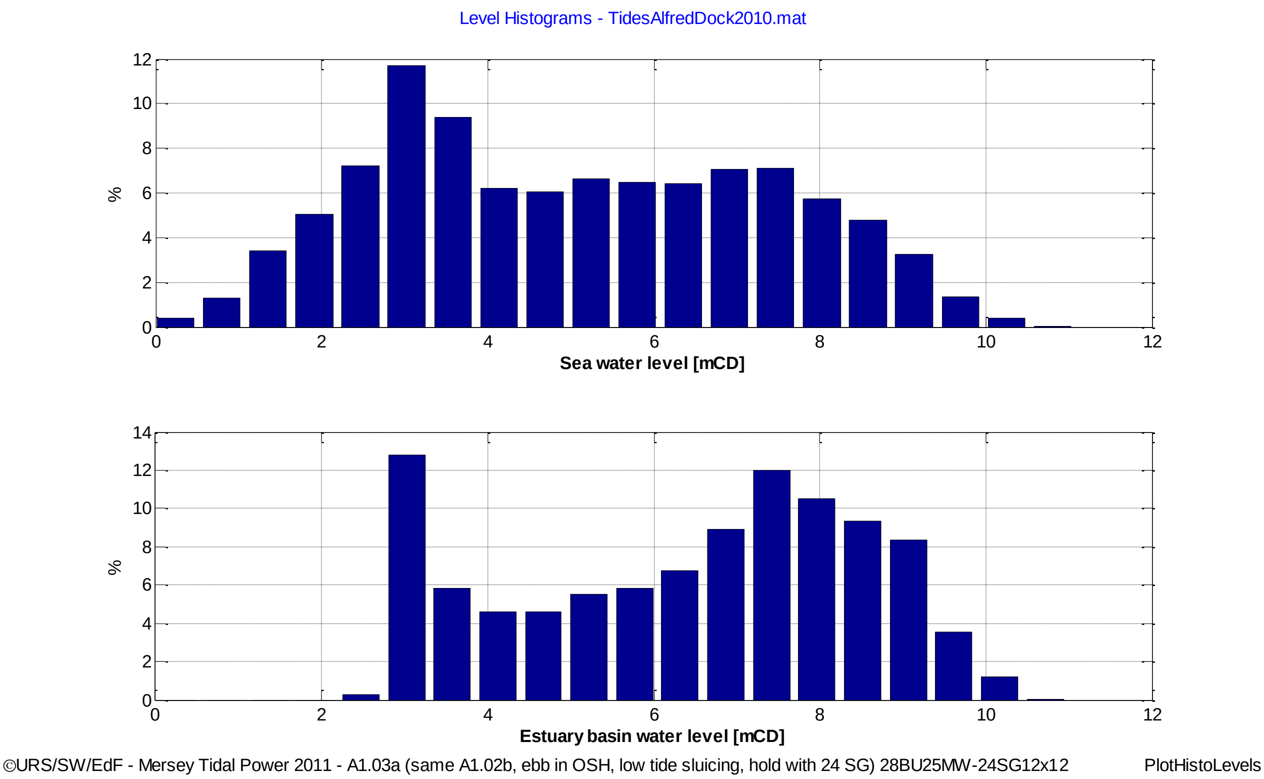


Figure G.46 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - water level histograms

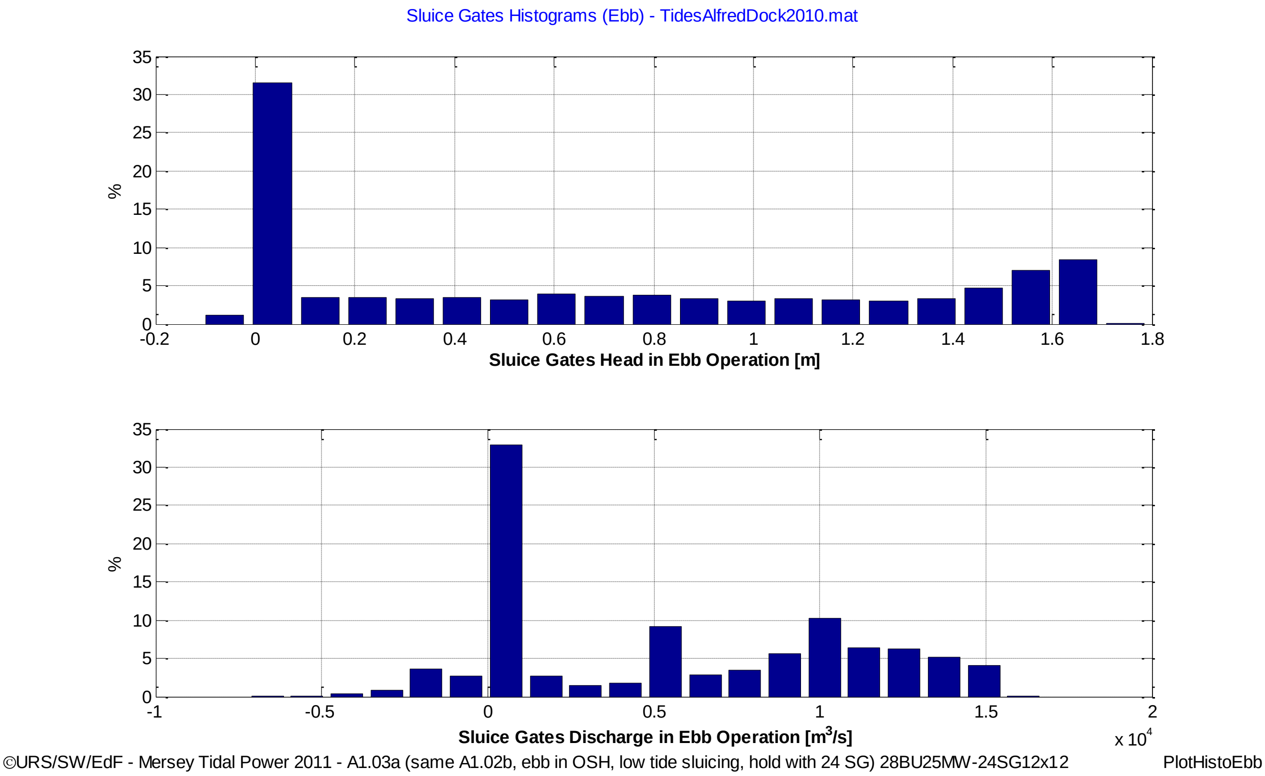


Figure G.47 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - sluice gates and orifice mode histograms (ebb)

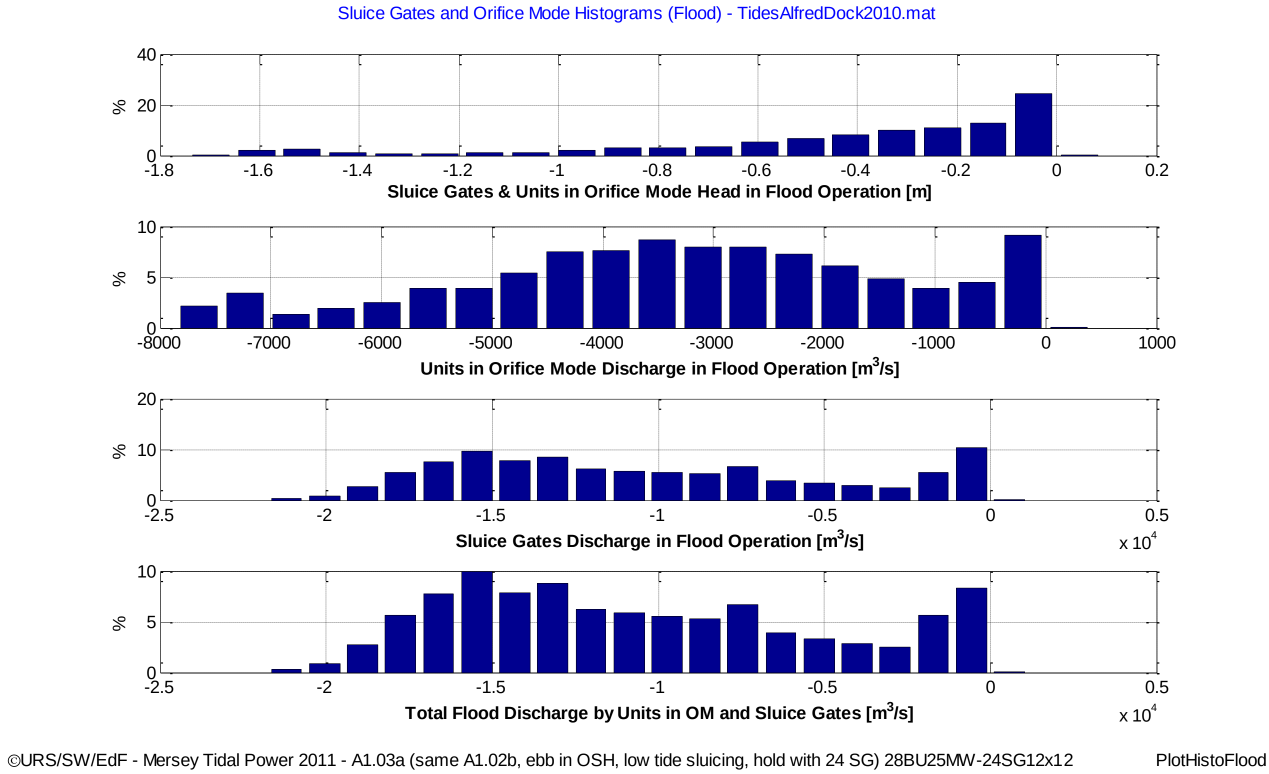


Figure G.48 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - sluice gates and orifice mode histograms (flood)

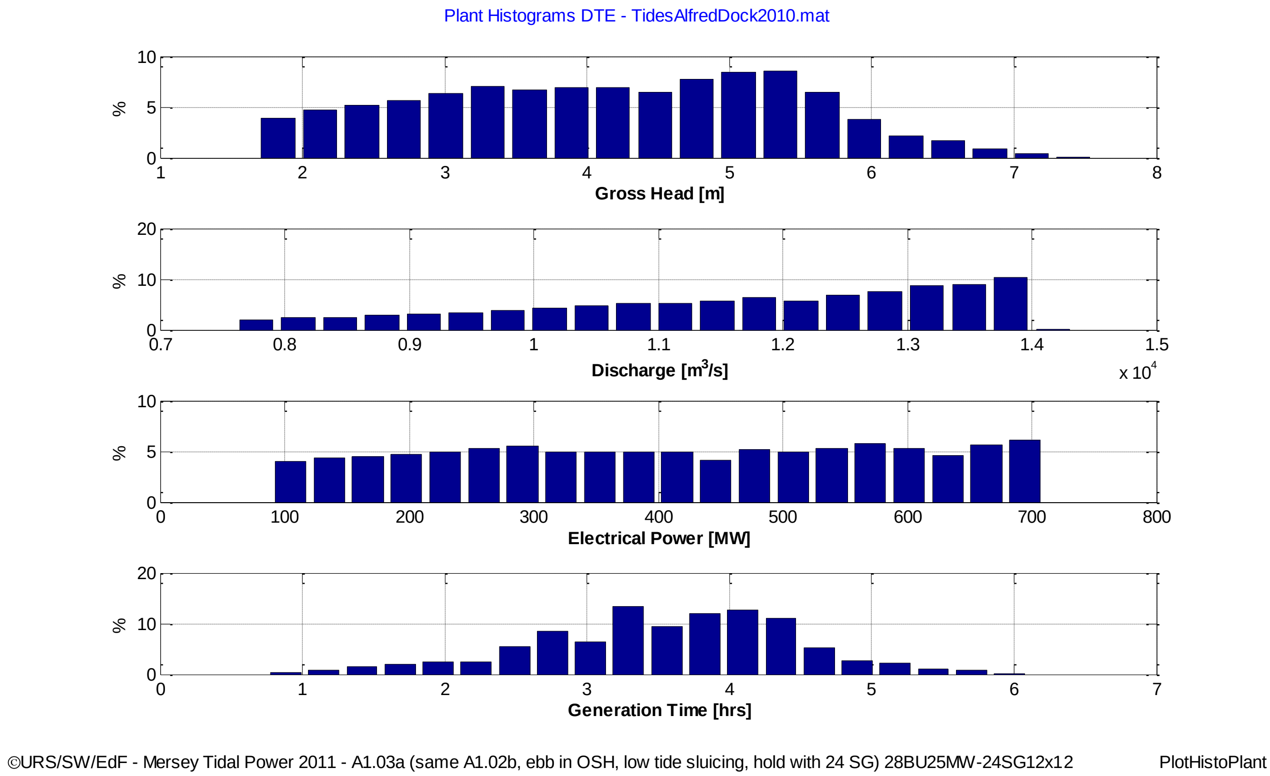


Figure G.49 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - plant histograms (direct turbining)

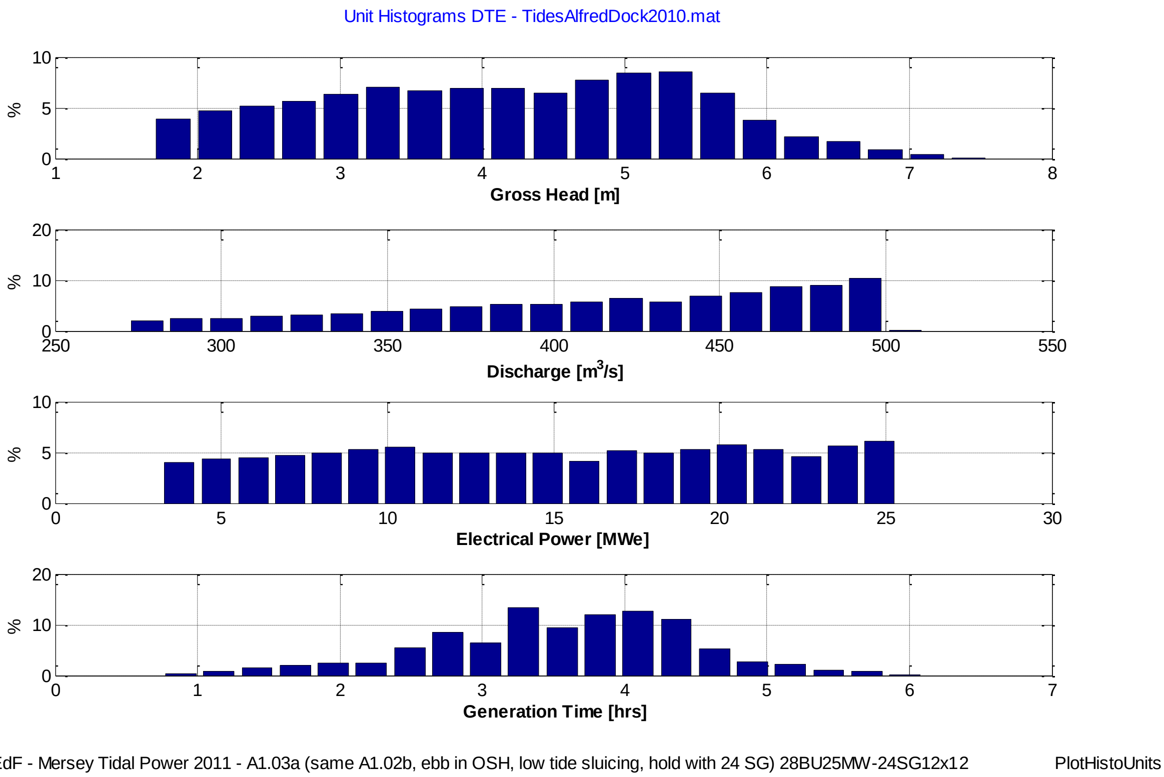


Figure G.50 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - unit histograms (direct turbining)

Balance Sheet Listing

```
 ---SIMULATION CASE A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with
24 SG) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level .................. 10.44 m
Minimum Estuary Level ..................  2.47 m
Maximum Estuary Range ..................  7.97 m

 - Init Estuary Level minus Max Sea Level:
Starting value ......................... -0.60 m
Maximum ................................  0.00 m
Minimum ................................ -0.60 m

 - Ebb Generation:
Energy production in Ebb ............... 1013 GWh
Generation Time ........................ 2495.5 hrs
Mean Output ............................ 410 MW
Mean Discharge ......................... 11607 m^3/s
Max. Discharge ......................... 14000 m^3/s
Head control choice .................... in OSH operation
Starting Head .......................... optimised
Mean Head .............................. 4.14 m
Max  Head .............................. 7.27 m
Stopping Head .......................... 1.70 m
```

```
 - Ebb Sluicing:
Generation Time ....................... 421.7 hrs
Mean Discharge ........................ 6037 m^3/s
Max. Discharge ........................ 15539 m^3/s
Mean Head ............................. 0.67 m
Max  Head ............................. 1.70 m

 - Flood Sluicing:
Operating Time ........................ 2413.6 hrs
Mean Discharge ........................ 10425 m^3/s
Max. Discharge ........................ 21768 m^3/s
Mean Head ............................. 0.41 m
Max. Head ............................. 1.74 m

 - Reverse Orifice Mode :
Operating Time ........................ 2413.6 hrs
Mean Discharge  ....................... 3278 m^3/s
Max Discharge ......................... 7854 m^3/s

 - Results :
Simulation Case ....................... A1.03a (same A1.02b, ebb in OSH, low tide
sluicing, hold with 24 SG) 28BU25MW-24SG12x12
Average Output ........................ 410 MW
Total Installed Capacity .............. 700 MW
Load Factor ........................... 16.6%
Direct Turbining Production (Ebb)....... 1013 GWh
Reverse Turbining Production (Flood) ... 0 MWh
Net Energy ............................ 1013 GWh
DT Generation Time .................... 2495.5 hrs (28.5%)
RT Generation Time .................... 0.0 hrs (0.0%)
Sluice Gates Operating Time ........... 2835.2 hrs (32.4%)
Orifice Mode Operating Time ........... 2413.6 hrs (27.6%)
Standing Time ......................... 3837.6 hrs (43.9%)

Theoretical hydraulic energy lost through the Sluices Gates ... 148 GWh (14.6%)
Theoretical hydraulic energy lost in Orifice Mode ............. 63 GWh (6.2%)
```

Average output for each hour of the day

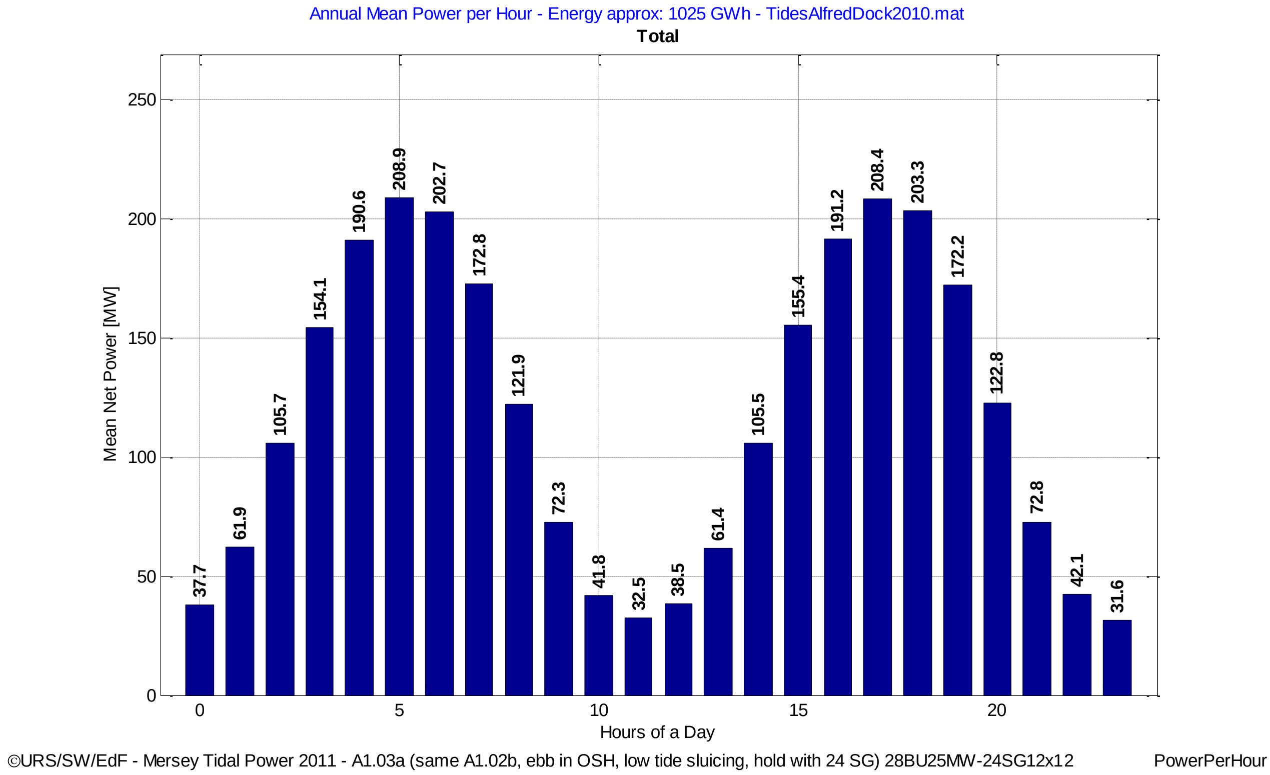
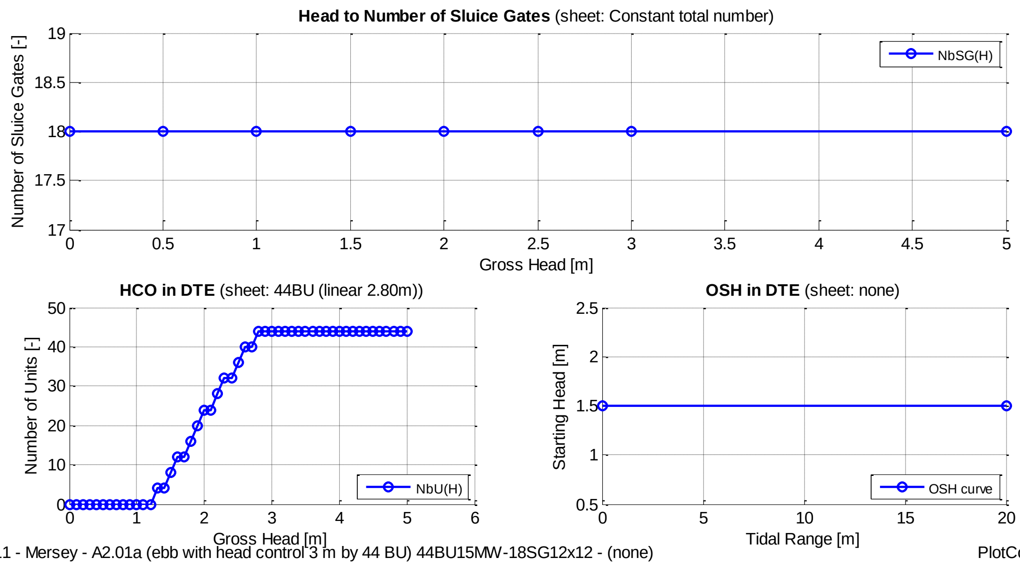


Figure G.51 - A1.03a (same A1.02b, ebb in OSH, low tide sluicing, hold with 24 SG) - mean power per hour

5 A2.01a (ebb with head control 3 m by 44 BU) - 44BU15MW-18SG12x12

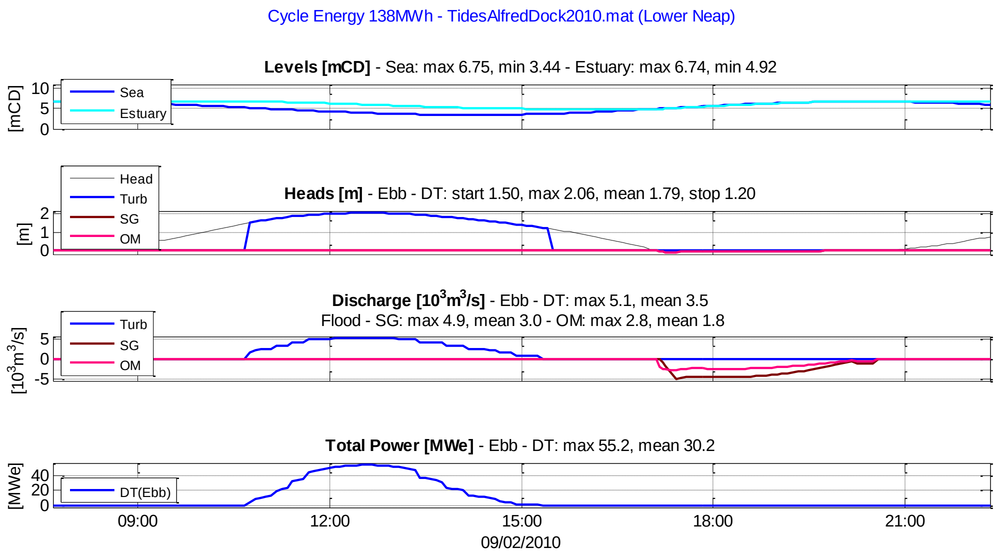
5.1 Control curves



©EDF 2011 - Mersey - A2.01a (ebb with head control 3 m by 44 BU) 44BU15MW-18SG12x12 - (none) PlotControlCurves

Figure G.52 - A2.01a (ebb with head control 3 m by 44 BU) - Control curves

5.2 5 typical tidal range results



©EDF 2011 - Mersey - A2.01a (ebb with head control 3 m by 44 BU) 44BU15MW-18SG12x12 PlotInTime

Figure G.53 - A2.01a (ebb with head control 3 m by 44 BU) - Lower Neap Tide operation

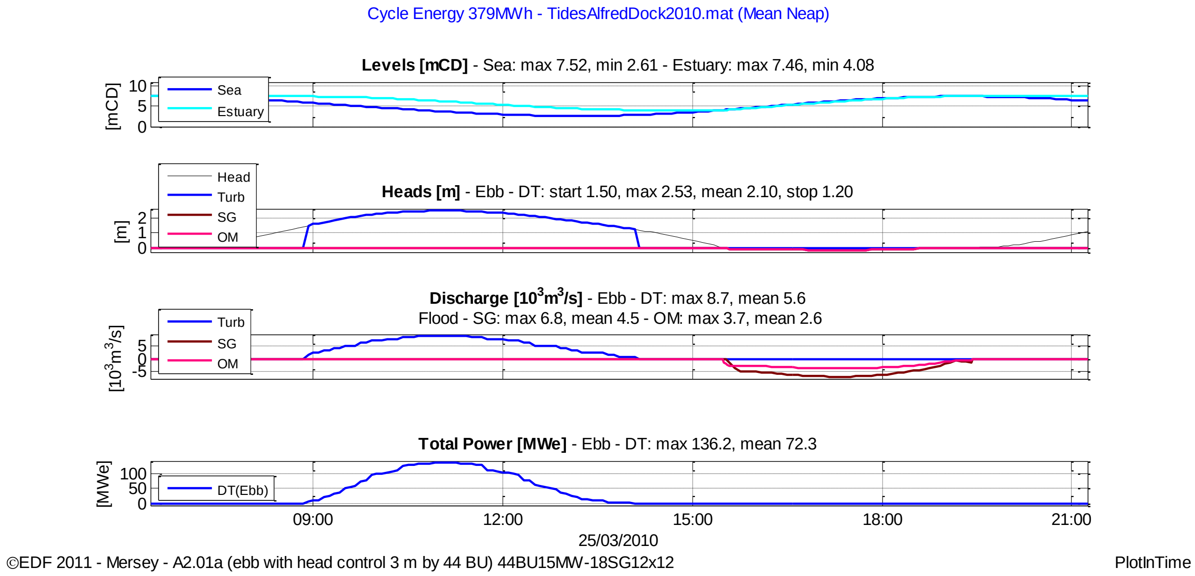


Figure G.54 - A2.01a (ebb with head control 3 m by 44 BU) - Mean Neap Tide operation

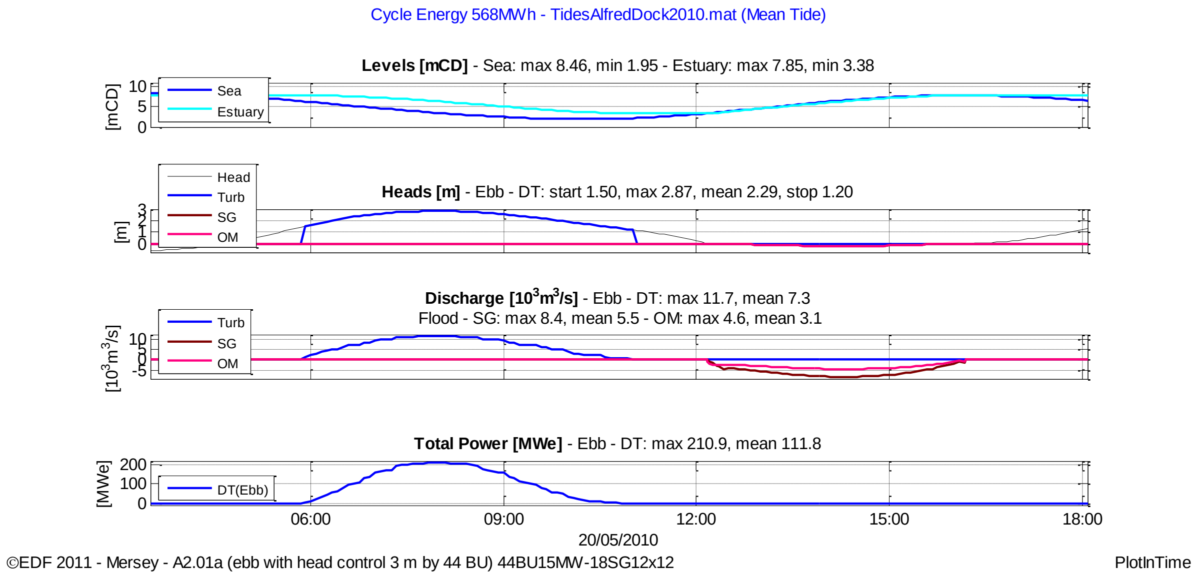


Figure G.55 - A2.01a (ebb with head control 3 m by 44 BU) - Mean Tide operation

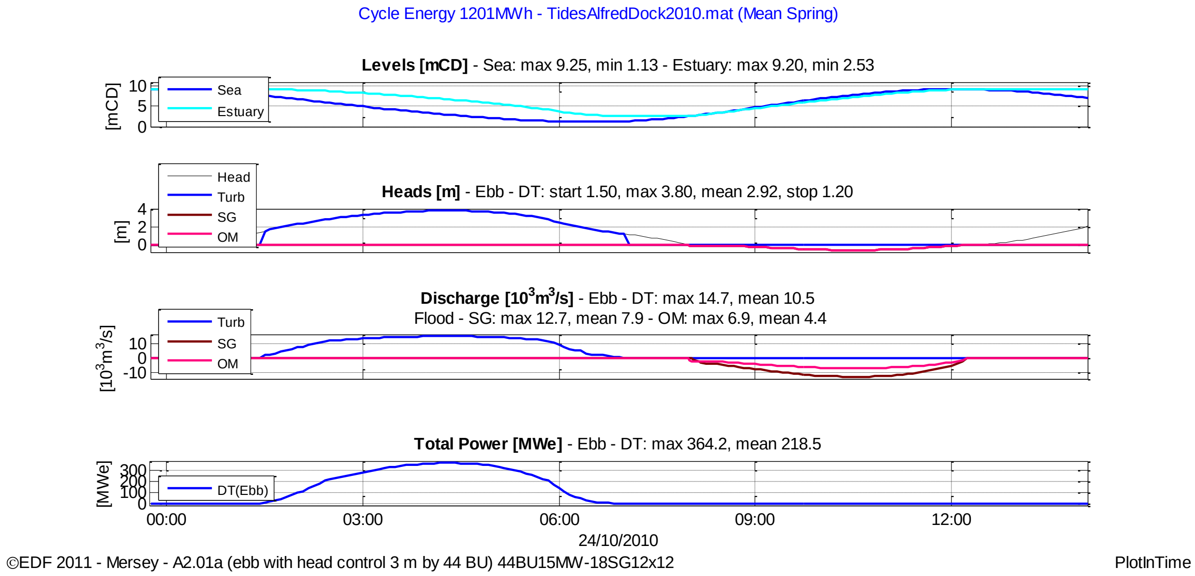


Figure G.56 - A2.01a (ebb with head control 3 m by 44 BU) - Mean Spring Tide operation

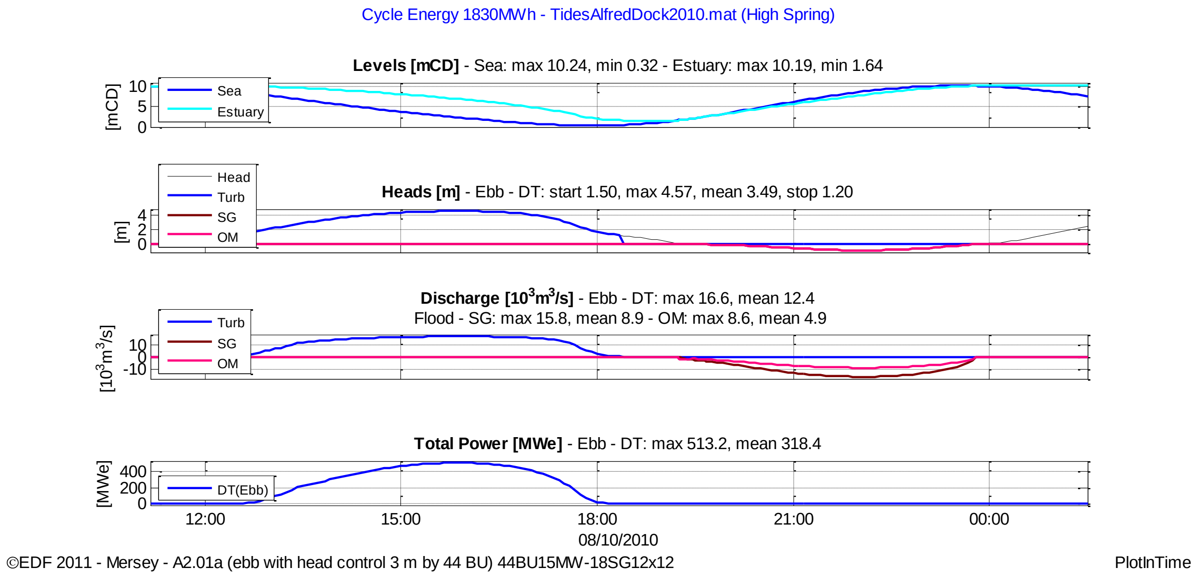


Figure G.57 - A2.01a (ebb with head control 3 m by 44 BU) - High Spring Tide operation

5.3 Year 2010 simulation

Graphics

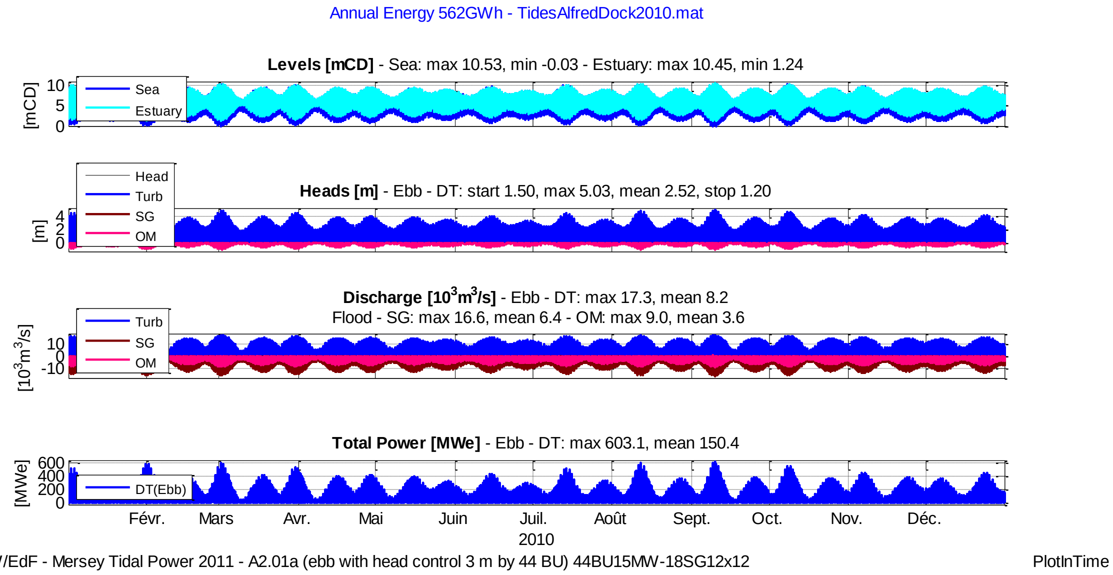


Figure G.58 - A2.01a (ebb with head control 3 m by 44 BU) - year 2010 time curves

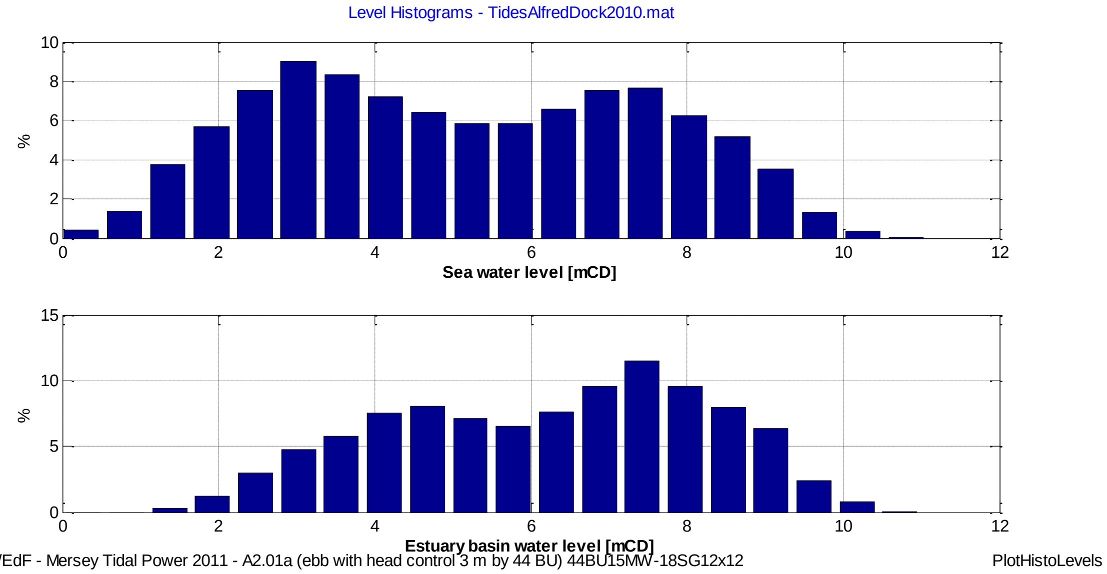
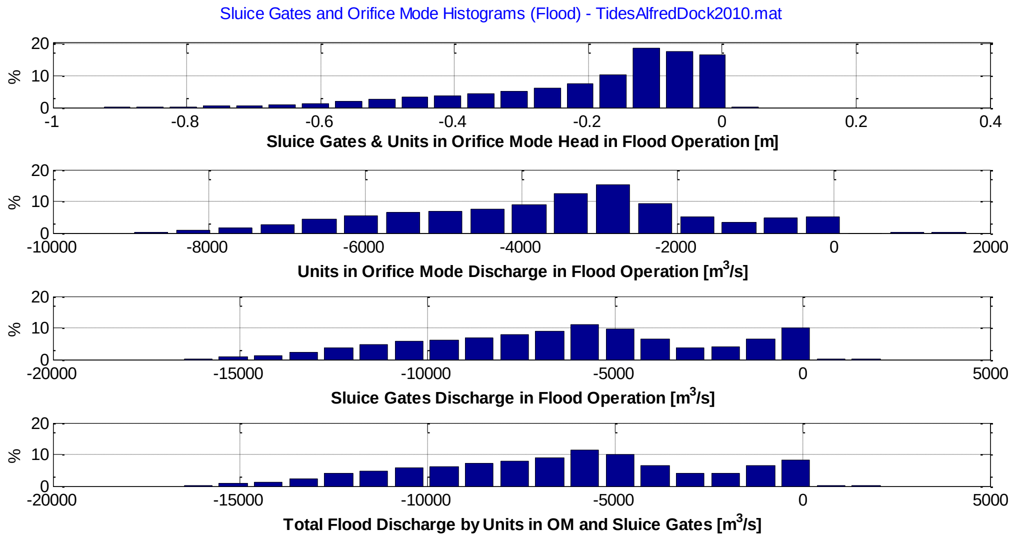
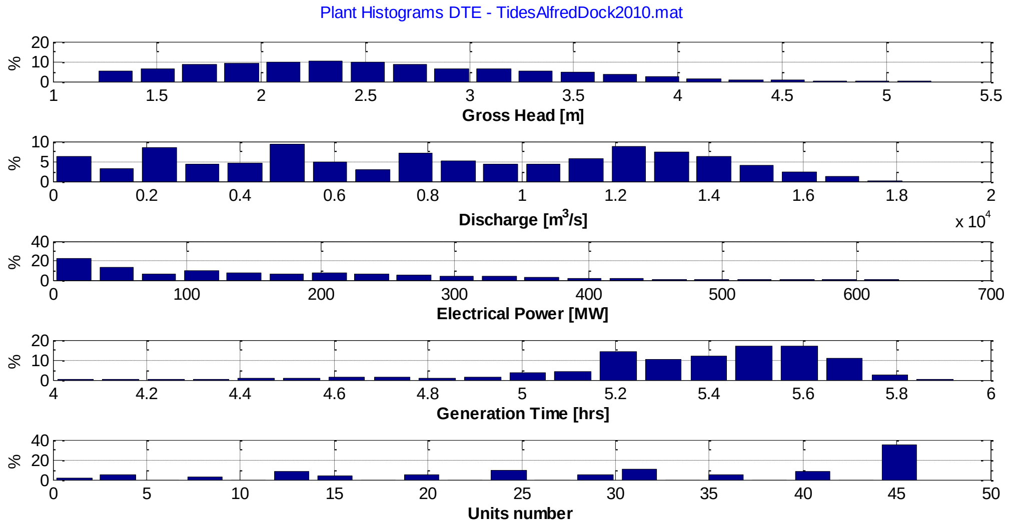


Figure G.59 - A2.01a (ebb with head control 3 m by 44 BU) - water level histograms



©URS/SW/EdF - Mersey Tidal Power 2011 - A2.01a (ebb with head control 3 m by 44 BU) 44BU15MW-18SG12x12 PlotHistoFlood

Figure G.60 - A2.01a (ebb with head control 3 m by 44 BU) - sluice gates and orifice mode histograms (flood)



©URS/SW/EdF - Mersey Tidal Power 2011 - A2.01a (ebb with head control 3 m by 44 BU) 44BU15MW-18SG12x12 PlotHistoPlant

Figure G.61 - A2.01a (ebb with head control 3 m by 44 BU) - plant histograms (direct turbining)

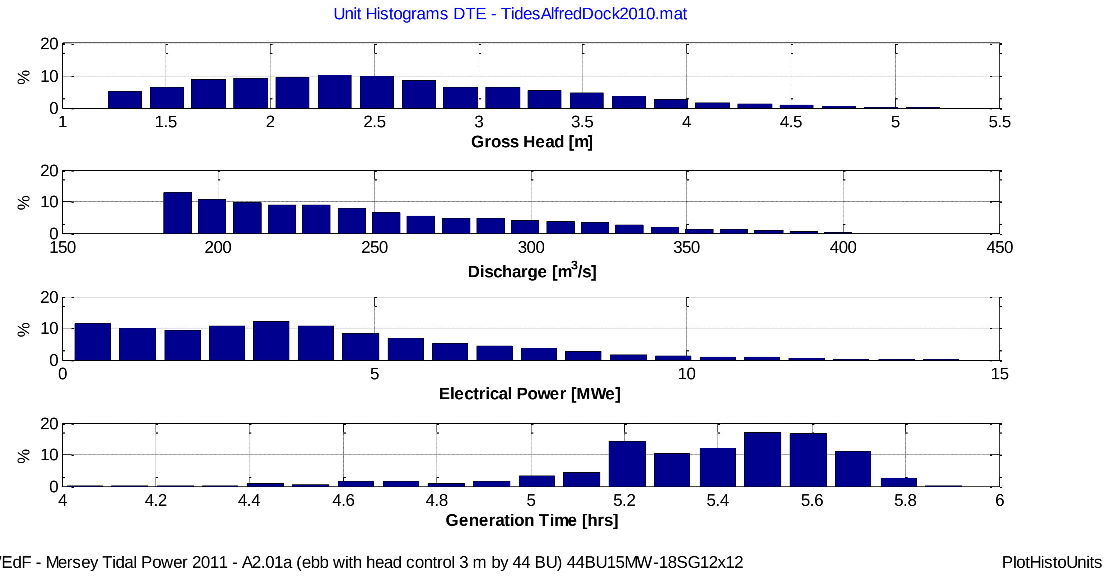


Figure G.62 - A2.01a (ebb with head control 3 m by 44 BU) - unit histograms (direct turbining)

Balance Sheet Listing

```
---SIMULATION CASE A2.01a (ebb with head control 3 m by 44 BU) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level .................. 10.45 m
Minimum Estuary Level ..................  1.24 m
Maximum Estuary Range ..................  9.21 m

 - Init Estuary Level minus Max Sea Level:
Starting value ......................... -0.60 m
Maximum ................................  0.00 m
Minimum ................................ -0.60 m

 - Ebb Generation:
Energy production in Ebb ............... 562 GWh
Generation Time ........................ 3781.0 hrs
Mean Output ............................ 150 MW
Mean Discharge ......................... 8230 m^3/s
Max. Discharge ......................... 17290 m^3/s
Head control choice .................... Nb Units variable
Starting Head .......................... 1.50 m
Mean Head .............................. 2.52 m
Max  Head .............................. 5.03 m
Stopping Head .......................... 1.20 m

 - Flood Sluicing:
Operating Time ......................... 2877.7 hrs
Mean Discharge ......................... 6391 m^3/s
Max. Discharge ......................... 16595 m^3/s
Mean Head .............................. 0.19 m
Max. Head .............................. 0.93 m

 - Reverse Orifice Mode :
Operating Time ......................... 2877.7 hrs
Mean Discharge  ........................ 3600 m^3/s
Max Discharge .......................... 9005 m^3/s

 - Results :
Simulation Case ........................ A2.01a (ebb with head control 3 m by 44
         BU) 44BU15MW-18SG12x12
Average Output ......................... 150 MW
Total Installed Capacity ............... 660 MW
Load Factor ............................ 9.7%
Direct Turbining Production (Ebb)....... 562 GWh
Reverse Turbining Production (Flood) ... 0 MWh
Net Energy ............................. 562 GWh
DT Generation Time ..................... 3781.0 hrs (43.2%)
```

```
RT Generation Time ..................... 0.0 hrs (0.0%)
Sluice Gates Operating Time ............ 2877.7 hrs (32.9%)
Orifice Mode Operating Time ............ 2877.7 hrs (32.9%)
Standing Time .......................... 2088.0 hrs (23.9%)

Theoretical hydraulic energy lost through the Sluices Gates ... 59 GWh (10.6%)
Theoretical hydraulic energy lost in Orifice Mode ............. 33 GWh (5.8%)
```

Average output for each hour of the day

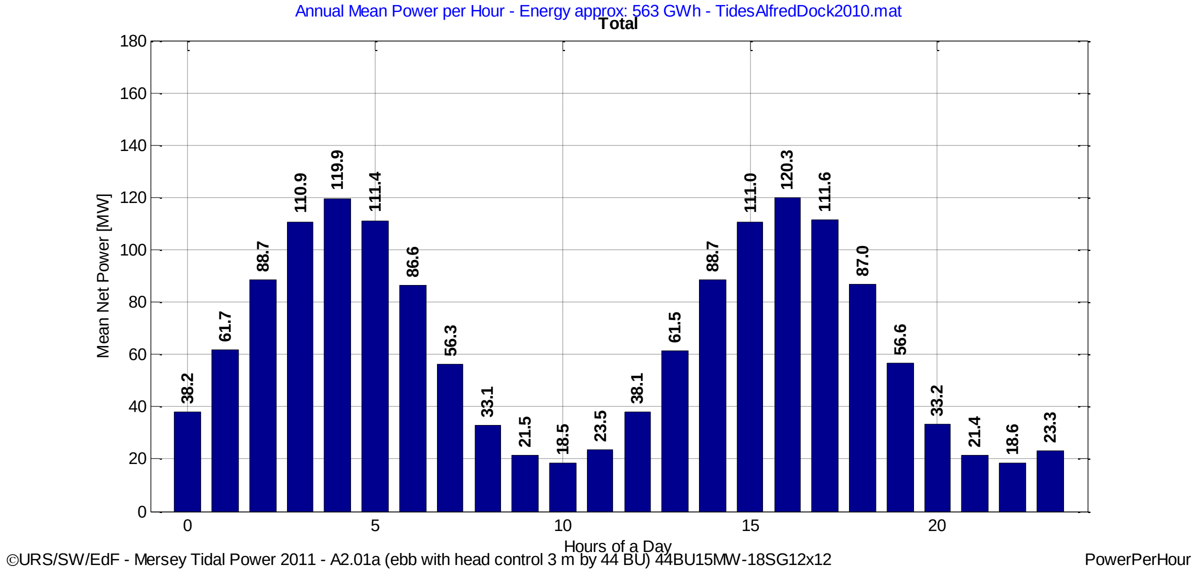


Figure G.63 - A2.01a (ebb with head control 3 m by 44 BU) - mean power per hour

6 A1.02e (ebb in OSH and pumping) - 28BU25MW-18SG12x12

6.1 Control curves

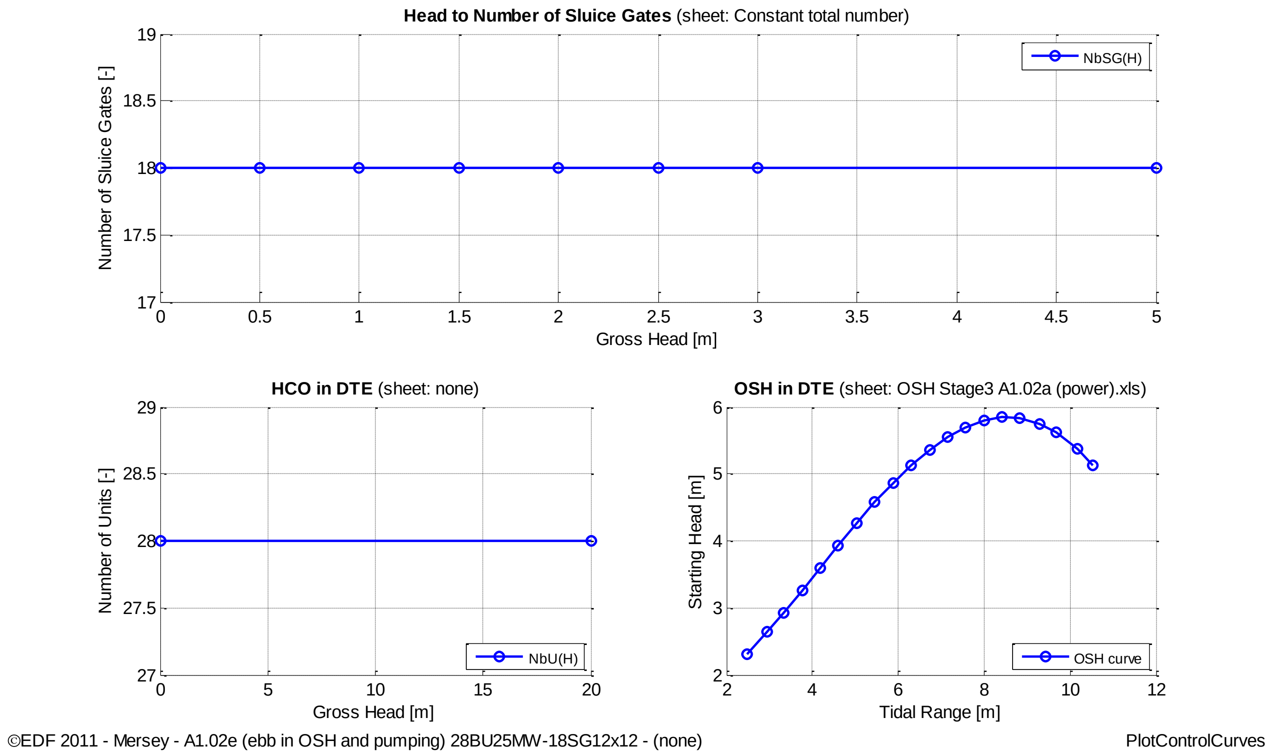


Figure G.64 - A1.02e (ebb in OSH and pumping) - Control curves

6.2 5 typical tidal range results

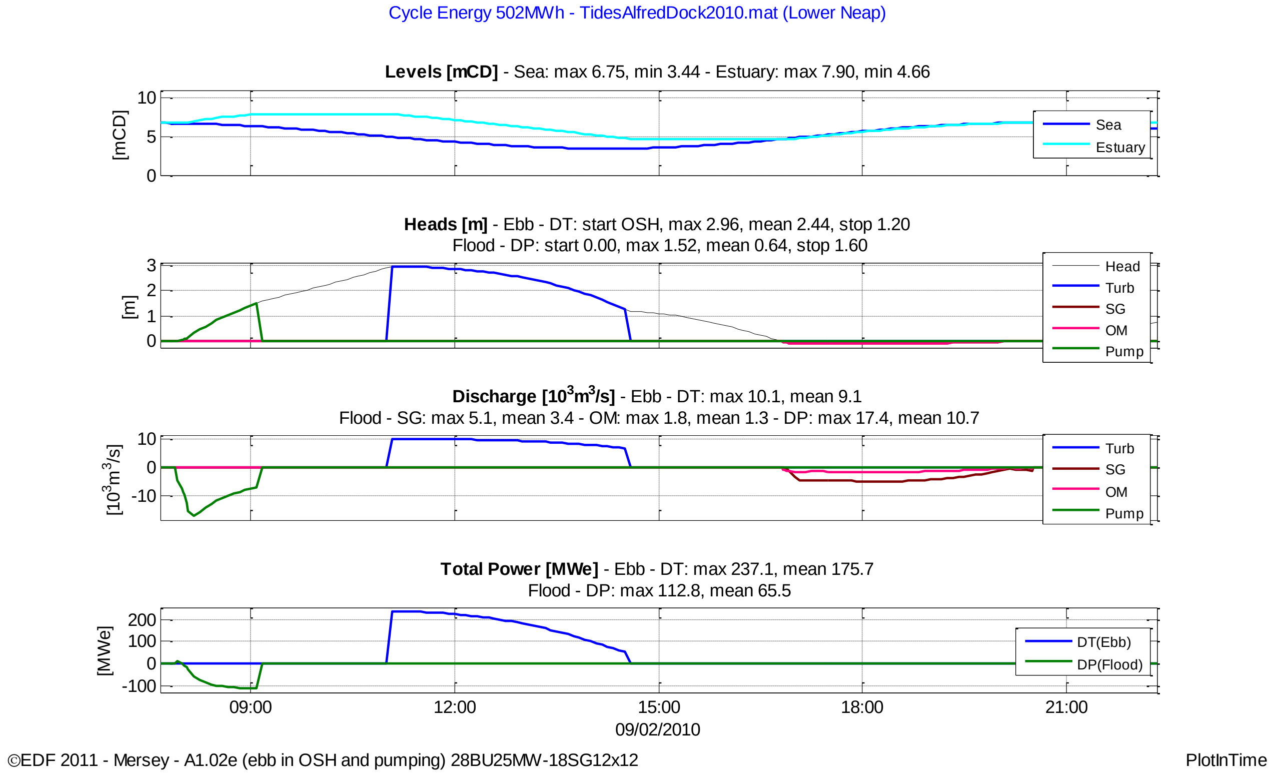


Figure G.65 - A1.02e (ebb in OSH and pumping) - Lower Neap Tide operation

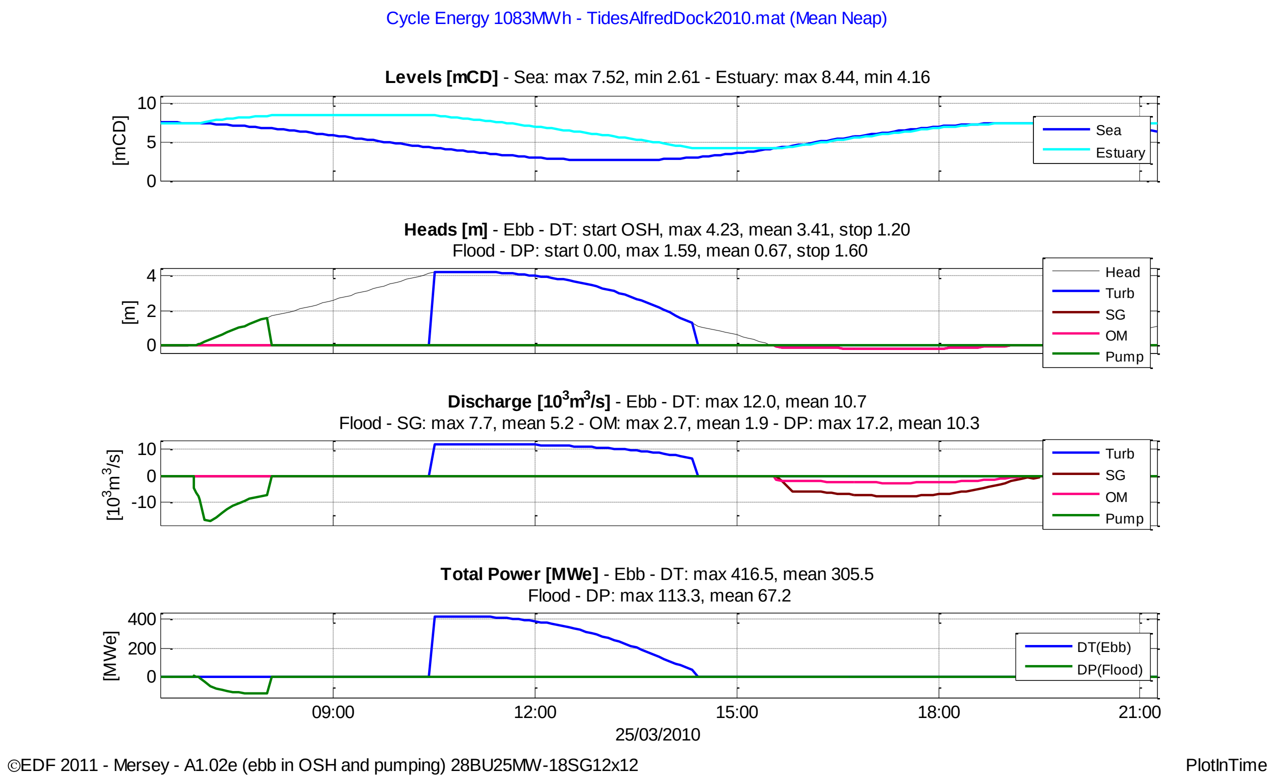


Figure G.66 - A1.02e (ebb in OSH and pumping) - Mean Neap Tide operation

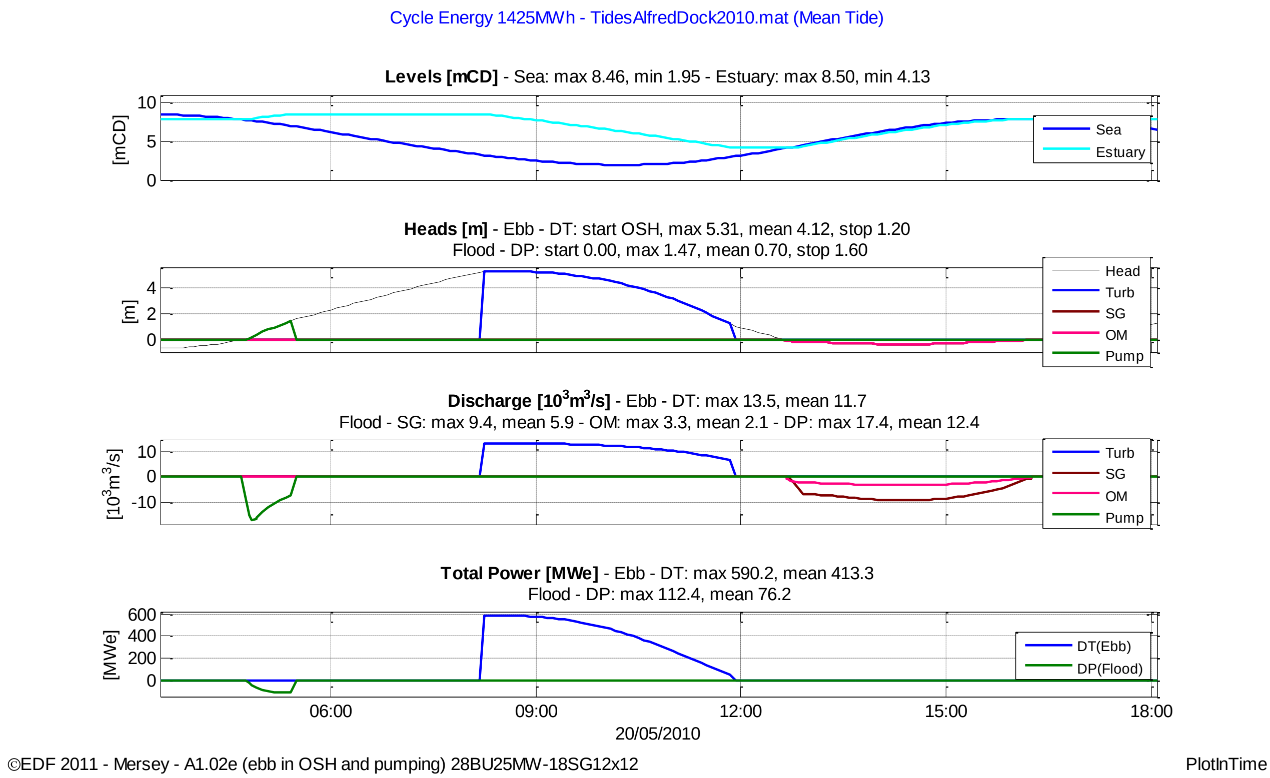


Figure G.67 - A1.02e (ebb in OSH and pumping) - Mean Tide operation

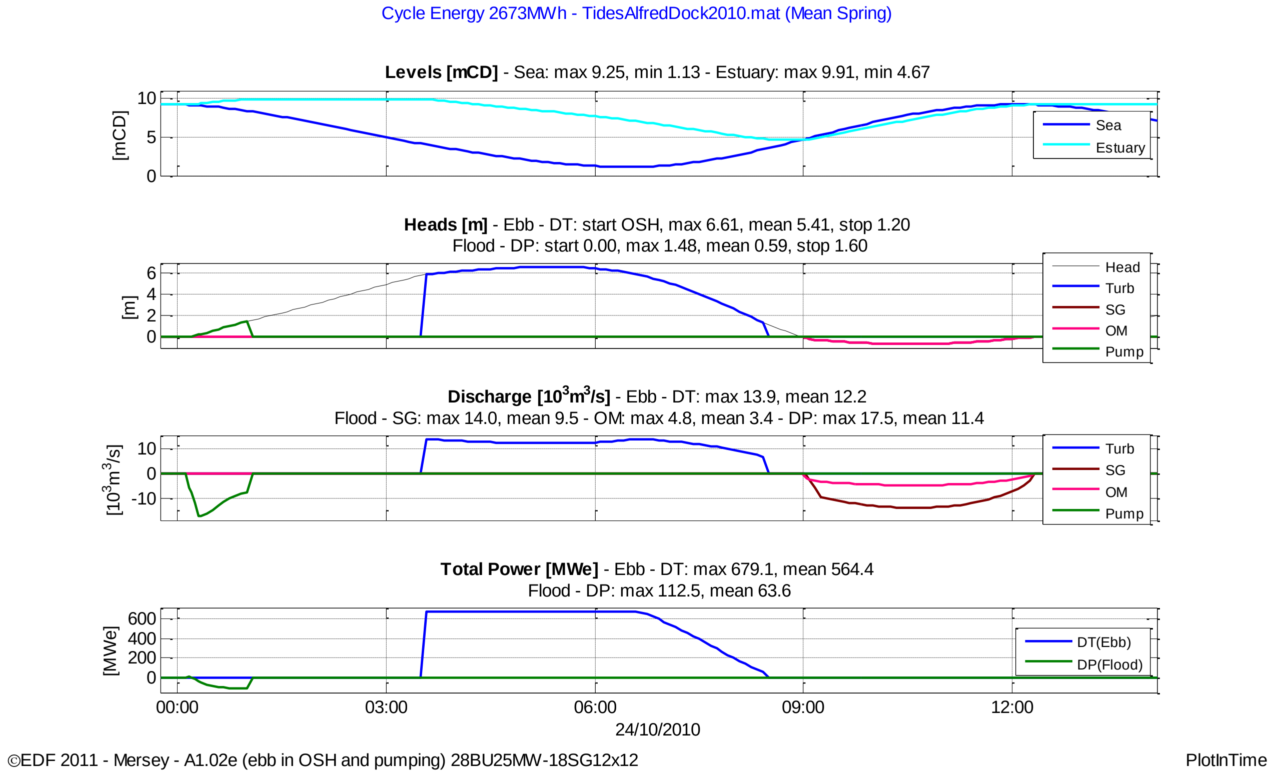


Figure G.68 - A1.02e (ebb in OSH and pumping) - Mean Spring Tide operation

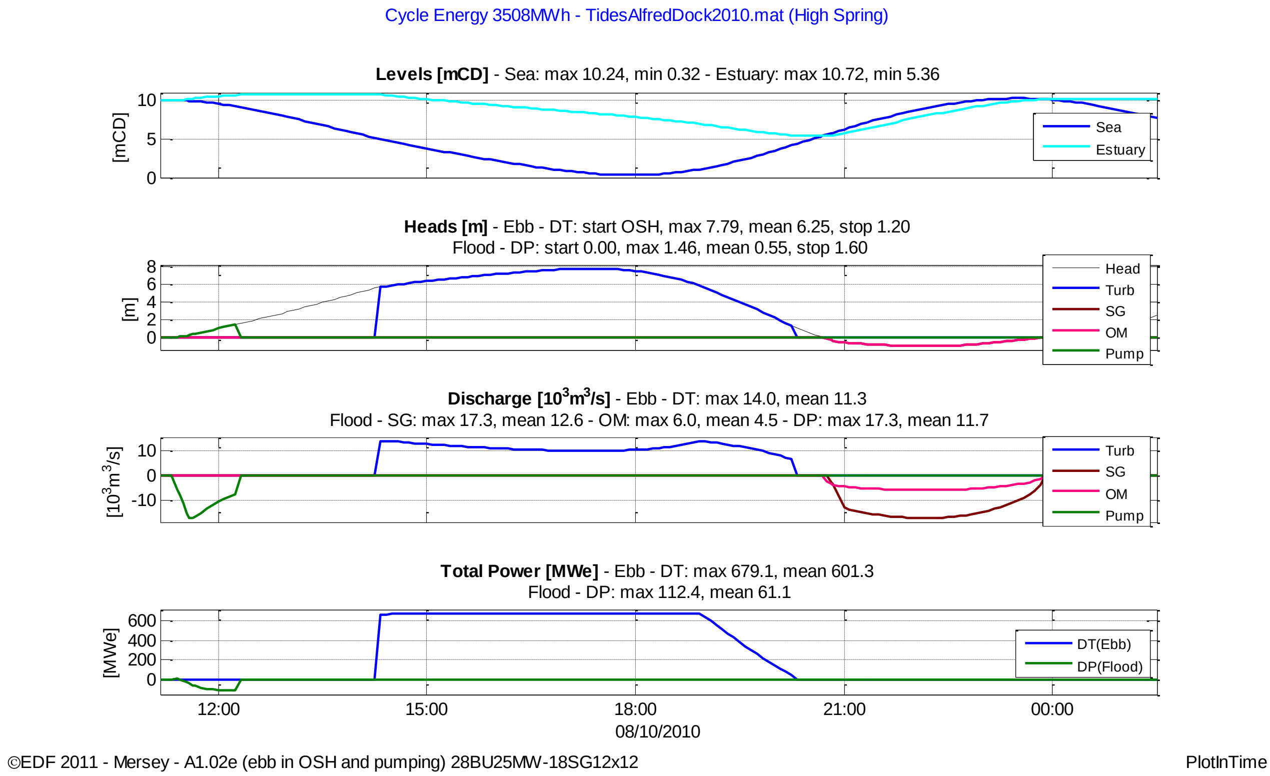


Figure G.69 - A1.02e (ebb in OSH and pumping) - High Spring Tide operation

6.3 Year 2010 simulation

Graphics

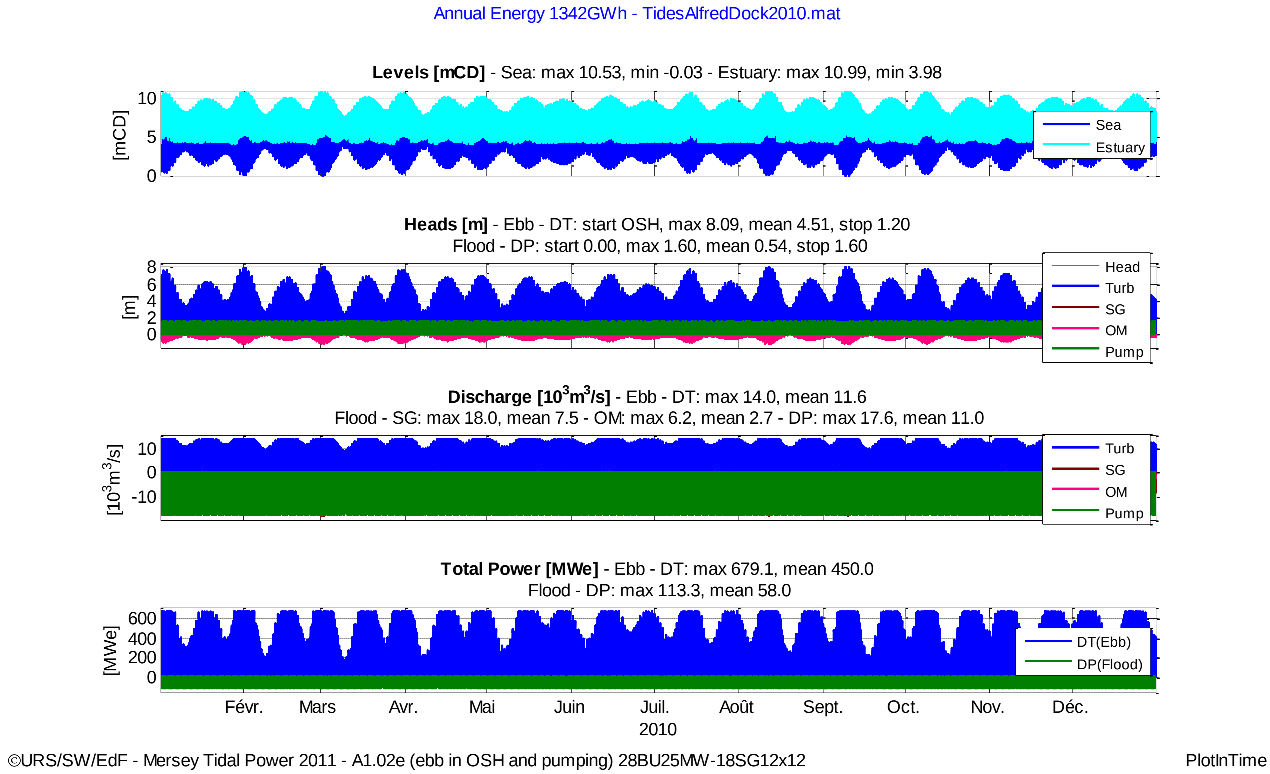


Figure G.70 - A1.02e (ebb in OSH and pumping) - year 2010 time curves

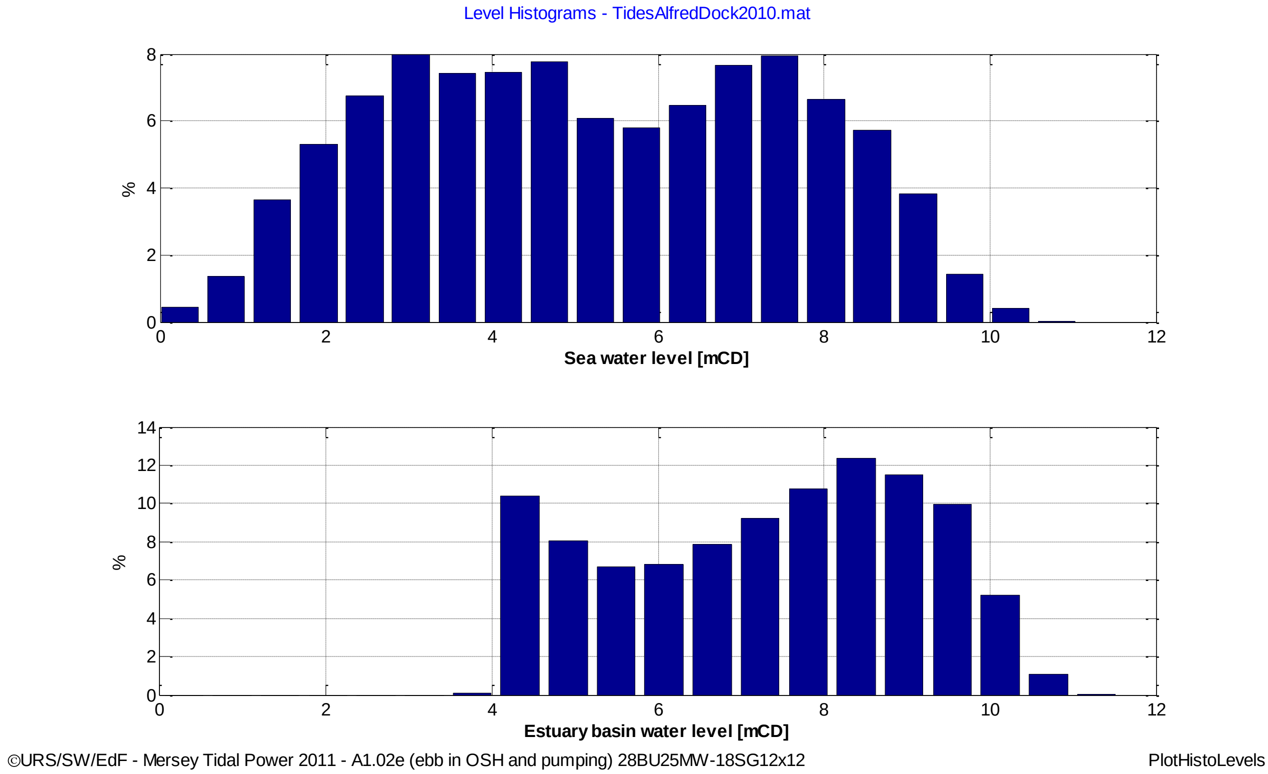


Figure G.71 - A1.02e (ebb in OSH and pumping) - water level histograms

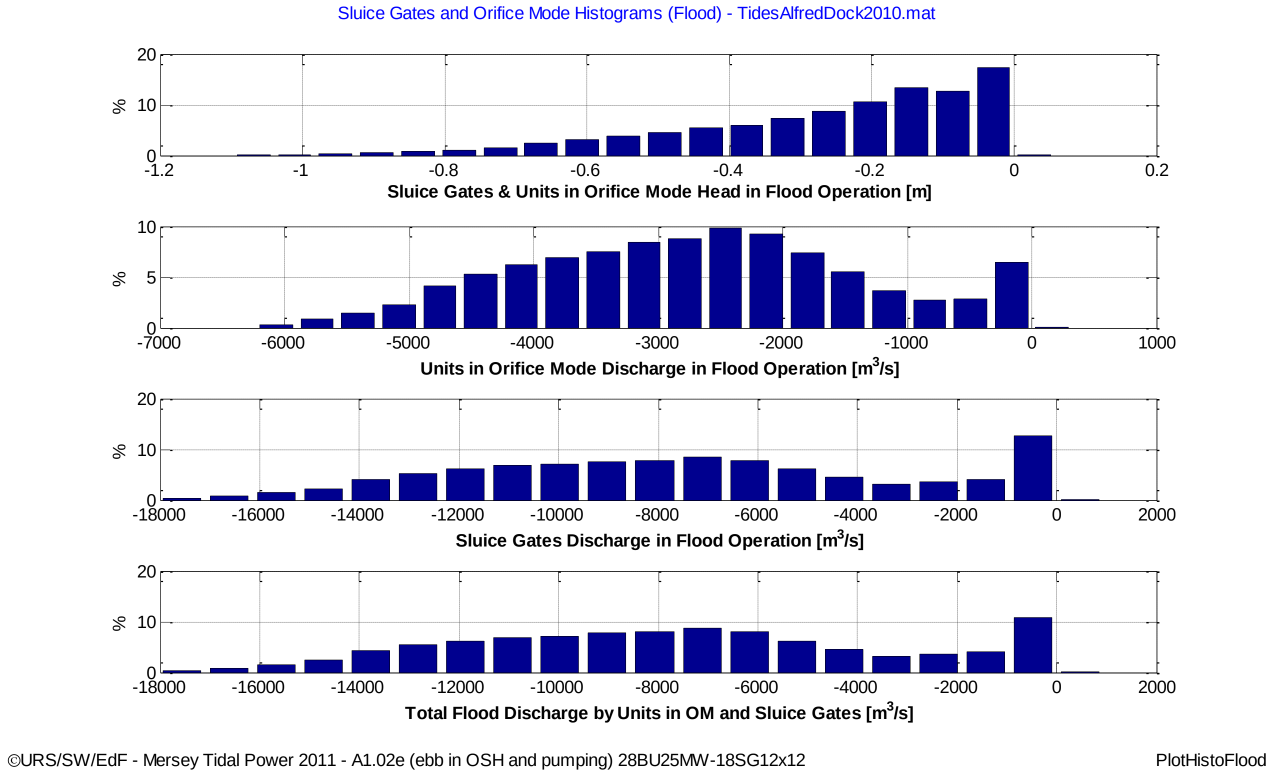


Figure G.72 - A1.02e (ebb in OSH and pumping) - sluice gates and orifice mode histograms (flood)

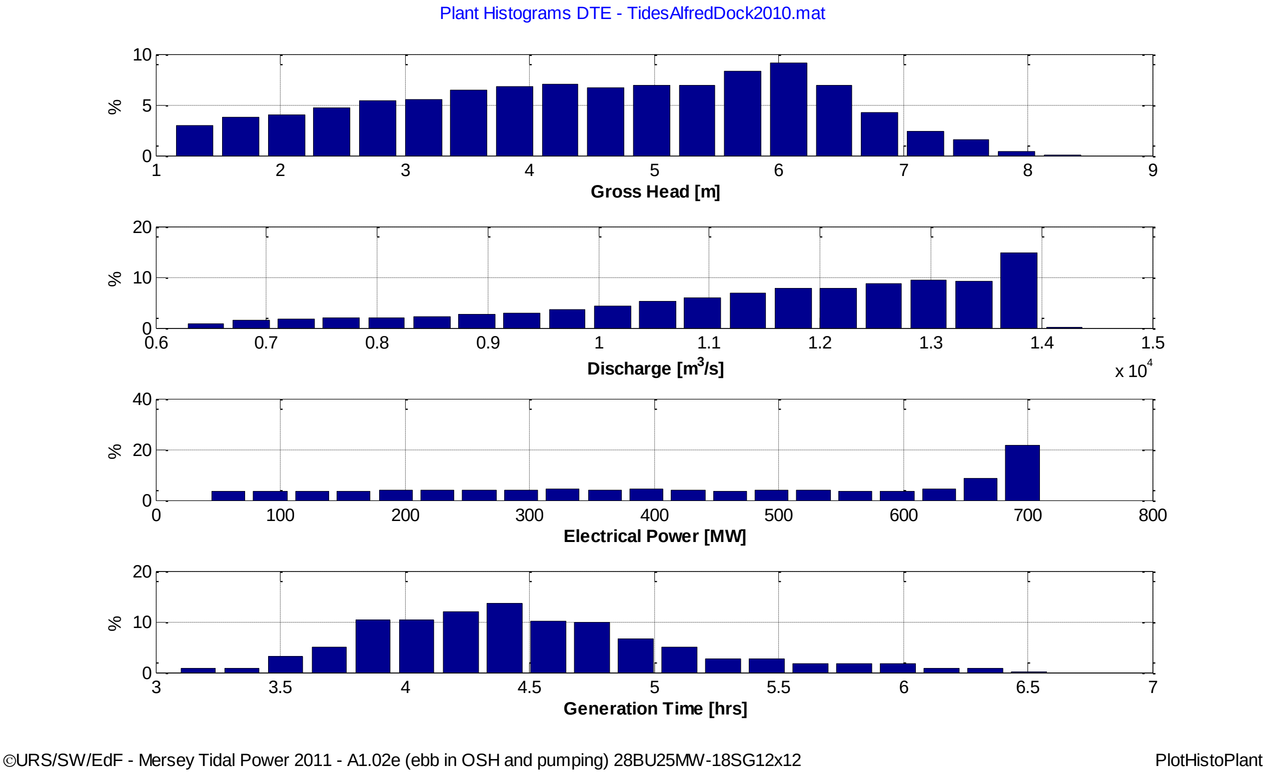


Figure G.73 - A1.02e (ebb in OSH and pumping) - plant histograms (direct turbining)

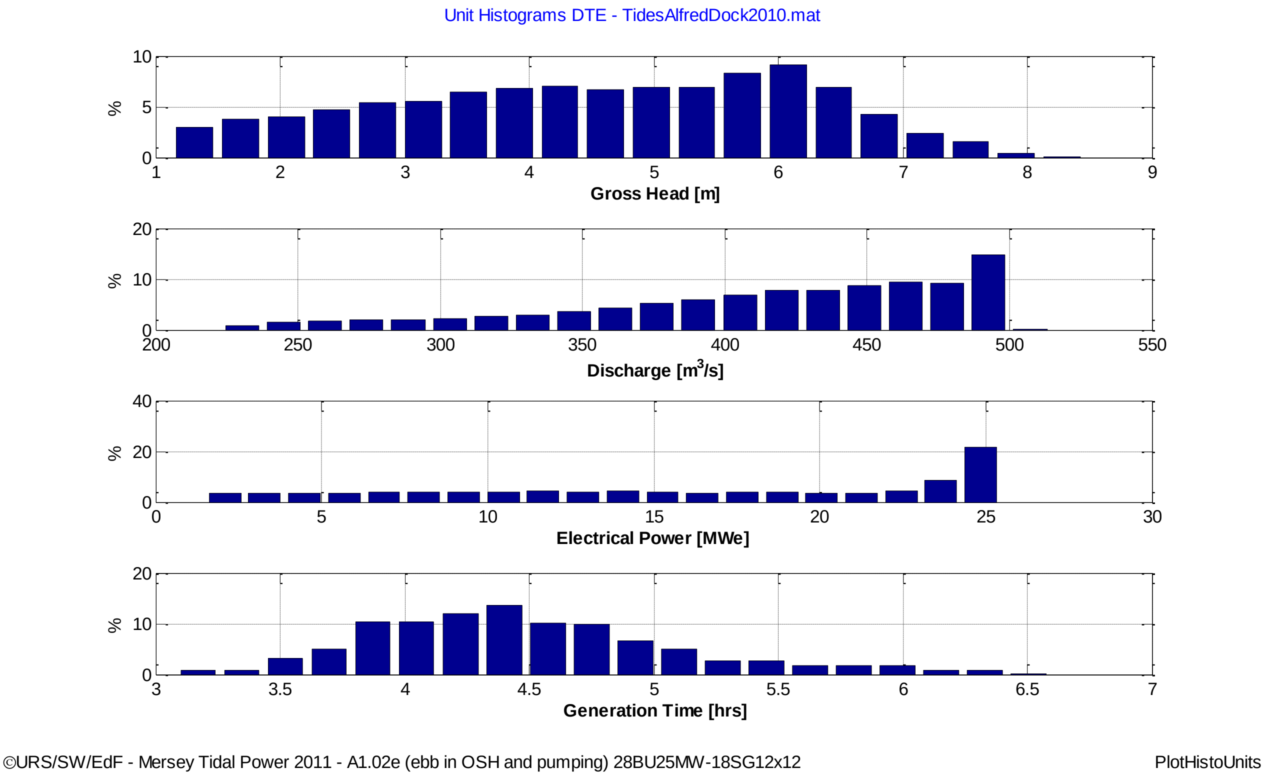


Figure G.74 - A1.02e (ebb in OSH and pumping) - unit histograms (direct turbining)

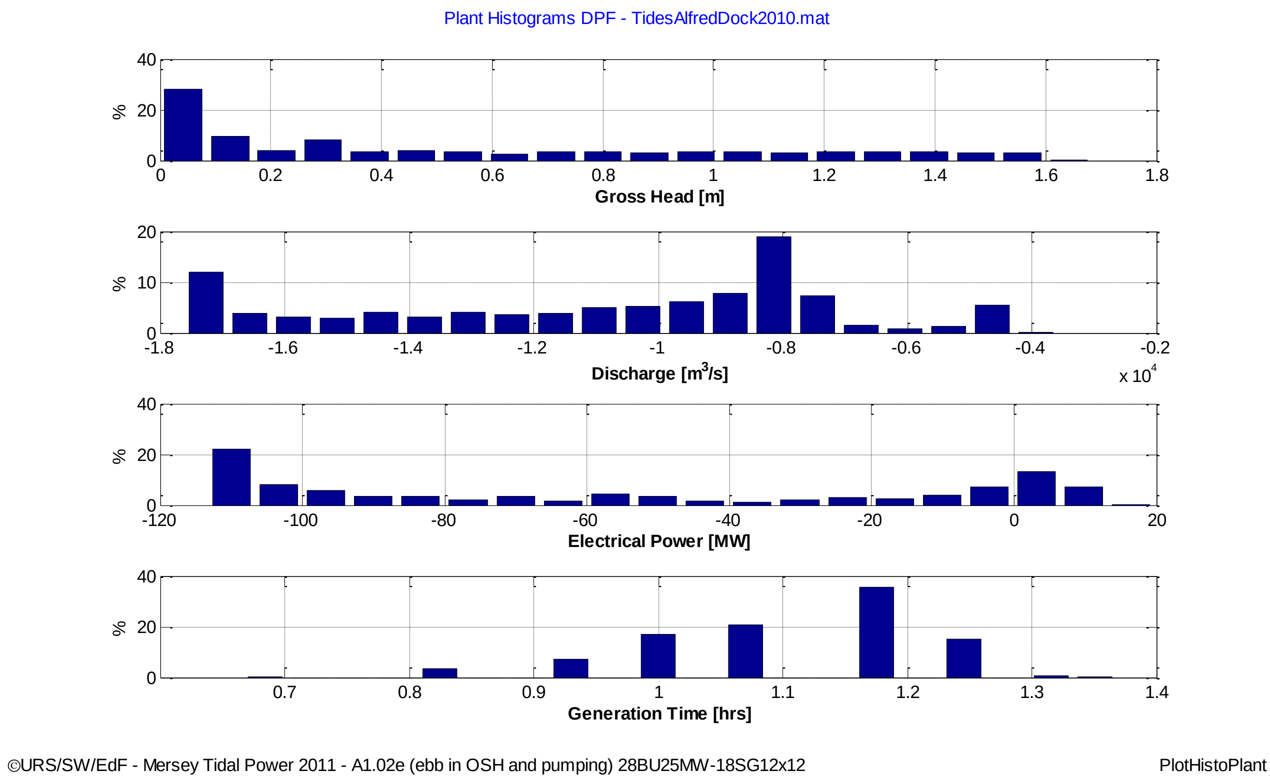


Figure G.75 - A1.02e (ebb in OSH and pumping) - plant histograms (direct pumping)

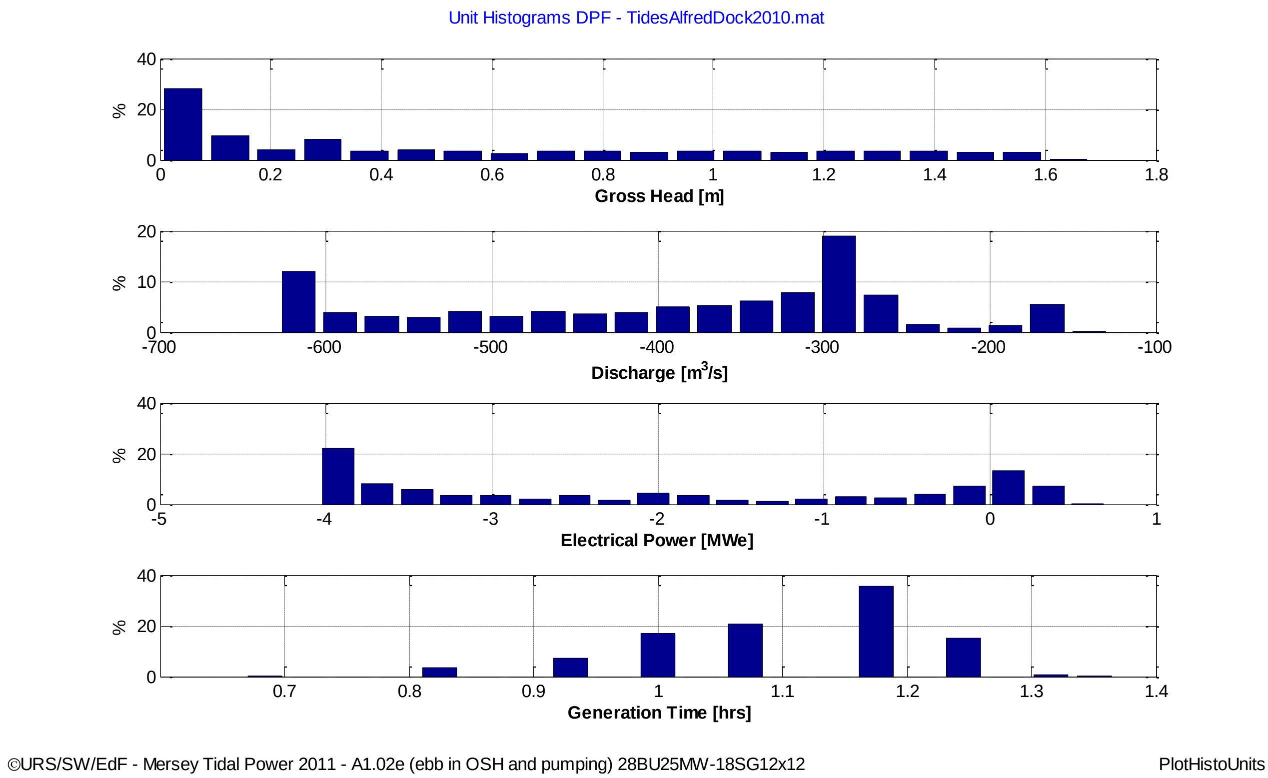


Figure G.76 - A1.02e (ebb in OSH and pumping) - unit histograms (direct pumping)

Balance Sheet Listing

```
 ---SIMULATION CASE A1.02e (ebb in OSH and pumping) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level .................. 10.99 m
Minimum Estuary Level ..................  3.98 m
Maximum Estuary Range ..................  7.01 m

 - Init Estuary Level minus Max Sea Level:
Starting value ......................... -0.07 m
Maximum ................................  1.22 m
Minimum ................................ -0.07 m

 - Ebb Generation:
Energy production in Ebb ............... 1405 GWh
Generation Time ........................ 3153.7 hrs
Mean Output ............................ 450 MW
Mean Discharge ......................... 11568 m^3/s
Max. Discharge ......................... 14000 m^3/s
Head control choice .................... in OSH operation
Starting Head .......................... optimised
Mean Head .............................. 4.51 m
Max  Head .............................. 8.09 m
Stopping Head .......................... 1.20 m

 - Pumping:
Power Consumption ...................... -63 GWh
Generation Time ........................ 777.3 hrs
Mean Discharge ......................... 10955 m^3/s
Max. Discharge ......................... 17610 m^3/s
Mean Head .............................. 0.54 m
Starting Head .......................... 0.00 m
Stopping Head .......................... 1.60 m

 - Flood Sluicing:
Operating Time ......................... 2506.2 hrs
Mean Discharge ......................... 7528 m^3/s
Max. Discharge ......................... 18043 m^3/s
Mean Head .............................. 0.26 m
Max. Head .............................. 1.10 m

 - Reverse Orifice Mode :
Operating Time ......................... 2506.2 hrs
Mean Discharge  ........................ 2719 m^3/s
Max Discharge .......................... 6231 m^3/s

 - Results :
Simulation Case ........................ A1.02e (ebb in OSH and pumping) 28BU25MW-
18SG12x12
Average Output ......................... 450 MW
Total Installed Capacity ............... 700 MW
Load Factor ............................ 21.9%
Direct Turbining Production (Ebb)....... 1405 GWh
Power Consumption in Pumping ........... -63 GWh
Reverse Turbining Production (Flood) ... 0 MWh
Net Energy ............................. 1342 GWh
DP Generation Time ..................... 777.3 hrs (8.9%)
```

```
DT Generation Time ..................... 3153.7 hrs (36.1%)
RT Generation Time ..................... 0.0 hrs (0.0%)
Sluice Gates Operating Time ........... 2506.2 hrs (28.7%)
Orifice Mode Operating Time ........... 2506.2 hrs (28.7%)
Standing Time .......................... 2309.5 hrs (26.4%)

Theoretical hydraulic energy lost through the Sluices Gates ... 81 GWh (6.1%)
Theoretical hydraulic energy lost in Orifice Mode ............. 29 GWh (2.1%)
```

Average output for each hour of the day

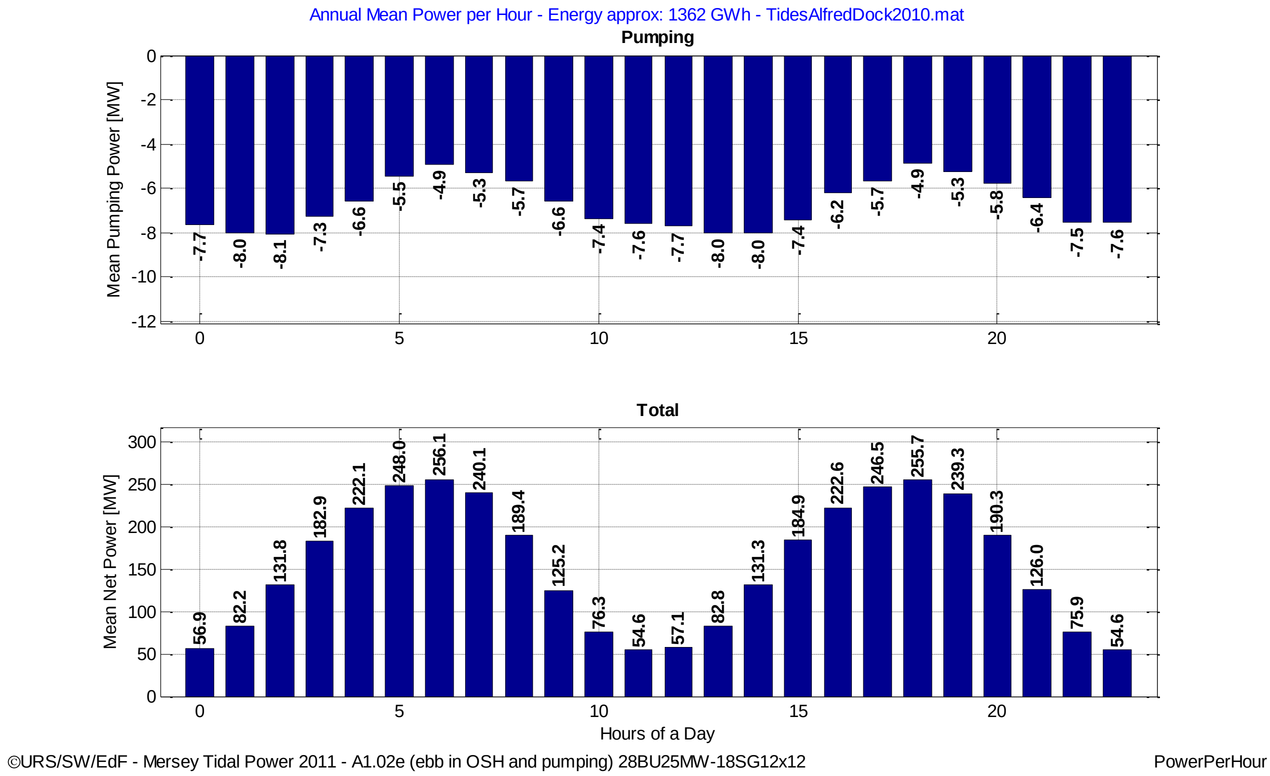


Figure G.77 - A1.02e (ebb in OSH and pumping) - mean power per hour

Annex H: Case Study – Ebb and Flood Tides Power Generation

1 A1.04a (E&F OSH) - 28RBU25MW - 18SG12x12

1.1 Control curves

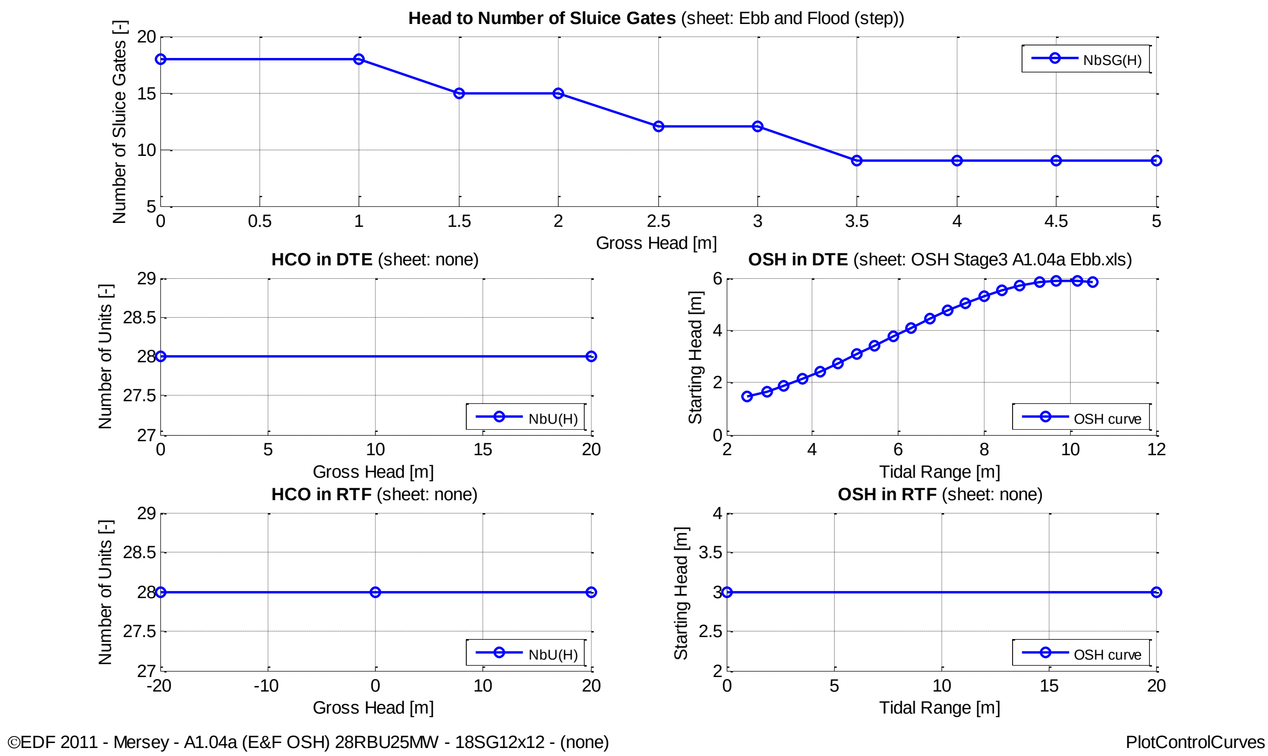


Figure H.1 - A1.04a (E&F OSH) - Control curves

1.2 5 typical tidal range results

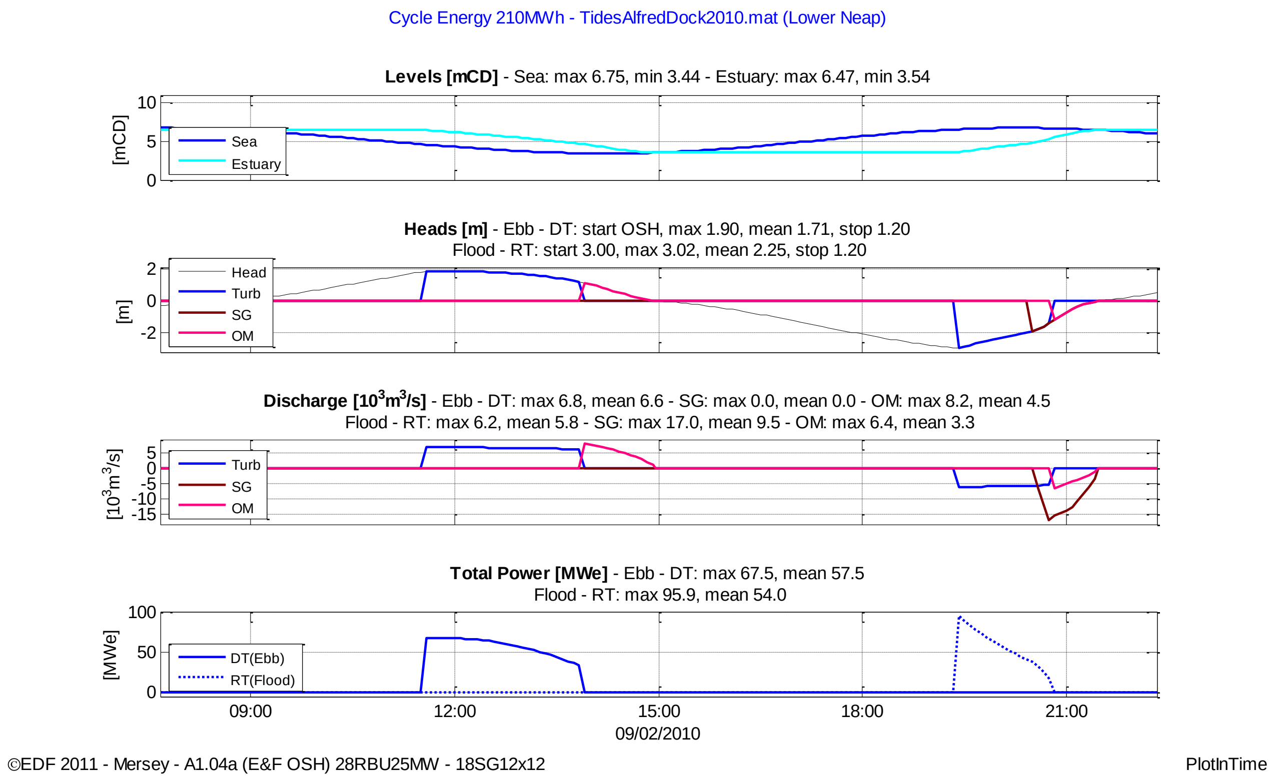
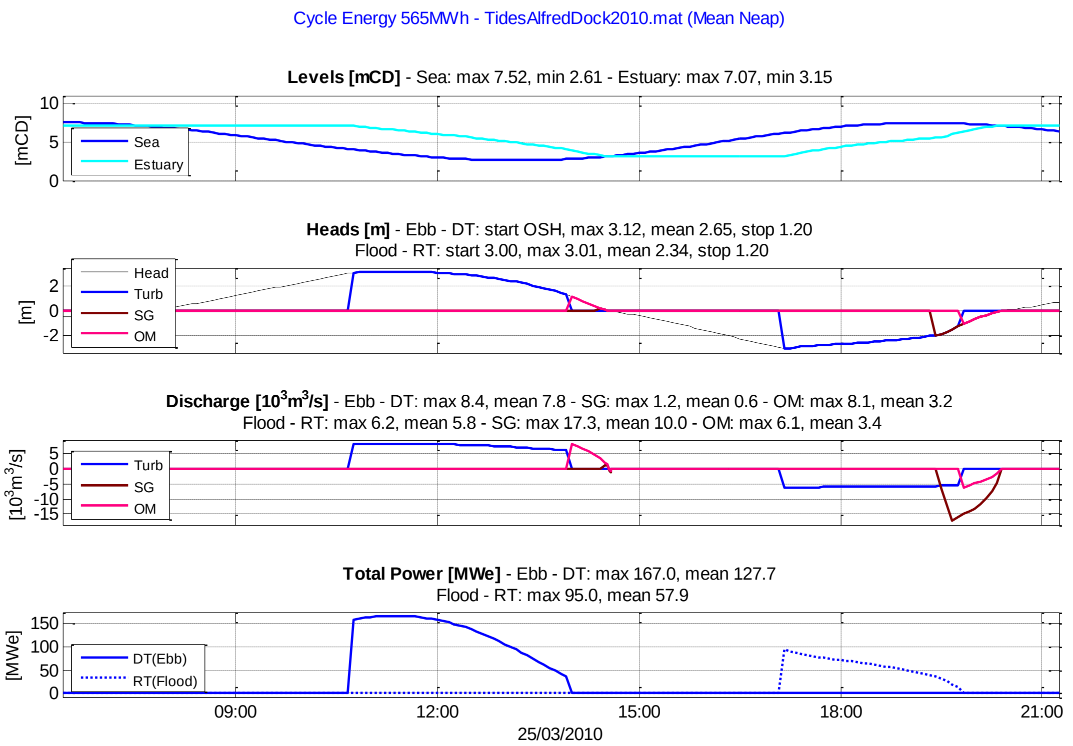
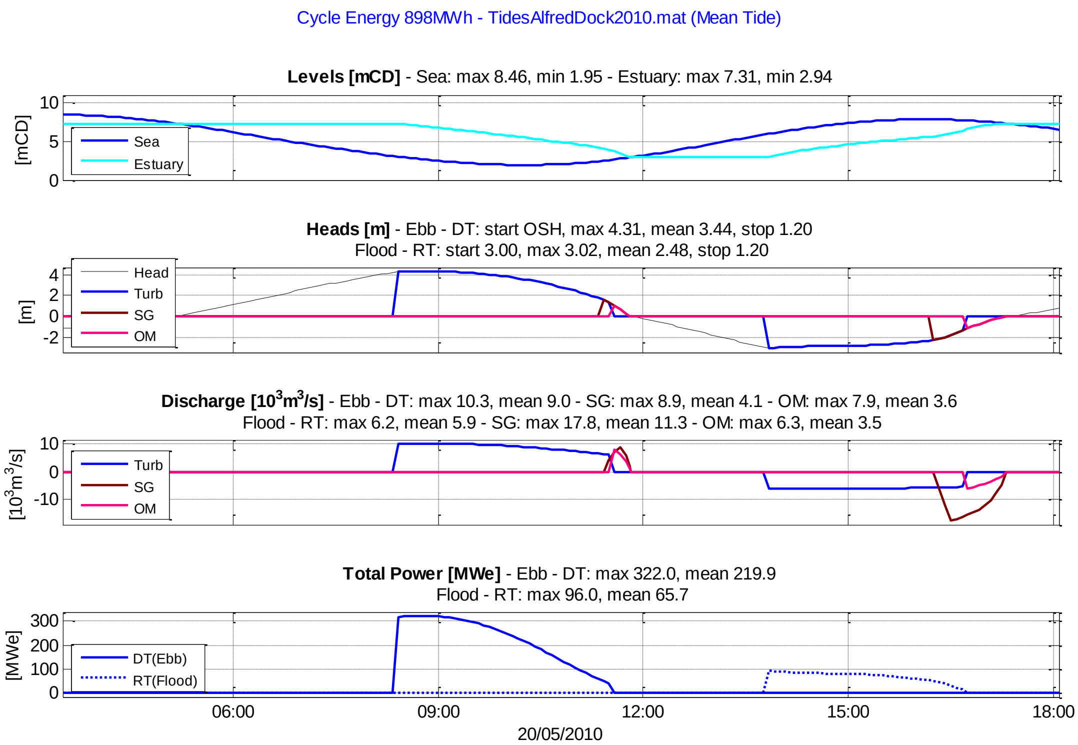


Figure H.2 - A1.04a (E&F OSH) - Lower Neap Tide operation



©EDF 2011 - Mersey - A1.04a (E&F OSH) 28RBU25MW - 18SG12x12 PlotInTime

Figure H.3 - A1.04a (E&F OSH) - Mean Neap Tide operation



©EDF 2011 - Mersey - A1.04a (E&F OSH) 28RBU25MW - 18SG12x12 PlotInTime

Figure H.4 - A1.04a (E&F OSH) - Mean Tide operation

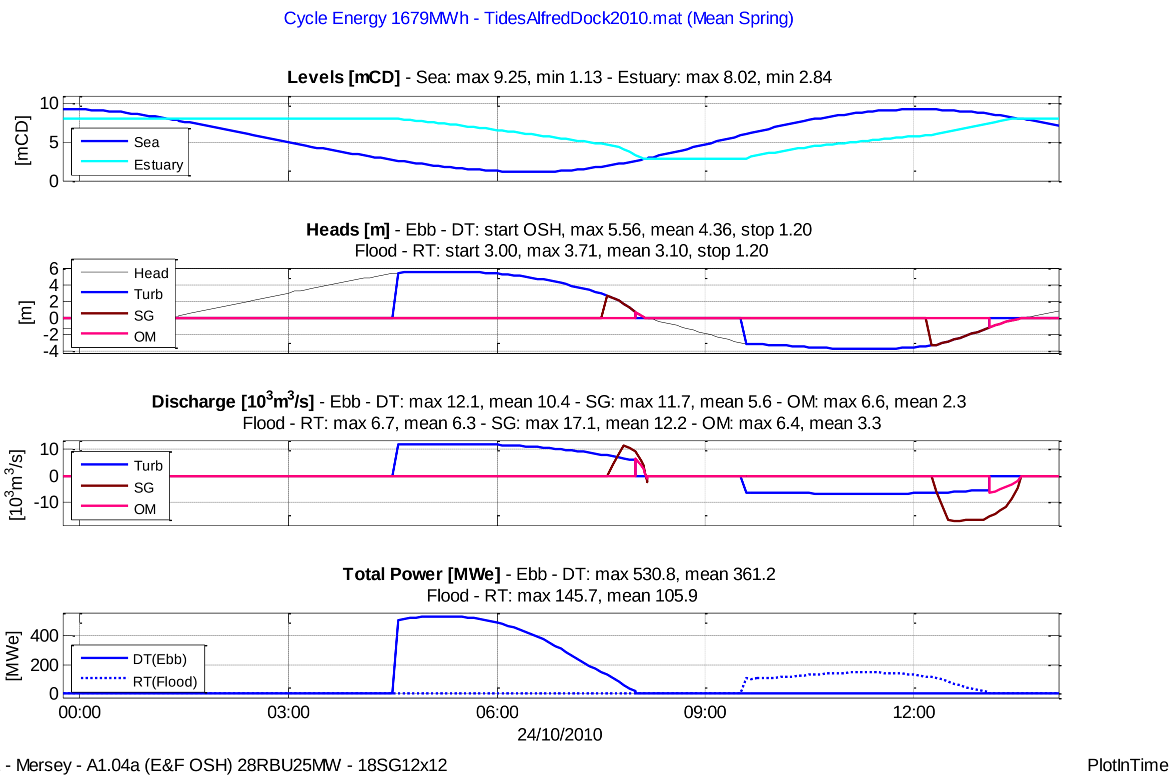


Figure H.5 - A1.04a (E&F OSH) - Mean Spring Tide operation

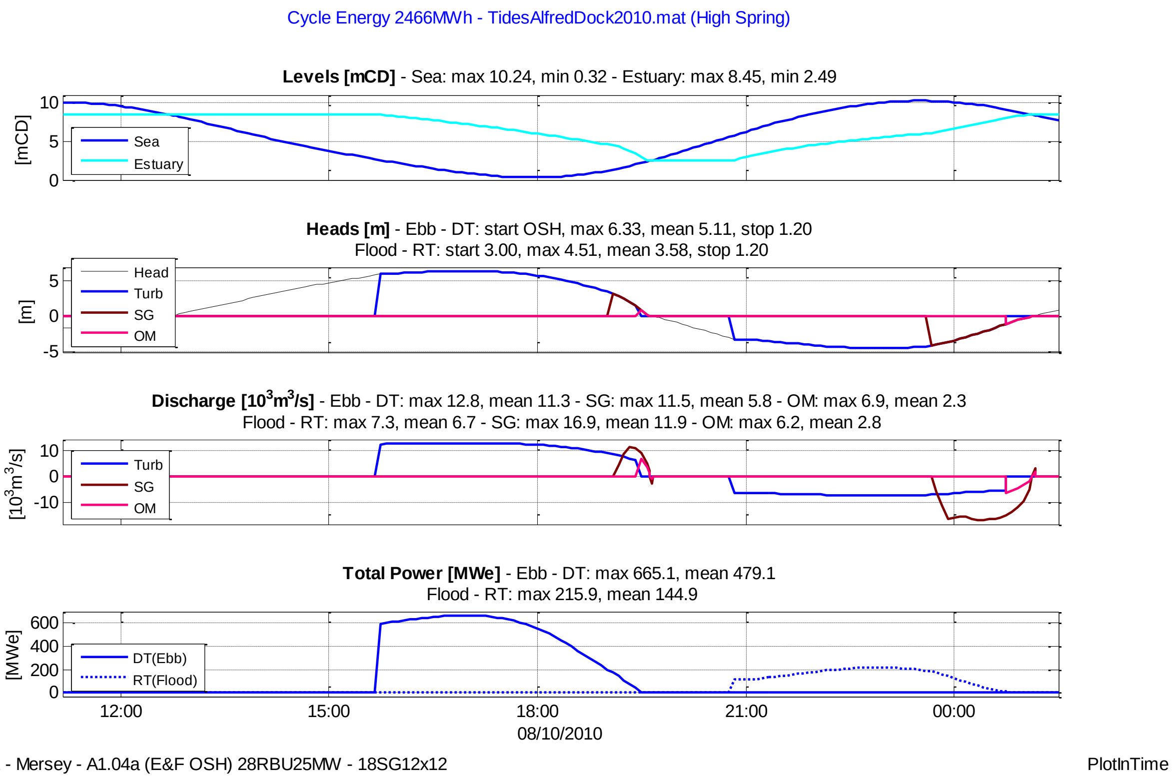


Figure H.6 - A1.04a (E&F OSH) - High Spring Tide operation

1.3 Year 2010 simulation

Graphics

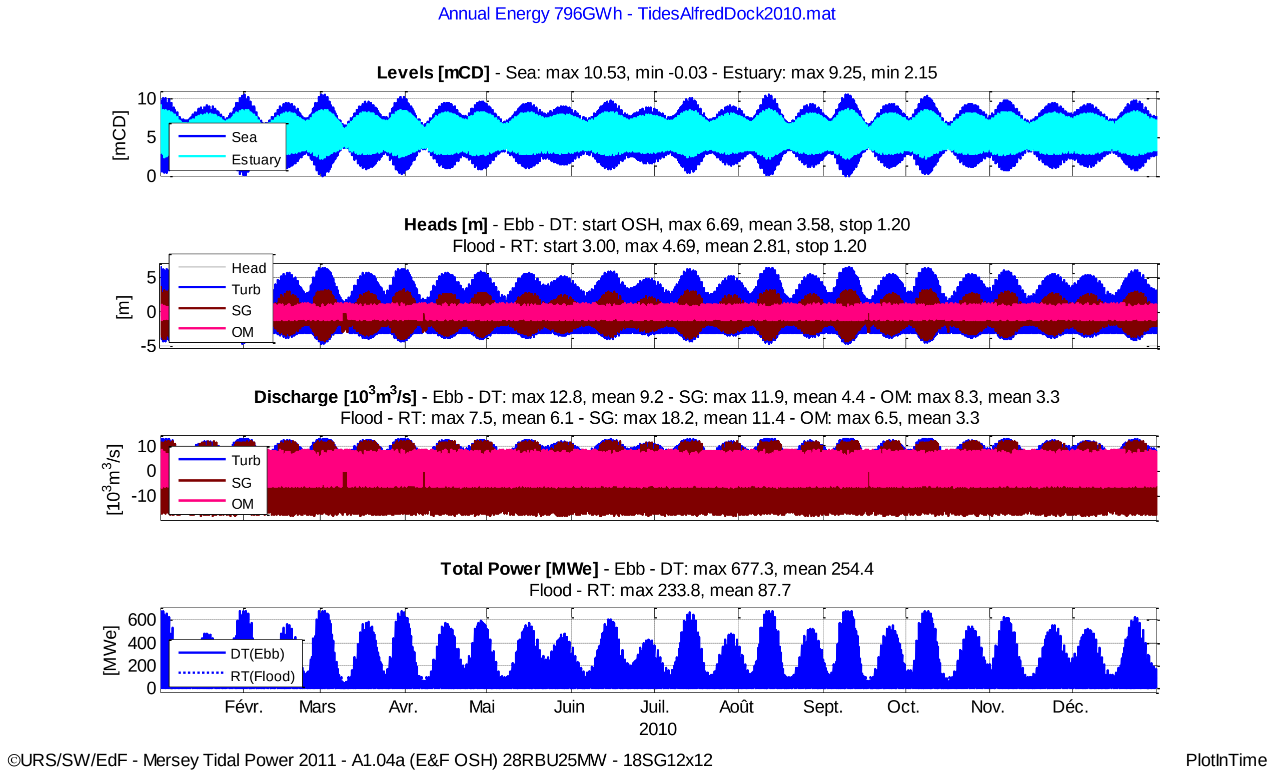


Figure H.7 - A1.04a (E&F OSH) - year 2010 time curves

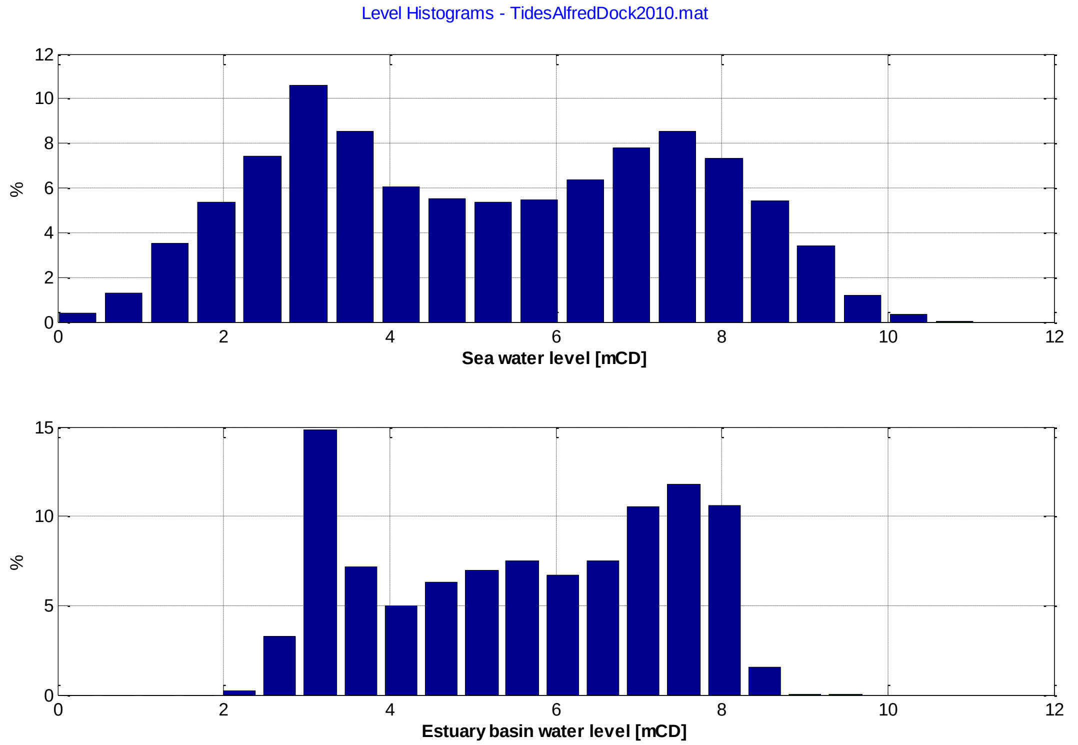


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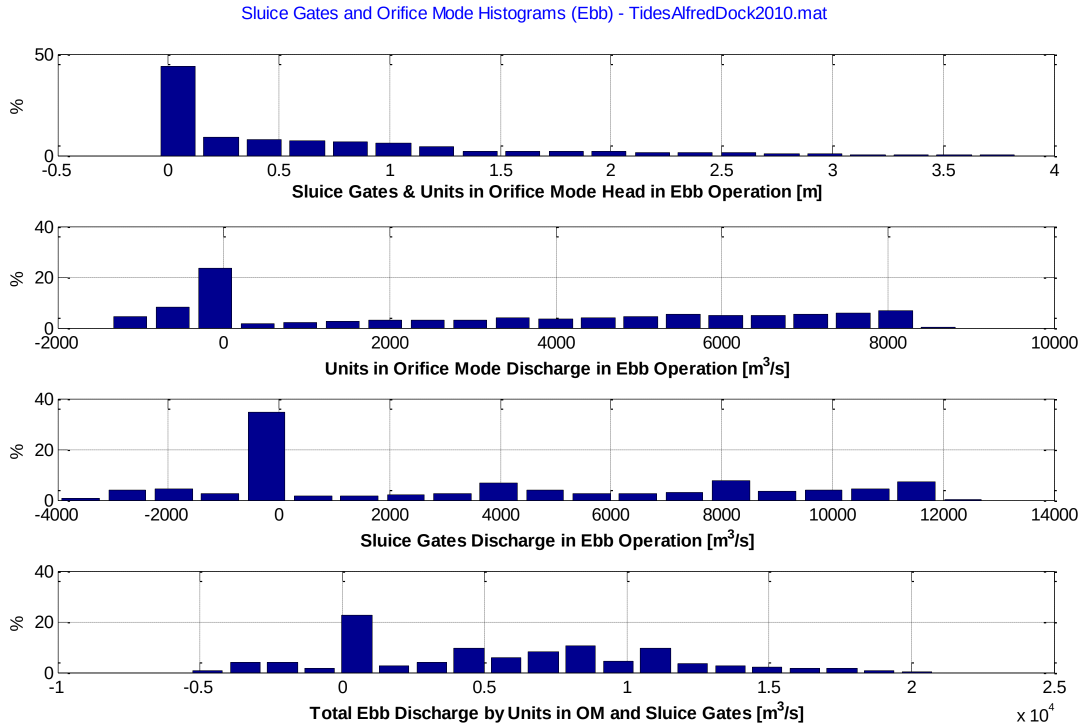
Figure H.8 - A1.04a (E&F OSH) - water level histograms



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.04a (E&F OSH) 28RBU25MW - 18SG12x12 PlotHistoEbb

Figure H.9 - A1.04a (E&F OSH) - sluice gates and orifice mode histograms (ebb)

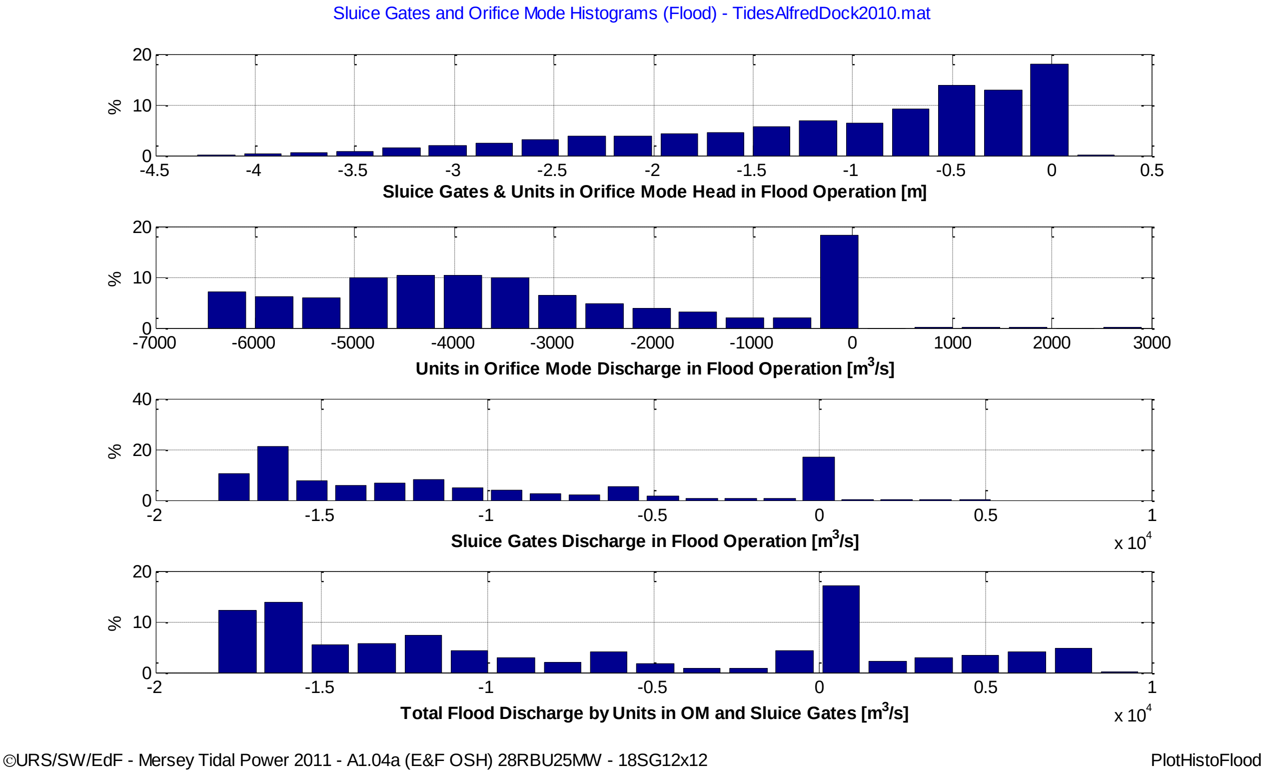


Figure H.10 - A1.04a (E&F OSH) - sluice gates and orifice mode histograms (flood)

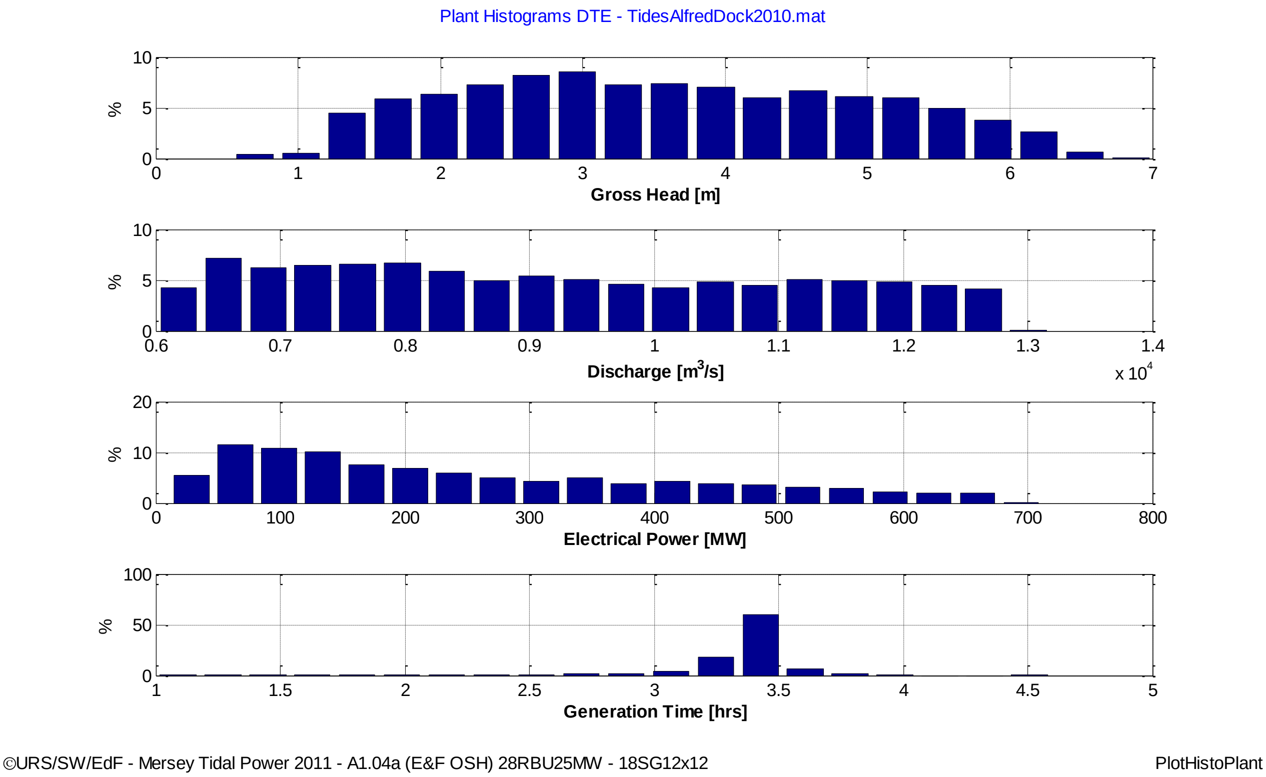


Figure H.11 - A1.04a (E&F OSH) - plant histograms (direct turbining)

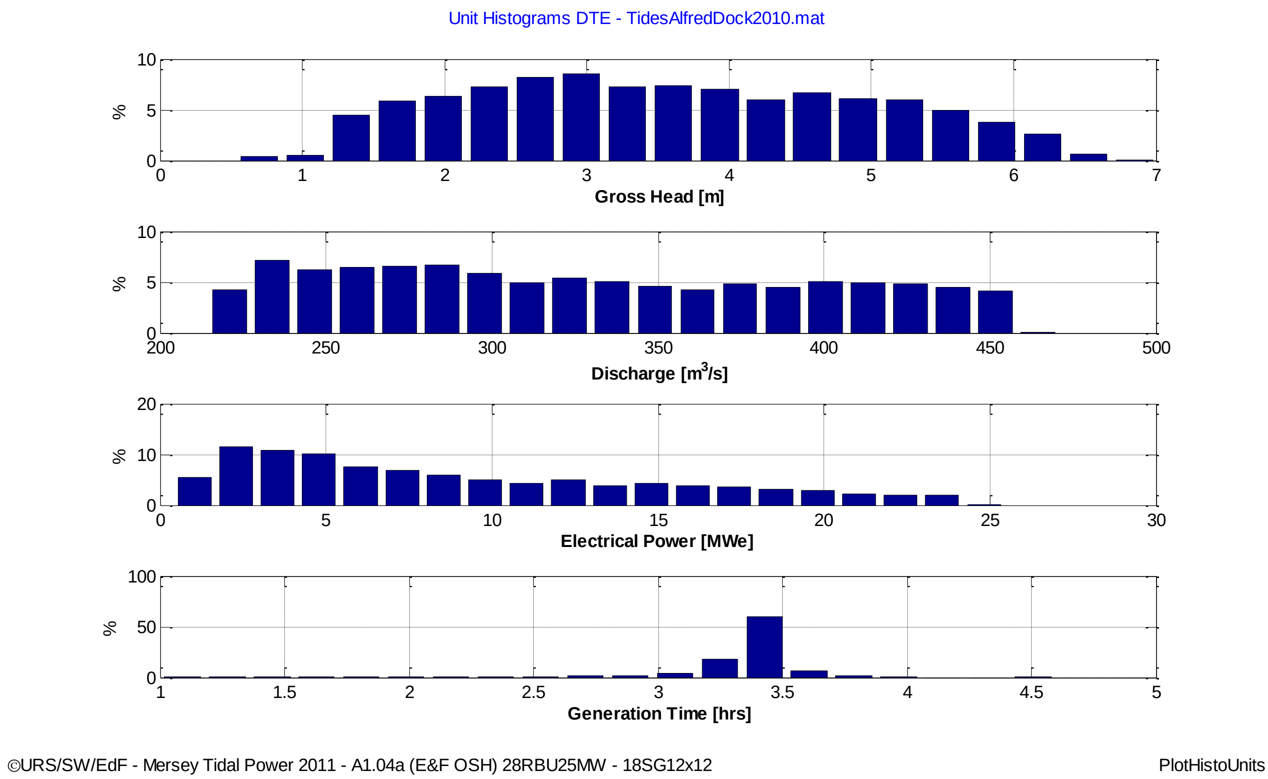


Figure H.12 - A1.04a (E&F OSH) - unit histograms (direct turbining)

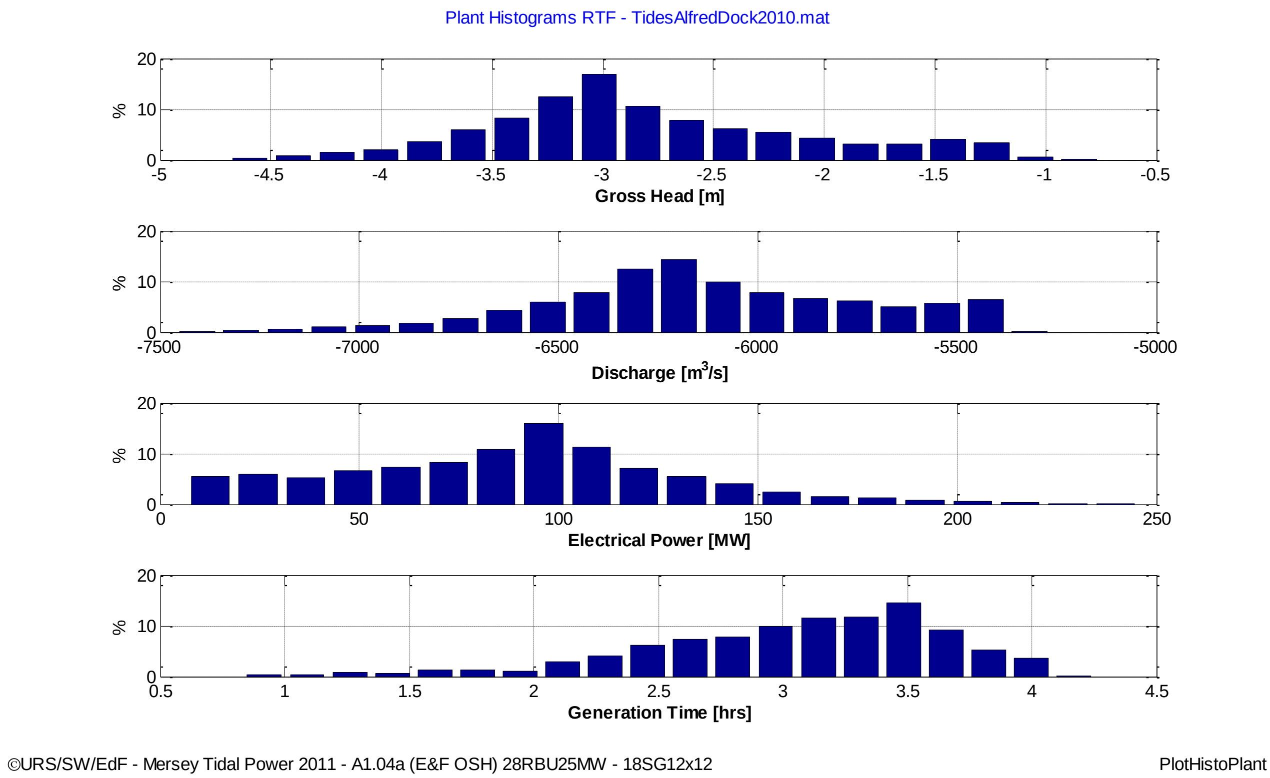


Figure H.13 - A1.04a (E&F OSH) - plant histograms (reverse turbining)

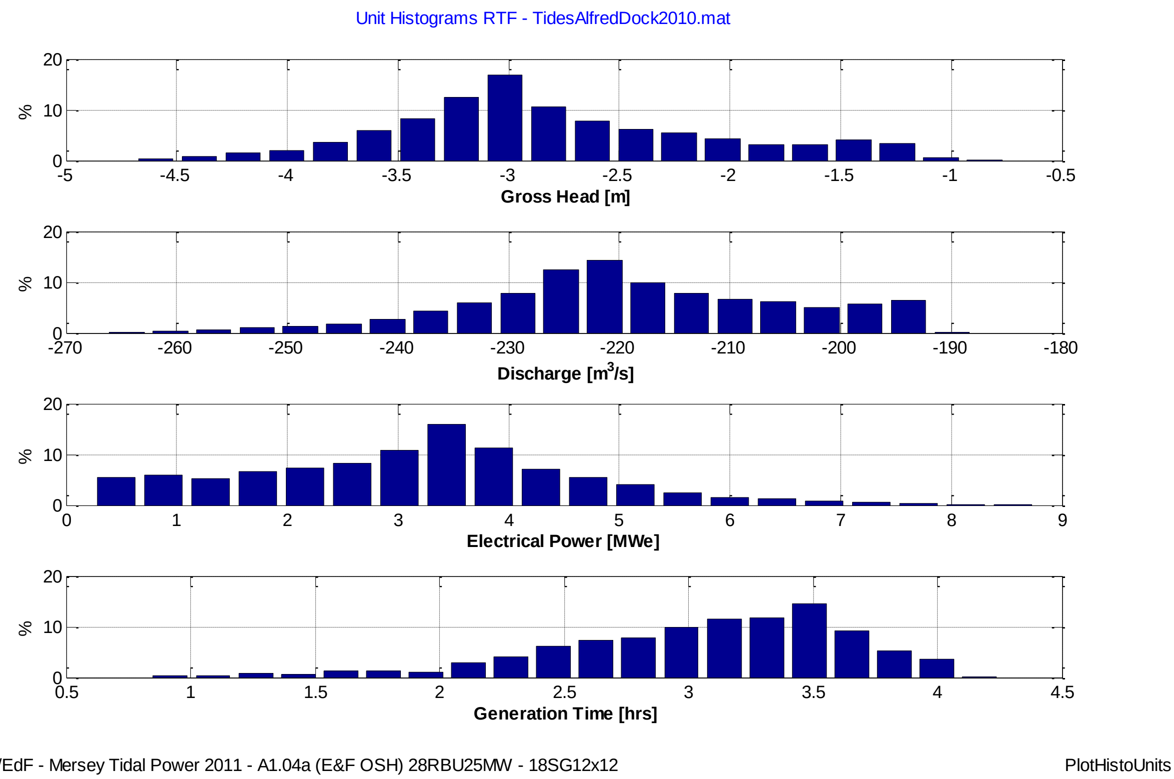


Figure H.14 - A1.04a (E&F OSH) - unit histograms (reverse turbining)

Balance Sheet Listing

```
 ---SIMULATION CASE A1.04a (E&F OSH) RESULTS ---

 - Tides:
Maximum Sea Level ..................... 10.53 m
Minimum Sea Level ..................... -0.03 m
        Sea Range ..................... 10.56 m

 - Estuary:
Maximum Estuary Level .................  9.25 m
Minimum Estuary Level .................  2.15 m
Maximum Estuary Range .................  7.10 m

 - Init Estuary Level minus Max Sea Level:
Starting value ........................ -0.60 m
Maximum ............................... -0.25 m
Minimum ............................... -1.98 m

 - Ebb Generation:
Energy production in Ebb .............. 603 GWh
Generation Time ....................... 2342.7 hrs
Mean Output ........................... 254 MW
Mean Discharge ........................ 9190 m^3/s
Max. Discharge ........................ 12825 m^3/s
Head control choice ................... in OSH operation
Starting Head ......................... optimised
Mean Head ............................. 3.58 m
Max  Head ............................. 6.69 m
Stopping Head ......................... 1.20 m

 - Flood Generation:
Energy production in Flood ............ 193 GWh
Generation Time ....................... 2106.3 hrs
Mean Discharge ........................ 6132 m^3/s
```

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Max. Discharge ........................ 7461 m^3/s
Starting Head ......................... 3.00 m
Mean Head ............................. 2.81 m
Max  Head ............................. 4.69 m
Stopping Head ......................... 1.20 m

 - Ebb Sluicing:
Generation Time ....................... 284.5 hrs
Mean Discharge ........................ 4399 m^3/s
Max. Discharge ........................ 11938 m^3/s
Mean Head ............................. 0.81 m
Max  Head ............................. 3.65 m

 - Flood Sluicing:
Operating Time ........................ 853.0 hrs
Mean Discharge ........................ 11406 m^3/s
Max. Discharge ........................ 18234 m^3/s
Mean Head ............................. 1.31 m
Max. Head ............................. 4.31 m

 - Orifice Mode :
Operating Time ........................ 284.3 hrs
Mean Discharge ........................ 3323 m^3/s
Max. Discharge ........................ 8346 m^3/s

 - Reverse Orifice Mode :
Operating Time ........................ 384.0 hrs
Mean Discharge  ....................... 3270 m^3/s
Max Discharge ......................... 6514 m^3/s

 - Results :
Simulation Case ....................... A1.04a (E&F OSH) 28RBU25MW - 18SG12x12
Average Output ........................ 254 MW
Total Installed Capacity .............. 700 MW
Load Factor ........................... 13.0%
Direct Turbining Production (Ebb)....... 603 GWh
Reverse Turbining Production (Flood) ... 193 GWh
Net Energy ............................ 796 GWh
DT Generation Time .................... 2342.7 hrs (26.8%)
RT Generation Time .................... 2106.3 hrs (24.1%)
Sluice Gates Operating Time ........... 1137.5 hrs (13.0%)
Orifice Mode Operating Time ........... 668.3 hrs (7.6%)
Standing Time ......................... 3629.3 hrs (41.5%)

Theoretical hydraulic energy lost through the Sluices Gates ... 217 GWh (27.3%)
Theoretical hydraulic energy lost in Orifice Mode ............ 13 GWh (1.7%)
```

Average output for each hour of the day

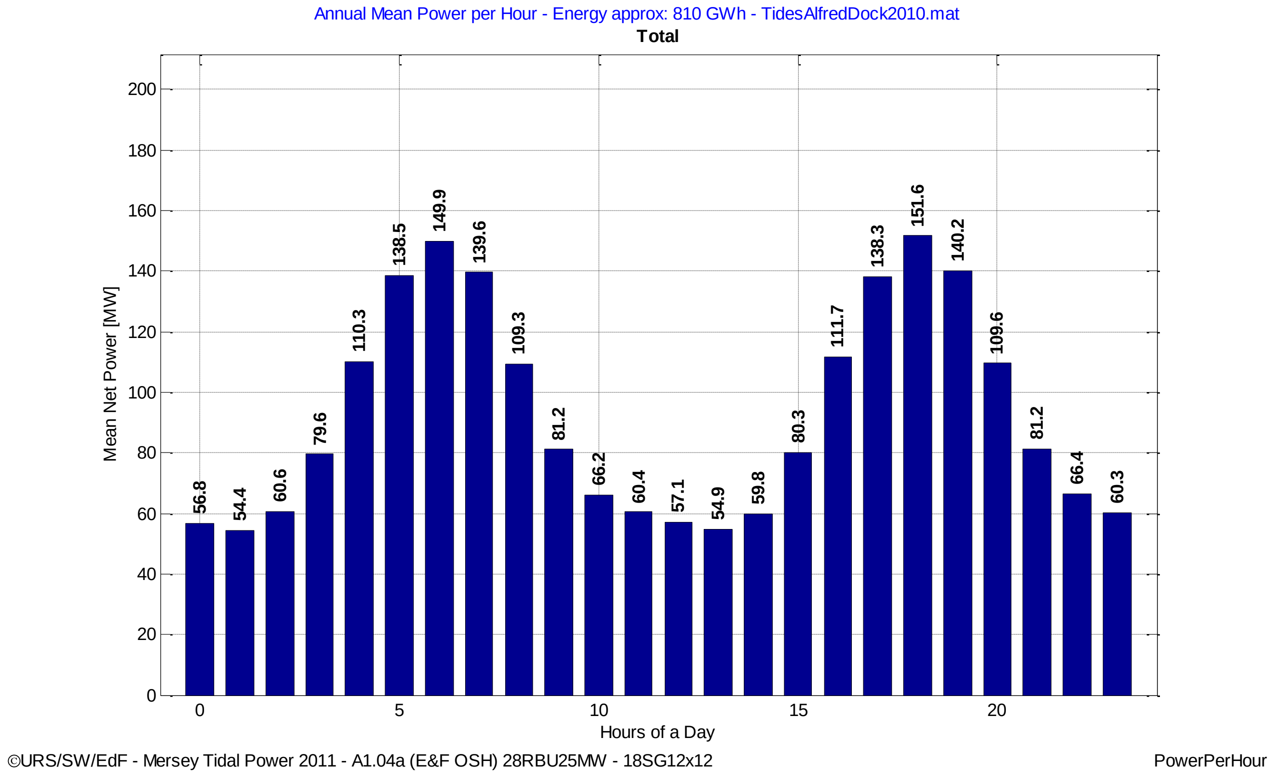


Figure H.15 - A1.04a (E&F OSH) - mean power per hour

2 A2.02a (E&F HCO) - 44RBU15MW - 18SG12x12

2.1 Control curves

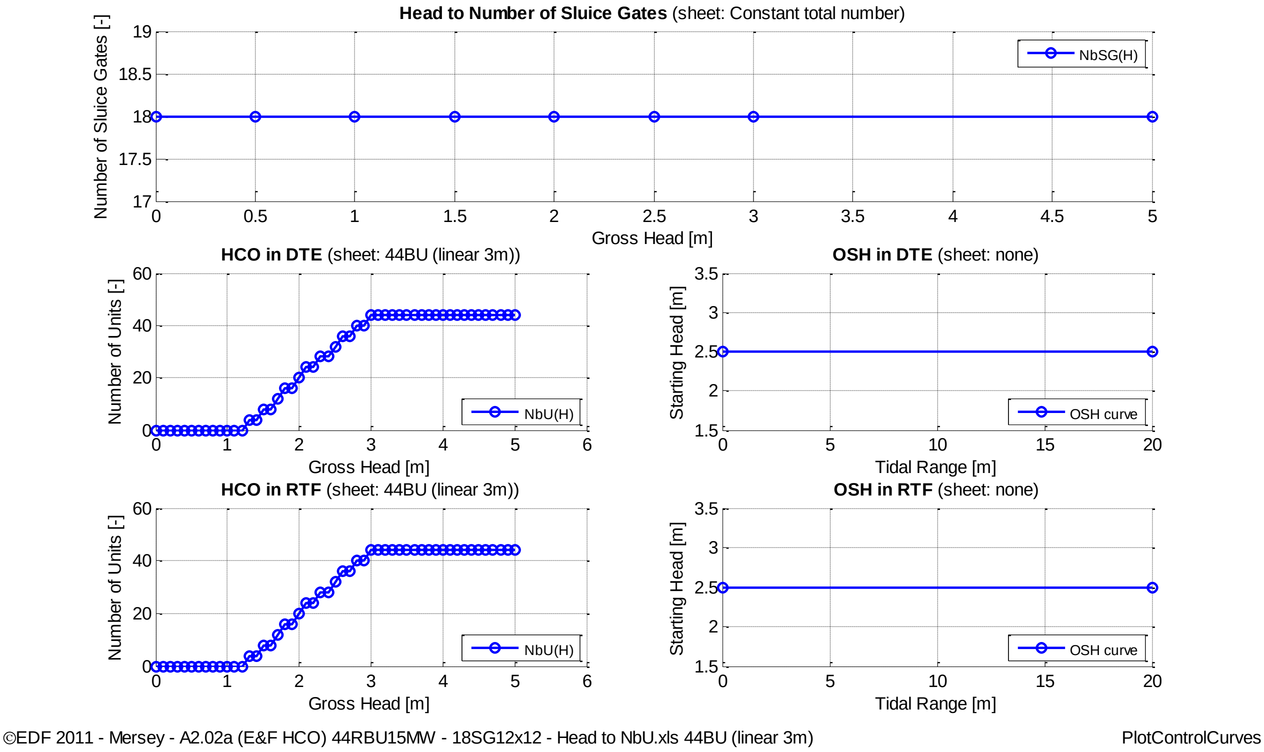


Figure H.16 - A2.02a (E&F HCO) - Control curves

2.2 5 typical tidal range results

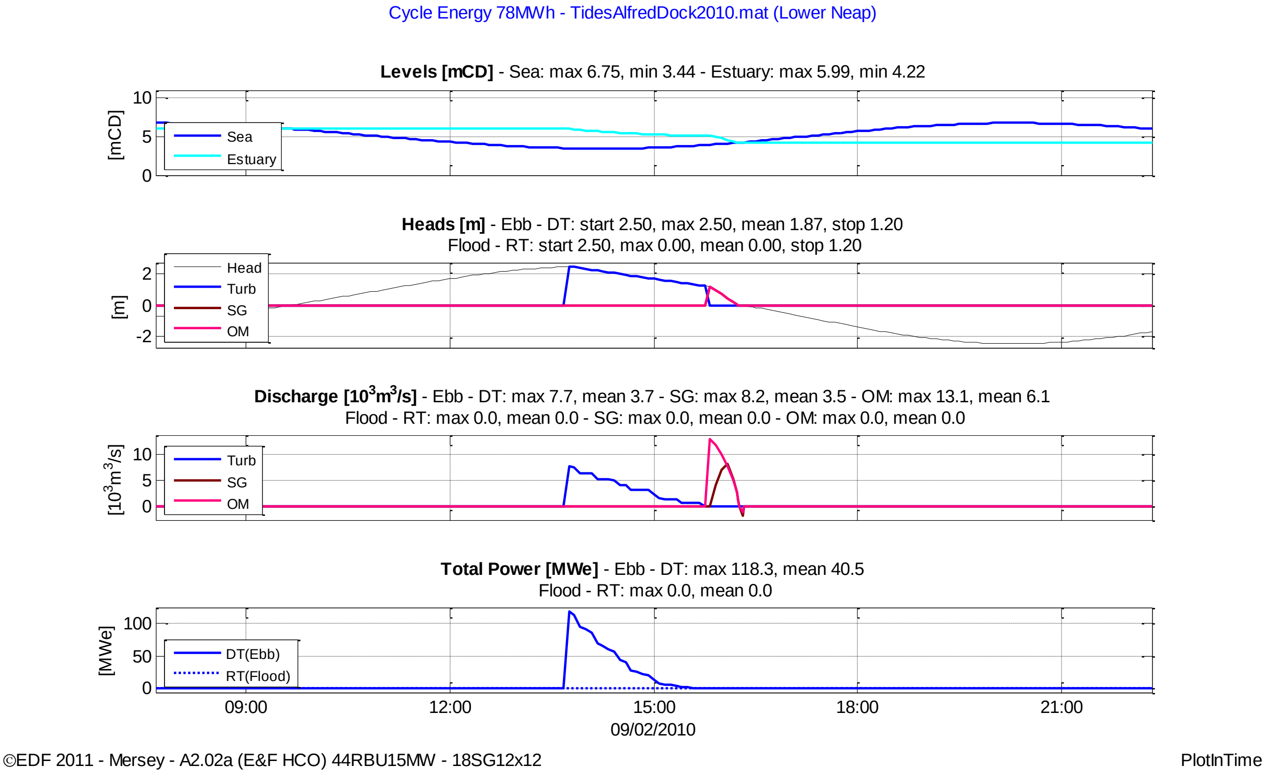


Figure H.17 - A2.02a (E&F HCO) - Lower Neap Tide operation

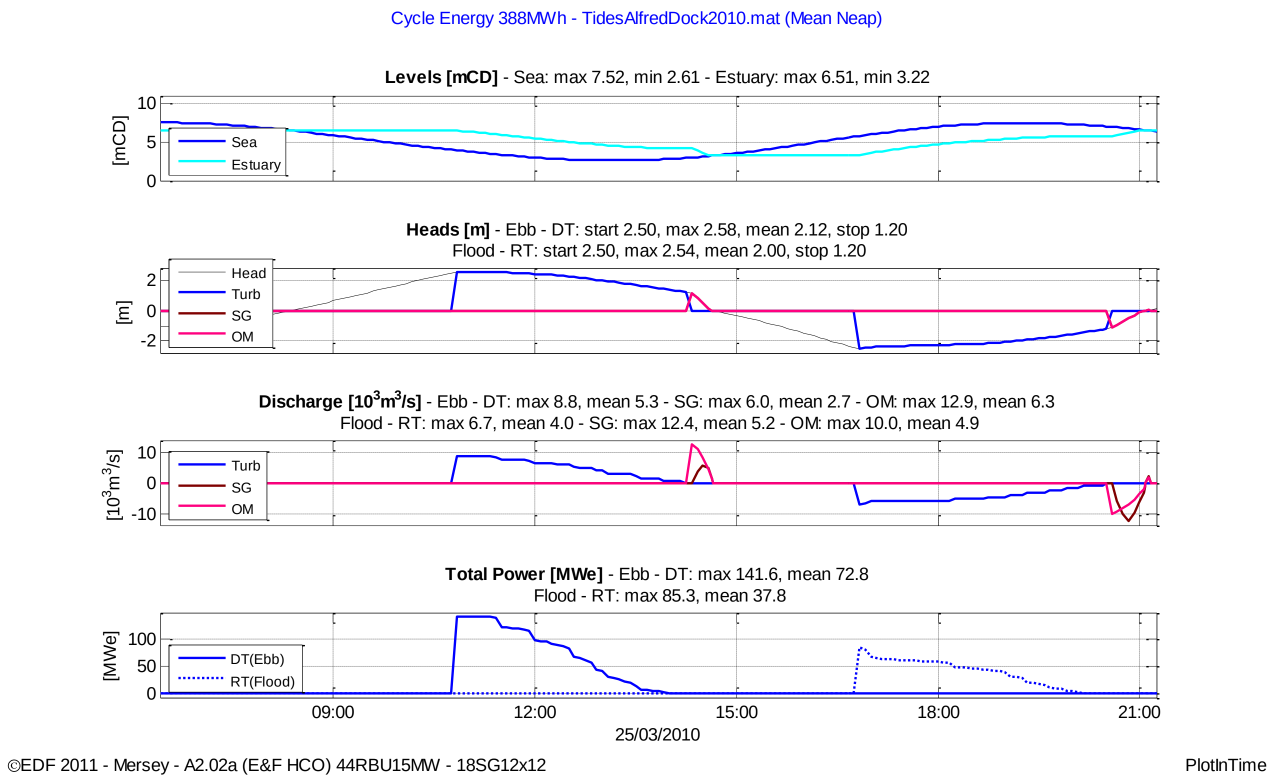


Figure H.18 - A2.02a (E&F HCO) - Mean Neap Tide operation

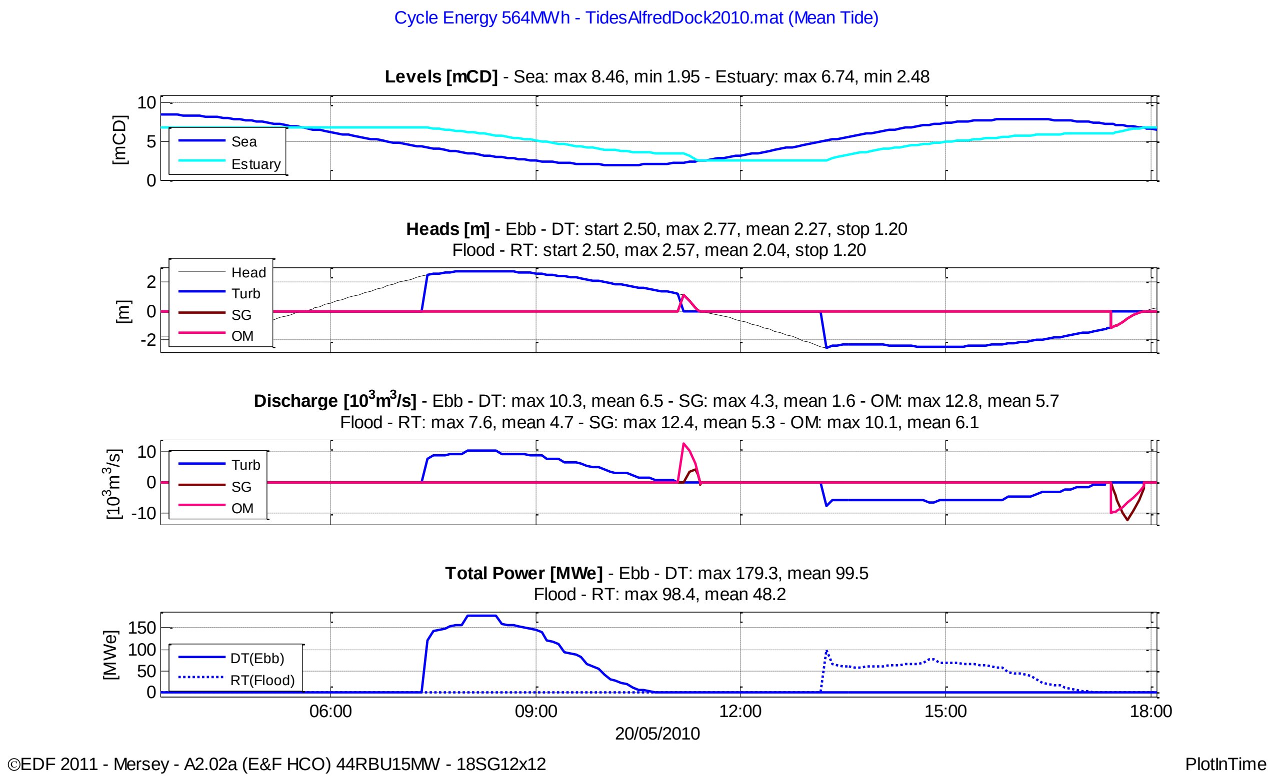


Figure H.19 - A2.02a (E&F HCO) - Mean Tide operation

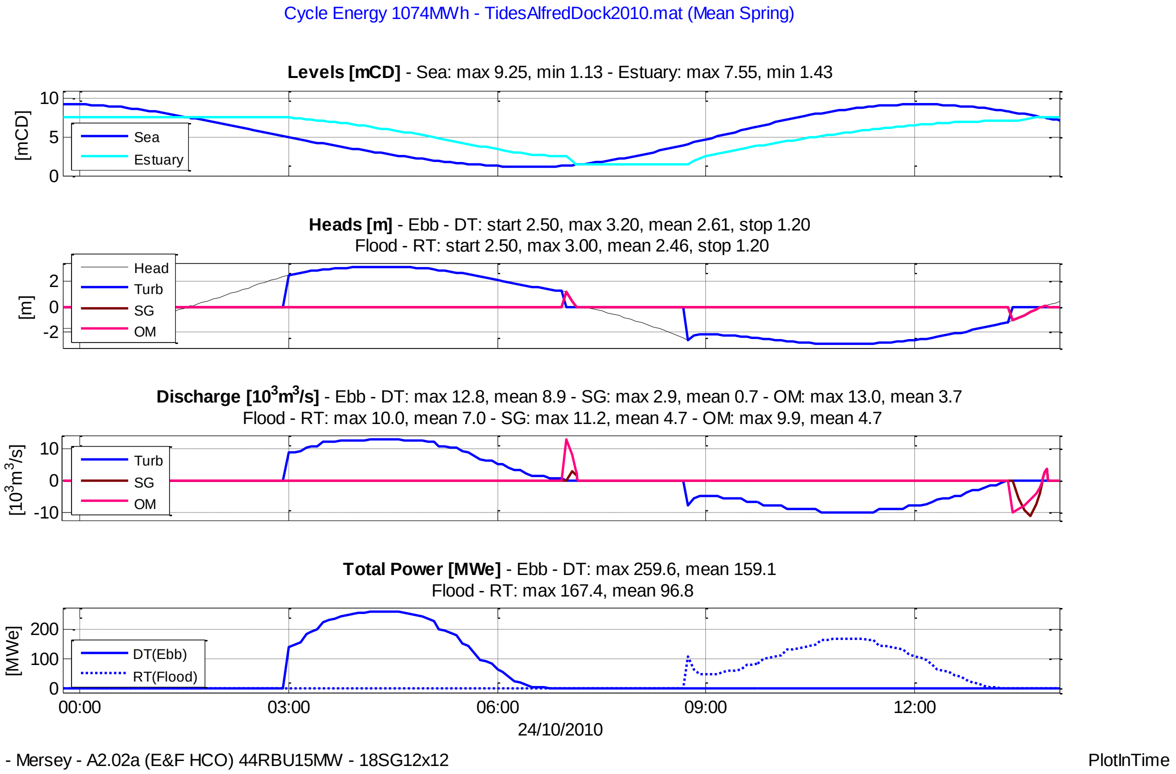


Figure H.20 - A2.02a (E&F HCO) - Mean Spring Tide operation

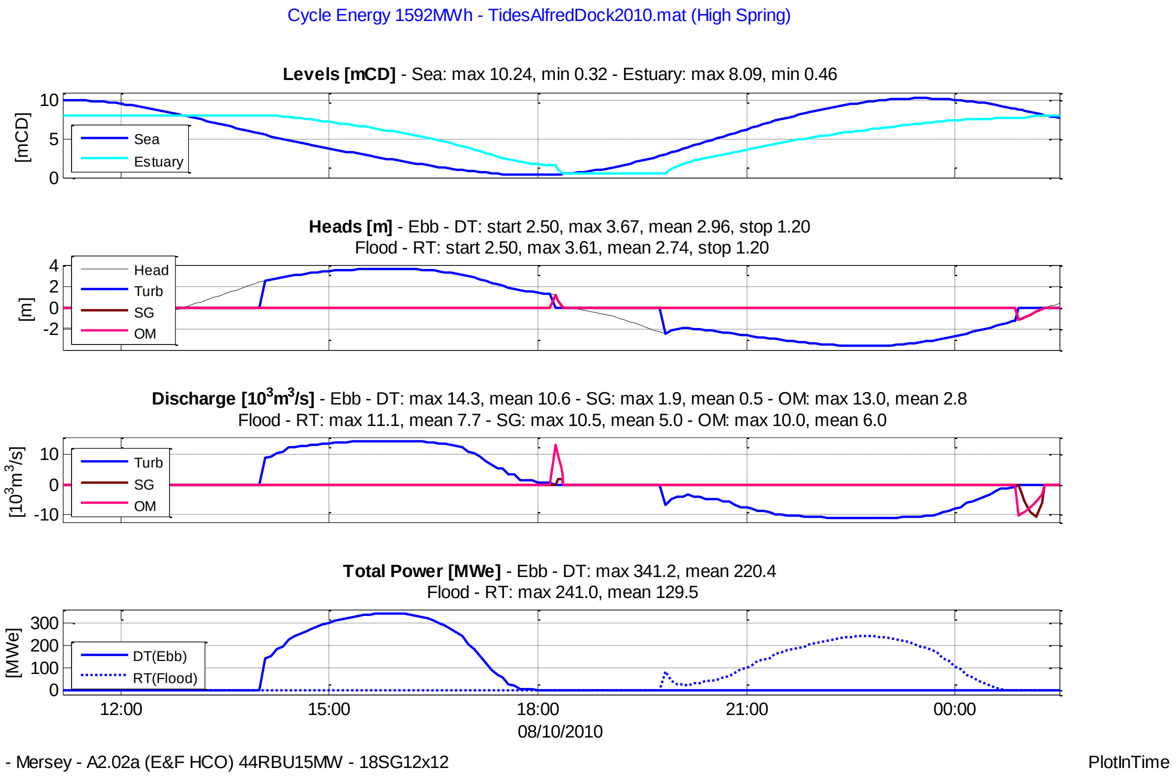


Figure H.21 - A2.02a (E&F HCO) - High Spring Tide operation

2.3 Year 2010 simulation

Graphics

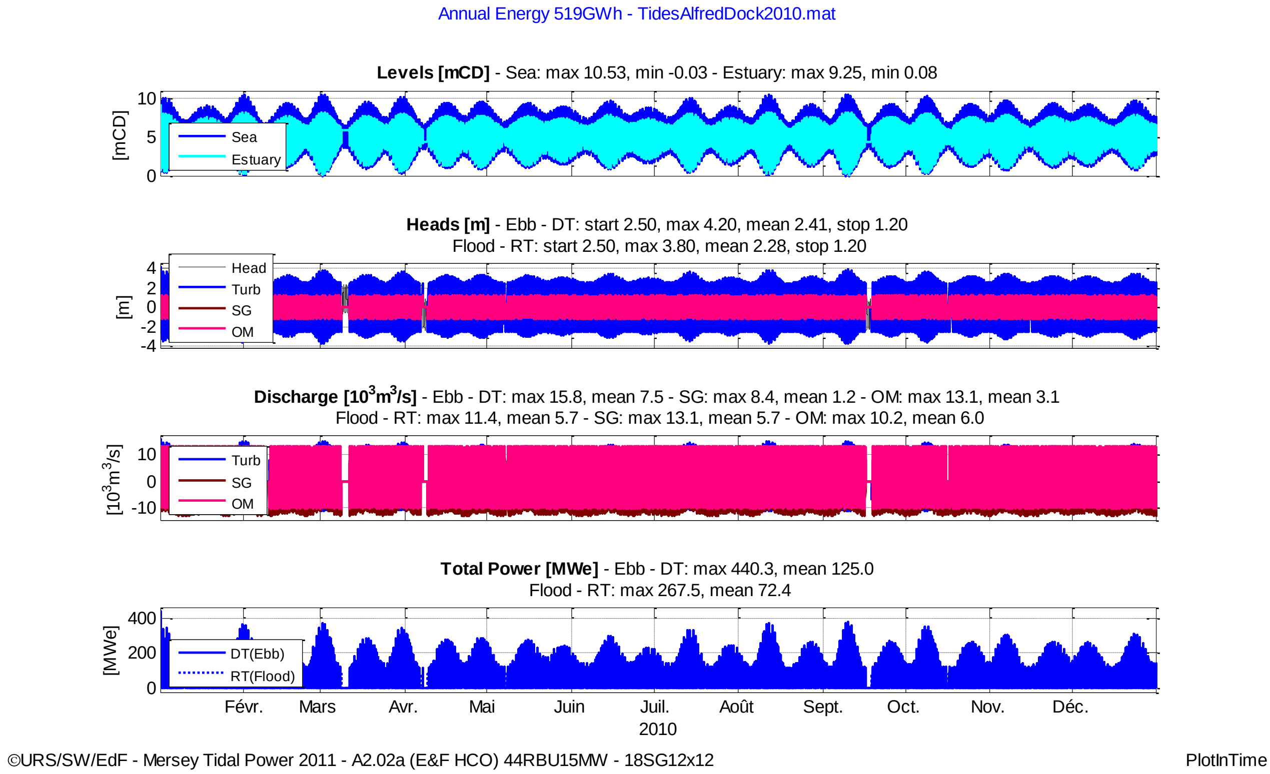


Figure H.22 - A2.02a (E&F HCO) - year 2010 time curves

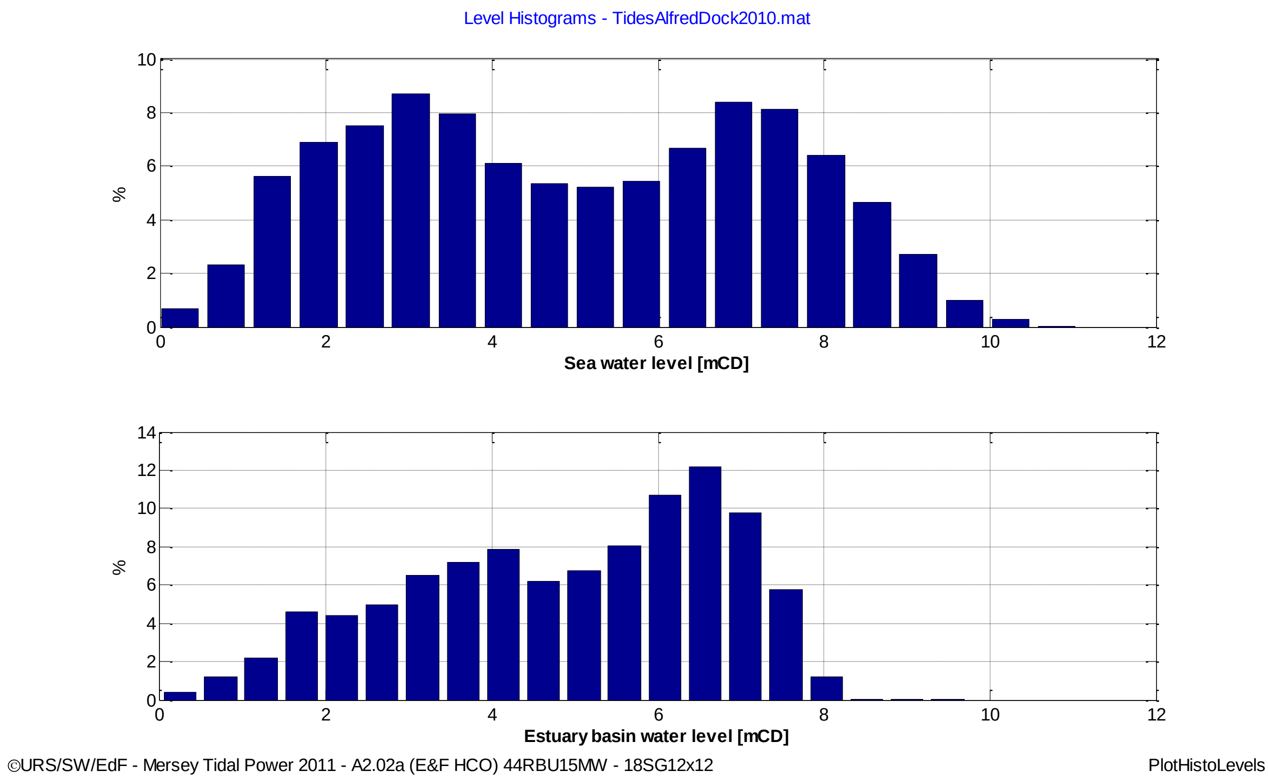


Figure H.23 - A2.02a (E&F HCO) - water level histograms

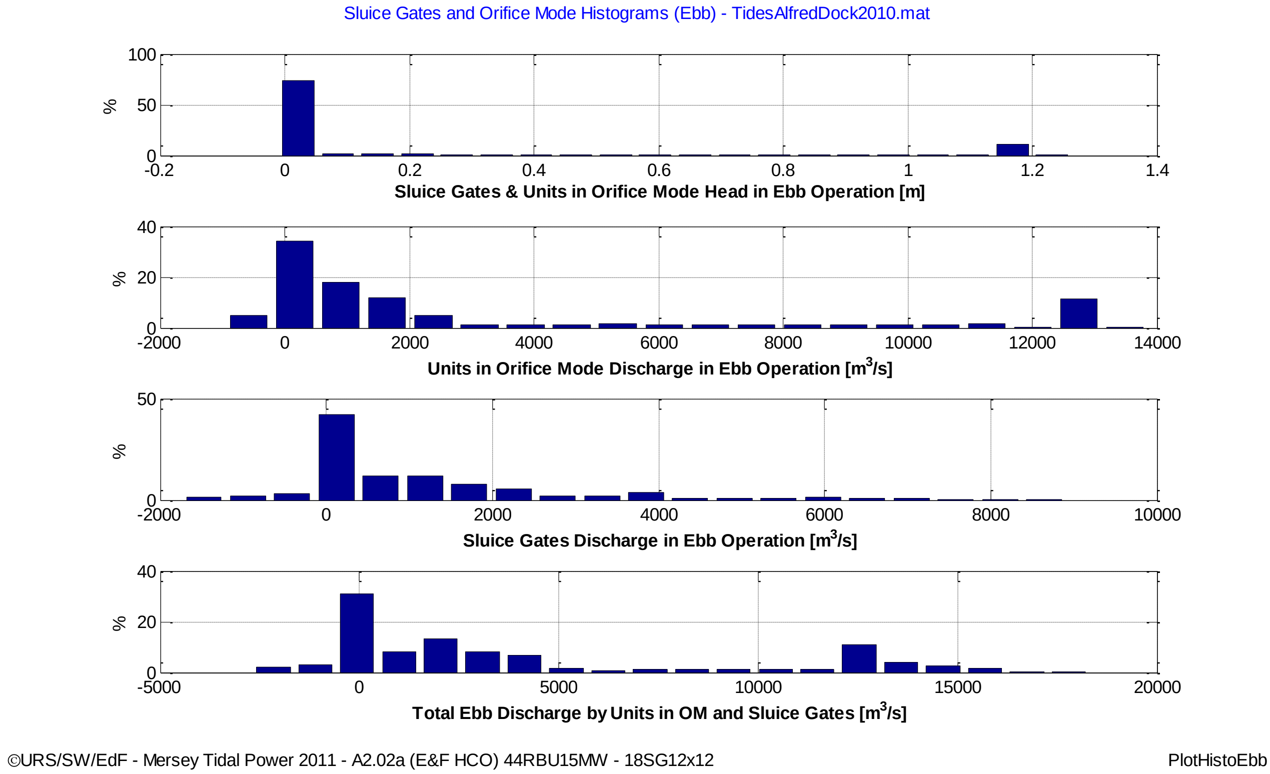


Figure H.24 - A2.02a (E&F HCO) - sluice gates and orifice mode histograms (ebb)

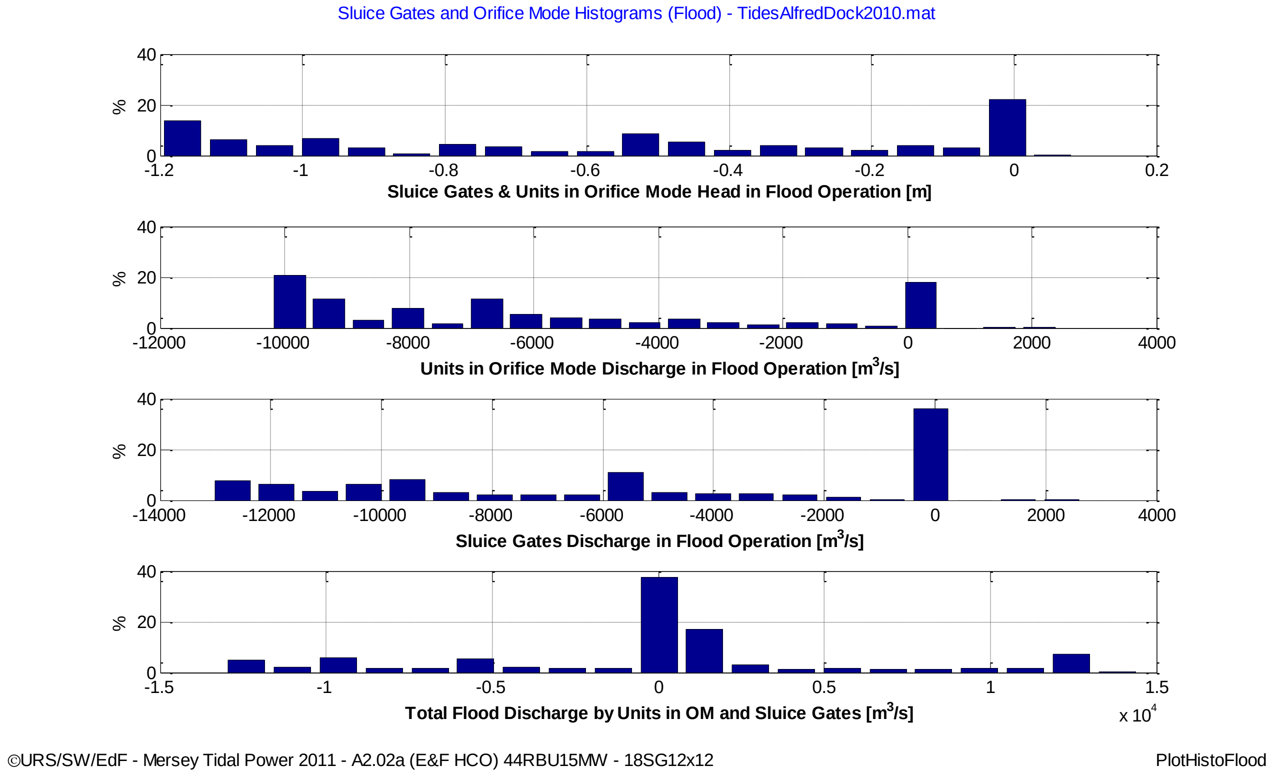


Figure H.25 - A2.02a (E&F HCO) - sluice gates and orifice mode histograms (flood)

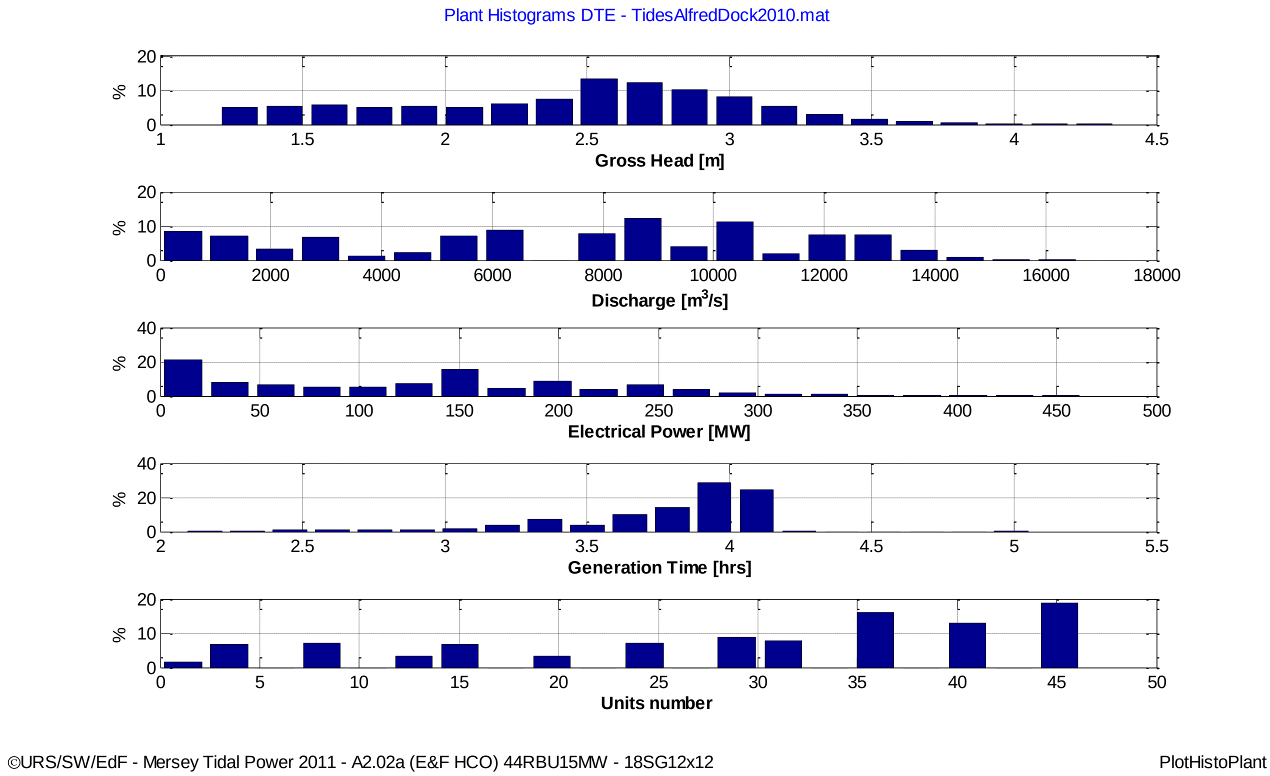


Figure H.26 - A2.02a (E&F HCO) - plant histograms (direct turbining)

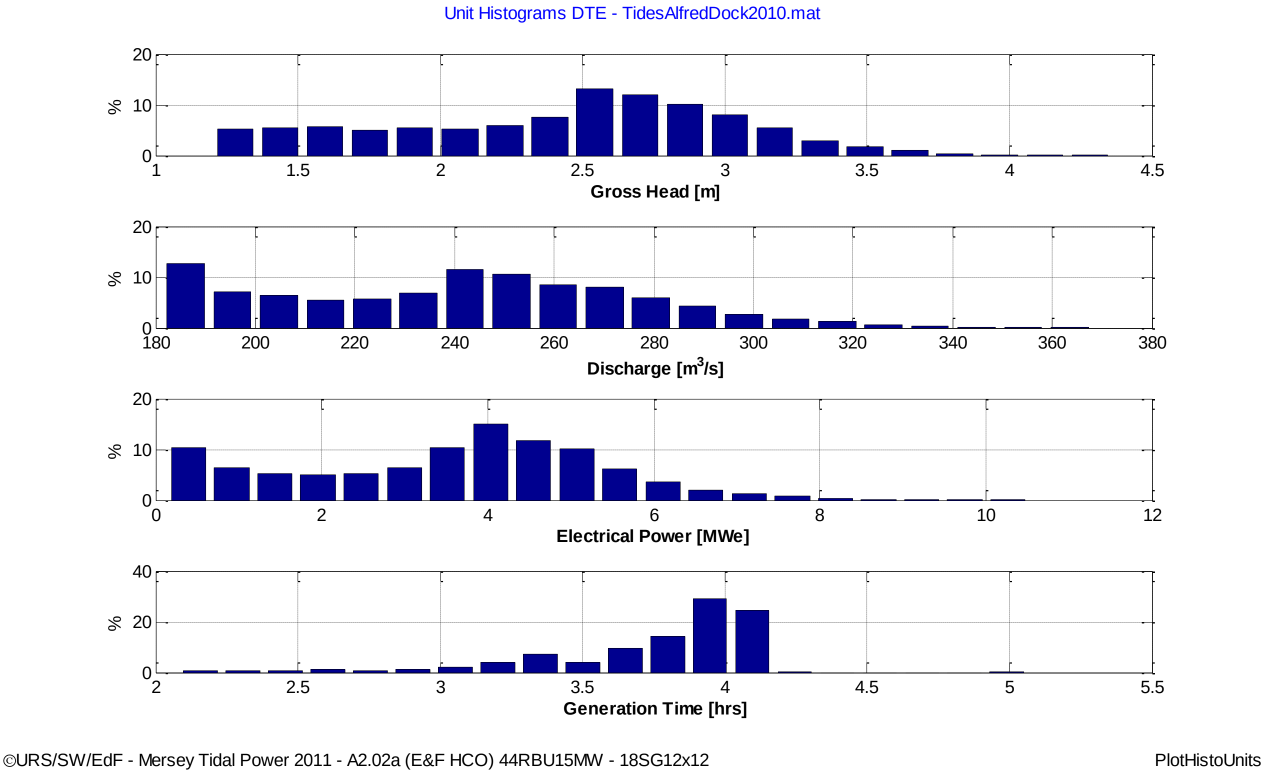


Figure H.27 - A2.02a (E&F HCO) - unit histograms (direct turbining)

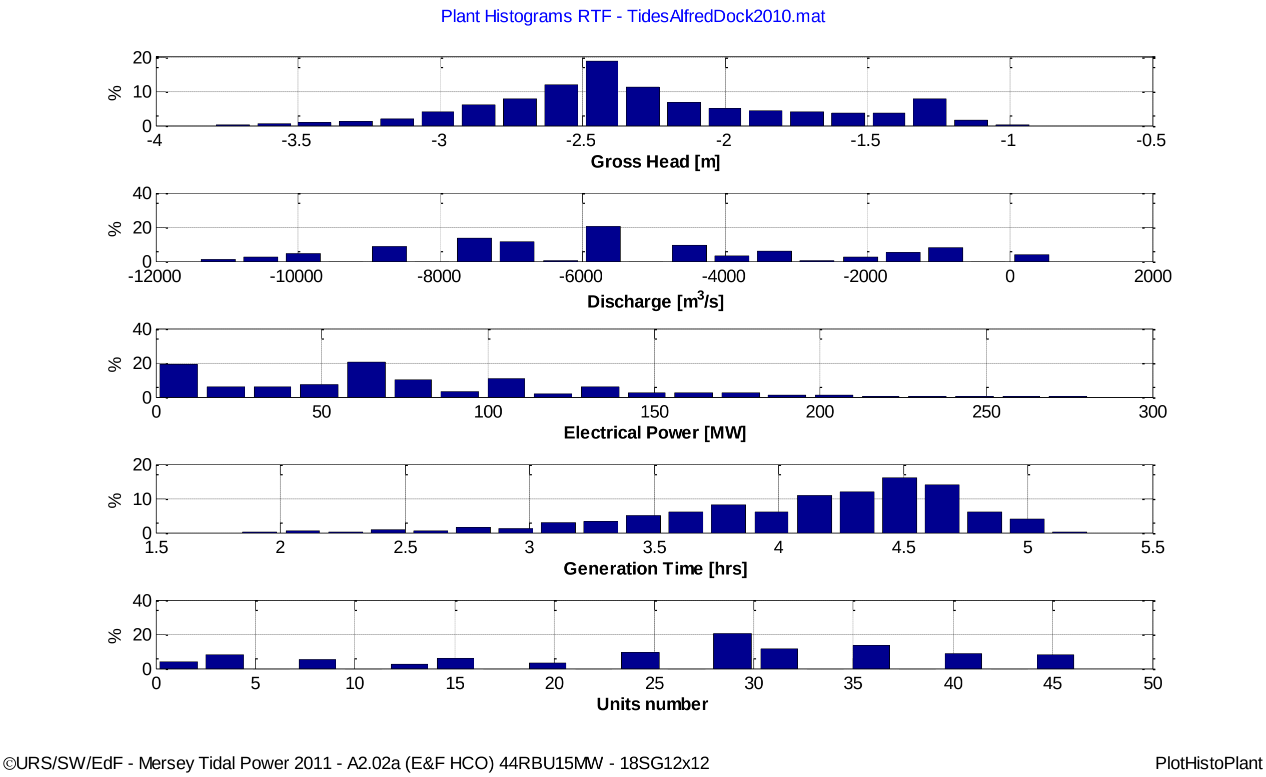


Figure H.28 - A2.02a (E&F HCO) - plant histograms (reverse turbining)

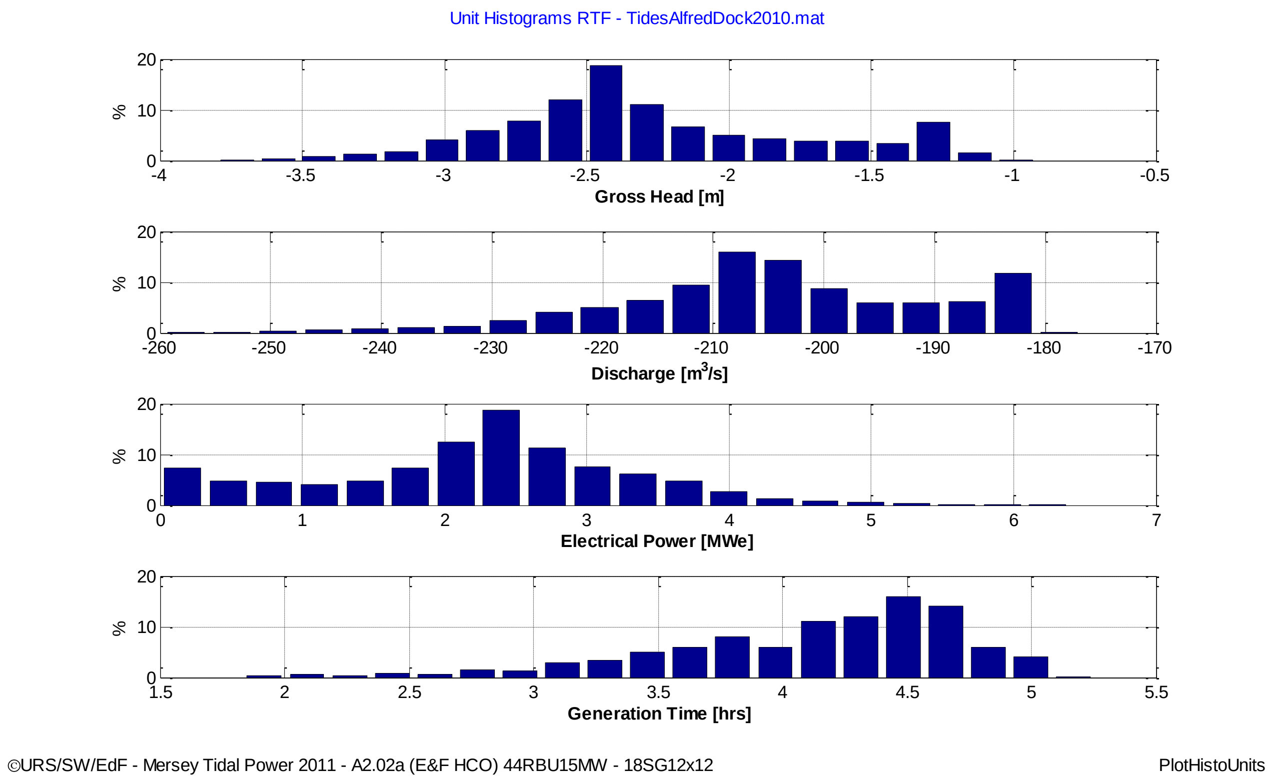


Figure H.29 - A2.02a (E&F HCO) - unit histograms (reverse turbining)

Balance Sheet Listing

```
 ---SIMULATION CASE A2.02a (E&F HCO) RESULTS ---

 - Tides:
Maximum Sea Level ..................... 10.53 m
Minimum Sea Level ..................... -0.03 m
        Sea Range ..................... 10.56 m

 - Estuary:
Maximum Estuary Level .................  9.25 m
Minimum Estuary Level .................  0.08 m
Maximum Estuary Range .................  9.17 m

 - Ebb Generation:
Energy production in Ebb .............. 314 GWh
Generation Time ....................... 2568.8 hrs
Mean Output ........................... 125 MW
Mean Discharge ........................ 7453 m^3/s
Max. Discharge ........................ 15788 m^3/s
Head control choice ................... Nb Units variable
Starting Head ......................... 2.50 m
Mean Head ............................. 2.41 m
Max  Head ............................. 4.20 m
Stopping Head ......................... 1.20 m

 - Flood Generation:
Energy production in Flood ............ 206 GWh
Generation Time ....................... 2802.8 hrs
Mean Discharge ........................ 5702 m^3/s
Max. Discharge ........................ 11427 m^3/s
Head control choice ................... Nb Units variable
Starting Head ......................... 2.50 m
Mean Head ............................. 2.28 m
Max  Head ............................. 3.80 m
```

```
Stopping Head ......................... 1.20 m

 - Ebb Sluicing:
Generation Time ....................... 258.3 hrs
Mean Discharge ........................ 1250 m^3/s
Max. Discharge ........................ 8377 m^3/s
Mean Head ............................. 0.21 m
Max  Head ............................. 1.20 m

 - Flood Sluicing:
Operating Time ........................ 348.2 hrs
Mean Discharge ........................ 5745 m^3/s
Max. Discharge ........................ 13080 m^3/s
Mean Head ............................. 0.56 m
Max. Head ............................. 1.20 m

 - Orifice Mode :
Operating Time ........................ 258.3 hrs
Mean Discharge ........................ 3116 m^3/s
Max. Discharge ........................ 13121 m^3/s

 - Reverse Orifice Mode :
Operating Time ........................ 348.2 hrs
Mean Discharge  ....................... 5971 m^3/s
Max Discharge ......................... 10237 m^3/s

 - Results :
Simulation Case ....................... A2.02a (E&F HCO) 44RBU15MW - 18SG12x12
Average Output ........................ 125 MW
Total Installed Capacity .............. 660 MW
Load Factor ........................... 9.0%
Direct Turbining Production (Ebb)....... 314 GWh
Reverse Turbining Production (Flood) ... 206 GWh
Net Energy ............................ 519 GWh
DT Generation Time .................... 2568.8 hrs (29.4%)
RT Generation Time .................... 2802.8 hrs (32.0%)
Sluice Gates Operating Time ........... 606.5 hrs (6.9%)
Orifice Mode Operating Time ........... 606.5 hrs (6.9%)
Standing Time ......................... 2768.5 hrs (31.7%)

Theoretical hydraulic energy lost through the Sluices Gates ... 18 GWh (3.5%)
Theoretical hydraulic energy lost in Orifice Mode ............. 31 GWh (6.0%)
```

Average output for each hour of the day

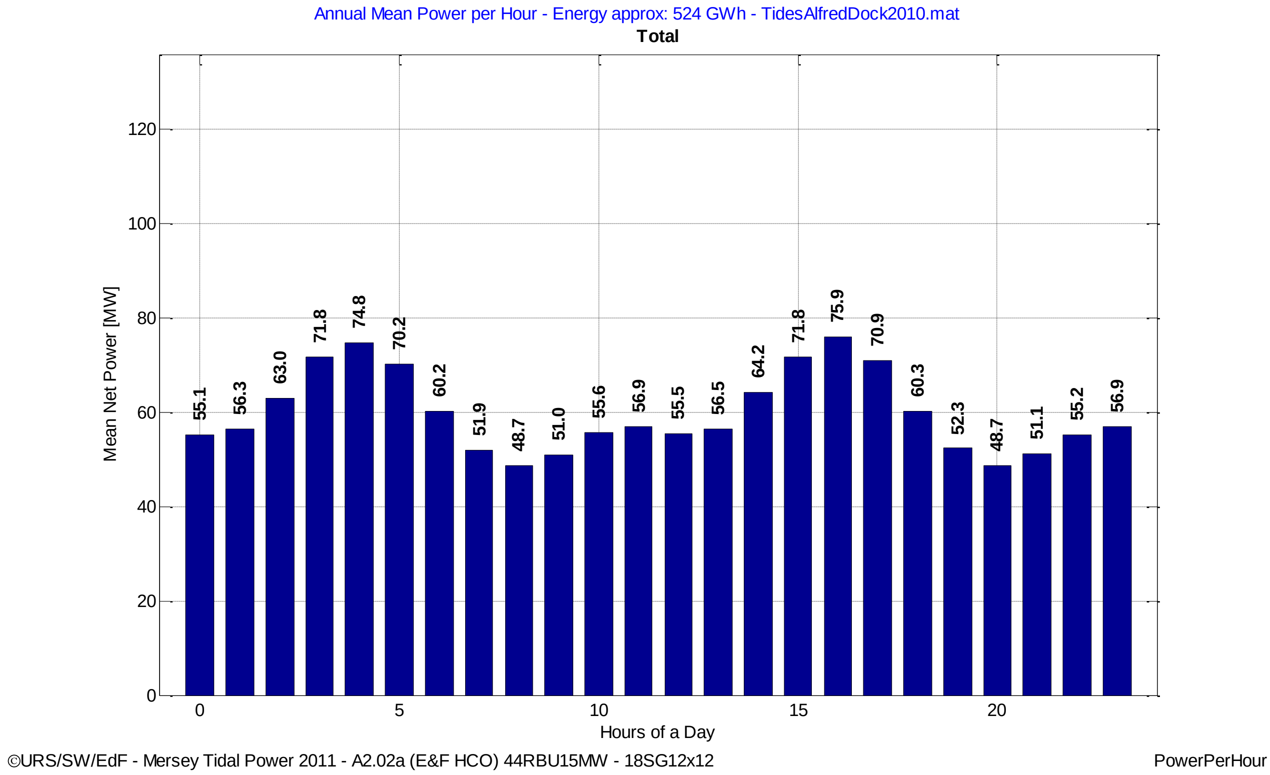


Figure H.30 - A2.02a (E&F HCO) - mean power per hour

3 A1.04c (E&F OSH + P) - 28RBU25MW - 18SG12x12

3.1 Control curves

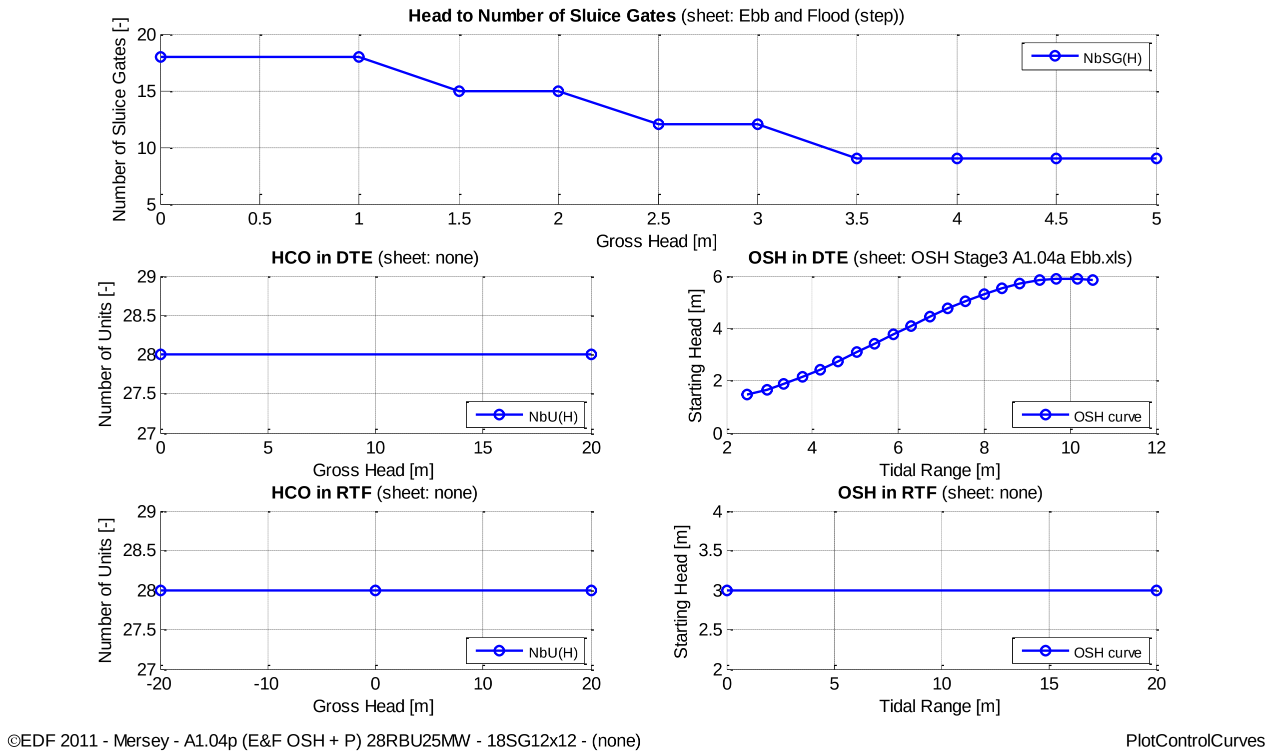


Figure H.31 - A1.04c (E&F OSH + P) - Control curves

3.2 5 typical tidal range results

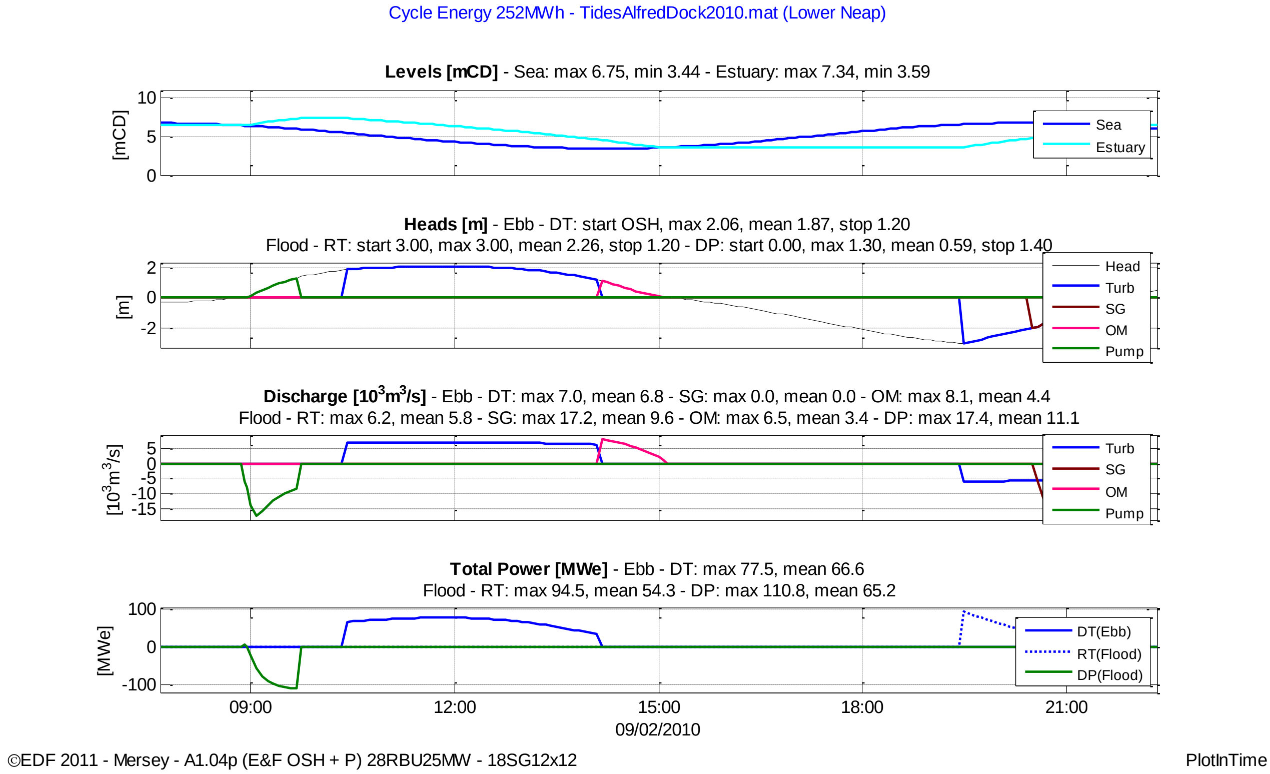
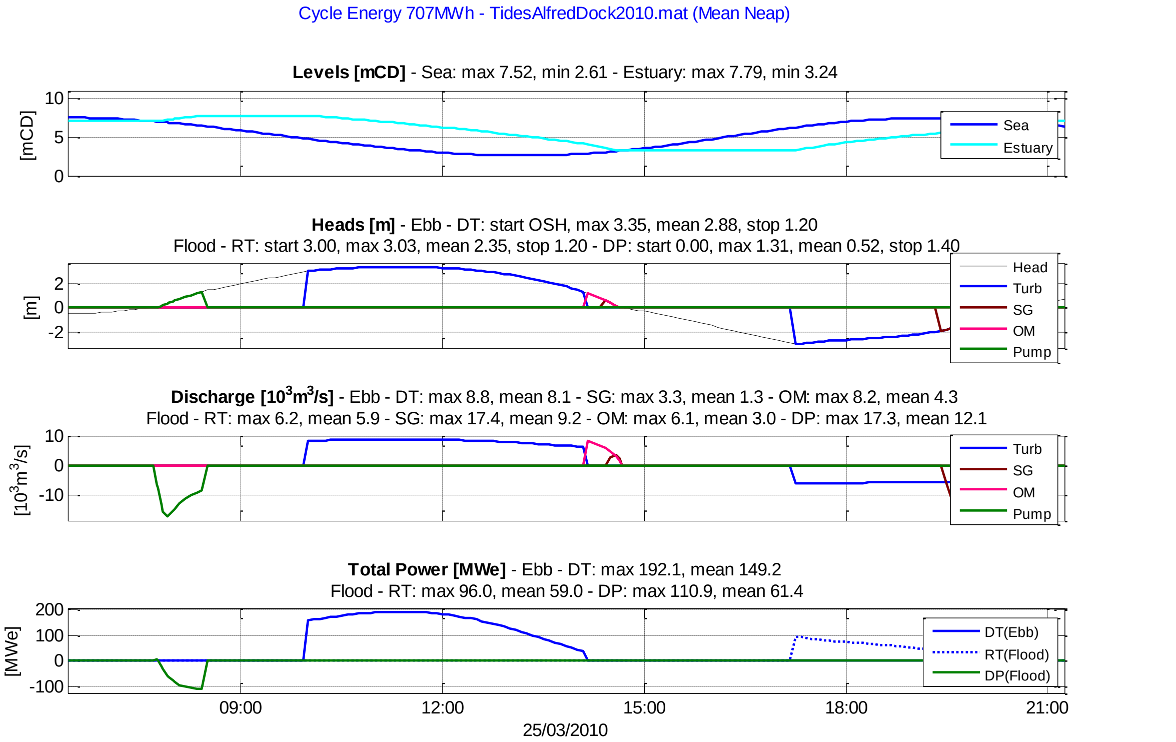


Figure H.32 - A1.04c (E&F OSH + P) - Lower Neap Tide operation



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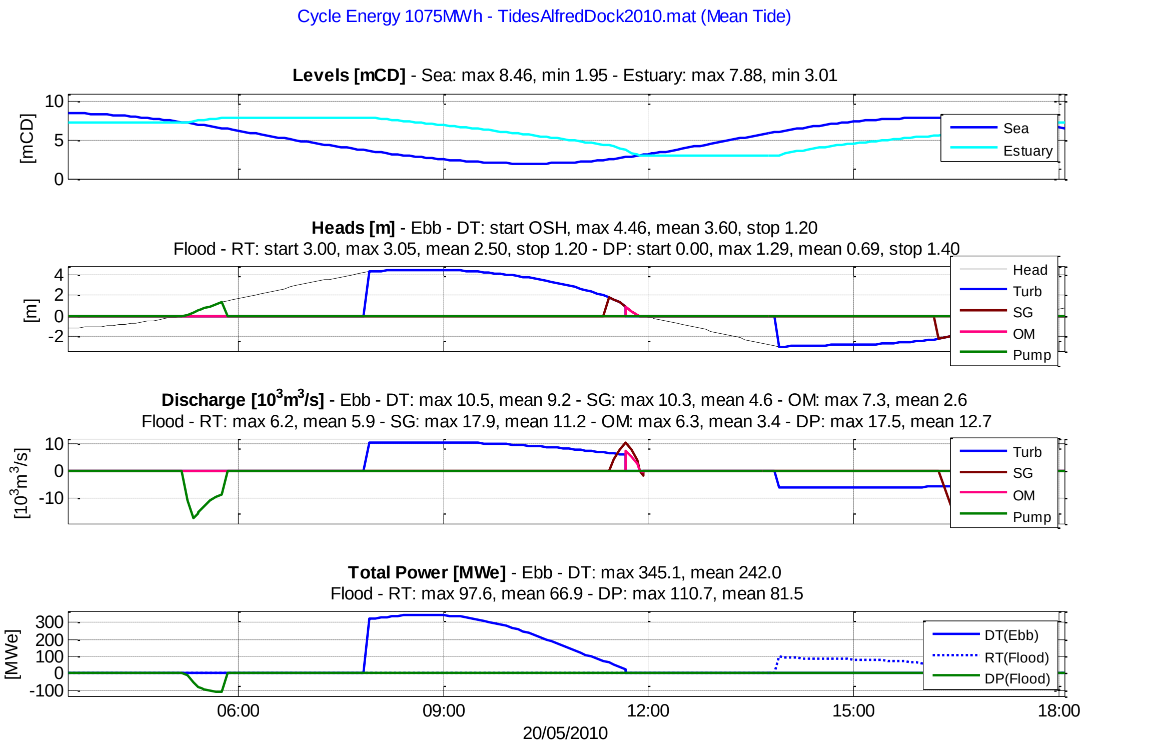
PlotInTime

Figure H.33 - A1.04c (E&F OSH + P) - Mean Neap Tide operation



©EDF 2011 - Mersey - A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12

PlotInTime

Figure H.34 - A1.04c (E&F OSH + P) - Mean Tide operation

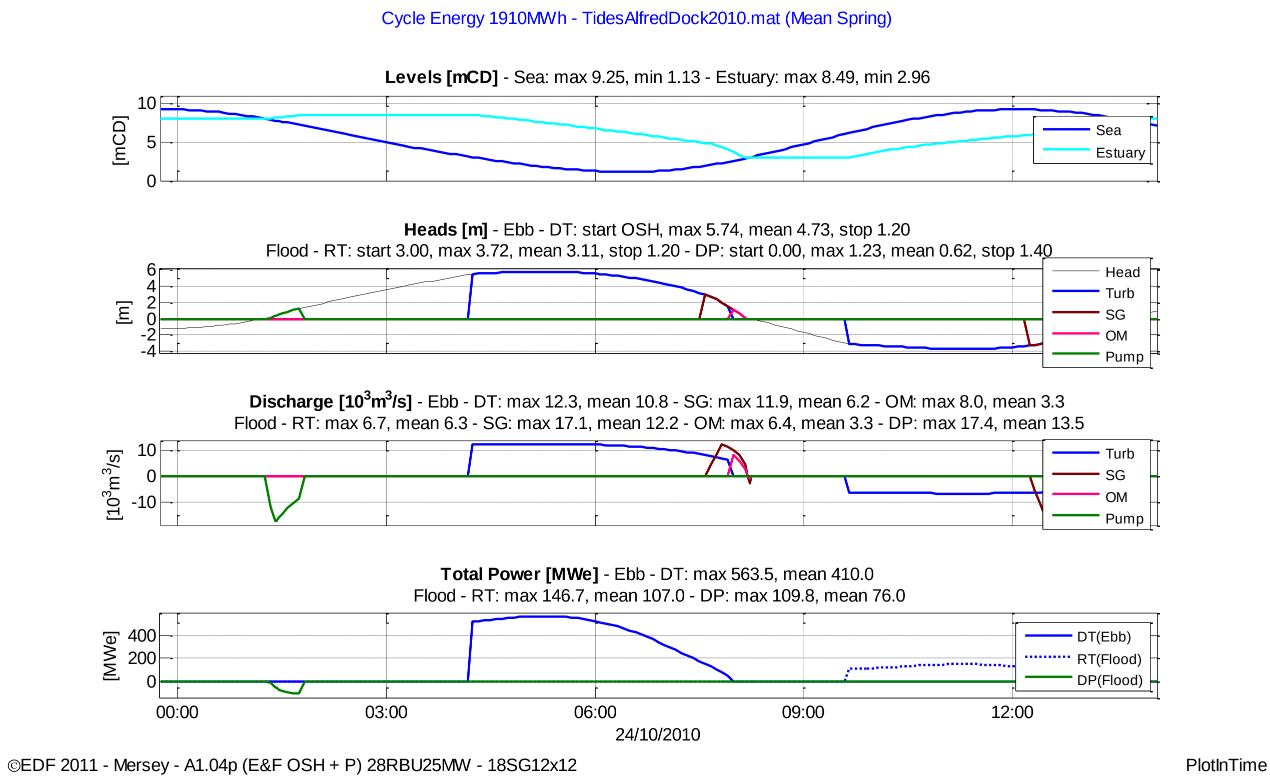


Figure H.35 - A1.04c (E&F OSH + P) - Mean Spring Tide operation

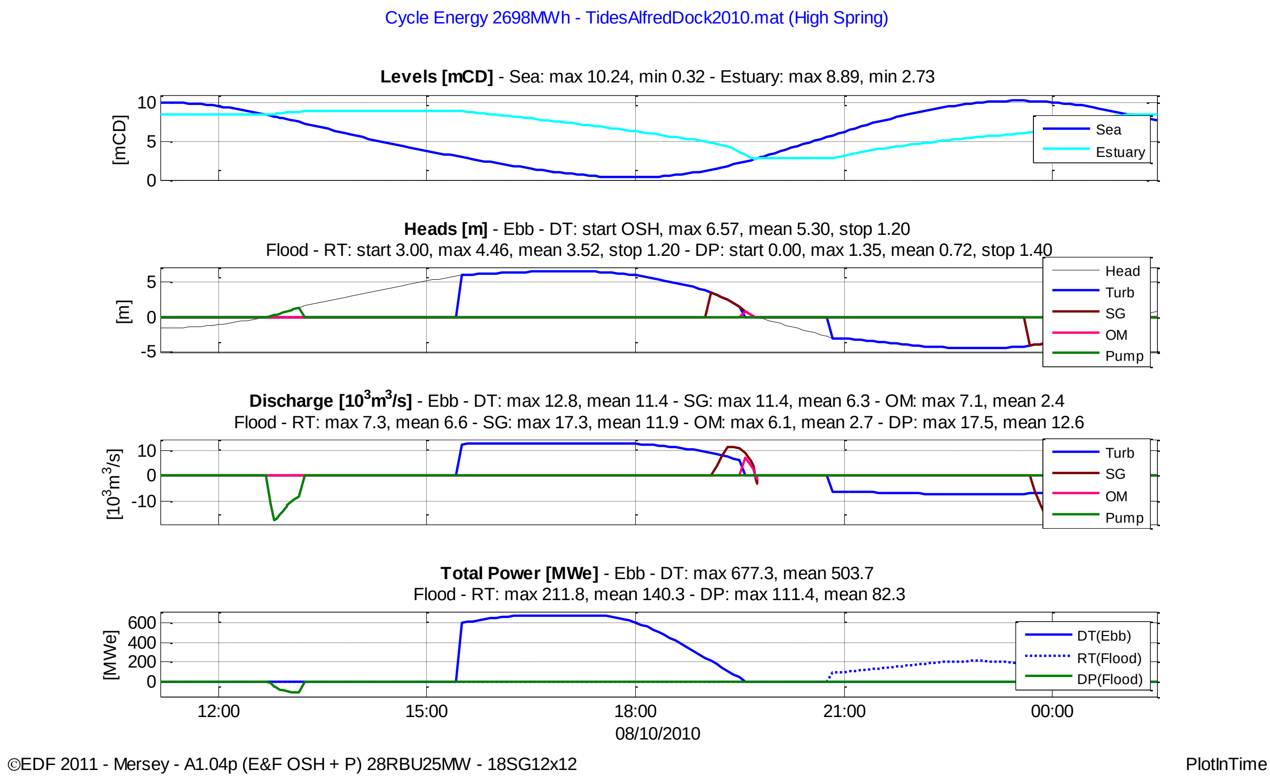


Figure H.36 - A1.04c (E&F OSH + P) - High Spring Tide operation

3.3 Year 2010 simulation

Graphics

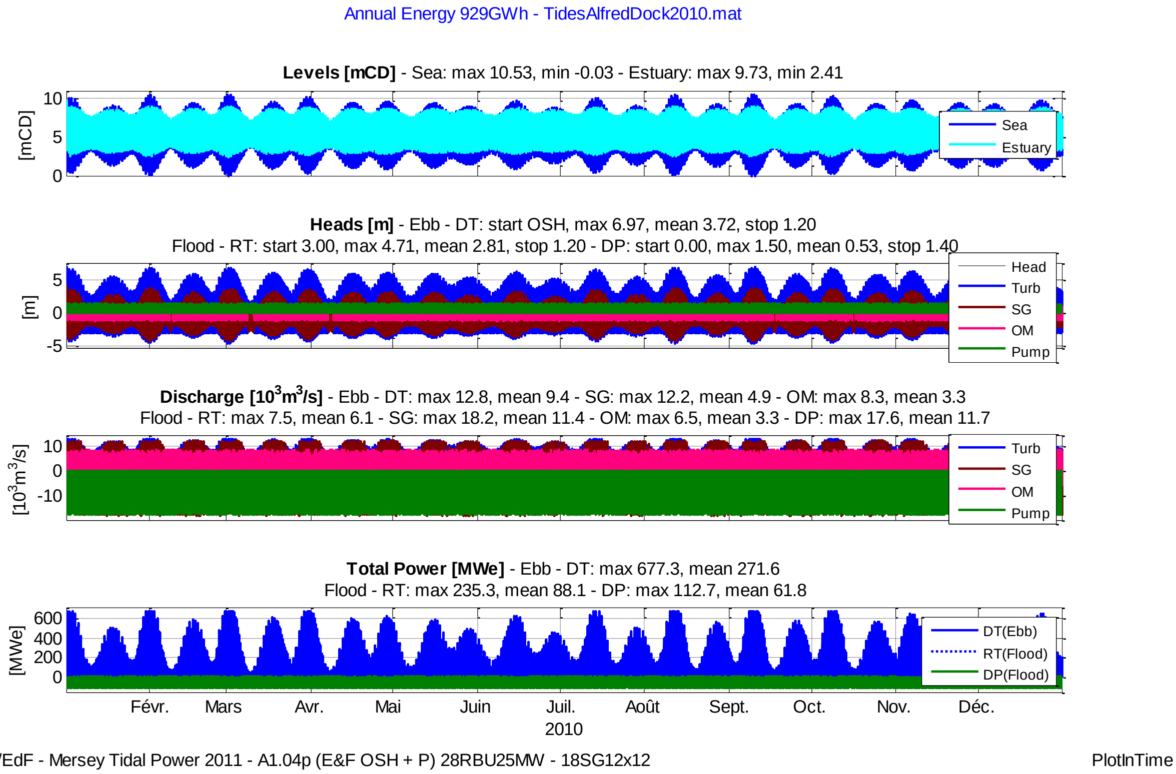


Figure H.37 - A1.04c (E&F OSH + P) - year 2010 time curves

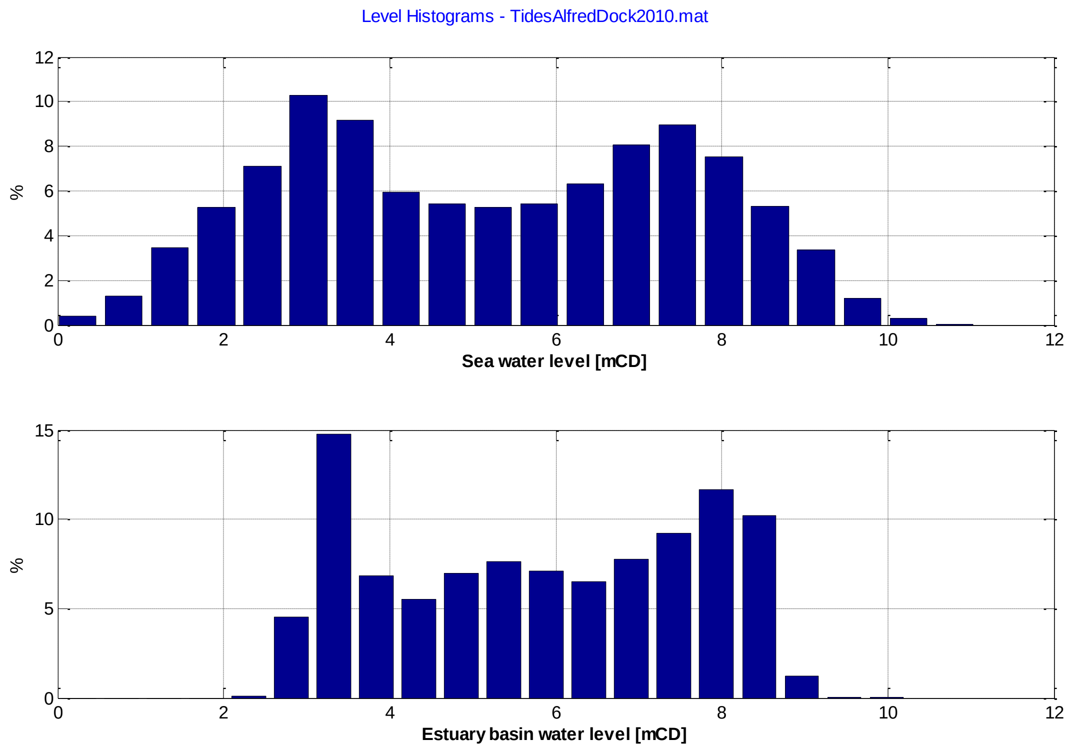


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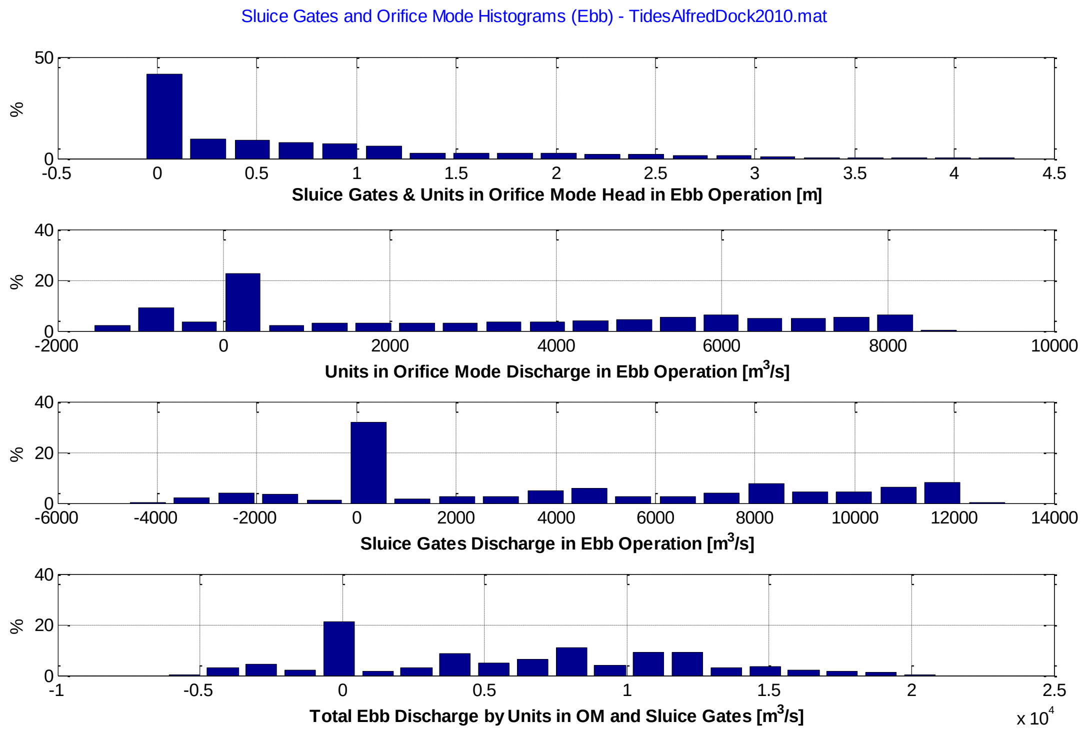
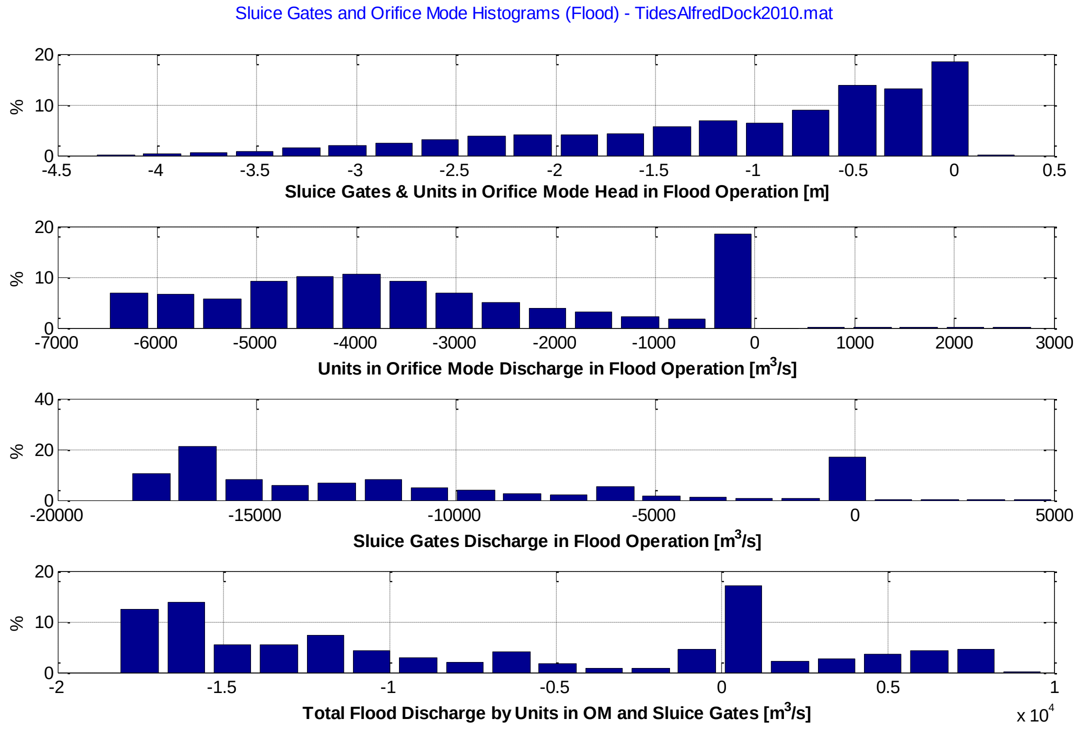
Figure H.38 - A1.04c (E&F OSH + P) - water level histograms



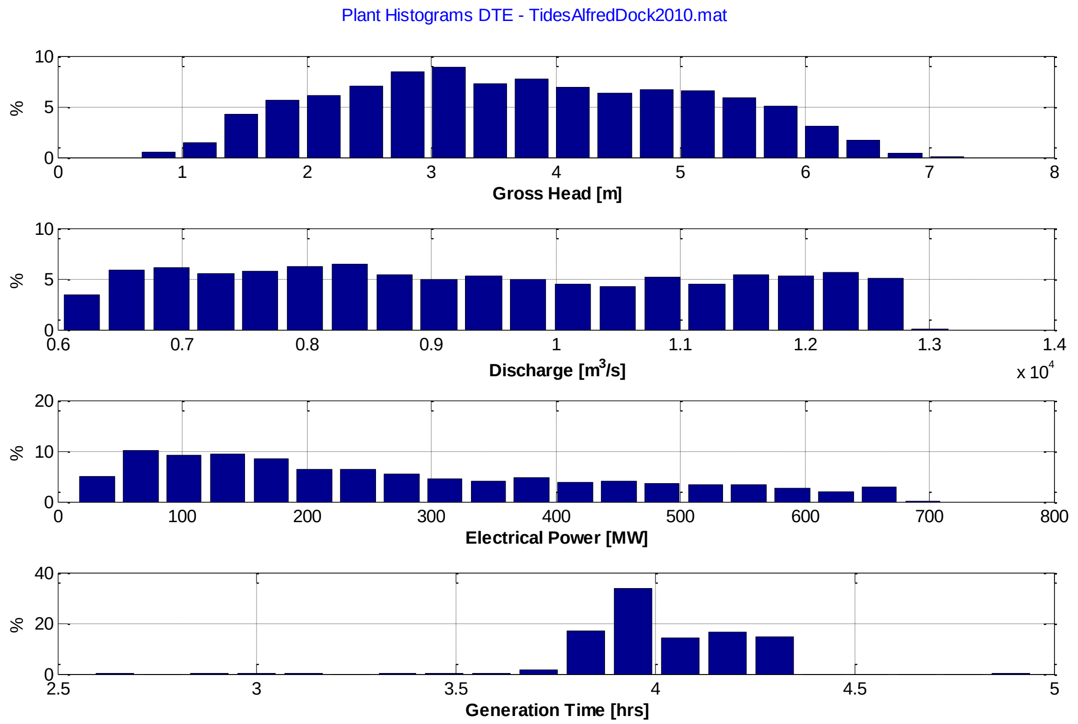
©URS/SW/EdF - Mersey Tidal Power 2011 - A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12 PlotHistoEbb

Figure H.39 - A1.04c (E&F OSH + P) - sluice gates and orifice mode histograms (ebb)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12 PlotHistoFlood

Figure H.40 - A1.04c (E&F OSH + P) - sluice gates and orifice mode histograms (flood)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12 PlotHistoPlant

Figure H.41 - A1.04c (E&F OSH + P) - plant histograms (direct turbining)

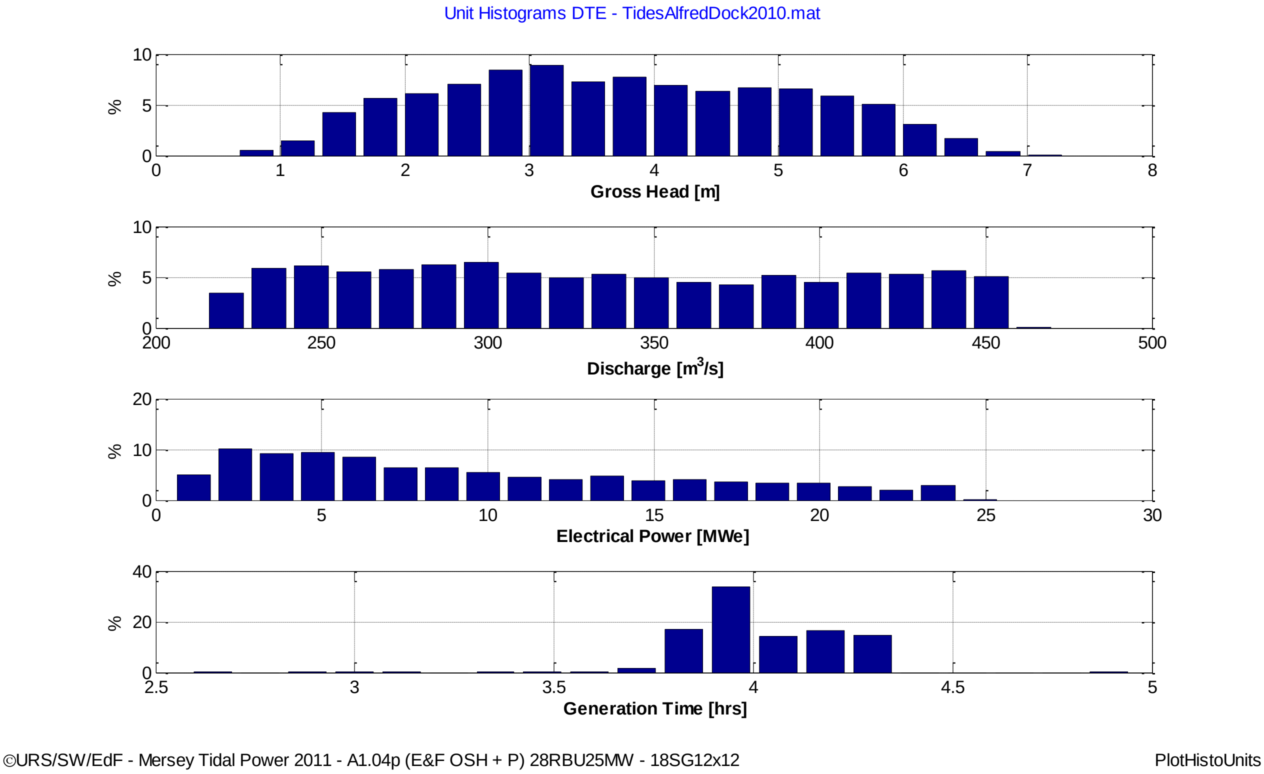


Figure H.42 - A1.04c (E&F OSH + P) - unit histograms (direct turbining)

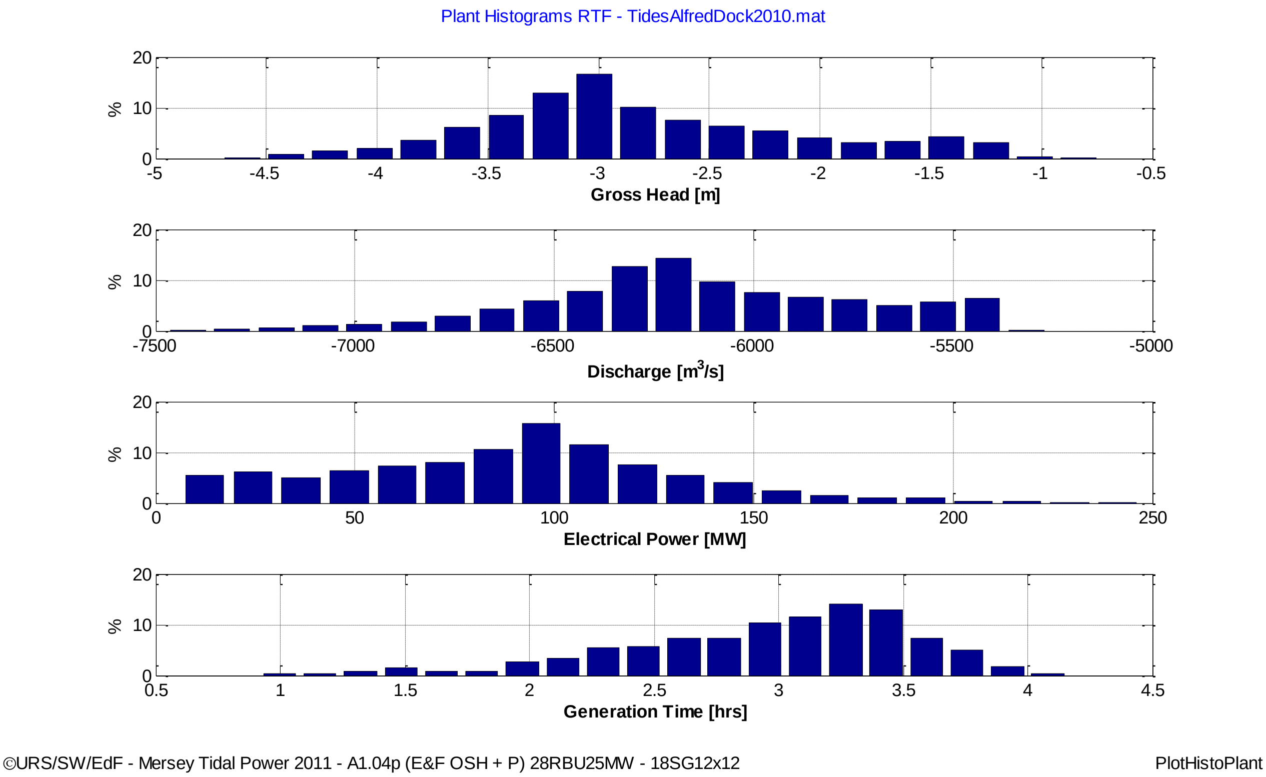
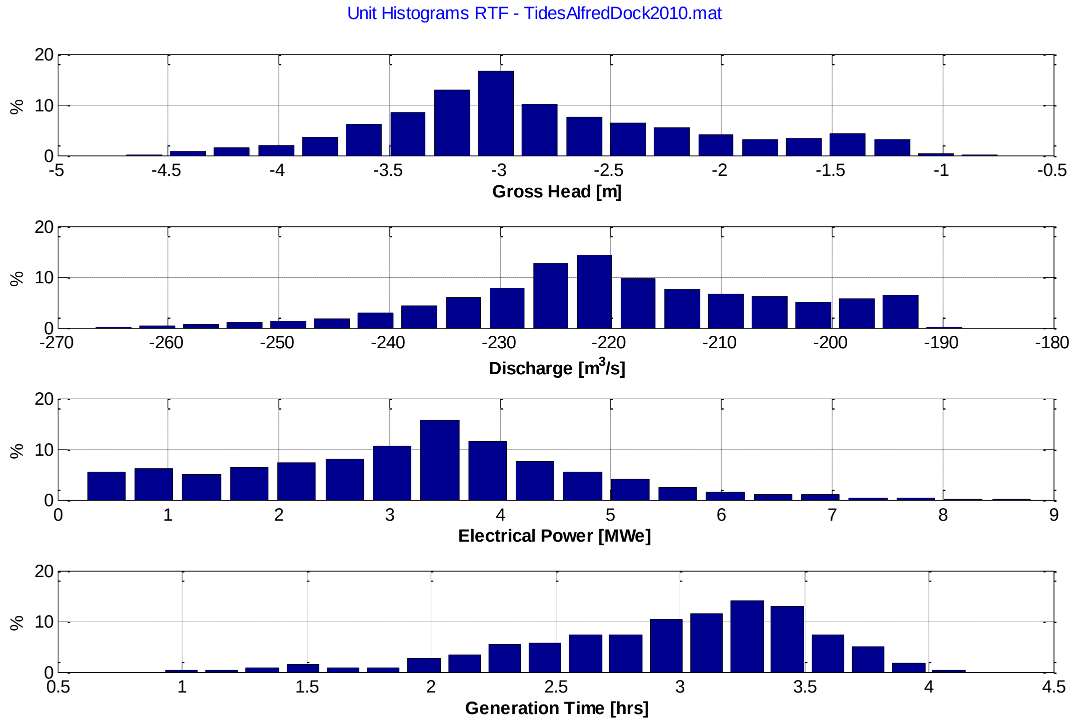
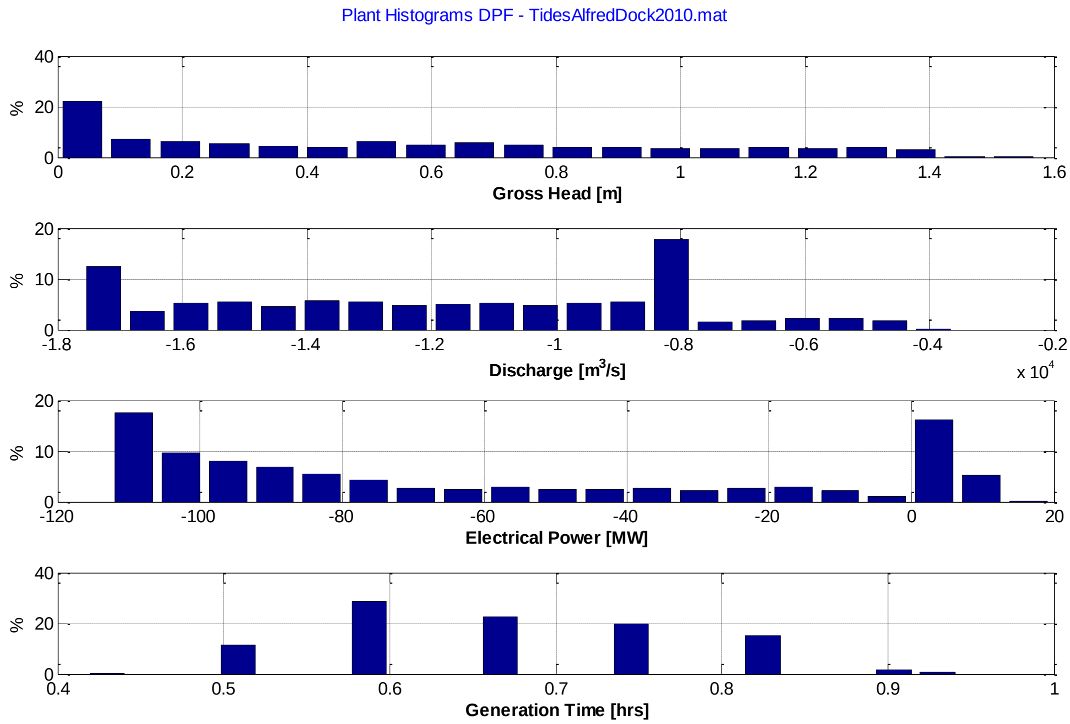


Figure H.43 - A1.04c (E&F OSH + P) - plant histograms (reverse turbining)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12 PlotHistoUnits

Figure H.44 - A1.04c (E&F OSH + P) - unit histograms (reverse turbining)



©URS/SW/EdF - Mersey Tidal Power 2011 - A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12 PlotHistoPlant

Figure H.45 - A1.04c (E&F OSH + P) - plant histograms (direct pumping)

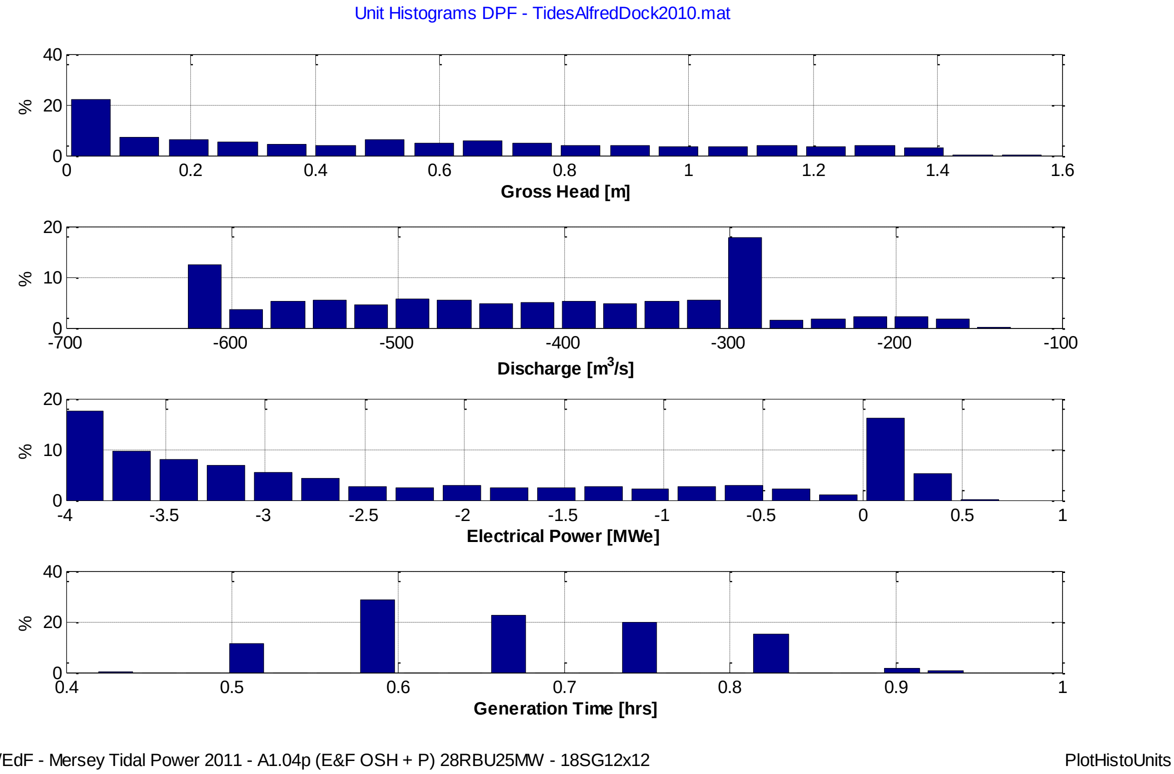


Figure H.46 - A1.04c (E&F OSH + P) - unit histograms (direct pumping)

Balance Sheet Listing

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 ---SIMULATION CASE A1.04c (E&F OSH + P) RESULTS ---

 - Tides:
Maximum Sea Level ...................... 10.53 m
Minimum Sea Level ...................... -0.03 m
        Sea Range ...................... 10.56 m

 - Estuary:
Maximum Estuary Level ..................  9.73 m
Minimum Estuary Level ..................  2.41 m
Maximum Estuary Range ..................  7.32 m

 - Init Estuary Level minus Max Sea Level:
Starting value ......................... -0.11 m
Maximum ................................  0.70 m
Minimum ................................ -1.56 m

 - Ebb Generation:
Energy production in Ebb ............... 779 GWh
Generation Time ........................ 2822.9 hrs
Mean Output ............................ 272 MW
Mean Discharge ......................... 9375 m^3/s
Max. Discharge ......................... 12826 m^3/s
Head control choice .................... in OSH operation
Starting Head .......................... optimised
Mean Head .............................. 3.72 m
Max  Head .............................. 6.97 m
Stopping Head .......................... 1.20 m

 - Flood Generation:
Energy production in Flood ............. 190 GWh
Generation Time ........................ 2055.2 hrs
Mean Discharge ......................... 6136 m^3/s
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Max. Discharge ........................ 7474 m^3/s
Starting Head ......................... 3.00 m
Mean Head ............................. 2.81 m
Max  Head ............................. 4.71 m
Stopping Head ......................... 1.20 m

 - Pumping:
Power Consumption ..................... -40 GWh
Generation Time ....................... 471.3 hrs
Mean Discharge ........................ 11740 m^3/s
Max. Discharge ........................ 17609 m^3/s
Mean Head ............................. 0.53 m
Starting Head ......................... 0.00 m
Stopping Head ......................... 1.40 m

 - Ebb Sluicing:
Generation Time ....................... 338.4 hrs
Mean Discharge ........................ 4913 m^3/s
Max. Discharge ........................ 12209 m^3/s
Mean Head ............................. 0.91 m
Max  Head ............................. 4.10 m

 - Flood Sluicing:
Operating Time ........................ 856.6 hrs
Mean Discharge ........................ 11426 m^3/s
Max. Discharge ........................ 18232 m^3/s
Mean Head ............................. 1.31 m
Max. Head ............................. 4.32 m

 - Orifice Mode :
Operating Time ........................ 266.6 hrs
Mean Discharge ........................ 3298 m^3/s
Max. Discharge ........................ 8350 m^3/s

 - Reverse Orifice Mode :
Operating Time ........................ 383.2 hrs
Mean Discharge  ....................... 3268 m^3/s
Max Discharge ......................... 6514 m^3/s

 - Results :
Simulation Case ....................... A1.04p (E&F OSH + P) 28RBU25MW - 18SG12x12
Average Output ........................ 272 MW
Total Installed Capacity .............. 700 MW
Load Factor ........................... 15.2%
Direct Turbining Production (Ebb)....... 779 GWh
Power Consumption in Pumping .......... -40 GWh
Reverse Turbining Production (Flood) ... 190 GWh
Net Energy ............................ 929 GWh
DP Generation Time .................... 471.3 hrs (5.4%)
DT Generation Time .................... 2822.9 hrs (32.3%)
RT Generation Time .................... 2055.2 hrs (23.5%)
Sluice Gates Operating Time ........... 1195.0 hrs (13.7%)
Orifice Mode Operating Time ........... 649.8 hrs (7.4%)
Standing Time ......................... 2747.3 hrs (31.4%)

Theoretical hydraulic energy lost through the Sluices Gates ... 219 GWh (23.6%)
Theoretical hydraulic energy lost in Orifice Mode ............ 13 GWh (1.4%)
```

Average output for each hour of the day

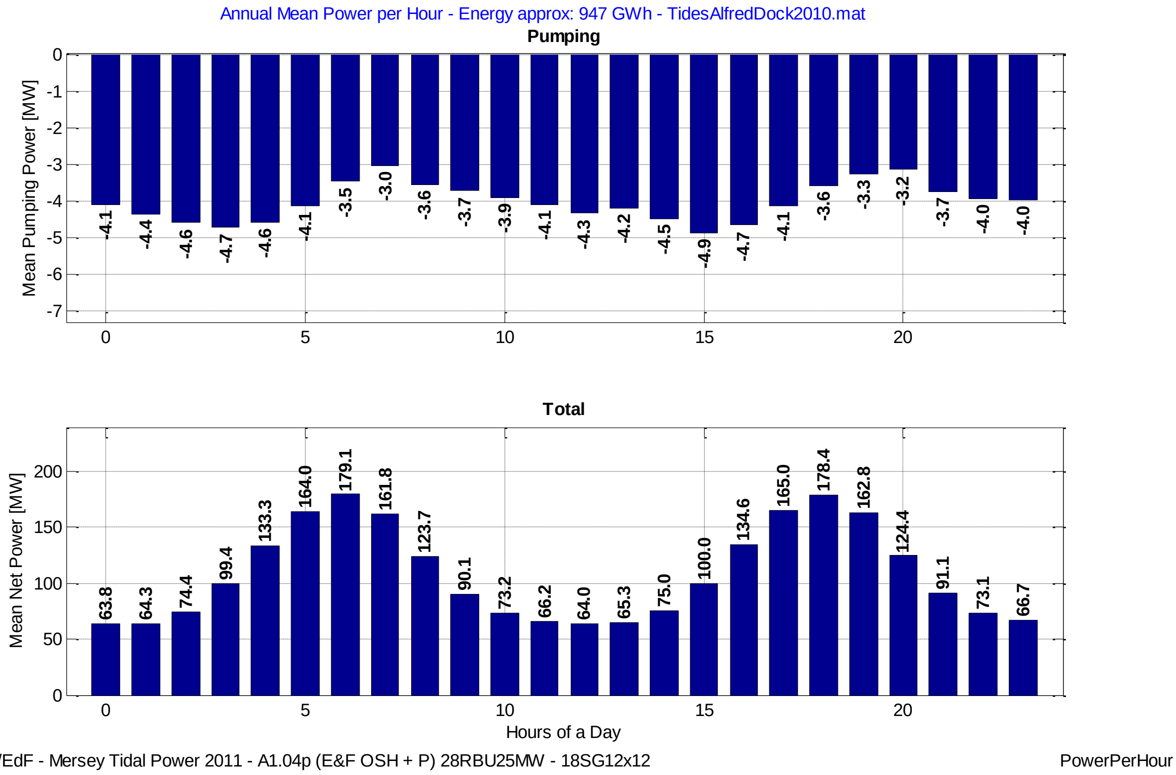

Figure H.47 - A1.04c (E&F OSH + P) - mean power per hour

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