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Lewis, Matthew; Angeloudis, A.; Robins, Peter; Evans, P.S.; Neill, Simon

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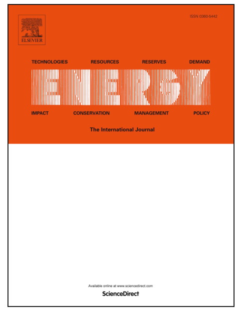

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M.J. Lewis, A. Angeloudis, P.E. Robins, P.S. Evans, S.P. Neill

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Influence of storm surge on tidal range energy

Lewis M.J[1], Angeloudis A[2,3], Robins P.E[1], Evans P.S[3], Neill S.P[4]

[1] Centre for Applied Marine Sciences, School of Ocean Sciences, Bangor University
[2] Department of Earth Science and Engineering, Imperial College London
[3] School of Engineering, Cardiff University
[4] School of Ocean Sciences, Bangor University

Abstract:
The regular and predictable nature of the tide makes the generation of electricity with a tidal lagoon or barrage an attractive form of renewable energy, yet storm surges affect the total water-level. Here we present the first assessment of the potential impact of storm surges on tidal-range power. Water-level data (2000-2012) at nine UK tide gauges, where tidal-range energy is suitable for development (e.g. Bristol Channel), was used to predict power. Storm surge affected annual resource estimates -5% to +3%, due to inter-annual variability, which is lower than other sources of uncertainty (e.g. lagoon design); therefore, annual resource estimation from astronomical tides alone appears sufficient. However, instantaneous power output was often significantly affected (Normalised Root Mean Squared Error: 3%-8%, Scatter Index: 15%-41%) and so a storm surge prediction system may be required for any future electricity generation scenario that includes large amounts of tidal-range generation. The storm surge influence to tidal-range power varied with the electricity generation strategy considered (flooding tide only, ebb-only or dual; both flood and ebb), but with some spatial and temporal variability. The flood-only strategy was most affected by storm surge, mostly likely because tide-surge interaction increases the chance of higher water-levels on the flooding tide.

Keywords:
Tidal energy; barrages; lagoons; storm surge; resource; reliability

1. Introduction:

The population of the world is approaching 7.5 billion, with high energy usage and an over-reliance on fossil fuels. Climate change and energy security concerns have driven an interest in renewable energy sources to provide electricity (e.g. Hooper and Austen 2013; Borthwick 2016). For example, 24-30% of UK electricity is planned to be generated by renewable sources by 2020, and almost entirely de-carbonised by 2050 (Hooper and Austen 2013; Postnote 2014). The transition from predictable and reliable energy sources (e.g. coal and nuclear) to intermittent renewable sources (e.g. wind and solar) is a major concern (Delucchi and Jacobson 2011; Coker et al. 2013; Postnote 2014; FES2015).

Electricity generation must match demand (unless large amounts of energy storage or interconnectors are constructed), hence the development of significant amounts of renewable energy schemes may jeopardise the inherent stability of the power grid (Petley and Aggidis 2016). One solution could be the development of tidal energy schemes, which are often presented as a firm, predictable, baseload renewable energy source (Clarke et al. 2006; Waters and Aggidis 2016); here we seek to investigate the predictability and reliability of tidal-range power due to storm surges.

1.1. Tidal range energy

Tidal energy is an attractive form of renewable energy because of the reliable and predictable nature of the astronomical tides (Lewis et al. 2015; Neill et al. 2016). The Earth-moon and Earth-sun systems are responsible for the astronomical tide, which is caused by gravitational forces in combination with the rotation of the Earth. The result of the astronomical tide is observed as regular, and predictable, rise and fall of the sea's surface; see Pugh (1996) for further details. Tidal range power utilizes the potential energy (E) from the water-level difference between two bodies of water, often called head (h), within the regular rise and fall of the tide; as described in Equation 1 derived by Prandle (1984). A wall and hydraulic structures block the incoming (flooding) or outgoing (ebbing) tide, separating these two bodies of water and creating the head (h) that drives flow through turbines (Xia et al. 2012), as described in Equation 1 (where A is the area of the internal basin, ρ is the density of water and g is acceleration due to gravity), and thus generates electricity. Further details can be found in Waters and Aggidis (2016), who provide a review of tidal range energy, including descriptions of lagoon or barrage design and strategies.

$$E = \frac{1}{2}\, A\, g\, \rho\, h^2 \qquad [1]$$

Tidal range power stations can be thought of in two forms: barrages and lagoons. Barrages span the entire width of a channel, with turbines embedded in the retaining wall, whilst lagoons work in the same way as barrages, except that a perimeter embankment is employed to impound the water (further details, see Waters and Aggidis 2016). For both tidal lagoon and tidal barrage schemes, electricity can be produced during the flooding tide (i.e. flow through turbines to fill up the landward basin) or ebbing tide (i.e. flow through turbines as the basin empties); hence there are three operating designs: "flood only", "ebb only", or two-way (both flooding and ebbing tides) - which we call "dual" here.

Flood only generation schemes have been calculated to be less efficient than ebb-only or dual (both flooding and ebbing tides) generation schemes in some cases (e.g. Xia et al. 2010), but could be more useful in flood defence (see Angeloudis et al. 2016a), as water-levels in the basin must be kept low (Baker 1991). Dual generation designs will produce more power, but require turbines to operate in both directions, and thus may be more costly (Waters and Aggidis 2016; Angeloudis and Falconer, 2016). All strategies have the option of "pumping" to optimise electricity generation (see Petley and Aggidis 2016), and it should also be noted that tidal-range schemes have been suggested for energy storage. No consensus on the tidal range electricity generation strategy exists, each having benefits and penalties that are not discussed here; however the power produced from any tidal range power scheme will depend on the square of head (h^2) within Equation 1, used to drive a flow (Q, in m^3/s) through the turbines (e.g. Angeloudis et al. 2016b; Waters and Aggidis 2016). Therefore, small variations in tidal elevation (i.e. h of equation 1) may result in large changes to power generation, and so we aim to investigate the reliability and predictability of tidal range power from small changes to water-levels due to non-astronomical tide effects.

Around 30 sites throughout the world have been identified as suitable for tidal range power (Charlier 2003), with schemes already in operation (or under development) in France, South Korea, Russia and China; see Hooper and Austen (2016). The UK is a macro-tidal region that includes one of the largest tidal ranges in the world (the Bristol Channel, see Lewis et al. 2014a); hence tidal energy in UK is extremely attractive (Neill et al. 2016). A number of sites within UK waters have been noted as suitable, which is defined as where the mean tidal amplitude is above 2.5 m (i.e. mean tidal range greater than 5m, see Baker 1991); for example, Mersey, Conwy and the Solway Firth (see Waters and Aggidis 2016). Indeed, Xia et al. (2012) states that a configuration of eight tidal lagoon power stations could produce ~10% of all UK current electricity demand, and so the predictability and reliability of tidal power in the UK should be investigated.

1.2. Tides and storm surges

The gravitational forcing of the Earth-moon system results in a semi-diurnal tide at potential tidal range sites (period of 12hours 25minutes and thus around two high waters a day), described by the principal semi-diurnal lunar constituent harmonic called M2. The spring-neap cycle, which arises from the interaction between the sun-Earth-moon systems, is described by the interaction of the M2 harmonic and the principal semi-diurnal solar constituent harmonic (S2); giving the fortnightly cycle of variation in tidal range called the spring-neap cycle (e.g. Robins et al. 2015; Neill et al. 2016). Much research has focused on the variability and predictability of the astronomical resource (e.g. Iyer et al. 2013; Robins et al. 2015; Neill et al. 2016), with increasing attention being made to predicting resource variabilities from non-astronomical effects, including implications of waves on the tidal-stream resource (e.g. Lewis et al. 2014b); however, no research has yet investigated storm surge impact to tidal range power.

Storm surges are the sea-level response to meteorological conditions (see Pugh, 1996), and in combination with the astronomical tide, result in the total still water level (i.e., excluding waves); often referred to as the storm tide (Lewis et al. 2011; Lewis et al. 2013). It is this storm tide that tidal range power will use to generate electricity. Negative storm surge events can counteract the astronomical tide, reducing the total storm tide, whilst positive storm surges raise sea-level above the astronomical tide and can result in coastal flooding; such as the disastrous 1953 North Sea flood (McRobie et al. 2005; Horsburgh et al. 2008).

In the UK, the magnitude of tidal amplitude is such that storm surges only represent a flooding threat in combination with high water, which has led to research into tide-surge interaction (Horsburgh and Wilson, 2007). The interaction of storm surges with the astronomical tide, due to shallow water and bottom friction, alters the magnitude and timing of high water (see Prandle and Wolf, 1978). A negative surge would retard tidal propagation, whilst a positive surge would advance the time of high water (Rossiter, 1961), with the water-level time-series also affected, as the surge peak is most likely to occur during a rising tide due to this tide-surge interaction (e.g. Horsburgh and Wilson, 2007). The result of tide-surge interaction is such that positive storm surges are more likely to occur on a flooding tide; see Horsburgh and Wilson (2007).

1.3. Storm surges and tidal range energy

Uncertainty in tidal height, due to interaction of tidal range power stations and the resource, has been investigated within the context of annual power estimation (i.e. resource assessment) for tidal range energy (see Xia et al. 2012; Yates et al. 2013); however the effect of storm surges to the predictability and reliability of power has not been investigated. If tidal power is to become a significant source of renewable electricity, then it is essential to understand the reliability and predictability of the resource (see Iyer et al. 2013). We hypothesise that storm surges will have a significant effect on the reliability of electricity supply from tidal range schemes: positive storm surges will increase water-levels and the resource, whilst negative surges will reduce the amount of electricity generated. Furthermore, resource estimates may be over-predicted by tide-only hydrodynamic modelling methods, due to tide-surge interaction processes (storm surge more likely to occur on a rising tide – see Horsburgh and Wilson, 2007), which would reduce the tidal range available for generating electricity.

Here, we investigate the effect of storm surges to the predicted power from tidal range energy, determining if “tide-only” (i.e. no storm surge) hydrodynamic models are acceptable for resource estimation, and if variability on power output due to storm surges warrants a tidal power electricity supply prediction system for grid planning measures. . In a site of (a) known tidal conditions, (b) a given plant operation sequence and (c) appropriate formulae that represent the performance of constituent hydraulic structures, it is feasible to simulate the overall performance of a tidal range power plant over transient conditions (Angeloudis and Falconer, 2016). The operation can be modelled using a water level time series as input. This corresponds to the 0D modelling approach of tidal range energy. Differences in the power estimated by the 0D modelling approach of

Angeloudis et al. (2016a; 2016b) will be investigated using tide gauges records of storm tide and the tide-only water-levels at all potential tidal range energy sites around the UK.

2. Methodology and power estimation

Quality controlled data from all UK A-class tide gauges is available from the National Tidal and Sea Level Facility (ntslf.org), through the British Oceanographic Data Centre (bodc.ac.uk). Both the storm tide water-level and the residual component (i.e. storm surge) are available at 15 minute intervals for each tide gauge site, with the residual calculated by subtracting the harmonic tidal prediction from the observed storm tide (Horsburgh and Wilson, 2007). We use this data to estimate the difference in tidal power estimation between the astronomical tide (harmonic "tide-only" estimates of sea level) and the actual sea level (storm tide).

Nine tidal gauges within the National Tidal and Sea Level Facility (ntslf.org) of UK waters were identified as potential tidal range energy sites where the M2 tidal component was greater than 2.5 m (i.e. the mean tidal amplitude). These nine tide gauge sites are shown in Figure 1, with the M2 amplitude calculated from a well validated 3D ROMS tidal model described in Lewis et al. (2014b). Interestingly, it should be noted that all sites identified using this method are on the west coast of the UK, with some sites on the east and south coast having M2 amplitudes just under the 2.5m threshold when the tide gauges were analysed (e.g. Dover).

An example of tide and storm tide data is shown in Figure 2 for a 36-hour period of an extreme positive storm surge (residual of 0.98m at HW, 30-Oct-2000 20:00) and negative storm surge (residual of -0.90m at HW, 13-Feb-2005 21:30) at the Mumbles tide gauge (site 5 – Table 1). Based on Equation 1, the difference in the maximum potential energy density can be calculated for the tidal range (difference between High Water, HW, and Low Water, LW) of the Figure 2. Figure 2a provides an example time-series of an extreme positive surge (0.98m storm surge) and reveals, if tide-only data is used, a 14.6% over-prediction of power on flooding tides (LW to the following HW), and a 14.8% over-prediction on ebbing tides (HW to the following LW). Figure 2b provides an example time-series of an extreme negative surge (-0.90m storm surge) and reveals, if tide-only data is used, a 3.1% under-prediction of power on flooding tides (LW to the following HW), and a 4.8% over-prediction on ebbing tides (HW to the following LW). Therefore, we show in the Figure 2 example that storm surge can have a theoretical influence on tidal range power.

To more accurately estimate the effect of storm surges on tidal range power, the 0D modelling approach of Angeloudis et al. (2016) is applied to 12 years of sea-level data, extracted at each of the nine sites; see Table 1. Our "0-D" modelling approach is based on the principles of Prandle (1984), Burrows et al. (2009) and Aggidis and Benzon (2013); details of the modelling method can be found in Angeloudis et al. (2016b), and are included here briefly for completeness only. The "0D" modelling approach is a backward difference numerical model that calculates the upstream water-level at the next time-step by using the previous upstream water-level, which defines the discharge (Q) through the tidal power structure (between the sea and the basin), and thus the amount of power available for the turbines (P); calculated using the hill chart of Figure 3 and the assumptions summarised in Table 2.

It should be noted that similar findings were found for small tidal power plant designs when comparing our "0D" modelling approach and depth-averaged shallow water equation, or "2D", modelling approaches that include many more physical processes coupled with operation algorithms of tidal range power plants (Yates et al. 2013; Angeloudis et al. 2016a; 2016b); hence the 0-D method is sufficiently accurate at estimating tidal-range power (Burrows et al. 2009; Yates et al. 2013) – especially as we shall explore the *relative difference* in predicted power between astronomical tide data (tide-only) and storm tide data (tide and storm surge). Water-level records at the nine tide gauges were between 76% and 94% complete (see Table 1), thus when no water-level data is present, no power is calculated with the 0D model. We therefore remove one tidal cycle (12.42hours) of the 0D model power estimate after a gap to allow the model to attain equilibrium. Such gaps will clearly affect the annual power estimations, but this will not affect our analysis here because it is the *relative difference* between the tide and storm tide power that is compared. An example of this 0D modelling method is shown in Figure 4, taken from the Newport tide gauge between 3-Dec-2006 and 4-Dec-2006, for the three electricity generation strategies (flood-only, ebb-only, and dual). In this 24-hour period, the amount of electricity generated was calculated as 1661.5 MWh, 1554.3 MWh and 2242.1 MWh for the flood-only, ebb-only and dual generation strategies, respectively.

3. Results

The tide and storm tide records for 12 years (2000-2012 to account for natural variability), at sites identified in Table 1, were applied to the 0D model and the instantaneous theoretical power estimated (see Section 2). Maximum positive storm surge events were recorded at Avonmouth (+2.34 m) and at Liverpool (+2.26 m), whilst minimum negative surges occurred at Liverpool (-1.26 m) and Newport (-1.25 m); although all sites experienced sizeable positive (> +1.3 m) and negative surges (< -0.7 m), with a near zero mean surge (see Table 3) - as is expected (hence the term mean sea level, which both tides and surges oscillate upon). However, frequently storm surges were greater than 10% of the measured tide in the water-level time-series (28% to 45% for the nine sites – see "EXC" in Table 3), and so surges do appear to alter the available resource for tidal-range power stations.

3.1. Tide-surge interaction

Times of high water (HW) and low water (LW) were calculated using the astronomic tide-only time-series, and the storm surge height relative to the time of HW used to investigate tide-surge interaction at each site; as is summarised in Table 3. At site 1 (Avonmouth) and site 3 (Hinkley Point), the mean storm surge tended to be positive at HW and during the flood stage of the tide, whilst the storm surge tended to be negative at LW and during the ebb stage of the tide. Site 2 (Newport) also exhibited similar trends to sites 1 and 3 (see Table 3), with the exception that the mean low water (LW) surge is near zero instead of negative. Other tide gauge locations (sites 4-9) showed a less pronounced trend, and can be considered to typically exhibit less tide-surge interaction; we demonstrate this with Fast Fourier Transform (FFT) analysis of the residual ("storm surge") time-series, with the amplitude of the peak closest to 12.42 h being shown in Table 3 as a percentage of the mean astronomical tide amplitude (M2). This FFT analysis of the storm surge component aims to quantify the magnitude of tide-surge interaction, by calculating the magnitude of the oscillation of the storm surge time-series with the period of the tide; showing that sites 1 (Avonmouth), 2 (Newport) and 3 (Hinkley Point) have the strongest tide-surge interaction measure (see Table 3).

To further demonstrate tide-surge interaction, we show the mean tide-surge climate for a number of interesting sites, by plotting the surge magnitude likelihood at different times relative to HW. Storm surge was discretised into ½ hour and 5 cm 'bins' and plotted in Figure 5. The storm surge distribution relative to the time of High Water (HW) for the 12-year record at Hinkley Point (site 3) is shown in Figure 5, and shows that a positive storm surge is more likely before high water during the flooding tide with a negative surge more likely at low water. The contrasting site of Mumbles tide gauge, where little tide-surge interaction was found, is shown in Figure 6. Intra-tidal storm surge distributions for all nine tide gauge sites can be found in the online supplement.

3.2. Propagation of tide and storm tide data through to power estimation

Power estimates were calculated using the 0D model approach, with an example shown in Figure 7 for the extreme positive surge event of 0.98m (Figure 2a), and in Figure 8 for the extreme negative surge event of -0.90m (Figure 2b) recorded at Mumbles tide gauge. In the extreme positive surge event of Figure 7, flood-only peak power was under-predicted by tide-only data, yet net electricity generated was similar (<1% under-prediction with tide data); which differs from our theoretical assessment in Figure 2a, and is likely because tidal range power station operating behaviour is included within the 0D modelling approach. Power was over-predicted using tide-only data for both dual and ebb-only strategies in Figure 7; with ~14% difference at peak power times and ~10% for electricity produced (i.e. MWh) in this 36 hour period. Tide-only power was found to over-predicted estimated power in the negative storm surge event of Figure 8 for all three strategies; ~20% (flood), 9% (ebb) and 5% (dual). Therefore, it appears storm surges can result in differences to estimates of tidal range power (both the timing and magnitude of estimated power output).

To summarise the influence of storm surge on tidal range power, the performance of technical power prediction using tide data was compared with storm tide data, an example of which is shown in Figure 9 for Hinkley Point (site 3), with results for all nine tide gauge sites shown in the online supplement. Assuming the storm tide power estimate is "actual", and the tide-only power is "predicted", the Normalised Root Mean Squared Error (NRMSE) was calculated to be between 4% and 5% for all electricity generation scenarios in Figure 9. The error is calculated as the difference between power estimated using storm tide data (Ptotal) and power estimated using tide-only data (Ptide); hence the Root Mean Squared Error (RMSE) was calculated using Equation 2, where *n* is the number of observations and thus NRMSE is calculated as the RMSE divided by the range of Ptotal values. We also find that there is a large amount of variability (spread of data) in comparison between storm tide and tide power in Figure 9; with a Scatter Index (SI) of 29% and 31% for ebb-only generation and flood-only generation strategies respectively, and 15% for dual generation (see also Table 4). The scatter index is calculated as the RMSE divided by the mean of power estimated with storm tide data (Ptotal); see Equation 3.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Ptotal_i - Ptide_i)^2}{n}} \qquad [2]$$

$$SI = \frac{RMSE}{\overline{Ptotal}} \qquad [3]$$

Values of zero power estimated in Figure 9 are due to timing differences in generated power (e.g. see Figure 7 and 8) and were present at all sites (see online supplement). Comparing only peak power generated per tide (i.e. irrespective of timing) we find the Scatter Index (SI) reduces considerably (to 9%, 8% and 5% for flood, ebb and dual respectively) but the mean error and bias remain similar. At Hinkley Point therefore, storm surges affect water-levels (see Figure 9) which affect the timing and the magnitude of electricity generation, but overall, the mean annual resource is affected by only a small amount; with an under-prediction of the resource with tide-only data by 1%.

A comparison of power estimated with tide-only and storm tide data for a contrasting site, the Mumbles tide gauge, where relatively minimal tide-surge interaction was found (see Figure 6), is shown in Figure 10. A similar amount of scatter to Hinkley Point (Figure 9) can be seen in Figure 10, but much less bias and annual resource differences, as can be seen in Table 4, which summarises the influence of storm surge at all nine tide gauge locations. Spatial variability to the effect of surges was found between the tide gauges; sites 1-3 (Avonmouth, Newport and Hinkley) exhibited stronger tide-surge interaction (see Table 3) and showed annual power estimates were typically under-predicted with a tide-only model. Furthermore, the flood-only generation strategy appears the most affected at these high tide-surge interaction sites (sites 1, 2 and 3) - with higher bias measures and annual resource differences (see Table 4). Furthermore, the Scatter Index (SI) and the Normalised Root Mean Squared Error (NRMSE) was consistently high for all sites in Table 4 (3% to 8%) with over

100% differences in predicted power due to surges occurring for ~50% of the time at all sites (see Table 4).

Averaged for the nine sites, the mean annual power between tide and storm data differed by 0.7% for both flood-only and ebb-only generation strategies. The flood-only strategy was slightly more influenced by storm surge than the ebb-only strategy; with a SI of 37% and bias of -0.38 (for flood-only) compared with 33% (SI) and -0.27 (bias) for ebb-only. The dual generation strategy reported the smallest scatter (SI of 18%), bias (-0.09) and mean annual power difference (-0.2%) when averaged for the nine sites; hence the dual strategy appears the least affected by storm surges. Moreover we find, on average, the mean annual resource estimate is under-predicted with tide-only data (for any electricity generation strategy), but by less than 1%; hence tide-only resource assessments appear sufficient.

4. Discussion

Power generation from tide-only data was compared with power generation from storm tide data (i.e. the astronomical tide plus the storm surge) for nine potential tidal range power station locations in the UK (see Baker 1991). The inclusion of storm surge in estimating the available power reduced the mean annual resource estimate by <1% for the 12-year tide gauge records when averaged for all nine sites, but some spatial and temporal variability was found, as summarised in Figure 11; with storm surges increasing the annual resource by 5% (at Avonmouth and at Newport in 2007) or reducing the annual resource by 3% (at Avonmouth in 2003; see Table 4). Therefore, the storm surge climate will affect tidal range resource estimates, and hence the use of a tide-only resource assessment will typically under-predict the available resource by ~1%. However, storm surge effects to the annual resource estimation that we observe are small in comparison to other uncertainties, such as the resource interaction with the lagoon or barrage scheme itself (reported to be ~10% - 30% by Yates et al. (2013) and Angeloudis et al. (2016a)) or due to operational strategy and design (~20%, see Petley and Aggidis 2016).

An important coastal phenomenon in the context of this study is tide-surge interaction, as described by Horsburgh and Wilson (2007). Our analysis isolates three out of nine UK sites where tide-surge interactions were significant, which resulted in positive surges being more likely on a flooding tide, and negative surges more likely on an ebbing tide (Table 4). The net result being a mean increase in the annual resource estimate by 1% due to storm surges, with the flood-only generation strategy more affected than the other generation strategies at these sites (see Figure 12a), which is counter to the hypothesis that tide-surge interaction reduces the tidal range and thus the resource. Instead, storm surges typically increase the technical resource, as lagoon filling and emptying characteristics (included in the 0D model) often omit any tide-surge interaction effects hypothesised; see Figures 12a and 12c. As tidal range power schemes will alter the local and potentially far-field tidal dynamics (Hooper and Austen 2013), and storm surge magnitude is dependent on water depth (Pugh 1996), future work should investigate the interaction of storm surges and tidal energy infrastructure – including likely effects to actual electricity production, as well the interaction of tidal energy schemes with the interaction of other marine processes (including the effects of the structures on waves and hence on the resource, see Fairley et al. 2014).

Comparing the difference in instantaneous power between tide-only and storm tide data, a mean error between 3% and 8% was calculated for the nine sites, with a large amount of variability found; as summarised in Figure 12. Differences in the storm surge effect to predicted power were also found between electricity generation strategies, with flood-only generation being the most affected and the duel generation strategy least affected (Table 4 and Figure 12). Calculating the error in predicting instantaneous power output from tide-only data, the mean Scatter Indices (SI) of 37%, 33% and 18%, were calculated at the nine sites for flood-only, ebb-only and dual generation strategies respectively. Therefore, the variability to predicted electricity due to storm surges alters the often-stated idea of the “firm and reliable” renewable energy potential of the tides (e.g. Lewis et al. 2015).

The intermittency and reliability of renewable electricity supply have been raised as issues warrant of investigation by the National Grid, who own and manage the UK electricity network (Coker et al. 2013; Postnote 2014; FES2015). In a recent review, Borthwick (2016) stated that energy storage is essential to rectify the temporal variability in ocean energy output, yet it should be emphasised that storm surges are routinely and accurately predicted as part of the early warning flood forecast system for the UK (Horsburgh et al. 2008; Flowerdew et al. 2013), and therefore accurate prediction of electricity supply from tidal-range schemes is easily achievable several days in advance.

The Normalised Root Mean Squared Error (NRMSE) of estimated power between tide and storm tide data, showed flood-only and ebb-only generation strategies were influenced equally by storm surges when averaged through the nine sites (average impact of 5%), with the dual strategy having a slightly lower NRMSE of 4% and a lower Scatter Index (see Figure 12). Although dual-mode tidal-range power may be less efficient because of turbine costs (Waters and Aggidis 2016), this strategy appears less affected by storm surges, and thus is a more predictable and reliable form of renewable electricity.

Finally, if we compare the measures of error and accuracy between using tide only data and total water-level data to predict tidal-range power, as shown in Figure 12, we see there is a trend of an increasing storm surge effect to predicted power with increasing tidal range (defined here as the sum of M2 and S2 amplitude components, called the Mean High Water Spring or MHWS). For example, locations with the largest tidal range were found to have the biggest difference when comparing predicted power between the two methods (Figure 12e and 12f). Therefore, from a global perspective, where large tidal range is required for tidal power (mean tidal range above 5 m; Baker 1991) or in areas where climate change may increase storminess (Lewis et al. 2011), we should expect that storm surge is likely to affect electricity generated by tidal range power stations.

5. Conclusion

Renewable energy sources are intermittent, and pose a challenge with integration to the electricity supply network due to concerns of reliability. Tidal power is often presented as a firm renewable energy source with predictable intermittency based on the tidal period. Using data from UK tide gauge records, we show storm surges alter water-level in regions suitable for tidal energy, which can affect the theoretical instantaneous power of a tidal-range energy scheme. Although a roughly equal number of positive and negative storm surges occur within a year, annual resource estimation was shown to be influenced by the storm surge climate, most likely due to wave-tide interaction effects, but the effect to annual resource estimation was small – especially compared to other sources of uncertainty. Therefore, tide-only resource assessments appear largely accurate, but, due to the large amount of variability in instantaneous power, storm surge predictions may be required for incorporation of tidal range electricity into an electricity grid – something already done routinely as part of coastal flood risk early warning system in the UK. Further, of the three electricity generation methods for tidal range power, the flood-only strategy is most influenced by storm surges and dual electricity strategy the least, which could be an important factor in consideration of scheme design.

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Figure Captions:

Figure 1: The amplitude of the major semi-diurnal lunar tidal constituent (M2) around the UK when above 2.5 m (thus suitable for tidal range power), taken from the validated ROMS model of Lewis et

al. (2014b). Tide gauges are shown as black dots, with tide gauges at potential lagoon sites (M2 > 2.5 m) shown as red stars.

Figure 2: Example of a tide gauge observed water-level data (η) for the Mumbles tide gauge (site 5 in Table 1), with the total water-level (storm tide) shown as a red line, and the storm surge component used to calculate the astronomical tide (tide-only), shown as a blue line. A 36 hour record of an extreme positive storm surge (0.98m at HW) is shown in panel a, and a 36 hour record of an extreme negative storm surge (-0.90m at HW) is shown in panel b.

Figure 3: Hill-Chart calculated according to the turbine specifications of Table 2.

Figure 4: Computed power using a 0D modelling approach for three electricity generation strategies; Flood-only, Ebb-only and Dual for a 24 hour period. The 0D model takes tidal elevation data (panel a), to estimate water-level difference within a basin or lagoon and thus the estimated flow rate through turbines (panel b), which is used to calculate the theoretical power time-series (panel c).

Figure 5: Hinkley Point (site 3) intra-tidal storm surge distribution, calculated with 12 years of data. The storm surge (residual from tide gauge), with hourly mean (red line) including two standard deviations (red dashed line) is shown in Panel A; Panel B is the probability of storm surge climate (coloured %) discretised into ½ hour and 5 cm storm surge bins. Panel C shows the probability distributions when these storm surges are grouped according to tidal stage (flooding, ebbing, HW and LW).

Figure 6: The Mumbles tide gauge (site 5) intra-tidal storm surge distribution. The storm surge (residual from tide gauge), with hourly mean (red line) including two standard deviations (red dashed line) is shown in Panel A; Panel B is the probability of storm surge climate (coloured %) discretised into ½ hour and 5 cm storm surge bins. Panel C shows the probability distributions when these storm surges are grouped according to tidal stage (flooding, ebbing, HW and LW).

Figure 7: The effect on estimated tidal power during an extreme positive storm surge (0.98m at HW) observed at Mumbles tide gauge (see Panel a). The effect on predicted power when using tide-only water levels or the storm tide is shown for three electricity generation strategies Flood-only (b), Ebb-only (c), and in panel d, Dual (both flood and ebb generation).

Figure 8: The effect on estimated tidal power during an extreme negative storm surge (-0.90m at HW) observed at Mumbles tide gauge (see Panel a). The effect on predicted power when using tide-only water levels or the storm tide is shown for three electricity generation strategies Flood-only (b), Ebb-only (c), and in panel d, Dual (both flood and ebb generation).

Figure 9: The difference of predicted instantaneous power when using tide-only or storm tide data (2000-2012) from Hinkley Point tide gauge for three electricity generation strategies: (a) flood-only, (b) ebb-only, and (c) dual; which allows the probability distribution of the difference in power (δ Power) between tide-only and storm tide predicted tidal-range power to be calculated (bottom right panel)

Figure 10: The difference of predicted instantaneous power when using tide-only or storm tide data (2000-2012) from Mumbles tide gauge for three electricity generation strategies: (: (a) flood-only, (b) ebb-only, and (c) dual; which allows the probability distribution of the difference in power (δ Power) between tide-only and storm tide predicted tidal-range power to be calculated (bottom right panel)

Figure 11: Temporal variability of the difference in the estimated mean annual tidal range power between tide and storm tide data for the 9 tide gauge sites and three electricity generation scenarios; flood (a), ebb (b) and dual; both flood and ebb tide generation (c). The mean of all sites is shown as a solid black line with one standard deviation either side of this mean as a dotted line, and the grey shaded area showing the range of values. Note, a negative change in the annual power estimate indicates the tide-only resource assessment over-predicts the resource.

Figure 12: The difference between tidal range power predicted using tide-only and storm tide (tide and storm surge) sea-level data for 9 UK tide gauge sites suitable for tidal energy development, shown here as a product of their Mean High Water Spring (MHWS) tidal range height.

Table 1: Tide gauge information used for tidal energy variability analysis between 2000 and 2012, ranked in order of M2 amplitude (amp), the combination of M2 with S2 amp gives rise to the estimated Mean High Water Spring Range (MHWSR) and Mean High Water Neap Range (MHWNR) relative to mean sea level.

N	Tide gauge name	Position		M2 amp (m)	S2 amp (m)	MHWSR (m)	MHWNR (m)	Data availability (%)
1	Avonmouth	51.51°N	2.72°W	4.27	1.51	11.56	5.52	87
2	Newport	51.55°N	2.99°W	4.14	1.47	11.22	5.34	88
3	Hinkley Point	51.21°N	3.13°W	3.92	1.40	10.64	5.04	79
4	Heysham	54.03°N	2.92°W	3.17	1.03	8.40	4.28	80
5	Mumbles	51.57°N	3.98°W	3.12	1.12	8.48	4.00	82
6	Ilfracombe	51.21°N	4.11°W	3.04	1.10	8.28	3.88	76
7	Liverpool	53.45°N	3.02°W	3.04	0.98	8.04	4.12	83
8	Workington	54.65°N	3.57°W	2.74	0.88	7.24	3.72	94
9	Llandudno	53.33°N	3.82°W	2.69	0.87	7.12	3.64	89

Table 2. Assumptions and specifications of the 0-D modelling approach used to estimate the tidal range power.

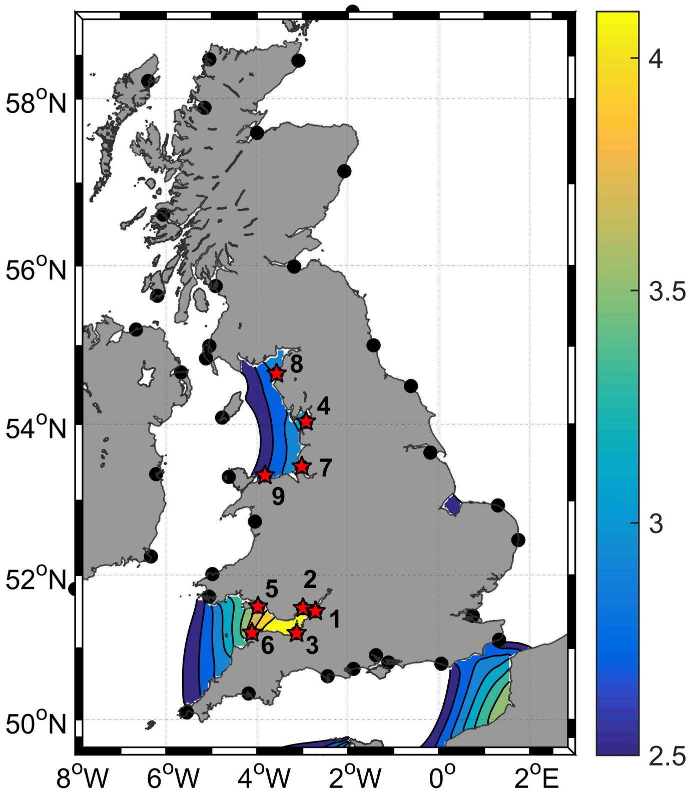
Impounded Surface Area (A)	10 km^2
Turbine Number (N_t)	15
Sluice Gate Number (N_s)	10
Sluice Gate Area (A_s)	100 m^2
Turbine Capacity (C_p)	20MW
Turbine Diameter (D)	7.35m
Minimum Generation Head (h_{min})	1.0m
One-way Starting Head (h_{st})	4.0m
Two-way Starting Head (h_{st})	2.5m
One-way Holding Time (h_t)	3.5hours
Two-way Holding Time (h_t)	2.0hours
Impounded Surface Area (A)	10 km^2

Table 3. The storm surge climate at nine potential tidal-range energy sites around the UK based on 12-year data records. We calculate tide-surge interaction (measured as a percentage of the mean tidal amplitude); maximum, minimum and mean surges; and mean surges relative to the tidal stage. EXC, shows the amount of time the storm surge was measured to be above 10% of measured astronomical tidal height.

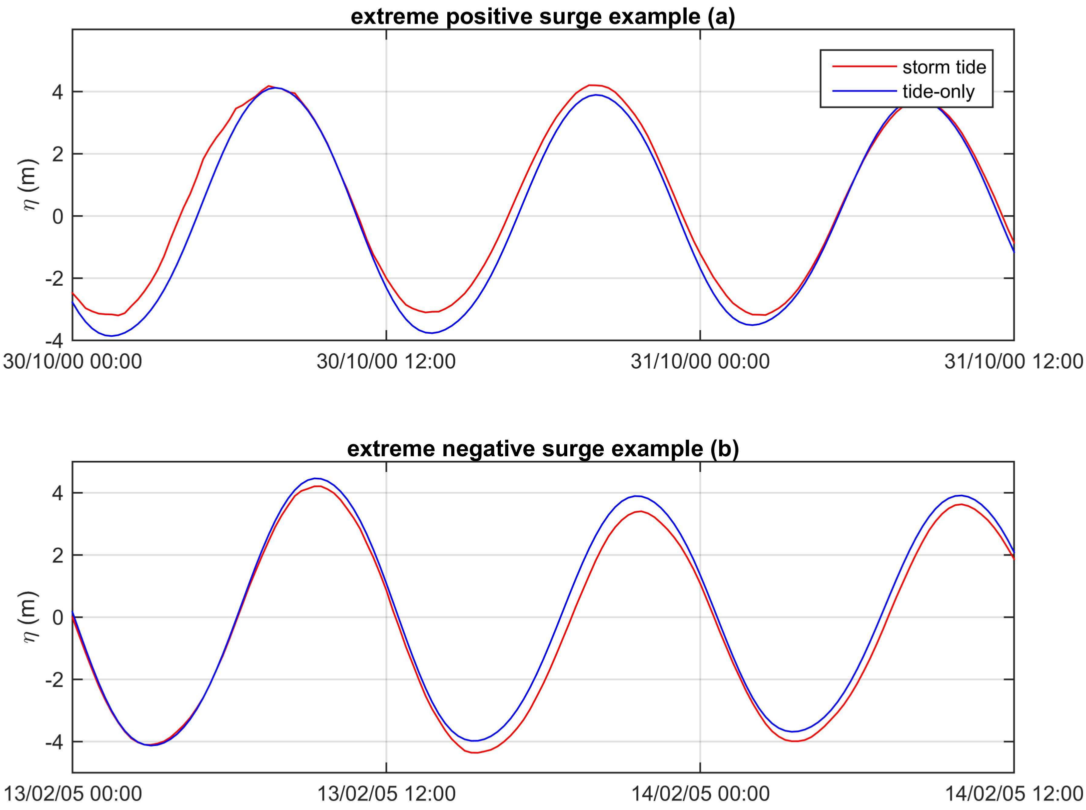
	Site name	Amplitude of M2 signal (~12.42hrs) within residual	EXC	Surge event (m)			Mean surge (m) for:			
				max	min	mean	HW	LW	flood	ebb
1	Avonmouth	2.1% (0.09m)	39%	2.34	-1.20	0.04	0.12	-0.03	0.05	-0.09
2	Newport	1.7% (0.07m)	34%	2.22	-1.25	0.05	0.10	0.01	0.04	-0.04
3	Hinkley Point	1.4% (0.06m)	28%	1.99	-0.94	0.01	0.06	-0.03	0.04	-0.02
4	Heysham	0.6% (0.02m)	38%	2.12	-1.23	0.06	0.07	0.04	0.08	0.06
5	Mumbles	0.9% (0.03m)	32%	1.41	-0.90	-0.02	0.00	-0.03	-0.01	-0.02
6	Ilfracombe	1.2% (0.04m)	30%	1.11	-0.70	0.05	0.08	0.02	0.04	0.06
7	Liverpool	0.7% (0.02m)	39%	2.26	-1.26	0.06	0.08	0.05	0.07	0.07
8	Workington	0.7% (0.02m)	45%	1.90	-1.37	0.01	0.02	-0.01	0.02	0.00
9	Llandudno	0.6% (0.02m)	36%	1.3	-1.07	0.00	0.01	-0.01	0.00	0.00

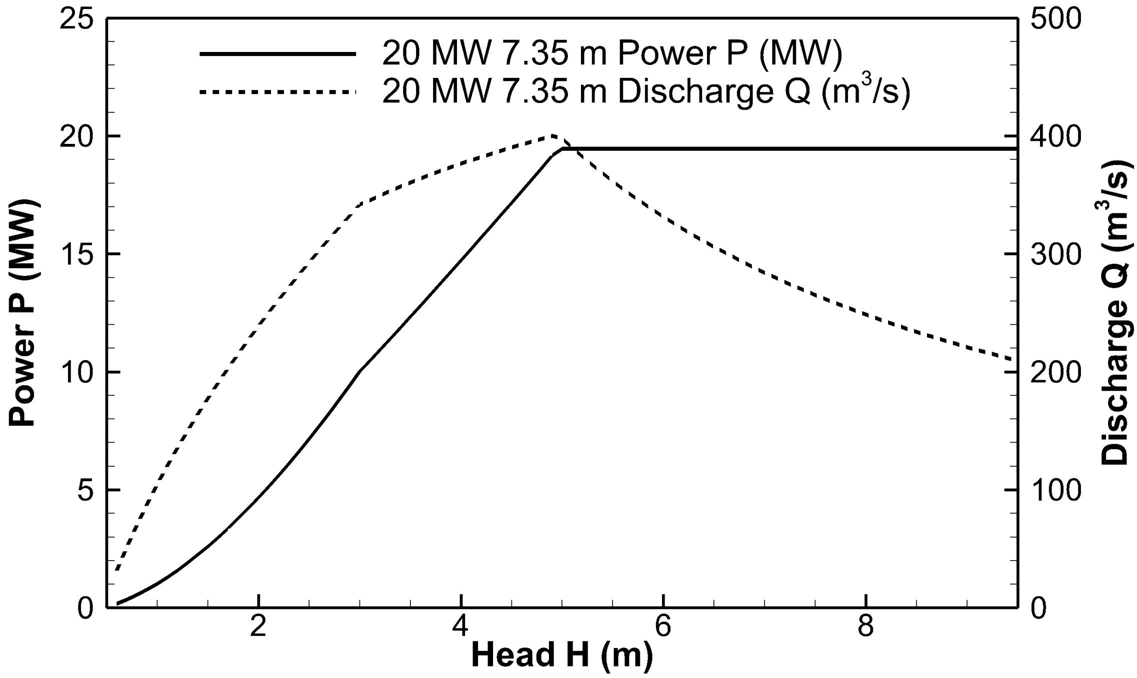
Table 4: Summary of the predicted power difference when using tide-only water-levels compared with the storm tide water levels, for the nine potential tidal-range energy sites around the UK. Root Mean Squared Errors (RMSE) of instantaneous power differences and mean annual power differences (tide vs. storm tide) were calculated for 12 years (2000-2012) with Scatter Index (SI) and bias. R^2 values were also calculated from linear regression of power estimated with tide-only or storm tide data.

Site number and electricity generation strategy		Power differences exceeded 100% as % of record length	RMSE (MW) NRMSE as % in brackets	R^2 (%)	SI (%)	Bias	Mean annual power error (%)		
							mean	min	max
1 (Avonmouth)	flood	57%	23.75 (8%)	94	41	-1.50	-3	-5	0
	ebb	50%	20.03 (7%)	94	38	-0.62	-1	-5	2
	dual	55%	12.05 (5%)	97	16	0.86	1	-1	3
2 (Newport)	flood	49%	21.18 (7%)	95	36	-1.37	-2	-5	0
	ebb	50%	16.65 (6%)	96	29	-0.21	0	-3	2
	dual	52%	13.8 (6%)	96	17	-0.12	0	-2	2
3 (Hinkley)	flood	46%	16.03 (5%)	97	31	-0.6	-1	-3	1
	ebb	45%	15.1 (5%)	97	29	-0.68	-1	-4	1
	dual	45%	10.85 (4%)	97	15	-0.91	-1	-3	0
4 (Heysham)	flood	46%	13.41 (5%)	96	39	0.00	0	-1	2
	ebb	45%	10.66 (4%)	97	32	-0.21	-1	-2	1
	dual	47%	8.5 (4%)	97	18	-0.28	-1	-2	1
5 (Mumbles)	flood	48%	10.24 (4%)	97	33	0.09	0	-2	1
	ebb	48%	10.62 (4%)	97	32	-0.22	-1	-3	1
	dual	51%	8.22 (4%)	97	17	-0.02	0	-2	1
6 (Ilfracombe)	flood	52%	9.11 (3%)	97	39	0.21	1	-1	2
	ebb	54%	8.94 (3%)	98	34	0.05	0	-1	1
	dual	59%	7.19 (3%)	98	20	0.23	1	-1	1
7 (Liverpool)	flood	51%	13.53 (5%)	96	41	0.02	0	-2	2
	ebb	44%	10.37 (4%)	96	37	-0.28	-1	-3	1
	dual	49%	8.61 (4%)	96	20	-0.23	0	-2	1
8 (Workington)	flood	42%	9.66 (4%)	97	37	-0.21	-1	-3	0
	ebb	43%	8.43 (4%)	97	34	-0.21	-1	-3	1
	dual	48%	7.41 (5%)	96	20	-0.19	-1	-2	1
9 (Llandudno)	flood	44%	9.67 (4%)	97	38	-0.08	0	-2	1
	ebb	47%	8.02 (4%)	96	36	-0.08	0	-2	1
	dual	47%	6.46 (4%)	97	18	-0.17	-1	-2	1

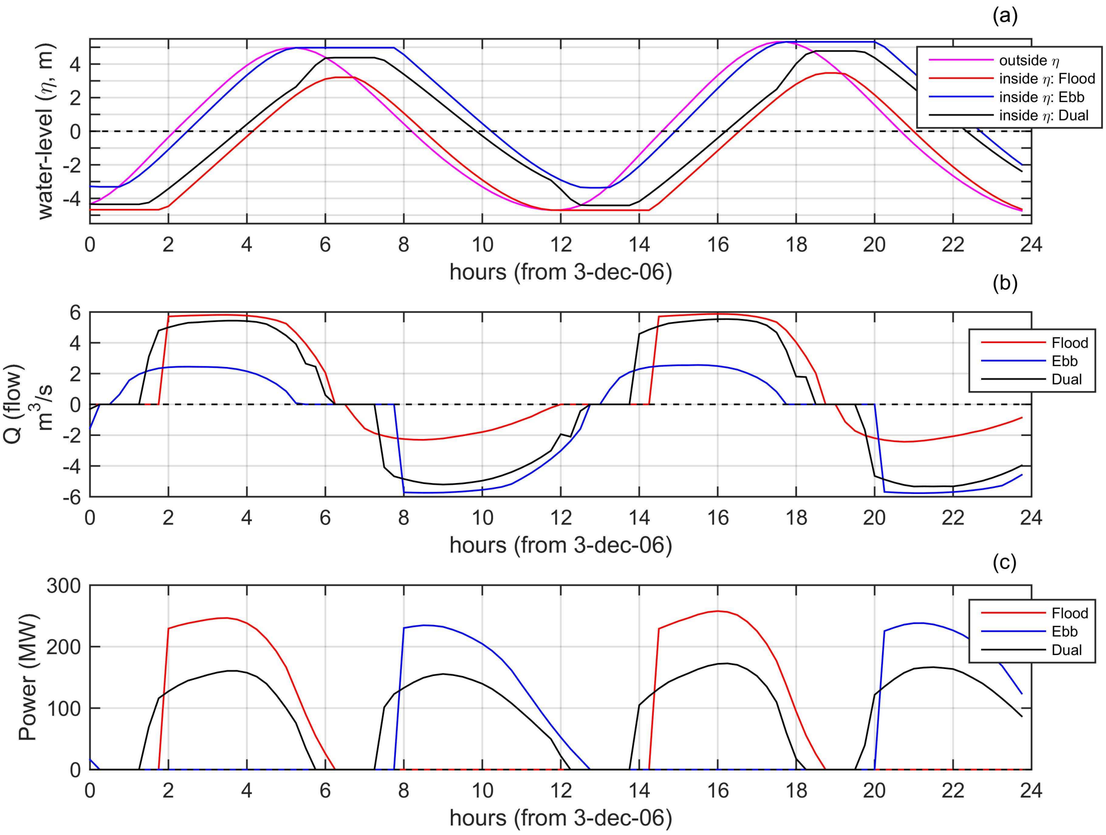


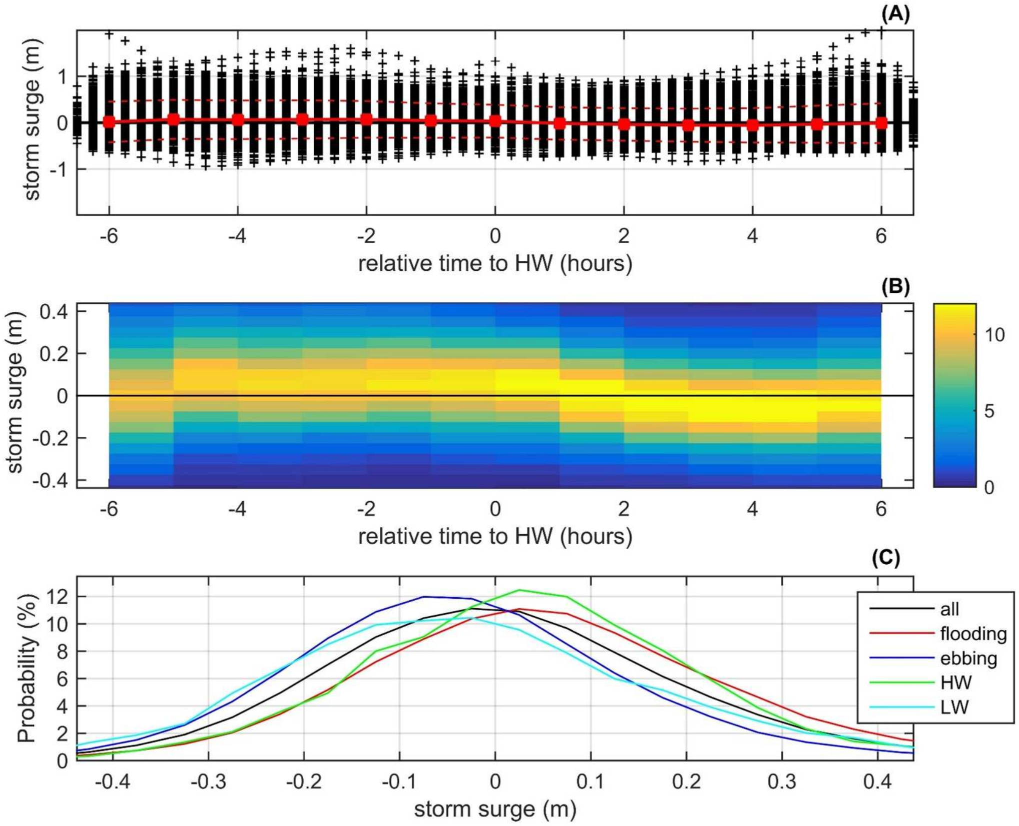
58°N
56°N
54°N
52°N
50°N
8°W
6°W
4°W
2°W
0°
2°E
1
2
3
4
5
6
7
8
9
4
3.5
3
2.5

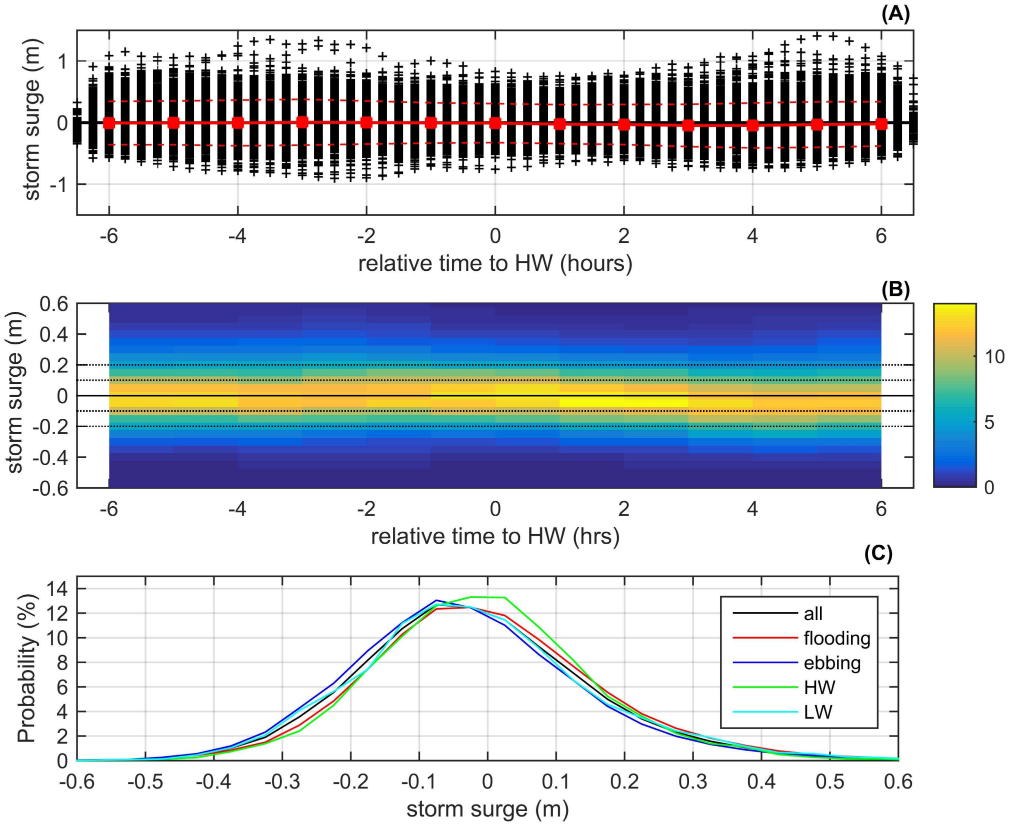

extreme positive surge example (a)
storm tide
tide-only
η (m)
4
2
0
-2
-4
30/10/00 00:00
30/10/00 12:00
31/10/00 00:00
31/10/00 12:00
extreme negative surge example (b)
η (m)
4
2
0
-2
-4
13/02/05 00:00
13/02/05 12:00
14/02/05 00:00
14/02/05 12:00

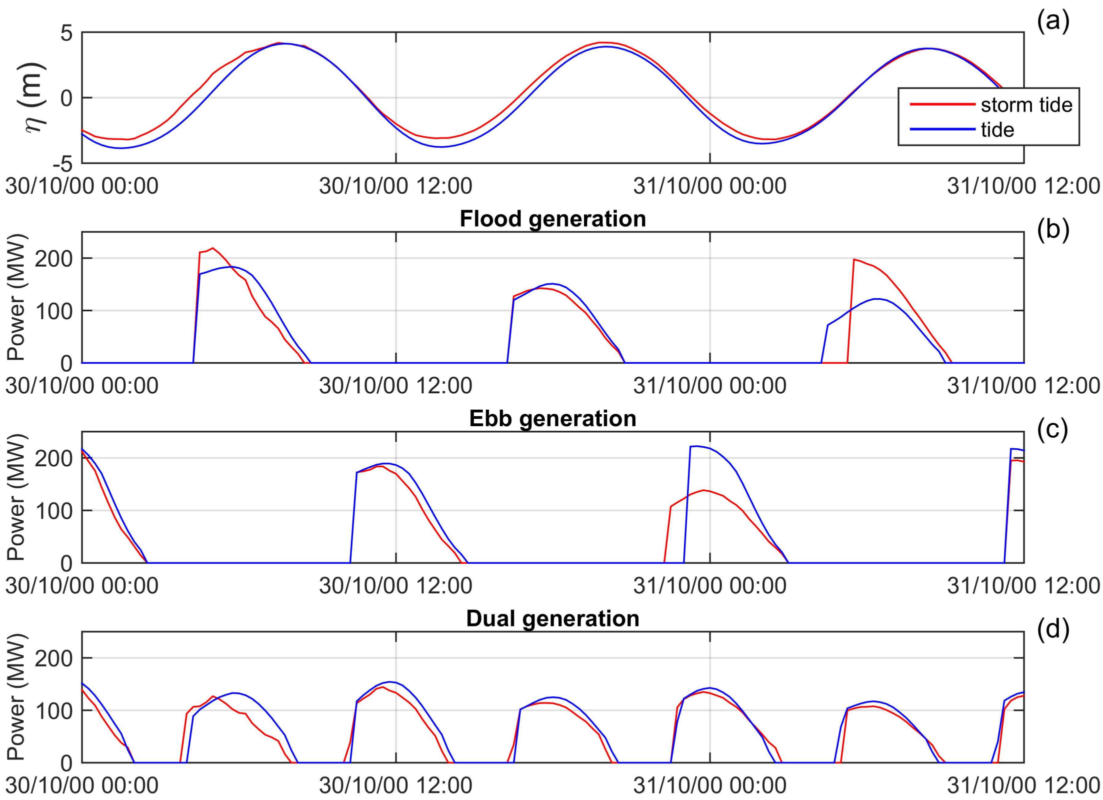


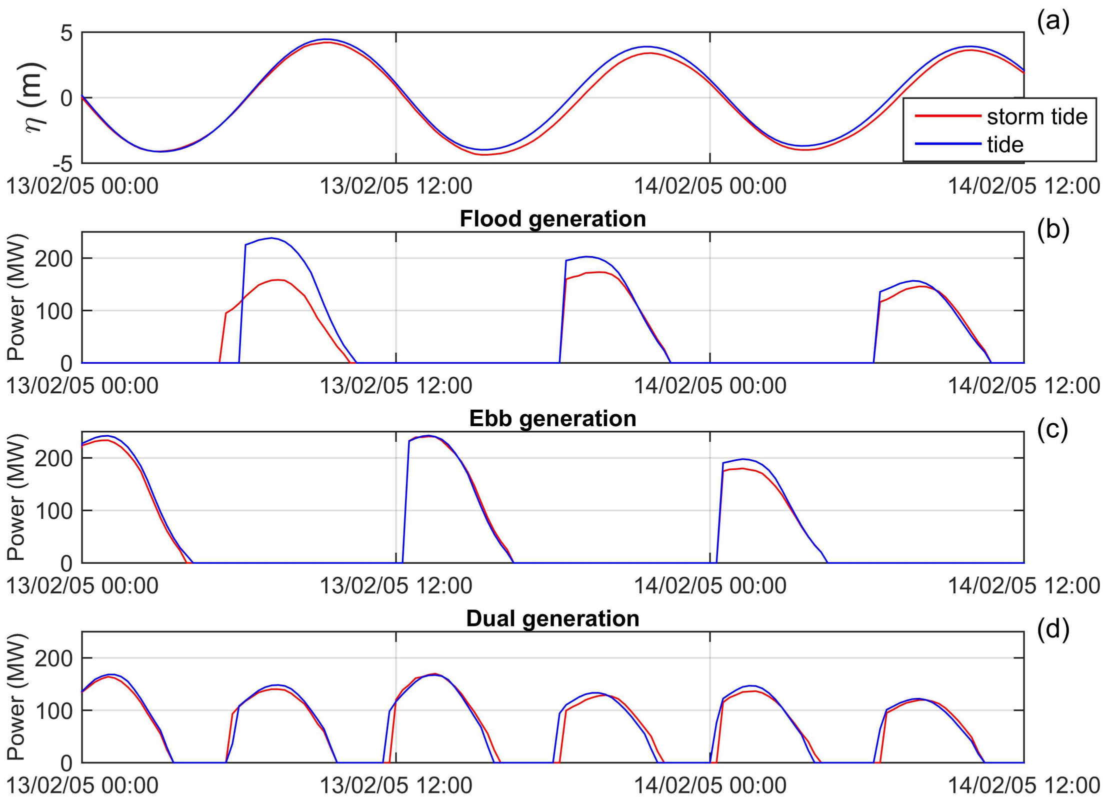
20 MW 7.35 m Power P (MW)
20 MW 7.35 m Discharge Q (m3/s)
Power P (MW)
Discharge Q (m3/s)
Head H (m)
0
5
10
15
20
25
0
100
200
300
400
500
2
4
6
8

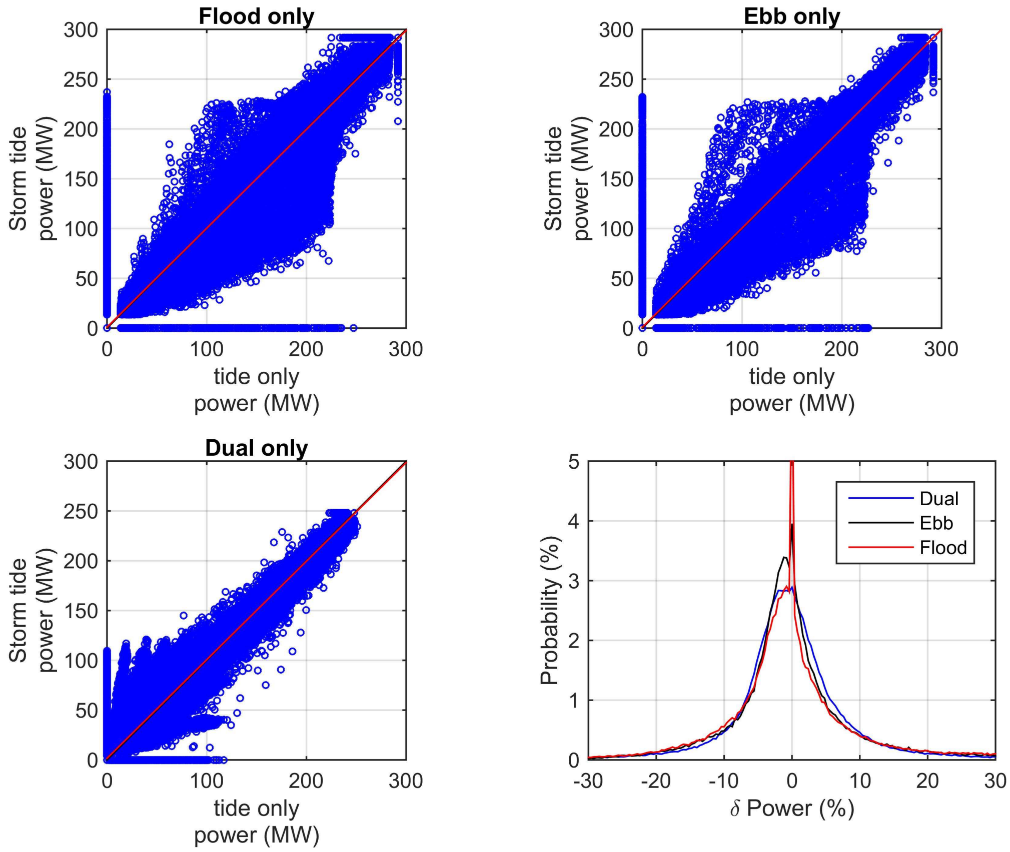

(a)
water-level (η, m)
outside η
inside η: Flood
inside η: Ebb
inside η: Dual
hours (from 3-dec-06)
(b)
Q (flow) m^3/s
Flood
Ebb
Dual
hours (from 3-dec-06)
(c)
Power (MW)
Flood
Ebb
Dual
hours (from 3-dec-06)

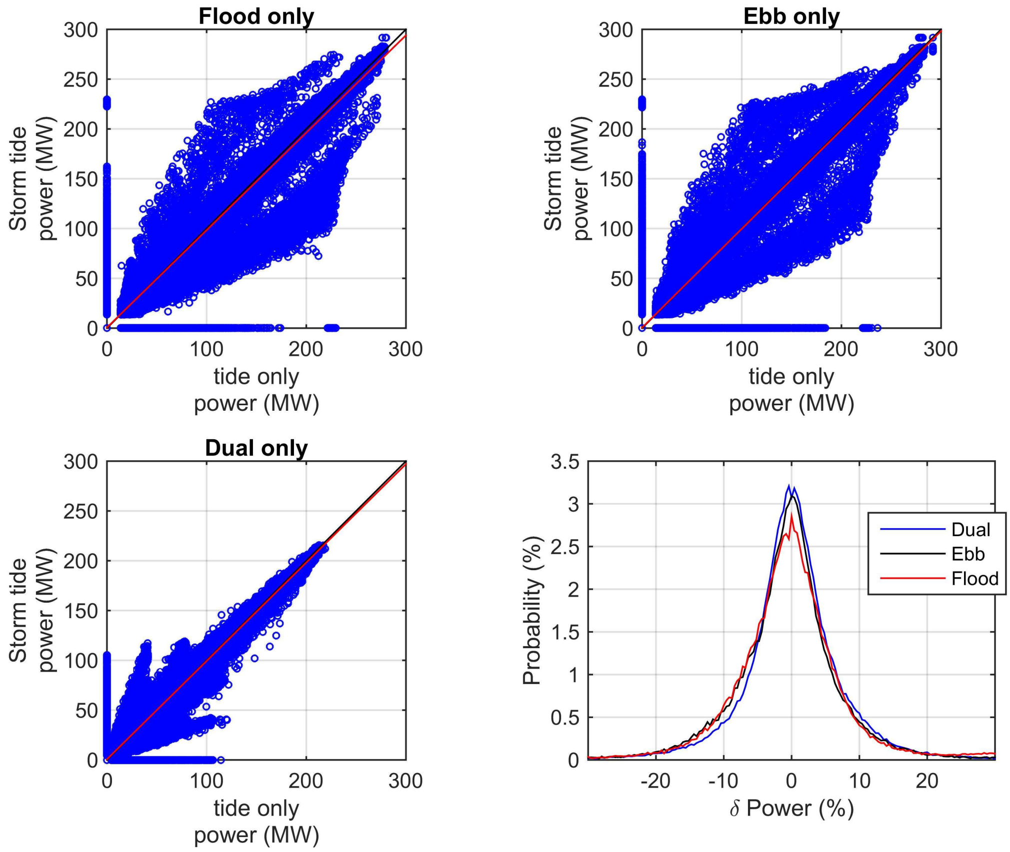

(A)
storm surge (m)
relative time to HW (hours)
(B)
storm surge (m)
relative time to HW (hours)
(C)
Probability (%)
storm surge (m)
all
flooding
ebbing
HW
LW

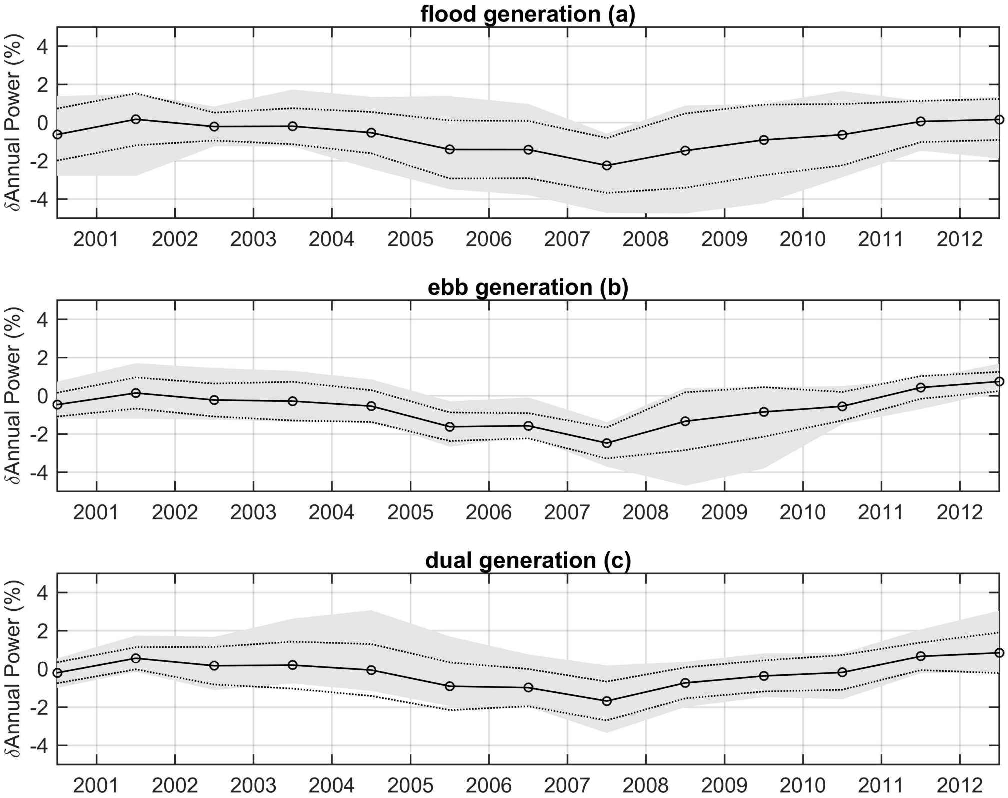

(A)
storm surge (m)
1
0
-1
-6
-4
-2
0
2
4
6
relative time to HW (hours)
(B)
storm surge (m)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
10
5
0
relative time to HW (hrs)
(C)
Probability (%)
14
12
10
8
6
4
2
0
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0.1
0.2
0.3
0.4
0.5
0.6
storm surge (m)
all
flooding
ebbing
HW
LW

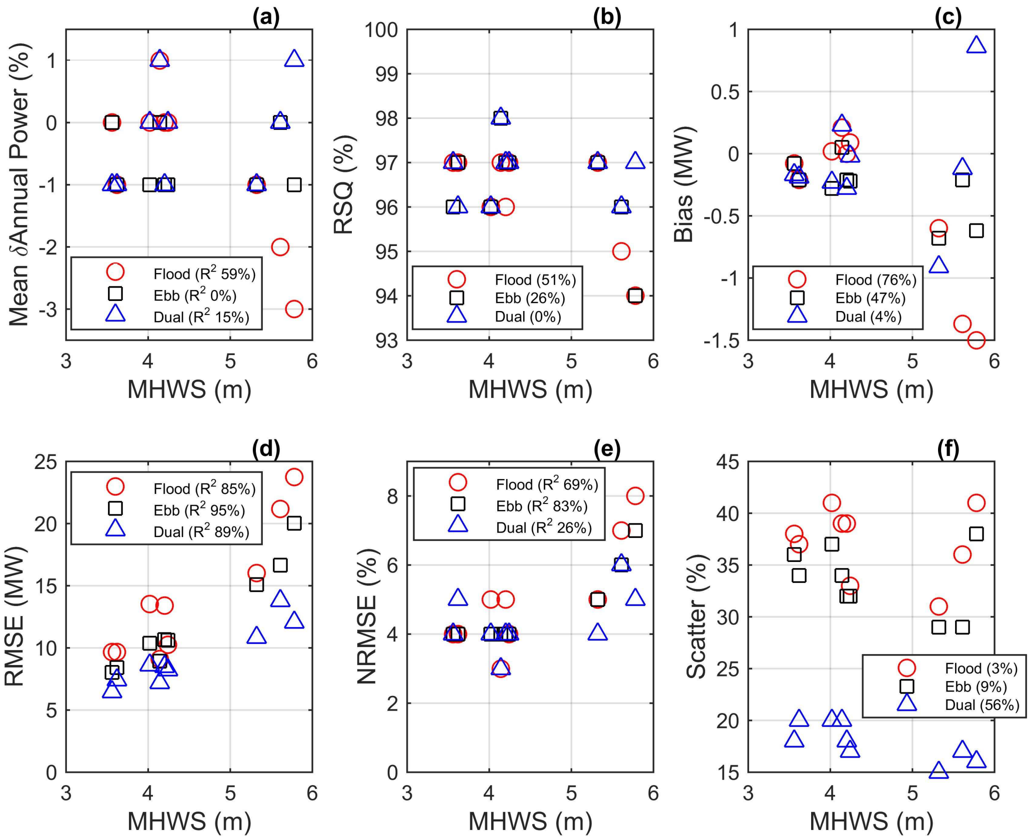

(a)
5
0
-5
η (m)
storm tide
tide
30/10/00 00:00
30/10/00 12:00
31/10/00 00:00
31/10/00 12:00
Flood generation
(b)
Power (MW)
200
100
0
Ebb generation
(c)
Dual generation
(d)


(a)
5
0
-5
η (m)
storm tide
tide
13/02/05 00:00
13/02/05 12:00
14/02/05 00:00
14/02/05 12:00
Flood generation
(b)
Power (MW)
200
100
0
Ebb generation
(c)
Dual generation
(d)


Flood only
Ebb only
Dual only
Storm tide power (MW)
tide only power (MW)
0
50
100
150
200
250
300
Probability (%)
δ Power (%)
Dual
Ebb
Flood
-30
-20
-10
10
20
30
1
2
3
4
5


Flood only
Storm tide power (MW)
tide only power (MW)
Ebb only
Storm tide power (MW)
tide only power (MW)
Dual only
Storm tide power (MW)
tide only power (MW)
Probability (%)
Dual
Ebb
Flood
δ Power (%)


flood generation (a)
δAnnual Power (%)
4
2
0
-2
-4
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
ebb generation (b)
δAnnual Power (%)
4
2
0
-2
-4
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
dual generation (c)
δAnnual Power (%)
4
2
0
-2
-4
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012



(a)
(b)
(c)
(d)
(e)
(f)
Mean δAnnual Power (%)
RSQ (%)
Bias (MW)
RMSE (MW)
NRMSE (%)
Scatter (%)
MHWS (m)
Flood (R² 59%)
Ebb (R² 0%)
Dual (R² 15%)
Flood (51%)
Ebb (26%)
Dual (0%)
Flood (76%)
Ebb (47%)
Dual (4%)
Flood (R² 85%)
Ebb (R² 95%)
Dual (R² 89%)
Flood (R² 69%)
Ebb (R² 83%)
Dual (R² 26%)
Flood (3%)
Ebb (9%)
Dual (56%)

Highlights:

- Storm surge effect to tidal range power was investigated
- Tide-only theoretical and technical annual resource assessment is sufficient
- Storm surges do affect timing and magnitude of power generated
- Tidal range energy flood-only generation strategy most affected by surges
- Electricity forecast system may be necessary for tidal-range development