Diversified renewable energy resources

An assessment of an integrated wind, wave and tidal stream electricity generating system in the UK, and the reliability of wave power forecasting.

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United Kingdom Wave & Tidal Energy Study

Diversified Renewable Energy Resources

Final Report

Executive Summary

Overview

The development of marine and tidal stream power resources in the United Kingdom is likely to occur in parallel with wind power and other renewable resource developments. This report examines two scenarios for diversified wind, wave and tidal stream power system development, and considers the implications of these diversified portfolio approaches for renewable resource development. In addition, this report presents an assessment of the reliability of wave power forecasting in the UK.

The United Kingdom Integrated scenario

This study examines the characteristics of the United Kingdom Integrated (UKI) scenario, a renewable electricity system comprised of wind, wave and tidal stream power. This scenario is dominated by wave power (52%) and wind power (43%), with tidal power accounting for around 5% of total renewable electricity generation.

In comparison to a wind-only renewable energy scenario supplying 20% of UK electricity demand, the UKI scenario:

- Increased the capacity credit of the renewable energy portfolio by around 20%;
- Reduced the variability of the renewable electricity supply by around 38%, and
- Reduced additional balancing costs by around 37%.

Tidal stream power has a higher variability than either wind or wave power, however:

- The inclusion of tidal stream power lowered the overall variability of the UKI scenario, and
- Around 30% of the UK tidal stream resource would be developed under the UKI scenario.

The Renewable Networks Impact scenario

This study examines the characteristics of the Renewable Networks Impact (RNI) scenario, a renewable electricity system based on the high demand renewable energy scenario for 2020 presented in the Renewable Networks Impact Study, where 20% of UK electricity demand is met by renewable electricity. This scenario is dominated by wind power (71%); wave power accounts for 6.5%, tidal stream power accounts for 1.25%, while the remaining 22% of renewable energy is supplied by other non-variable sources (eg landfill gas and biomass).

In comparison to a wind-only renewable energy scenario supplying 20% of UK electricity demand, the RNI scenario:

- Increased the capacity credit of the renewable energy portfolio by around 30%;
- Reduced the variability of the renewable electricity supply by around 6%, and
- Reduced additional balancing costs by around 5%.

Again, the inclusion of tidal stream power lowered overall variability of the renewable electricity supply, however this effect was modest given the small contribution from the tidal stream resource.

Wave power prediction

Forecast information from the UK Waters wave model was used to assess the reliability of estimates of future wave power output at a range of forecast time horizons. This analysis suggests that:

- There is a good relationship between the pattern of wave device power output calculated from observed and model data;
- The model tends to underestimate the actual wave power output, however this is less apparent during higher wave energy conditions when electricity generation would be greatest, and
- The reliability of forecasts is greater where a diversified portfolio of wave power devices is developed, rather than the exclusive use of one device.

Contents

Introduction

The Carbon Trust commissioned the Environmental Change Institute to carry out the Diversified Renewable Energy Resources project as part of the Marine Energy Challenge. This report follows on from the Variability of UK Marine Resources report (ECI 2005), which assessed the characteristics of the United Kingdom's wave and tidal stream resource, with particular focus on patterns of availability and the hour to hour variability of the resource.

This report extends the previous wave and tidal stream research by assessing the implications of developing an integrated wind, wave and tidal stream power scenario for renewable electricity generation in the UK. Characteristics of such an approach, including the contribution of different renewable resources to the total supply, overview comments on transmission, and the likely impact on costs are provided.

In addition, this report extends previous work on the current accuracy of wave power prediction through a review of wave model forecast data for UK waters.

Approach

This report presents two scenarios for the development of diversified renewable energy portfolios in the UK.

The United Kingdom Integrated scenario

The United Kingdom Integrated scenario (UKI scenario) represents a diversified approach to the development of renewable electricity generation that provides a low variability renewable electricity supply from a range of wind, wave and tidal stream sites located throughout the UK.

The Renewable Networks Impact scenario

The Renewable Networks Impact scenario (RNI scenario) is similar in approach to the UKI scenario, however the energy contribution from wind power and marine renewables is constrained by the high demand 2020 scenario in the Renewable Networks Impact Study.

In each case, the variability of this system is measured, and it's potential for reducing the need for conventional capacity while maintaining existing levels of security of electricity supply are estimated. Through a separate analysis, the cost of providing backup capacity in response to the variability of the renewable electricity supply is determined from an assessment of the variability properties of these resources, and reference to previous work.

The accuracy of wave power prediction output at a range of forecast horizons is assessed for three locations off the west coast of the UK. This assessment relies on wave model forecast results from the UK Waters wave model operated by the Met Office.

Limitations of this study

The objective of this study is to explore the principle of diversification between different renewable energy resources, and to gauge the impact that a diversification strategy would have on aspects of renewable energy development such as balancing cost and capacity credit.

This study achieves this by considering two scenarios, the UKI and RNI scenarios, which achieve low variability in the combined supply of renewable electricity from the different renewable resources. There are a range of assumptions that will impact on the results presented from these two scenarios, or suggest that additional scenarios should be considered, including:

- the objective of the scenario;
- the location of wave power sites;
- the availability of tidal power development areas;
- the expansion of offshore wind power developments;
- the capacity factors achieved by different devices;
- the development of other variable energy resources such as solar pv, micro wind power or domestic chp;
- device-specific operational characteristics;
- the ability to provide transmission capacity to all developments;
- the economic feasibility of developing some sites;
- future electricity demand patterns, etc.

<u>As a result, these are not the only scenarios that could be examined, and should not be seen as the definitive solution to the question of diversified renewable energy systems.</u> However, the scenarios do demonstrate some key features of diversified portfolios, and allow the implications of diversified renewable energy strategies that encompasses a range of renewable resources and technologies to be assessed.

A diversified renewable energy approach

The United Kingdom Integrated scenario

Overview

The United Kingdom integrated (UKI) scenario is a high level assessment of the potential for smoothing renewable electricity supply from a range of wind, wave and tidal power systems. The purpose of developing this scenario is to investigate the impact that a diversified, multiple-resource portfolio of variable electricity generators would have on key aspects of the electricity network including:

- Degree of supply variability
- Capacity credit
- Balancing costs

The UKI Scenario

The objective of the UKI scenario was to determine a mix of renewable energy resources and sites that would result in a lower variability in the renewable electricity supply than was possible with a single-resource strategy. Supply variability is defined as the standard deviation of the differences between successive hourly output levels, expressed as a percentage of the installed renewable energy capacity.

Under this scenario, there is no restriction on the contribution that either wind or wave power can make to the overall renewable electricity supply, nor is there any restriction on how much capacity can be developed in any region where the resource is available.

There are, however, capacity restrictions on tidal power that reflect the individual levels of development possible at each site. These capacity limits were determined from Black & Veatch (2005).

A time series model was developed which allowed the evaluation of different combinations of wind, wave and tidal stream power. A linear programming application was used to identify a scenario that resulted in low variability in the renewable electricity supply (the objective function was to minimise the standard deviation of the change in aggregate renewable power output from one hour to the next).

Following identification of the mix of renewable sites and resources that would form the UKI scenario, an assessment of the properties of the renewable electricity supply from this scenario was carried out, including the regional aspects of the scenario, transmission issues, and the capacity credit and balancing costs associated with the scenario.

Scenario data

A combination of observed and model datasets are used as the base data for the report; the potential hourly power output from these renewable resources is then calculated using data relating resource conditions to device power output.

This section of the report provides a summary of the data sources used – for a fuller explanation of the data sources and methods, refer to Annex 1.

Tidal stream data

The size and location of the tidal stream power sites in the UK was adapted from Black & Veatch (2005). Data on tidal stream velocities, and the timing or phase of tides at the different sites was obtained from the PolPred CS20 model (Proudman Oceanographic Laboratory), while site-specific turbines performance characteristics were developed for each site. Tidal stream data was available for the period 1994 to 2003.

Wave data

(Note that this data description relates to the UKI scenario only – the wave power forecast analysis uses data from the UK Waters model, also operated by the UK Met Office.)

Wave data were obtained from the European Wave Model operated by the UK Met Office for nine sites along the western coast of the UK. The sites were located around 20km offshore, and were grouped into three regions of three sites each. Note that there is considerable variation in wave energy with distance from shore – the location of these sites is likely to result in a conservative estimate of wave power performance compared to sites further offshore. Wave data was available for the period 1988 to 2004.

Wind data

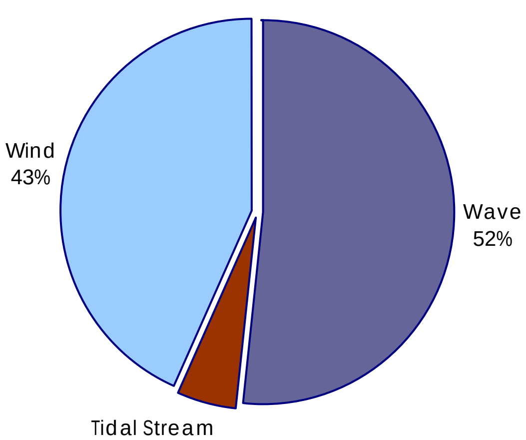
Observed wind speed data were obtained for 66 sites in the UK for the period 1994 to 2003. As the wind speed data were collected at close to ground level, the observed speeds were corrected to reflect speeds at turbine hub height. This corrected wind speed was converted into hourly power output using a wind turbine power transform function and assumes an average UK long-term capacity factor of 30%. Individual wind power sites were grouped into regions, with the hourly power output of the region equal to the average of the output of each site within the region.

Scenario results

Scenario results

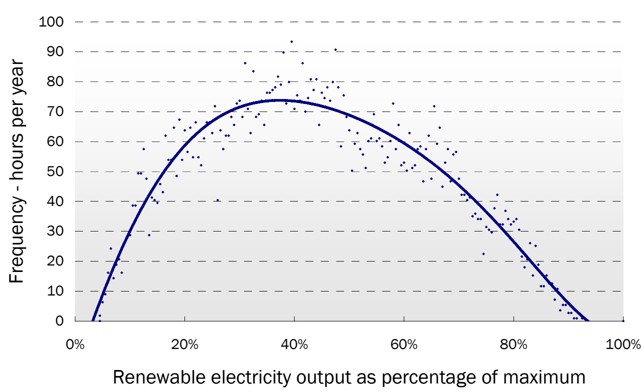
Results from the evaluation of the UKI scenario strongly suggest that there is a benefit in diversifying renewable electricity generation away from a wind-only scenario. Under the UKI scenario, wind and wave power are the dominant sources of renewable electricity, accounting for around 95% of total supply – of this, wave power accounts for 52% of renewable electricity, however wind power remains a major contributor under this scenario, delivering 43% of total output. Tidal stream power delivers around 5% of the total renewable electricity supply (1% of total UK demand) under this scenario; while this may initially seem a modest contribution, it represents around 30% of the currently estimated UK tidal stream resource.

Contribution of wind, wave and tidal stream power to a 20% renewable electricity scenario



The UKI scenario results in a relatively symmetrical distribution of power output levels during high demand periods – low power output events are rare, with output never falling below 4.5% of maximum, while high outputs never exceed 92.5% of maximum.

Distribution of renewable electricity output levels during high electricity demand hours



Impact on variability

The inclusion of wind, wave and tidal power into a national renewable resource portfolio significantly reduces the hour to hour variability of the renewable electricity supply. The table below shows the variability in supply from the UKI scenario in comparison to that from a tidal stream-only, wind-only or wave-only scenario (variability is expressed as the standard deviation of the hourly change in output as a percentage of installed renewable energy capacity).

Renewable supply	Variability – percent of installed capacity
Tidal stream power only	6.3% - 22.4%
Wind power only	3.2%
Wave power only	2.6%
UKI scenario	**2.0%**

The variability of the tidal stream resource increases as the overall level of development of the resource increases. This occurs because high development levels require capacity to be concentrated in a number of large development sites with similar patterns of electricity generation – the supply pattern from these large sites then tend to dominate the overall supply pattern.

As a result, low levels of variability from the tidal stream resource are achieved when development levels are low, and installed capacity is distributed across a range of tidal stream sites with different patterns of tidal stream power availability. As a result, the tidal power development assumed for this scenario includes small and remote tidal stream sites.

In comparison to tidal stream power, diversified wind and wave power systems exhibit considerably lower supply variability. However, it is through combining the different resources that the UKI scenario achieves a low electricity supply variability.

The adoption of a diversified renewable energy approach leads to a 37% reduction in electricity supply variability in comparison to a wind-only scenario. Furthermore, despite the relatively high variability associated with tidal stream power, its inclusion in the UKI scenario results in lower overall supply variability than would have been achieved without this resource.

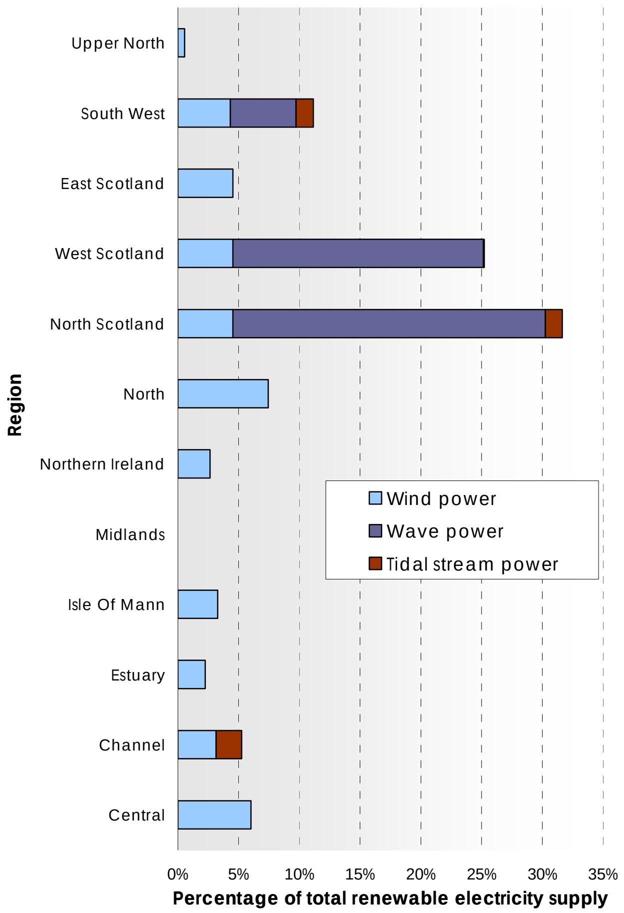
Regional characteristics

To achieve the outcome of the UKI scenario, a national strategy for the development of renewable energy would have to guide development at a regional level. This section summarises the regional aspects of the UKI scenario.

The figure below shows the contribution of renewable electricity by region and resource type for the UKI scenario. Scotland (including north, west and east Scotland) accounts for just over 60% of total electricity production, with the South West region being the next-largest regional contributor with around 11% of total renewable electricity generation. Note that the availability of high wave energy conditions to the north/north-west and south-west of the UK limits the number of regions that have the opportunity to develop this resource.

Wind power is relatively well distributed amongst the regions, although the three Scottish regions combined account for around 30% of UK wind power development, while the tidal stream resources of the South West region and Channel Isles are extensively developed.

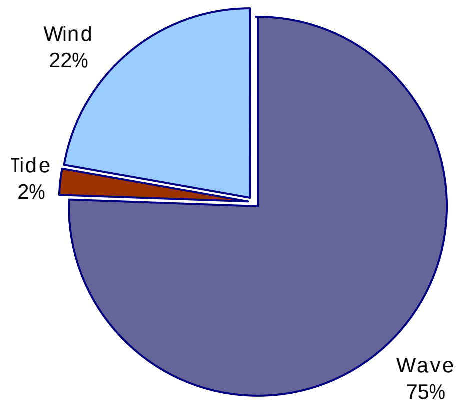
Regional distribution of wind, wave and tidal stream power under the UKI scenario



Scotland

Within Scotland there is an emphasis on wave power development, which accounts for over 70% of total Scottish renewable electricity. This contrasts with the current emphasis on wind power development, however the UKI scenario would still result in wind power development of around 4GW occurring in Scotland. Tidal stream power development is small compared to the available resource in the region, with just 8% of the available resource being developed under this scenario.

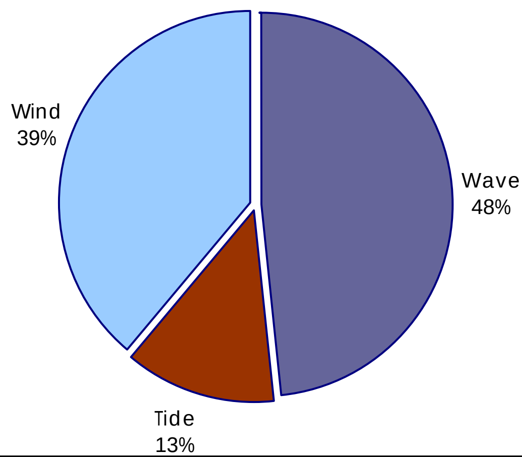
Contribution of wind, wave and tidal stream power in Scotland



South West Region

The South West region has the most even contribution from the three resource types; tidal stream power is a significant contributor to overall output, and in absolute terms the South West region delivers slightly more electricity from tidal stream power than Scotland. Overall, 93% of the South West's tidal stream resource is developed under this scenario, reflecting the diversity of tidal generating patterns in this region.

Contribution of wind, wave and tidal stream power in the South West region



Capacity credit and balancing costs

Overview

The introduction of variable sources of renewable electricity generation into an electricity network has implications for the operation of that network. Two areas in which impacts are felt are the:

- amount of conventional plant that can be decommissioned due to the addition of renewable generating capacity (capacity credit), and
- costs involved in accommodating the additional variability introduced by the renewable electricity supply.

These two areas of network impact are considered below.

Capacity Credit

The capacity credit of renewable electricity generating capacity is the amount of conventional generating capacity that is displaced by the introduction of renewable energy capacity. There are a range of factors that influence capacity factor of a renewable electricity supply, however the pattern of electricity supplied by the renewable resources, and the amount of renewable electricity generating capacity connected to the network, have a strong influence over capacity credit.

The table below shows the conventional capacity requirement for three different renewable electricity scenarios, as determined from a loss of load probability model. The data reported are for an idealised UK electricity network as proposed by Dale et al (2004), with a UK annual demand of 400TWh, peak demand of 70GW and conventional capacity supplied by 500MW combined cycle gas turbine generators.

The demand requirements of the conventional system (without renewable electricity generation) are met by a generating capacity of 84GW. The conventional capacity requirement for the two renewable electricity scenarios assumes 20% of annual electricity demand is met by renewable electricity supplies.

Scenario	Conventional Capacity	Capacity credit
Conventional system[1]	84GW	- - -
Wind-only scenario[1]	79GW	5GW
UKI scenario	**78GW**	**6GW**

1 – results reported by Dale et al (2004).

The capacity credit calculated for the UKI scenario is higher than that reported for the wind-only renewable energy scenario. This outcome arises from the diversity of renewable resources that are included in the UKI scenario, and the patterns of availability between the different resources and their relationship to electricity demand patterns.

It has previously been shown that wave power contributes significantly more energy at times of peak electricity demand, resulting in a higher than average capacity factor at these times (ECI 2005); similarly, wind power contributes more energy on average at times of peak demand than at other times. Tidal power does not show this trend; the availability of tidal power is essentially uncorrelated to wind or wave power, or to electricity demand patterns.

As a result, the availability of the diversified renewables scenario shows lower variability than a wind-only scenario, providing confidence that the combination of wind, wave and tidal stream power will contribute to meeting electricity demand during high demand periods. This result suggests that by delivering renewable electricity via a diversified portfolio of wind and marine renewables, around 20% more conventional generating capacity could be retired than under a wind-only renewable energy scenario.

Balancing costs

The addition of renewable energy to an electricity network can result in additional network balancing costs. These costs arise from the need to respond to changes in renewable output – by reducing the variability of the renewable electricity supply, the additional balancing costs will also be reduced. Furthermore, Mott MacDonald (2003) has noted that improved prediction will allow further significant balancing cost reductions – the inclusion of tidal power in the UKI scenario acts to improve the overall predictability of the system, which will also tend to lower balancing costs (this benefit was not assessed in this study).

The lower variability renewable electricity supply from the UKI scenario results in a balancing cost estimate of around £1.80/MWh when 20% of UK electricity demand is met by renewables. This represents a reduction of around 37% on the wind-only balancing costs; refer to Annex 2 for details.

Scenario	Additional balancing cost
Wind-only scenario[1]	£2.85/MWh
UKI scenario[2]	**£1.80/MWh**

1 – NGC data: refer to Mott MacDonald (2003)

2 – refer to Annex 2

Transmission implications

Overview

At a regional level, significant amounts of transmission capacity may need to be developed to ensure that electricity generated by renewable energy systems is available to demand centres. Transmission capacity needs to be able to accommodate peak output to ensure that all renewable electricity is available to the network.

The variability of renewable energy systems results in periods when the transmission network will be under-utilised. For regions where their renewable electricity generating capacity is dominated by wave power, and to a lesser extent wind power, this will be particularly apparent during summer when both these resources are at their seasonal low. Given the low utilisation of the transmission network at these times, there may be an opportunity to further develop other renewable energy sources that will utilise this spare transmission capacity.

Tidal stream power is one resource that could be developed in this manner – tidal stream power has an essentially constant output on a seasonal or monthly basis, and its pattern of supply is uncorrelated to either wind or wave power supply patterns. For these reasons, there may be an opportunity to further develop tidal power within the regional transmission requirements of the UKI scenario.

Scotland

The transmission capacity required to meet peak output from a diversified renewable energy development in Scotland of around 12.5GW. In the north of Scotland (Orkney and Shetland Islands, Pentland Firth and surrounding waters), the combined wind, wave and tidal stream power developments would have a peak output of around 6.5GW that would need to be accommodated by the transmission network. The bulk of the remaining capacity would be required to link wave power systems to the west and north west of Scotland, with additional connections required for wind power on mainland Scotland.

Tidal stream power accounts for 2.4% of renewable electricity generation in Scotland, representing around 8% of the potential Scottish tidal resource. However, Scotland has the largest tidal stream resource of any region in the UK, with the Pentland Firth being the most energetic tidal stream location in the UK – under the UKI scenario, this resource is essentially undeveloped.

However, further development of the Pentland Firth and Northern Isles tidal stream resource may be possible without exceeding the peak generating level of 6.5GW from northern Scotland. Increasing the development level of the Pentland and Northern Isles tidal stream resource from 8% to 100% of the available resource would see renewable energy production in Scotland rising by 27%. Around 98% of the additional tidal stream-generated electricity would be delivered within the 6.5GW peak supply limit, as it would be generated at times of low transmission utilisation.

One less desirable impact of this change would be to significantly increase the hourly variability of the renewable electricity supply from the region – thus the cost implications arising from further tidal development would have to be balanced against the additional energy recovered from the region.

South West region

The relationship between transmission capacity and tidal stream power development in the South West region is markedly different to that found in Scotland. Tidal stream power contributes 13% of the regions combined renewables output, representing 93% of the identified tidal stream power potential in the region. Transmission capacity in the South West region would need to accommodate a renewable supply peak of almost 4GW (although this must be balanced against the South West region being a net electricity importer).

By fully developing the tidal stream power resource of the South West region, the contribution of tidal power to the region would rise modestly from 13% to 14% - this could be accomplished within the same peak renewable electricity supply level with virtually no loss of energy due to transmission limitations. Total renewable energy production would rise by around 1% with this modification.

There would be a minor increase in the variability of the renewable electricity supply from this region, which would be almost undetectable at the national level. The reason for the limited impact of additional tidal power on levels of variability lies partly in the nature of the resource – it has previously been found that the a fully developed tidal stream power system in the South West region has the lowest variability of any region in the UK (ECI 2005). In addition, the tidal contribution from the South West region is small compared to the overall UKI scenario.

These observations emphasises the need to examine a range of scenarios for the regional development of diversified renewable electricity generating systems.

Linkage to
Renewable Network Impacts Study

The Renewable Networks Impact scenario

Overview

While the UKI scenario has identified an allocation of generating capacity between wind, wave and tidal stream sites that achieves low variability of the aggregate electricity supply pattern, the conditions to achieve this include a major investment in wave power technologies in the medium term. This level of development of the wave resource (and supporting industry) may not be seen by 2020, and it is therefore important to consider the implications of a lower penetration of wave power into the overall UK renewable energy portfolio.

The Renewable Network Impacts study, carried out by the Carbon Trust in 2004, provides a number of scenarios for the development of the renewable energy sector to 2020. The RNI scenario has been developed from this study, and is a targeted assessment of the potential for smoothing the supply of renewable electricity within the contribution limits presented in Annex 1 of the RNI study.

RNI high demand scenario

Annex 1 of the RNI Study, Capacity Mapping & Market Scenarios for 2010 and 2020 (Mott MacDonald 2004), sets out a number of scenarios for the development of the UK renewable energy sector to 2010 and 2020. For analysis purposes, the results presented below relate to the energy output characteristics of the high demand scenario presented in Annex 1, p22 of the RNI Study. The contribution of energy from different renewable resources is summarised in the table below.

Technology	Installed Capacity - MW	Generation - TWh	Percent of Target
Onshore Wind	9,345	22.9	30.5
Offshore Wind	9,292	30.1	40
Wave and Tidal	1,479	5.8	7.7
Landfill Gas	359	2.7	3.6
Biomass	2,276	13.0	17.2
Small hydro	184	0.7	1
Total	22,934	75.2	100

Under the high demand scenario, wind power meets 70.5% of the 2020 renewables obligation target, with wave and tidal power meeting around 7.7% of the target.

The remainder of the target is met by a combination of landfill gas (3.6%), biomass (17.2%) and small scale hydro (1%). The output characteristics of these resources are more closely aligned with conventional generating capacity; landfill gas and biomass generators have high operational availability, and can be treated as dispatchible plant on the network (small hydro is a minor overall contributor to renewable generation). As a result, the variability characteristics of these resources are considered analogous to conventional generators, and therefore do not contribute to an increase in overall system variability (as they substitute for the variability in displaced conventional generators).

The RNI scenario's 20% high demand scenario for renewable electricity generation results in around 15.6% of total electricity generation arising from renewable electricity resources with variable supply patterns, and the balance arising from convention-plant-mimicking sources (see table below).

Resource Group	Percent of Target	Percent of Total Generation	Percent of Variable Generation
Wind	70.5	14.1	90.2
Wave and Tidal	7.7	1.54	9.8
Total Variable Renewables	**78.3**	**15.64**	**100**
Other non-variable renewables	21.8	4.36	---
Total	100	20	100

This has an important implication for the impact of variability – most recent studies (eg Dale et al, 2004) assume that the 20% target will be met entirely by wind power; as a consequence, 20% of annual electricity production has the variability characteristics of wind power. By recognising that around one-quarter of the 2020 target will be met by capacity that does not induce additional variability on the network, and that the remaining three-quarters of the target is met by renewable resources that have a variety of supply patterns, a more realistic view of the impact of supply variability on the overall system can be obtained.

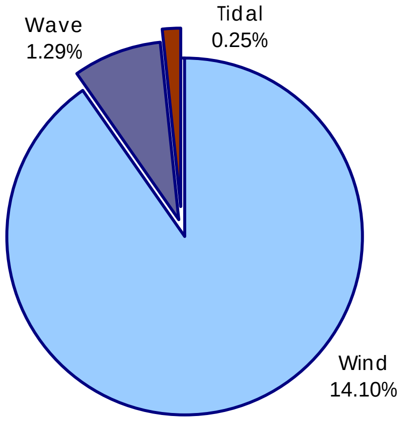
Wind, wave and tidal power in the RNI scenario

The RNI scenario separates wind power into onshore and offshore wind resources, and assumes a significantly higher capacity factor for the offshore resource. The approach taken in this work is based on the energy contribution of the resources, and this separation of resource implies that there may be different electricity supply characteristics between the two wind resources. Preliminary work carried out by the ECI (unpublished) suggests that, while the capacity factor may vary between onshore and offshore locations, the correlation of electricity generation between onshore and offshore locations follows a similar pattern to that identified for onshore sites (Sinden 2005).

As a result, the variability characteristics of the offshore resource are not expected to differ significantly from that identified in the onshore resource. For the analysis performed in this report, the onshore and offshore wind resources are treated as a single resource supplying 70% of total renewable electricity generation in 2020, rather than two separate resources.

The contribution of wave and tidal stream power to total renewable electricity generation is presented as an overall figure in the RNI study, rather than separating out the contribution of the two resources. This presents a slight limitation from a supply characteristics perspective, as the patterns of resource availability and variability are extremely different between the two resources. This problem is addressed here by setting the contribution from wave and tidal stream resources to 7.7% of the total renewable electricity supply in 2020, and identifying (via an optimisation method) the division between wave and tidal stream resources that results in low overall variability of renewable electricity supply. Following this process, the variable supply component of the total renewables contribution (ie 78.3% of renewable contribution or 15.6% of total generation) was allocated as shown (below).

Contribution of wind, wave and tidal stream power to total generation under the RNI study scenario



Supply variability

The wind, wave and tidal stream power components of the renewable electricity supply will introduce additional variability to the network (the non-variable supply is assumed to have the same variability properties as the conventional plant on the network, and therefore does not introduce additional variability).

The relative contribution of wave and tidal power is far lower than that proposed in the previous section – in the RNI scenario, only around 10% of the variable electricity production is derived from marine resources, while in the UKI scenario over 50% of the variable electricity generation is derived from wave and tidal resources. The dominance of wind in the RNI scenario does not provide the lowest possible variability in the electricity supplied by these three renewable resources. However, it is again apparent that the inclusion of high variability tidal stream energy lowers the variability of the overall renewable electricity supply (table below).

Renewable supply	Variability – percent of installed capacity
Tidal stream power only	6.3% - 22.4%
Wind power only	3.2%
Wave power only	2.6%
RNI scenario	3.0%
UKI scenario	2.0%

It must be emphasised that:

1. This variability relates to the wind, wave and tidal stream component of the renewable electricity supply (ie around three-quarters of total renewable output), and
2. The inclusion of wave and tidal stream developments in the RNI scenario reduces the overall variability of the system when compared to a wind-only solution.

Capacity credit and balancing costs

Capacity Credit

The capacity credit of the RNI scenario is derived from two sources; variable renewable generating capacity offsetting the need for some conventional capacity, together with non-variable renewable capacity substituting for conventional capacity.

The non-varying component of the renewable energy installed capacity is assumed to substitute directly for existing conventional capacity, with a slight discount due to the lower availability of small hydro. (Note it could be argued that the capacity credit of small hydro is lower due to lower availability, or higher depending on its time of availability. Given the low installed capacity of small hydro in the RNI scenario, the assumption that small hydro will substitute (at a discount) for conventional capacity appears reasonable).

The capacity credit of the variable component of the installed renewable energy capacity is related to its availability during periods of high electricity demand. The results from the UKI scenario demonstrated that a higher capacity credit was achieved through the combined use of wind, wave and tidal stream resources – while these three resources are present in the RNI scenario, the limited development of marine renewables results in the capacity credit being heavily influenced by the characteristics of the UK wind resource. The table below summarises the findings on capacity credit.

Scenario	Conventional Capacity	Capacity credit
Conventional system[1]	84GW	- - -
Wind-only scenario[1]	79GW	5GW
UKI scenario	78GW	6GW
RNI scenario[2]	**77.5GW**	**6.5GW**

1 – Results reported by Dale et al (2004).

2 – Variable generation (wind, wave and tidal power) account for 15.6% of electricity generation. The remaining 4.4% of renewable electricity generation is from non-varying sources of generation.

The inclusion of non-variable renewables in the RNI scenario results in a higher capacity credit than both the wind-only and UKI scenarios, despite the dominance of wind power in the RNI scenario. The capacity credit of the RNI scenario is around 30% greater than that obtained from a wind-only scenario.

Balancing Costs

Balancing costs are associated with the RNI scenario show a modest reduction in comparison to a wind-only renewables scenario. The addition of wave and tidal stream developments in this scenario has resulted in a modest reduction in anticipated balancing costs (table below).

Scenario	Additional balancing cost
Wind-only scenario[1]	£2.85/MWh
RNI scenario	**£2.70/MWh**
UKI scenario[2]	£1.80/MWh

1 – NGC data: refer to Mot MacDonald (2003)

2 – Refer to Annex 2

The limited impact of marine renewables on balancing costs arises for two reasons. Firstly, the low proportion of variable electricity delivered by wave and tidal stream power limits the impact that the different patterns of variability from these resources on the overall renewable electricity supply pattern. Marine renewables in the RNI scenario account for less than 10% of total variable electricity supply from renewables, significantly below the 57% contribution required to achieve the low variability result reported for the UKI scenario.

Secondly, the reduction in the total contribution of variable renewables from 20% (wind only scenario) to 15.6% (RNI scenario) of total electricity demand has little impact as balancing costs are relatively insensitive to changes in penetration level in this range (Mott Macdonald, 2003).

Note that additional balancing costs are not associated with the renewable electricity contribution from the remaining renewable energy sources (4.4% of total demand, supplied by landfill gas etc) as the properties of generation from these sources are considered the same as from conventional generators in this scenario.

Evaluation of wave power prediction in UK waters

Wave power prediction

Background

Reliable wave resource data is of value to the UK's emerging wave energy industry. Wave data can be collected using wave buoys, but this can be impractical and expensive – alternatively, models simulating and predicting wave conditions can be used. For the wave energy industry, such models can be useful when planning new projects, providing data on sites where no buoys exist, and for operating wave power devices by using forecast information to estimate the electricity that can be generated and delivered to market.

For these benefits to be realised, the ability to forecast wave device power events output needs to be shown, and the performance of forecasting tools examined. The ECI has previously investigated some statistical aspects of wave power, confirming that effective forecasting of wave power availability at short forecast horizons is possible from simple models (ECI 2005). Accurate power prediction will also lower the balancing costs associated with variable electricity supplies (Mott Macdonald 2003).

The UK Waters model, operated by the UK Met Office, offers a far more advanced approach to wave power forecasting, with a forecast horizon of up to 120 hours in advance – this study was undertaken to provide an initial evaluation of the model's accuracy. A key aspect of the study was to examine ways in which the UK Waters model may be of use to the emerging UK wave energy industry.

Data sources and approach

Two sets of data were used for this analysis: model data from the Met Office UK Waters wave model and observed data from Met Office buoys. Three sites were chosen for study based on their potential as areas for wave energy development and the quality of the data at these sites. Model data were acquired for a range of forecast horizons from T0 (the nowcast) to T120 (five days ahead). Wave powers and device powers (for three wave devices) were calculated and then compared.

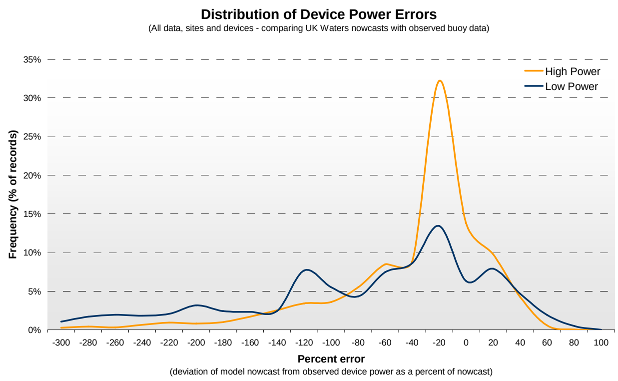
The study consisted of three main analyses: a baseline analysis, comparing model nowcasts with observed data; a forecast accuracy analysis, comparing model forecasts with observed data; and a forecast consistency analysis, comparing the model nowcasts with forecasts from previous iterations. These analyses were performed on the entire data set as well as subsets, based on site, device type, season (summer or winter) and wave or device power (high or low). The primary techniques used were correlation and analysis of error distribution.

Results

Full details on the analyses can be found in Annex 3.

Baseline analysis

Overall, the model provides a very good correlation with observed wave powers (r^2 = 0.74) and device powers (r^2 = 0.861). However the wave period was very poorly correlated (r^2 = 0.188). This is due to the resolution of both the observed and the model data, as observed period is measured in coarse one-second intervals. This makes assessing the model's performance extremely difficult, especially at low periods. For example, the overall median error in wave power was -37% but by examining high and low power data separately, it could be seen that most of the error occurred at low power levels. This sensitivity to low period values was most obvious at the inshore B62107 site and also led to errors in device output as high as 400%.



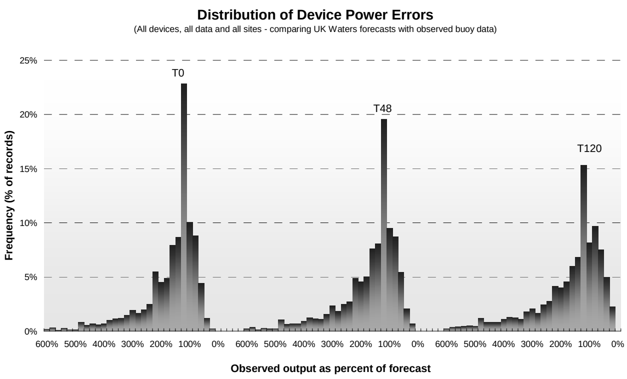
These large errors occur between pairs of forecast and observed data, e.g. the difference between a specific T6 forecast and its corresponding observed value. Examining the general trends in model output provides a much better match to observations. For example, at high power periods the device power error was -28%; at low power, -120%. However the errors in estimated capacities factors for these conditions are much lower (about 5% at high power, 20% at low error).

A major conclusion of the baseline analysis is that the model's error at low power levels cannot be properly assessed until higher resolution observed period data become available. However the model's performance in high wave power conditions is much better, and it is in these conditions that most wave energy generation takes place (e.g., the Pelamis device can achieve a capacity factor of around 60% in high wave conditions, versus 20% or less in low wave power conditions), correctly assessing the model's performance at low power conditions does not affect its applicability to the wave conditions during which the bulk of electricity would be generated.

Forecast accuracy

This analysis examined how the forecast accuracy changed over different forecast horizons from 0 hours to 120 hours. The trends in correlation for both wave power and device power are characterized by steady linear declines, e.g. for wave power from $r^2 = 0.74$ at T0 to $r^2 = 0.40$ for a five-day forecast. Device power correlations are consistently higher than wave power correlations, starting at $r^2 = 0.86$ and declining to r^2 of 0.65 at five days. Poor correlations for period, wave and device power in inshore low-power conditions persisted across all time horizons.

A typical distribution of device power errors at various forecasts is shown below, demonstrating that while the median errors (and their confidence intervals) were constant across nearly all forecast horizons, the shape of the distribution changes slightly. Of particular interest in



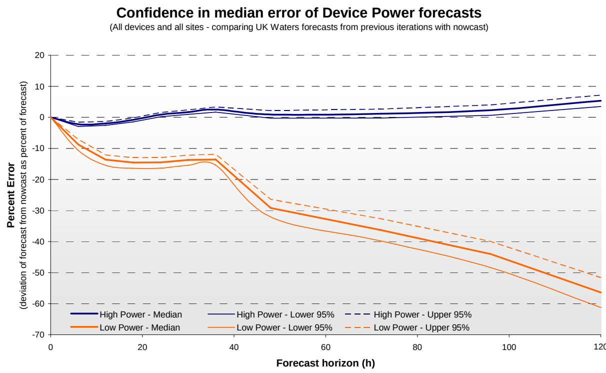
this graph is the concentration of errors in the narrow 120% to 100% band. At this level of error, capacity factors are approximately about 55%; however in the rest of the distribution the average capacity factor is about 35%, indicating that the large errors are associated with lower power output. This narrow concentration of error also suggests that it may be possible to improve the accuracy of device power forecasts by focusing on correcting this specific range of values so that they more accurately reflect the wave power transform function. This may be a particularly important approach if improving the resolution of the observed data proves to be too difficult.

This analysis also suggests that improved power forecasts will be obtained for a portfolio of different wave power devices than for any single device.

Forecast consistency

The model forecasts were also compared with nowcasts to determine how the consistent long-range forecasts were with nowcast values. The correlations for wave power, period, and height all showed a steady decline from an r^2 of 1 at T0 to 0.50 by T120. This suggests that up-to-the-minute information is important as the forecasts do change. Similar findings were identified for device power.

However by comparing subsets of the data, it was shown that the time of year (summer or winter) and power levels (high or low) are particularly important when deciding how frequently a forecast should be updated. For example, the winter device power forecast was consistently better correlated with the nowcast value. This can also be seen in the median errors, as the comparison of high and low power conditions below shows.



Summary

Wave models provide the emerging wave power industry with a powerful tool to assist with both planning and operating wave energy devices. The UK Waters wave model gives a very good representation of the high-power offshore wave conditions where wave energy is likely to be developed, but fully assessing the model's performance in low-power inshore conditions is complicated by the lack of high-resolution observed period data. If this obstacle cannot be overcome easily, alternative strategies may be useful to improve the accuracy of the model's output in these environments.

The model's good performance in strong wave conditions is a particular feature and can provide confidence to wave energy developers. For example, model data can create distributions of error, tailored to specific locations and devices, allowing future wave power output to be forecast to a predetermined level of confidence.

The particular strengths of wave models lie with both providing data for difficult-to-monitor sites, and with developing scenarios to guide the operation of these installations. The increasing importance and value of accurate wave power forecasts should ensure that there will be an ongoing incentive in further developing wave models.

Conclusion

Introduction

This report has examined the potential for a diversified portfolio approach to the development of renewable energy in the UK, together with an initial assessment of the degree to which the availability of electricity from wave power can be forecast. The report builds upon previous work carried out by the ECI for the Carbon Trust Marine Energy Challenge which examined the characteristics of wave and tidal stream resources in the United Kingdom, particularly in relation to their patterns of variability and availability.

Diversified renewables portfolios

The United Kingdom Integrated (UKI) scenario, together with the Renewable Networks Impact (RNI) scenario, were presented as examples of diversified portfolios for renewable electricity generation in the UK. Both scenarios incorporated wind, wave and tidal power resources from throughout the UK into a diversified renewable energy system, and identified a mix of resources and sites that would result in an electricity supply pattern that showed lower variability than that achievable from a wind power-only renewables scenario. The RNI scenario achieved this within the capacity limitations identified in the Renewable Network Impacts Study report.

The UKI scenario

The lower variability characteristics of the UKI scenario were achieved through a mix of renewable resources, with wave power and wind power contributing around 95% of total renewable electricity delivered by this system – wave power contributed slightly more than half of the total.

The contribution from tidal stream power represented around 5% of total renewable electricity generation – while this level of supply is small in comparison to wave and wind power in the UKI scenario, it would represent the development of around 30% of the known UK resource. In the South West region and the Channel isles, over 90% of the known tidal stream would be developed under this scenario. Furthermore, the inclusion of this tidal stream electricity supply contributes to both a low overall supply variability, and acts to increase the predictability of the overall renewable electricity supply.

Scotland dominates the overall renewable electricity supply, due to the availability of wave power resources and a desirable (from a variability perspective) wind power resource, while the South West region showed the most even contribution of renewable electricity from the three different resources.

Overall, the portfolio of renewable resources and sites included in the UKI scenario would:

- Reduce the long-term variability of the electricity supply around 37%;
- Increase the capacity credit of the renewable energy system by around 20%, and
- Reduce balancing costs associated with the variability of the renewable electricity supply by around 37%.

The RNI scenario

Limitations on the development of wave and tidal stream resources in the RNI scenario resulted in wind power dominating the variable supply component of renewable electricity generation in this scenario. However, it was noted that around one-quarter of the renewable electricity supplied under the RNI scenario was from non-variable renewable sources such as landfill gas and biomass.

Overall, the RNI scenario would:

- Reduce the long-term variability of the electricity supply around 6%;
- Increase the capacity credit of the renewable energy system by around 30%, and
- Reduce balancing costs associated with the variability of the renewable electricity supply by around 4%.

Forecasting wave power

An analysis of wave forecast data from the UK Waters wave model was carried out to determine the reliability of these forecasts for predicting wave device power output.

This analysis showed that overall there is a good relationship between the expected power output calculated from observed and model (nowcast) data, with a good correlation between the pattern of wave power availability determined from both the observed and model data. Model data tends to underestimate the device power output determined from observed data, however this is less apparent at higher wave energies where most electricity generation occurs.

Model forecasts were compared to observed data, and the correlation between the two datasets was observed to decrease with increasing forecast horizon. Poor correlations for inshore, low power conditions were noted at a range of forecast horizons. The relationship between observed and forecast data was consistently higher for device power output than for wave face power, reflecting the smoothing effect of wave transform matrices on wave power variability.

Annexes and bibliography

Annex 1 – Data treatment and modelling

Renewable energy modelling

A key aspect of this project was the determining the pattern and quantity of electricity generated from a range of wind, wave and tidal stream sites in the UK. The approaches used to model power output from the resource data are presented in this Annex.

Modelling tidal stream power

The modelling of hourly electricity generation at each tidal stream energy site is described below.

Step 1 – Tidal Current Velocity Time Series

Tidal current data was obtained from the Proudman Oceanographic Laboratory's CS20 model of tides and tidal currents for the UK. This model covered 30 of the 36 tide sites (representing 97% of the identified development potential of the UK), with data for the remaining six sites being derived from Admiralty Tidal Current Atlases.

The CS20 model allows site-specific tidal current data to be generated, however it was found that in some cases the model output was highly sensitive to minor changes in location (this is a characteristic of the model in complex coastal areas and not representative of the actual change in velocity across a site). Where this was observed, the peak tidal current velocity determined in other studies (eg Black & Veatch 2004) was used as a check to ensure the CS20 model output was close to the expected result. Tidal current velocities at the CS20 sites were determined at a six minute resolution, and averaged to hourly resolution.

The Admiralty Tidal Atlas provides hourly tidal current velocities at six sites – given the coarser resolution of these data, together with the complexity of the tidal currents at some sites, the accuracy of the tidal current data for these sites is considered to be lower than that for the CS20 model sites. Whilst the timing of the tidal currents modelled using this method is considered reliable, the magnitude of the velocities is considered questionable, and reference to previous studies was again used to ensure consistency with previous work (notes on any changes are included in Appendix 1). Given that the sites modelled using this method account for less than 3% of the available resource, the impact of any inconsistencies is considered minimal.

Step 2 – Conversion to Hourly Power Output

The annual electricity yield of each site was taken from the Tidal Stream Study – Phase II report (Black & Veatch, 2005). With the maximum annual yield at each site known, the hourly power output of the site was determined from tidal current velocity time series data. This combined approach allowed the energy yield estimates derived from 3D flow modelling to be incorporated into the model, while retaining the timing of hourly tidal power availability at the different sites.

Tidal current power is represented in this study by an axial rotor placed in a free-flowing tidal current. A power transform function at each site was used to represent the timing of power output from a turbine located at each site. The power (in kW) of a tidal current passing through a given area can be approximated by:

$$\text{Power} = \text{Area} \times \text{Density} \times (\text{Current Velocity})^3 \times 0.5/1000 \text{ kW}$$

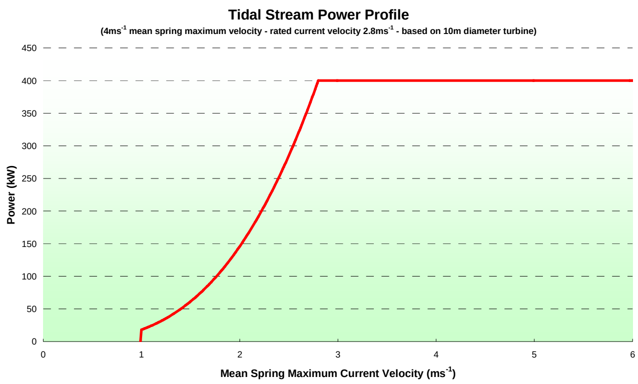
Area = the swept area of the rotor in m^2
Density = $1023 kg/m^3$
Velocity=instantaneous current velocity in ms^{-1}

With the annual site yield known from the flow modelling, this equation was used to determine the proportion of the annual yield being delivered during each hour. Following the advice of Peter Fraenkel from Marine Current Turbines Ltd, a range of site specific power transform functions were developed, with the key parameters being:

1. Cut-in velocity of $1ms^{-1}$;
2. Efficiency at rated velocity of around 45%;
3. Rated velocity (velocity at which maximum power output is achieved) typically set to around 70% of mean Spring maximum tide velocity, and

The resulting profile appears similar to a wind turbine power profile, except that there is no high-speed shutdown due to the limited velocity range of tidal currents. From this information, site-specific power transform functions have been developed, an example of which is shown below.

Finally, the six minute power output data was then grouped to give the average output at each site for each hour in the 10 year period.



Modelling wave power

Step 1 – Data sources

(Note – this section relates to the main report – the wave power forecast analysis was carried out using UK Waters model data.)

European Wave Model: The EWM is a medium resolution model, which includes the north-western European shelf seas, the Baltic Sea, Mediterranean and Black Sea. Sites are located on a grid measuring 0.25o latitude by 0.4o longitude (approximately 35km resolution), with the grid centred on 0o latitude, 0.06o W longitude. Wave data were obtained at three-hourly resolution for the period July 1988 to June 2004 for each of the 11 sites included in the analysis. There are minor amounts of missing data within the dataset – these missing data periods were excluded from the modelling process.

Observed Wave Data: Observed wave data were available from an array of fixed buoys owned and operated by the UK Met Office. Data is available since 1989 when one buoy (Channel Light Vessel - 62103) was operational. Buoys have since been deployed at 19 sites – in 2004 there were 11 operational buoys in the programme. Data is returned at a one-hour resolution and include wave height and period, together with wind speed and direction.

The period of data availability varies markedly between different sites - in addition, many of the datasets show significant periods of missing data. This limits their usefulness for long term modelling; however they remain useful for shorter-term, high resolution modelling.

Step 2 – Wave power time series

Long-term time series for each wave power site were generated from the EWM data, producing an historical record of sea state conditions (wave height and period) at three hour resolution. Wave face power (kW/m of wave face) could be calculated from these time series data.

Step 3 – Conversion to hourly power output

Power output levels were modelled from wave height and period time series data using a power transform function. Where the wave conditions were greater than the limits of the transform function, it was assumed that the device would continue to generate at rated capacity.

Step 3 – Inferring hourly variability

The use of hourly resolution wave power data allowed hour to hour matching of output data with similar data for wind power, tidal stream power and electricity demand patterns. As the model wave data was supplied at three hour resolution, hourly variability was inferred.

The approach adopted was to analyse observed wave power output data from offshore buoys, and develop a statistical representation of the likely power output levels at hours one and two that relate to all occurrences of a particular power level at hours zero and three. By matching the power output at hours zero and three to the power output levels in the model dataset, the resulting distributions of power output at hours one and two were sampled to provide a statistically representative power output level at an hourly resolution.

Step 4 – Regional characteristics

For the UKI scenario analyses, device output data for an attenuator-type converter (generic Pelamis transform) was used for all sites and regions. This approach provides comparability between different regions, however it must be recognised that using a single transform at the different sites results in significantly different capacity factors being achieved at each site.

Modelling wind power

Step 1 – Data source

Observed surface-level wind speed was obtained from the Met Office / British Atmospheric Data Centre for 66 sites throughout the UK. These data are provided at hourly resolution, and included the period 1994 to 2003.

Step 2 – Hub height correction and capacity factor

The surface level wind speeds were corrected to better represent the wind speeds that would be experienced at turbine hub height. In carrying out this correction, the final capacity factor for each wind speed site was checked to ensure that it was representative of the region in which the site was located (for example, higher capacity factors are typically associated with northern and coastal sites, with lower capacity factor sites typically occurring in southern inland areas – refer to Riso (1989) for further details). This process was carried out to achieve a UK average capacity factor for a diversified wind power system of 30%.

Step 3 – Conversion to hourly power output

A wind power transform function was used to convert wind speed to power output. The power transform function used for this stage is that published by Nordex for an N80 wind turbine (80m hub height, 2.5MW rated power output, cut-in speed of $4ms^{-1}$ and cut-out speed above $25ms^{-1}$).

Step 4 – Regional Grouping

The individual wind sites were grouped into ten regions, with each wind site in a region contributing equally to the average wind power output from the region each hour.

Annex 2 – Comparisons between wind, wave and tidal stream power fluctuations

Prepared by David Milborrow at the request of the ECI

Summary

Although a considerable amount of information has been published on the integration of wind energy into electricity networks, much less analysis has been carried out for wave and tidal stream energy. This paper builds on the analysis of wave and tidal stream power fluctuations made by the Environmental Change Institute and makes comparisons with comparable data for wind plant. The paper then estimates the additional backup costs associated with operation of wave plant in the UK electricity network, using standard analytical techniques. As it is doubtful that the latter can be used for tidal stream energy some observations have been made based on the limited amount of information that is available.

It is shown that the fluctuations from country-wide wave energy plant would be smaller than those from wind energy plant and costs of an additional operating margin would be correspondingly smaller as well. Further, modest reductions could be realised with a combination of wind, wave and tidal stream energy.

Introduction

The Environmental Change Institute has recently produced a comprehensive report on the variability of wave and tidal stream plant in United Kingdom[1]. This analysis builds on that work, principally to derive estimates of the extra back up costs required for these technologies in the UK electricity system, but also to compare data from the ECI simulations of wind plant with "real" power data, where available.

This analysis has four principal objectives: --

1. Compare the wind fluctuation data from the Environmental Change Institute that are based on simulations with "real" data derived from power measurements
2. By comparing the seasonal variations in wind and wave power, draw conclusions as to the likely "capacity credit" of wave energy.
3. Compare wind and wave power fluctuations and comment on the implications for the costs of additional reserve.
4. Comment on the possible implications of installing significant amounts of tidal stream plant. (The analytical techniques used to estimate the extra back up for wind and wave plant cannot be applied to tidal stream)

Monthly fluctuations

Wind Energy

The ECI have recently produced data showing the relationship between electricity demand and average capacity factor for both wind and wave plant. This has a considerable influence on the "capacity credit" of wind and wave energy plant. The general form of the relationship for wave energy corroborates data produced by other authors for wind energy: average capacity factor is highest at times when demand is highest. The ECI analysis for wind, based on modelling of wind power output from observed wind speed measurements, suggests that the average capacity factor when the electricity demand is between 85 and 100% of the peak is around 30% higher than the average capacity factor. This is consistent with analysis by the author[2].

Figure 1 addresses this issue in a slightly different way, by comparing actual wind plant outputs with synthesised data drawn from the information in the European Wind Atlas[3]. The advantage of the latter is that it presents long-term average wind speeds, the disadvantage is that these must be converted into power data. Individual years of data from wind farms may or may not, however, be representative of the long-term average. In Figure 1 the curve labelled "real data 1" comes from a wind farm with a capacity factor of about 45%; the second curve comes from a wind farm with a capacity factor about 22%.

In practice, there is a reasonable measure of agreement between all three datasets in the figure. They suggest that average power outputs from wind in the peak winter months are about 30% higher than the annual average, and two and half times those in the quietest months (May to September). This is consistent with findings from the ECI.

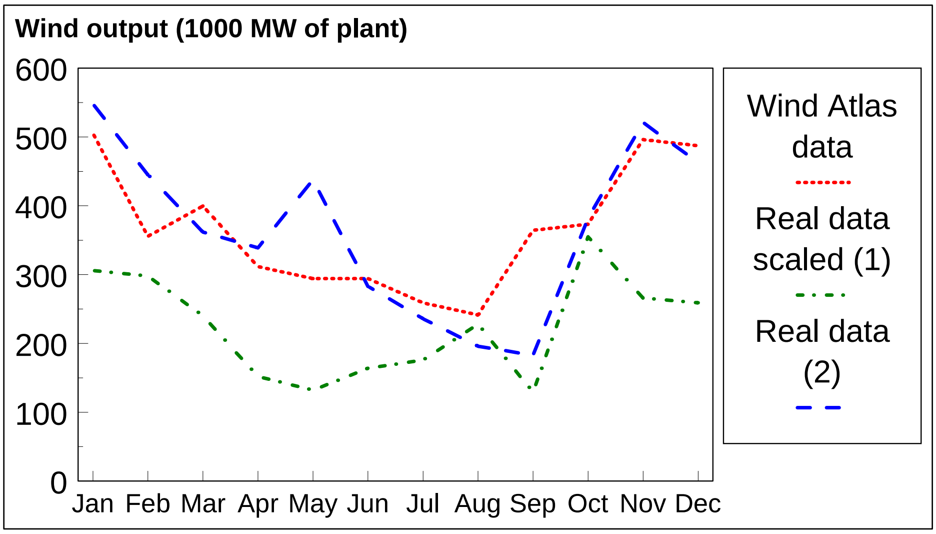


Figure 1 Average monthly power outputs from wind farms

Wave Energy

ECI's analysis of wave power data shows a similar pattern to wind: the output at peak times is about 30% higher than the annual average. The detailed analysis has been carried out for a site where the annual average capacity factor was 37% and so the capacity credit would be about 50%.

Note: it must be emphasised that this discussion of capacity credits assumes that the contribution from renewable energy source (wind or wave) is small. Capacity credits for these variable sources decline with increasing energy penetration.

Short-term fluctuations

There are various ways of presenting data to quantify the variability of renewable energy sources, but one widely-used method is to quantify the dispersion at fixed time intervals ahead. One hour data for a single wind farm, for example, suggest that the standard deviation of the power output one hour ahead will differ from the power output at time zero by 12% of the rated output of the plant. Four hours ahead the standard deviation is 21%[4]. These data, and others for wind wave and tidal stream plant are compared in table 1.

NB None of these datasets includes offshore wind, whose inclusion may be expected to reduce the wind fluctuations further.

Inspection of the data in table 1 enables a number of conclusions to be drawn: –

- Geographical dispersion significantly reduces the fluctuations for all the technologies. The country-wide standard deviation (one hour basis) for wind comes down from 12% to 3% and for wave from 7% to 2.5%.
- The variability of country-wide wave plant is slightly less than that of wind (2.5%, compared to 3%). [As the "single" wave installation modelled by ECI is very large, comparisons with the much smaller single wind farm are not valid].

- In the case of nation-wide wind, there is very good agreement between the data from ECI, based on simulations, and the actual power measurements from western Denmark.
- Tidal stream power outputs are much more variable than either wind or wave but, on the other hand, they are predictable. The implications of this are discussed later in this note.

Table 1. Power fluctuations from wind, wave, and tidal stream plant

	Standard deviations, %		Extremes, %	
Lead time, hr	1	4	1	4
WIND				
Single wind farm				
UK 5 MW farm (power data)	11.8	20.8	90	100
Nation-wide				
NGC[5]	3.1	6.0 (at 3.5 hr)	18	29
West Denmark	3	10	20	50
ECI (simulation)	3.2	10		
WAVE				
Single	6.9	10.8		
National	2.55	4.5	10	
TIDAL				
Single	32.3	56.7		
National	22.1	39.6	50	
WIND, WAVE, TIDAL	2.22	5.78	9	

Requirements for additional reserve.

Electricity generating options with variable output give rise to additional costs for System Operators, since additional reserve must be scheduled to cater for the additional uncertainty introduced into the supply/demand balance. Contrary to popular opinion, additional reserve does not need to be provided on a megawatt for megawatt basis, but to the extent that it increases the additional uncertainty[6]. In practice, with wind supplying 10% of the electricity on a network, the additional reserve is in the range 3 to 6% of the rated capacity of the wind plant[7]. The corresponding costs of this reserve depend on the costs of the plant and on the institutional framework in the country concerned, but there is nevertheless a reasonable agreement between analyses from a number of sources. With 10% wind the extra cost is between \$2.8 and \$4.5/MWh with 20% wind, it is between \$3/MWh and \$5/MWh, approximately[8].

In the UK, National Grid Transco uses various types of reserve to ensure the system operates satisfactorily and issues periodic tender invitations for most of this plant. It follows that the additional costs of reserve for the variable renewable energy sources are not fixed, but will vary, depending on prices for the various types of reserve.

A rigorous calculation of the requirements and cost of extra reserve is quite complex, especially as some balancing is now carried out under the New Electricity Trading Arrangements in the UK by individual suppliers, rather than the System Operator. As NGT has, however, published estimates of the extra costs for wind energy[9], that provides a useful benchmark against which to assess the corresponding costs for other technologies. The procedure adopted in this analysis has been to reproduce the NGT estimates for wind analytically, using estimates of the supply/demand uncertainty and of the cost of just two types of reserve[1]. This is the basis of the curve labelled "Wind (NGC)" in figure 1.

Having established reference data for wind energy, estimates of the costs of extra reserve associated with wave energy and with a combination of wind, wave and tidal, were derived using appropriate dispersion data from table 1. Electricity system data were not changed. This is the basis of the other two curves in figure 1. It may be noted that the curves start at the origin, so the implicit assumption is that the full benefits of geographical diversity are realised as the capacity builds up. This is probably a reasonable assumption in the case of wind energy, but wave and tidal may be less dispersed and, in the case of wave, possibly developed using larger installations. The particular plant capacities used by ECI in establishing the figures for temporal diversity are listed in table 1, together with the corresponding estimates of extra reserve costs. These are compared with estimates of the extra reserve costs for wind, for the same energy penetration level (not the same capacity).

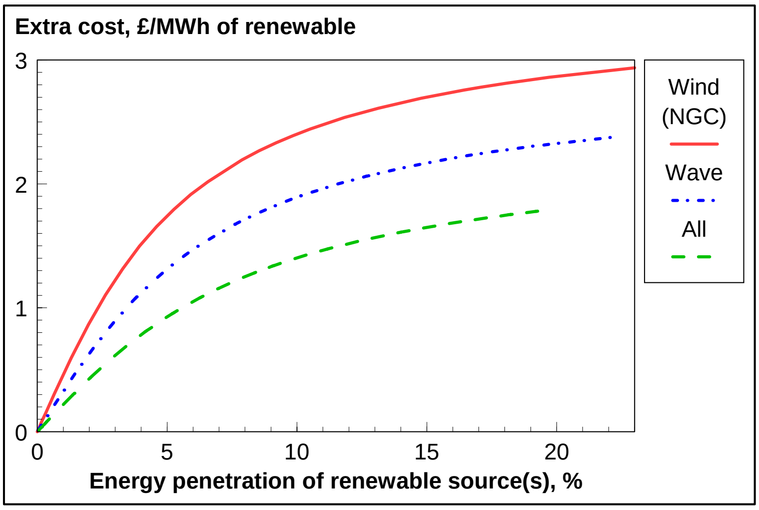


Figure 2 Extra back-up costs as a function of energy supply

It must be noted that the absolute levels of extra reserve costs in Figure 2 and Table 2 are not the important parameters, as the costs of reserve change. The costs of reserve changed after NGT published its estimates for wind and a later study derived lower values. Nevertheless, the differences between wave and wind costs in table 2 are of more interest (although they, too, will change in line with reserve prices). With this caveat, it appears that the extra reserve costs for "distributed wave" are about 20% lower than for distributed wind. With a combination of wind, wave and tidal, selected to achieve a low long-term hour-ahead variability, the extra reserve costs are about 44% less than for wind alone.

Table 2 Estimates of extra back-up costs for variable renewable sources

Technology	Capacity, MW	Energy Penetration, %	Extra cost of reserve, £/MWh
Wind	11,317	7.5	2.15
Wave	11,657	7.4	1.68
All	10,700	7.5	1.21

[1] One-hour and 4-hour reserve costs were used. A good fit was achieved: for example, NGT have suggested the extra costs with 10% wind are £2.38/MWh; the modelling suggests £2.40/MWh. The corresponding figures for 20% wind are £2.85/MWh and £2.86/MWh, respectively.

CARBON TRUST

Environmental Change Institute

Reduced back-up costs with better forecasting

Although there are significant differences in the way that electricity jurisdictions operate, there is a reasonable consensus on the savings that can be realised through good forecasting. These savings accrue since the uncertainties that System Operators face when handling wind energy are significantly reduced and this enables them to reduce the amount of extra reserve plant that is scheduled. Although the monetary savings depend on the costs of reserve, they are of the order £0.5-1/MWh at low wind energy penetrations (2-4%), rising to around £1.5-2/MWh with 10% wind energy.

It is worth noting that the economic value of Perfect Prediction - compared with "no prediction" is significant, but not large. In an early CEGB study[10], the break-even value of wind power came down by about 10% between No Prediction and Perfect Prediction (for 10% wind). In a second UK study[11], Perfect Prediction realised additional fuel cost savings of 2%, compared with Persistence. In terms of the reduced requirements for back up capacity, a recent American study[12] suggested that the requirements for back up reserve capacity, when the wind capacity amounts to 22.6% of peak demand, might be reduced from 7.6% of the wind capacity to 2.6%.

Assuming similar improvements can be made to wave energy this indicates that the costs of extra reserve for all the technologies can be reduced to around £2/MWh or below, up to around the 20% penetration level.

Tidal stream issues

Tidal stream exhibits quite different characteristics from wind or wave energy. The output various more or less continuously, which is reflected in the much higher values of temporal dispersion in table 1. On the other hand, that output is predictable. The latest document from the Severn Tidal Power Group[13] suggests that electricity prices from the proposed Severn barrage might command a premium over baseload electricity prices but that conclusion is at odds with previous CEGB work[14]. (The output from tidal stream devices does not vary in quite the same way, but there are similarities). The CEGB report suggested that cost of extra backup for the Severn barrage would be around 0.46p/kWh, (8% discount rate – 1988 prices), but no details of the calculations were provided. When the variation of this cost with discount rate is examined, the cost of the associated plant appears to be similar to present-day levels (around £350/kW, which implies, of course, that costs have fallen in real terms). This enables an "equivalent temporal dispersion" estimate to be made, which is about 5%. When allowance is made for the higher load factor of tidal stream, compared with tidal barrage, it is possible that the extra backup costs associated with tidal stream are similar to those for wind and wave. However, the very tentative nature of this analysis must be emphasised.

Despite its predictability, increasing amounts of tidal stream energy might occasionally incur significant operational penalties, due to the high rates of change of power output which are expected. The ECI data suggests that the one-hour standard deviation of the fluctuations is around 22%, and the extreme around 50%. In the event that the estimated maximum UK generating capacity for tidal was installed (3,836MW), the maximum hourly change per year would be around 1,900MW. Although this is comparable with the some of the highest hourly changes in system demand on the UK electricity network, it may be noted that a “worst case scenario” – demand falling, tidal power production rising – would not occur every year. Apart from this, NGT has modelled the impacts of 20% wind – where similar, but rare, extreme changes would occur - and not indicated that there are any undue problems.

Conclusions

By comparing simulations of wind plant outputs from ECI with actual power data from wind farms and from western Denmark, very similar conclusions are drawn concerning power fluctuations and wind plant capacity credits. The latter appear to be around 30% higher than the average capacity factor. In other words, 1000 MW of wind plant, with a capacity factor of 30% will have a capacity credit of about 400 MW. A similar conclusion applies to wave energy.

By examining the hour-by-hour dispersion of wind and wave, it is possible to derive estimates of the costs of extra backup required for dispersed wind and wave plant. After calibrating the analytical data against information from National Grid Transco, it is suggested that the extra backup costs for wave energy are about 20% lower than for distributed wind

(£1.7/MWh, compared with £2.1/MWh). The advantages of diversity can be exploited further by introducing tidal stream energy into the renewable mix, which reduces the backup costs (all at 7.5% energy penetration) to around £1.2/MWh.

There does not appear to be documented analysis on the impacts of tidal stream fluctuations on an electricity network. Although they are predictable, their magnitude is greater and this could have implications for the extra backup costs. Improved methods of wind and wave output prediction would reduce the extra backup costs for wind and wave by around 30% – possibly more.

Overall, the analysis did not identify any significant problems in absorbing wave energy fluctuations, but further analysis of the implications of using tidal stream energy may need to be carried out if it is anticipated that substantial developments are likely to occur.

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Annex 3 – Evaluation of wave power prediction in UK waters

Background

Designing an effective wave energy system begins with an assessment of the available wave resource. By observing how wave energy varies throughout the year and around the UK, wave energy devices can be installed and operated in an efficient manner. However, collecting wave data is a costly and difficult process. Currently the best observed data comes from buoys operated by the Met Office, covering 19 locations for various lengths of time since 1989. However these data do not provide coverage of all possible wave energy sites and the challenges of the marine environment mean that, for those locations where a buoy does exist, the data series are often only partially complete.

An alternative approach is to model wave conditions. Since March 2000, the Met Office has been running the UK Waters wave model to provide data on the sea-state at a much higher spatial resolution (approximately 12km by 12km grid size). The model is run every six hours and can simulate waves driven by remotely-generated swell conditions or local wind-driven waves.

The UK currently has an emerging wave energy industry and good wave resource data is essential to the sector's growth. Wave data is first required to locate wave energy devices in the most efficient locations. However once the devices have been installed, device operators will need to understand the patterns and amounts of generated electricity so that they can interact with the national grid. These two factors ensure that the wave energy industry will be looking for quality wave data in the coming years.

To date, no formal assessment of the UK Waters model has been conducted and therefore it is the aim of this report to provide an evaluation of the model's accuracy. Also the report will try to highlight ways in which the model may be of use to the emerging UK wave energy industry.

Outline

The report is structured as follows:

- **Data considerations and approach:** The data used to assess the model are introduced and a general overview of the analysis techniques presented.

- **Baseline assessment:** The analysis begins by comparing the model's estimates of current wave conditions (the "nowcast") with measured wave conditions. This assessment includes wave power, wave period, wave height, and device power.

- **Forecast accuracy:** The comparisons of observed and modelled data are then extended to determine the model's accuracy at a variety of forecast horizons, from one hour to five days ahead.

- **Forecast consistency:** The model's estimates of current wave conditions are compared with previous forecasts to estimate the consistency of model forecasts.

Data considerations and approach

Data sources

Two sets of data were used for this analysis: the model data, which comes from the Met Office UK Waters wave model; and the observed data, which comes from Met Office buoys. Details on these data sources are now provided as well as a discussion of the analytical approach and how the data were prepared for analysis.

Model data

The model data was provided from the UK Waters wave model, run at six-hour intervals between 1 January 2001 and 31 December 2002. At each time step, a number of sea-state parameters were returned but for this analysis, significant wave height and zero-upcrossing period were used to represent the wave climate. These values were also calculated at each time step for forecast periods of 0, 1, 2, 4, 6, 12, 18, 24, 30, 36, 48, 72, 96, and 120 hours. Throughout the document these forecast horizons are referred to as T*x*; e.g. T2 is the two-hour forecast. T0 is known as the nowcast.

Observed data

The Met Office maintains wave buoys at the study sites, which measure data and time, zero-upcrossing period, and significant wave height. The data are recorded at one-hour intervals and can therefore be matched with the model data at all forecast resolutions.

Three sites were chosen for study based on their potential as areas for wave energy development and the quality of the data at these sites. The sites include:

- B62106, Rahr buoy, representing the north-west (Outer Hebrides to Northern Ireland)
- B62107, Seven Stones Light Vessel, representing the south-west region (Cornwall, Severn, and Scilly)

B64046, K7 buoy, representing the north-east region (west of the Orkney and Shetland islands)

Data preparation

To prepare the data for analysis, wave height and period were transformed into *wave power*, as an indicator of the available wave resource at a particular site, and *device power*, i.e. the power an installed wave energy generator would actually produce at a given site.

The **wave power** (WP, kW per metre of wave front) was calculated from the observed and modelled significant wave height (H_{sig}, metres) and zero-upcrossing period (T_z, seconds) as follows:

$$WP = 0.49 H_{sig}{}^{2} (1.14 T_z)$$

Calculating the **device power** (DP, in kW) is more complicated as the output depends on the type of device installed. Three devices were used for this analysis: Pelamis Ocean Power Delivery, Wave Dragon and the Archimedes Wave Swing (AWS).

Each device has an associated transform matrix, which relates wave period and height into device output (ECI 2005). For the Pelamis, a single transform matrix was available for all three study sites (ie the device was not site-optimised). The Wave Dragon was sized according to site conditions, based on the annual average wave height. Finally, the transform matrix of the AWS indicates that it can have very high output in certain rare sea-states. This presents a practical dilemma, as it is unlikely that a developer would install the additional transmission capacity to accept these rare, high-output events.

Therefore capacity factors were used to size the AWS in a manner comparable to the other devices. Averaging across all three sites, the initial capacity factors were 0.38 for the Pelamis, 0.44 for the appropriately sized Wave Dragons, and 0.13 for the AWS. Then, a modified AWS was designed, by capping the output at various levels until the capacity factor was comparable with that of the other devices. This maximum output cap corresponded to the 85% quantile of the unrestricted AWS output at all sites. The final device selection is presented below (ECI 2005).

	Site		
	B62106	B62107	B64046
Avg. H_{sig} (m)	3.3	2.2	3.1
Avg. T_z (s)	7.6	8.7	7.4
Devices	Pelamis, WD33, AWS-800	Pelamis, WD23, AWS-700	Pelamis, WD33, AWS-900
Avg. capacity factor by site	0.41	0.39	0.43

AWS-x refers to an AWS device where all outputs above x are reduced to x. WD33, for example, is a Wave Dragon device suitable for a site with an annual average wave height of 3.3 metres.

As a final step before the analysis, negative, non-finite, and outlier data (at the 99% level) were removed from the series of calculated wave and device powers.

Analysis approach

The goal of the analysis was to quantify the reliability of wave energy forecasts from the UK Waters model and assess its applicability to the emerging UK wave energy industry. The primary analysis approach is described below, although some additional techniques were employed throughout the study where appropriate.

Primary comparisons

Two primary analyses were performed. First, the model's performance against observed data was compared. This was repeated for all forecast horizons (T0, T1, T2, T4, T6, T12, T18, T24, T30, T36, T48, T72, T96, and T120).

Secondly the consistency of the model's forecasts was also examined: for example, comparing the model's nowcast (T0) with the twelve-hour forecast (T12) generated twelve hours previously. Since the model was run every six hours, nowcast data is only available at this resolution and so the forecast periods used were T0, T6, T12, T18, T24, T30, T36, T72, T96, and T120.

Analysis techniques

Two primary techniques were used:

- **Correlations:** Pearson correlation tests were performed to determine if there were statistically significant correlations between the two data sets (at a 95% significance level). Results are reported as r^2, the percent of variation in one variable explained by the other. All correlations reported here are significant, except as noted.

- **Error distributions:** For each paired set of data (forecast/observed or forecast/nowcast), the percent error was calculated. For example, the forecast/observed error was calculated as:

$$\%Error = \frac{(Forecast - Observed)}{Forecast}$$

  In this way, a negative error represents how much the model forecast underestimates the corresponding observed or nowcast value. Shapiro tests were performed to determine if the distributions were normal but in nearly all cases, the distributions were skewed. Therefore non-parametric Wilcox tests were used to determine if the distribution was symmetric about zero. For this reason, the median error reported here is the Wilcox (pseudo) median, a value which lies between the true median and mean.

Data subsets

For each primary analysis, the full data set was analysed as well as subsets of the data. This included a seasonal subset, where winter is defined as December to February and summer as June to August. The forecast wave or device powers were also divided at their median into high and low power groupings.

Each data subset was also analysed by site. This therefore includes data from all sites, B62106, B62107, or B64046.

Wave and device powers

Once the data subset has been defined, separate analyses were done for the wave and device powers. For the wave power analysis, this includes analysing the wave power as calculated above, as well as the wave period and height. Analysing these variables separately provides a clearer picture of whether the model's accuracy is due to a particular component of wave power.

Device power was analysed for each device type (Pelamis, Wave Dragon, and AWS) as well as an average of all devices.

The following table summarizes these various analysis combinations.

Variable	Options
Primary comparison	Model forecast vs. observed, or Model forecast vs. model nowcast
Data subsets	• All data, Summer, Winter, Low Power, High Power • All sites, B62106, B62107, B64046 • T0, T1, T2, T4, T6, T12, T18, T24, T30, T36, T48, T72, T96, T120
Variable of interest	Wave power (as well as period and height) or device power (single device and all devices)
Analysis technique	Correlation and error distributions

Baseline assessment

Overview

The baseline assessment compares the model's most accurate forecast (the T0 nowcast) with observed data. This analysis provides context for the rest of the report, as well as highlighting some potential areas for improvements to the model. The wave power analysis is presented first, followed by the device outputs.

Wave power

Correlations

Overall the model explains 74% of the variation in observed wave power. This correlation is strongest at offshore sites (B64046, B62106). Seasonally, correlation is generally better in the winter, though this varies by site. The correlations by power subset are lower, with an average r^2 of 0.35 at low power and 0.63 at high power.

Sites	Data set	R^2
All sites	All data	0.742
	Summer	0.648
	Winter	0.693
	Low Power	0.353
	High Power	0.628
B62106	All data	0.756
	Summer	0.659
	Winter	0.737
	Low Power	0.508
	High Power	0.676
B62107	All data	0.643
	Summer	0.461
	Winter	0.672
	Low Power	0.208
	High Power	0.563
B64046	All data	0.773
	Summer	0.778
	Winter	0.672
	Low Power	0.445
	High Power	0.653

Wave period and height were also correlated with observed values. The table below shows a much better correlation in significant wave height (H_{sig}) than period (T_z). This difference can be explained by the resolution of each variable. Wave height is measured in 0.1m and 0.01m intervals, observed and model respectively. Period however is measured at one-second intervals in observed data and 0.25 seconds in the model. Since the range of values is similar for both variables, the coarse resolution in the period results in a poor correlation. This makes it extremely difficult to determine if there are errors in the model's estimates of period.

Sites	Data set	R^2 (H_{sig})	R^2 (T_z)
All sites	All data	0.833	0.188
	Summer	0.742	0.009
	Winter	0.792	0.190
	Low Power	0.529	0.003
	High Power	0.695	0.182

Error distributions

The wave power error was calculated as defined above, comparing individual pairs of observed and nowcast wave power. It was found that these errors are not normally distributed and that the model appears to underestimate observed wave power by 37% of the corresponding model estimate. Taking the population as a whole though, the median error in wave power is only -13%. The median error is much lower at high power values, which is the area of greatest interest for wave energy developers.

Sites	Data set	Median % Error
All sites	All data	-37.4
	Summer	-43.2
	Winter	-38.8
	Low Power	-64.4
	High Power	-16.3
B62106	All data	-29.4
	Summer	-28.2
	Winter	-32.9
	Low Power	-47.8
	High Power	-12.3
B62107	All data	-48.3
	Summer	-70.2
	Winter	-37.1
	Low Power	-91.0
	High Power	-14.7
B624046	All data	-40.6
	Summer	-48.1
	Winter	-53.9
	Low Power	-62.6
	High Power	-24.0

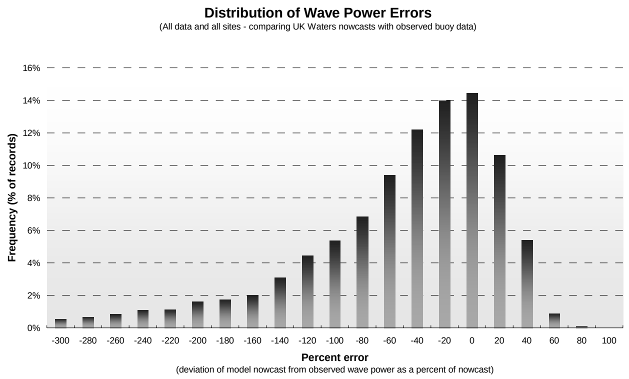
The errors for height and period indicate that most of the error in the model arises from the period and low power levels.

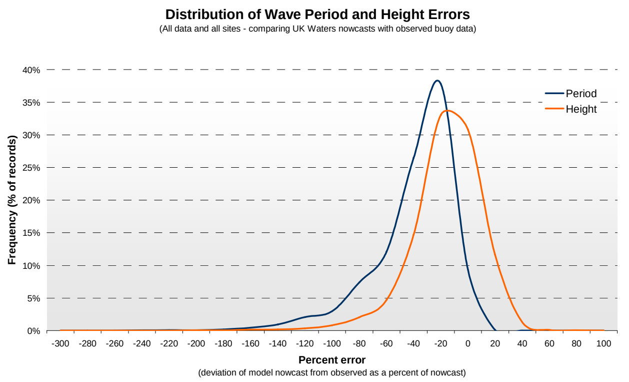
Sites	Data set	Median % Error (H_{sig})	Median % Error (T_z)
All sites	All data	-3.84	-25.8
	Summer	-3.75	-30.4
	Winter	-5.74	-21.9
	Low Power	-8.04	-37.3
	High Power	-0.04*	-15.2

**not significantly different from zero at 95% level*

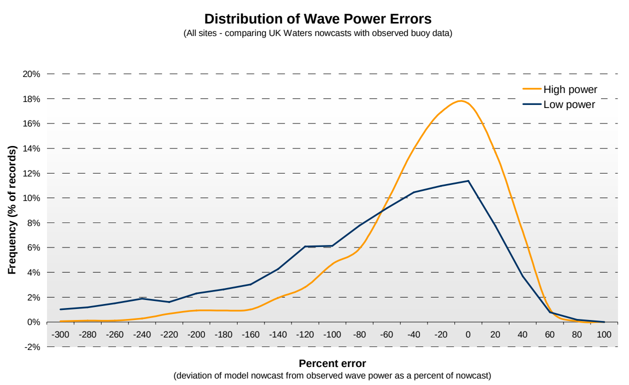
Error plots

The following two figures show the distribution of wave power errors for all sites. The distribution of wave height is much more symmetric about 0% error, whereas the wave period has a negative skew. These errors are then magnified in the wave power plot, as shown by the wider distribution of error.





The figure below compares the distribution of errors in wave power for the low power and high power data sets. The error in the high power subset is not only closer to zero but the distribution is also more symmetric, demonstrating that the model is more effective at predicting wave power at high power conditions.



Device power

Correlations

The nowcast device output correlates very well with the device power calculated from observed data. Using all data, the correlations between devices are similar, ranging from 0.692 for the AWS to 0.796 for the Wave Dragon. By site, the best correlations again appear at offshore sites B64046 and B62106; note that there is a different device correlation at each site (including devices that were appropriately sized for the site).

Devices	Sites	R^2
All devices	All sites	0.861
	B62106	0.856
	B62107	0.798
	B64046	0.869
Pelamis	All sites	0.759
	B62106	0.846
	B62107	0.759
	B64046	0.851
Wave Dragon	All sites	0.796
	B62106	0.762
	B62107	0.708
	B64046	0.780
AWS	All sites	0.692
	B62106	0.744
	B62107	0.541
	B64046	0.765

Using all sites, stronger correlations can be seen in winter and at times of high power. Good correlations at high power are largely due to the device's maximum output limit, thus giving similar powers in a range of high wave conditions.

Devices	Data set	R^2
All devices	Summer	0.702
	Winter	0.882
	Low Power	0.396
	High Power	0.823
Pelamis	Summer	0.652
	Winter	0.776
	Low Power	0.386
	High Power	0.580
Wave Dragon	Summer	0.566
	Winter	0.784
	Low Power	0.308
	High Power	0.676
AWS	Summer	0.465
	Winter	0.648
	Low Power	0.174
	High Power	0.489

Error distributions

The device power errors were calculated for all time-matched pairs of nowcast and observed device power. These are large percent errors but for the population as a whole, the error in device power is -11%. In other words, the population of modelled values corresponds well to observations; the large errors only occur when comparing a given model output to a corresponding observation. Note the low error for the Pelamis at B62107 is due to the low capacity factor of that device at that site, making the errors much more symmetric about zero.

Devices	Sites	Median % Error
All devices	All sites	-64.7
	B62106	-48.9
	B62107	-97.0
	B64046	-54.7
Pelamis	All sites	-16.4
	B62106	-21.7
	B62107	-1.61*
	B64046	-29.4
Wave Dragon	All sites	-62.6
	B62106	-45.4
	B62107	-94.2
	B64046	-49.2
AWS	All sites	-187
	B62106	-110
	B62107	-402
	B64046	-112

*not significantly different from zero at 95% level

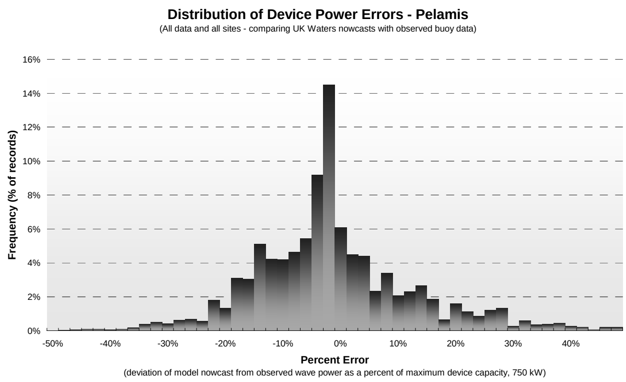
The second table shows that the large errors occur mainly at low power levels, where the percent difference may be large despite a small absolute difference in output. The capacity factors were calculated, confirming first that, at an aggregate level, the model's performance is much better and also that the model performs best at times of high wave energy.

Data set	All devices Median % Error	Pelamis at B62107 (P_{max} = 750 kW) Observed capacity factor	Forecast capacity factor	Error in capacity factor (%)
Summer	-108	0.288	0.224	-28.6
Winter	-45.8	0.660	0.643	-2.64
Low Power	-116	0.348	0.449	-22.5
High Power	-27.8	0.711	0.747	4.82

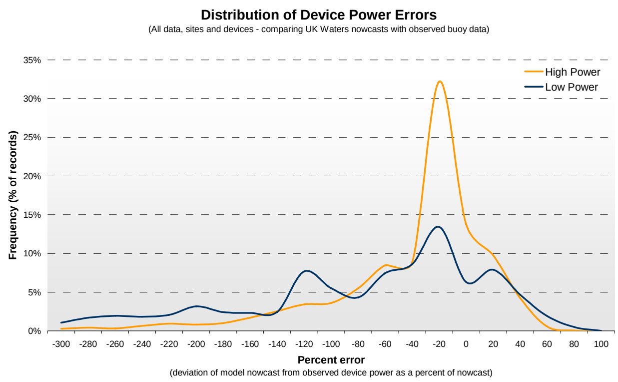
It should be noted that the largest errors occur at B62107. Examining a time domain matrix for this site reveals that this site experiences more low height and low period waves than the other sites (ECI 2005). The power transform matrices are particularly sensitive to small errors at this low energy state and therefore the errors of particular devices should not be interpreted as a weakness of a particular device. Rather these findings suggest that the accuracy of the overall model with regard to device output could dramatically improve by addressing its performance at low wave states; for example, by improving the resolution of model periods. (Improving the resolution of buoy measured periods would also be beneficial).

Error plots

The figure below shows the error in the modelled output of one device, as a percent of maximum device output. The most common errors are between -20% and 0%, suggesting that the model underestimates device power output quite consistently.



Dividing the data into high and low power groupings, it is apparent that paired errors in high power conditions are much more consistent. The low power distribution however covers a wide range of errors, suggesting that it would be difficult to predict the device output in for a specific low power situations (e.g. summer) with great confidence.



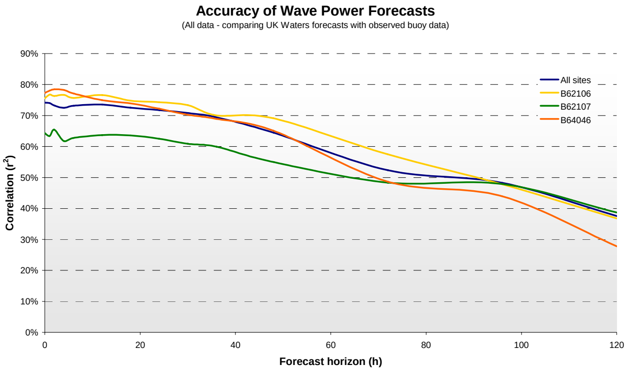
Overview

To extend the baseline analysis, the model's accuracy is assessed across a variety of forecast horizons, for both wave and device powers. This analysis will be particularly useful for those interested in forward-selling wave-generated electricity to the national grid.

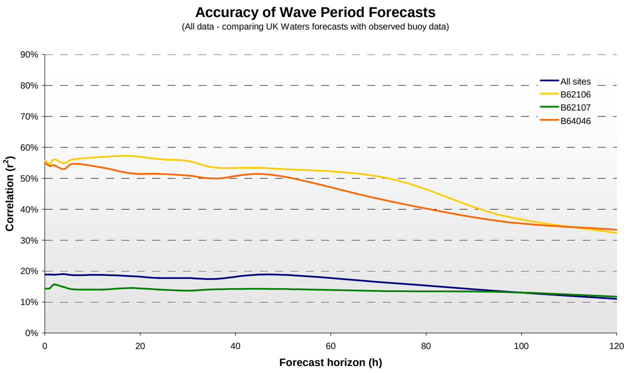
Wave power

Correlations

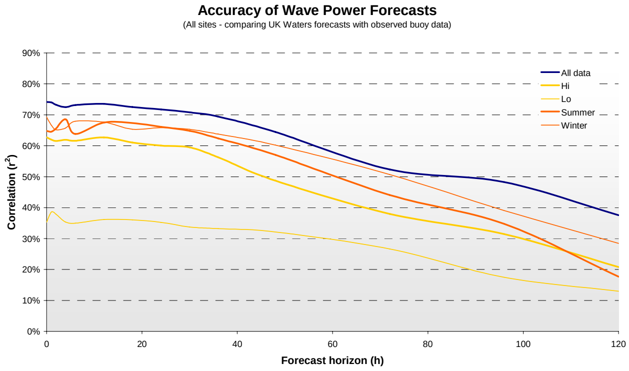
As expected, the correlation between forecast and observed wave power becomes weaker at longer forecast periods. A linear regression explains 95% of the observed variation (using all data), suggesting that the correlation for a given time horizon can be estimated with good confidence. The correlation trend in wave height is very similar.



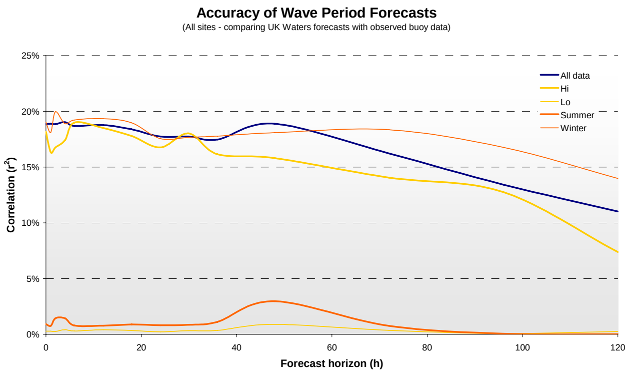
Examining the correlation trends for both wave period and height reveals that B62107 is the most poorly correlated site, especially for period. This suggests that the model's strength is in predicting offshore sites and therefore improvements in the modelling of low energy conditions, as mentioned above, could increase the model's overall performance for inshore areas.



Although the correlations by site are quite similar, there is a large spread in correlations between the different data sets. The relationships are again linear but a closer look at the wave power plot suggests that the correlation is fairly constant until about 24 hours, at which point it begins to decline. The poor correlation at low power can be clearly seen and wave height correlations are similar.

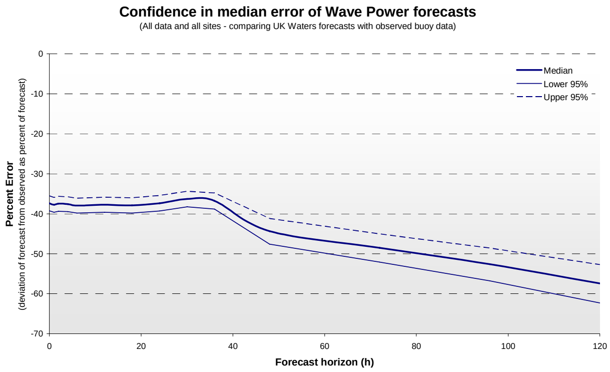


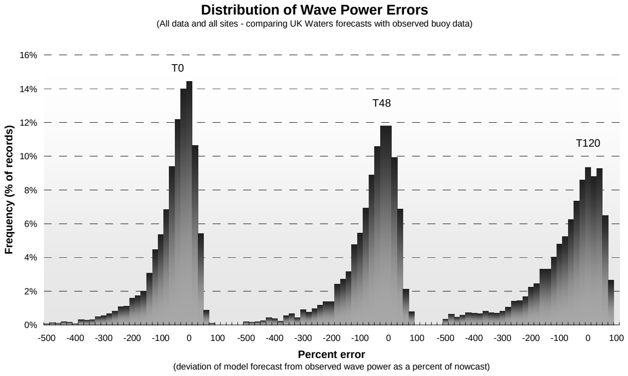
The poor baseline correlation between observed and forecast period holds for all forecast horizons, though it does begin to decline further past 48 hours. This plot also demonstrates the link between wave conditions and season; in other words, poor forecasts at low wave conditions will have a particularly negative effect on the effectiveness of the model in summer.



Error distributions

The upper and lower 95% confidence intervals for the median error were calculated over the forecast horizons. The overall wave power shows an increase in median error beyond 36 hours; the actual trend may be smoother as the Met Office runs separate models for forecasts less than and greater than 36 hours. The confidence interval for the median does increase slightly over time; this is shown better by the full distribution of errors (figure next page).



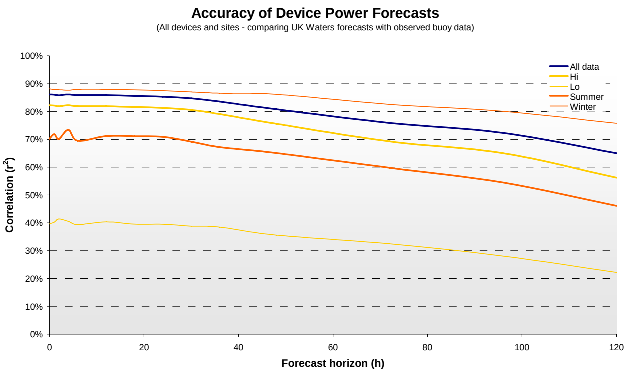


Period and height exhibit only slight changes in both median error and the confidence of this error over time.

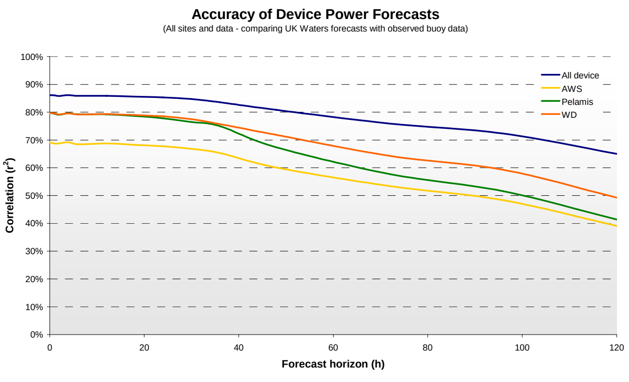
Device power

Correlations

Overall the device power correlation is very similar between sites, decreasing linearly from their T0 values to converge at an r^2 of 0.65 by five days. Looking at the data subsets though, a slight plateau can be seen with steady correlations for forecast periods less than 24 hours. Over the full five-day analysis period, correlations by device type consistently drop by about 30%.

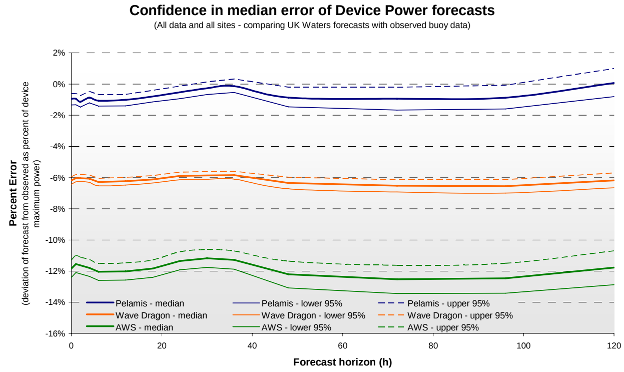


The average correlation for all devices drops less and is consistently higher than for a single device, showing that a portfolio of different wave devices can ensure that the correlation of a broader wave energy system remain high.

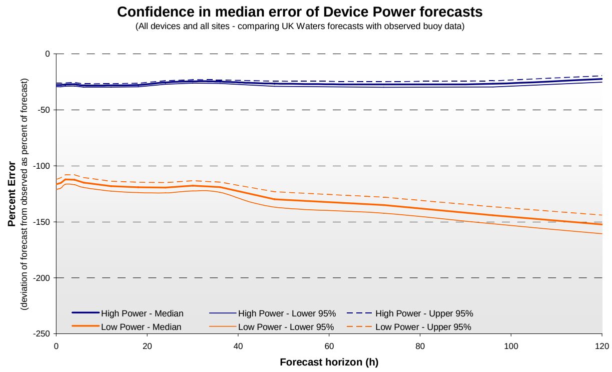


Error distributions

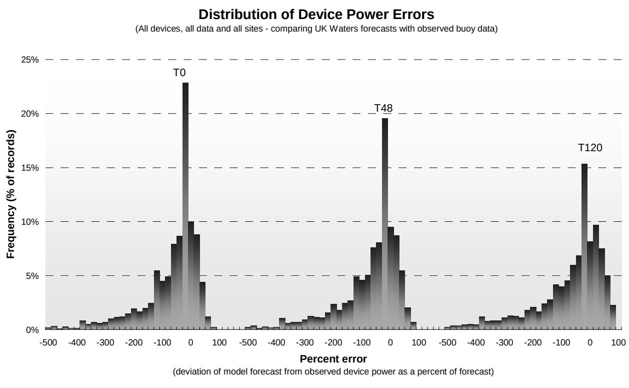
The median error of device power is constant for the various forecasts, though the confidence in the median of a specific device depends on how its transform matrix handles the low wave state issues identified above. As a percentage of each device's maximum output, these errors are quite low but consistently underestimating output.



As a percentage of the specific forecast value, the errors are much greater. However this error is greatly reduced at times of high forecast device power.



The detailed distributions of these errors for all devices at all sites, shows that most of the error in predicted device output occurs in the -20 to 0% range. This suggests that a correction might be made to the forecast model period and height so that the correct output value is determined from the transform matrix.



Forecast Consistency

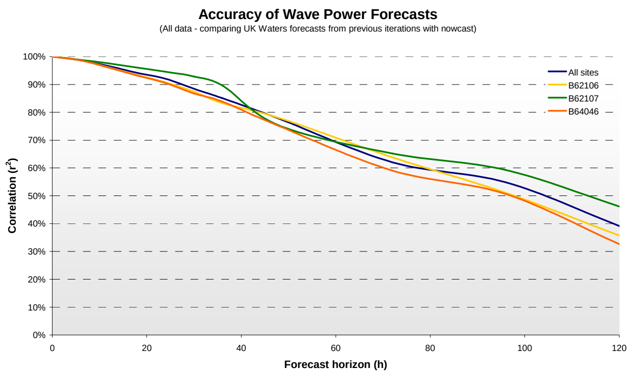
Overview

In this section, the consistency of the model is evaluated by comparing nowcasts with forecasts from previous time intervals; e.g. how well does the T6 forecast from six hours ago match with the current nowcast. This is particularly important as the model is only run at six-hour intervals but decisions about the operation of a wave energy system may need to be made at different horizons. Of course, the UK's environment dictates that the forecast is very likely to change across a five-day horizon; however examining the forecast consistency in detail will help users of the UK Waters model to pick the longest forecast horizon suitable for their needs.

Wave power

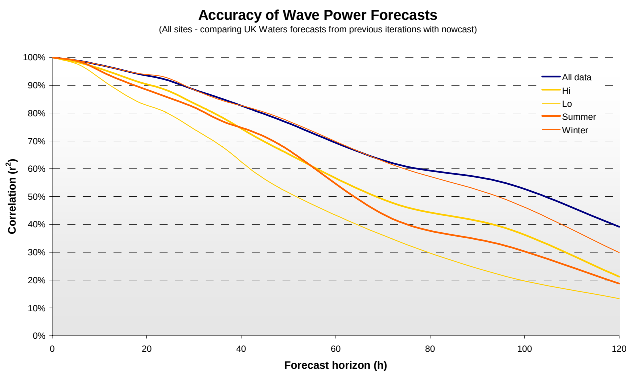
Correlations

The correlation between the present nowcast and previous forecasts drops significantly as longer forecast periods are selected. The following plot shows that this trend is almost identical at each of the model sites for estimates of wave power. Likewise, there is little difference between sites for wave period or height and



both values decrease linearly from 100% correlation at T0 to about 50% at T120.

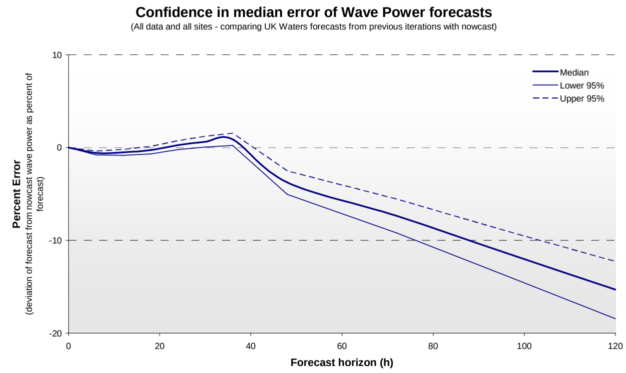
Comparing the trends by data subset is more interesting and reveals consistently stronger correlations for the winter subset. This is also seen in the period and height



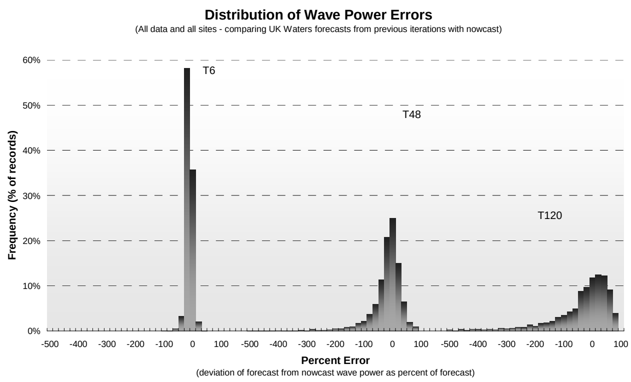
correlation trends and overall suggests that the model's predictions are more consistent in the winter. However it is surprising that the high power data subset (which is mainly winter data) does not exhibit similar behaviour.

Error distributions

The median error in wave power forecasts from observed data was nearly constant at the various forecast horizons. Compared with the nowcast data however, the median error changes notably at different timescales: in the short-term (less than 24 hours), the error is fairly constant with overestimates of height offsetting underestimates of period. By five days however, the initial forecast is almost 15% below the eventual nowcast with both forecast wave height and period underestimating the nowcast by approximately 3% and 1.5% respectively.



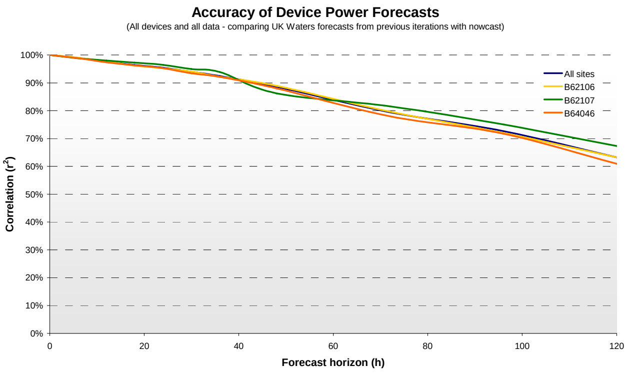
The other notable difference to the forecast/observed case is that the confidence interval for the median error increases steadily over time. This can be seen more clearly in the increased breadth of the error distribution below. The distribution of wave period errors remains very compact and the dispersion in wave power is mainly due to an increased range of errors in wave height at longer forecast horizons.

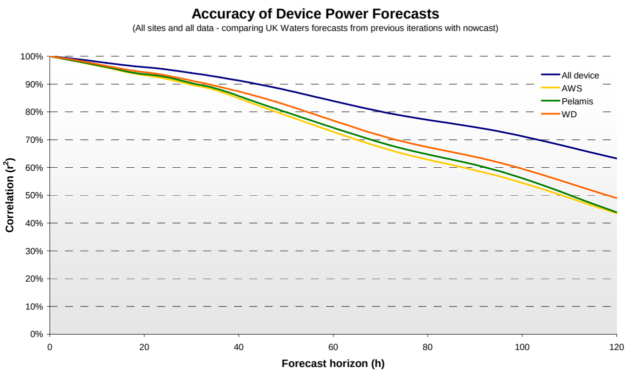


Device power

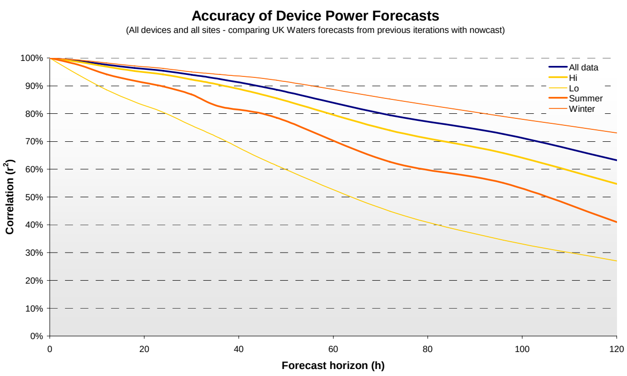
Correlations

As with wave power, the trends in correlation between forecasts and nowcasts are extremely similar between sites. They are also similar by device and again, a portfolio effect can be seen where the overall correlation is better for all devices than for any single device.



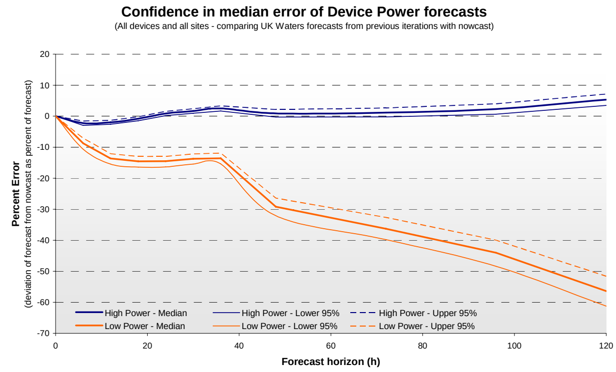


Larger difference can be seen between the different data subsets, in particular the difference between high and low power data subsets. This finding suggests that the consistency of a particular forecast is very sensitive to that forecast's context. One outcome of this is that a wave energy generator may wish to check the most recent forecasts more frequently in summer than in winter.

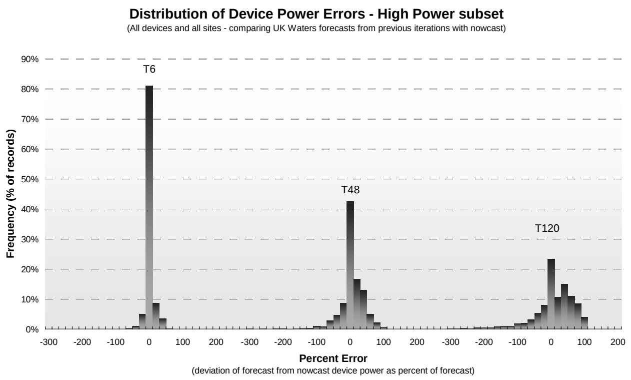


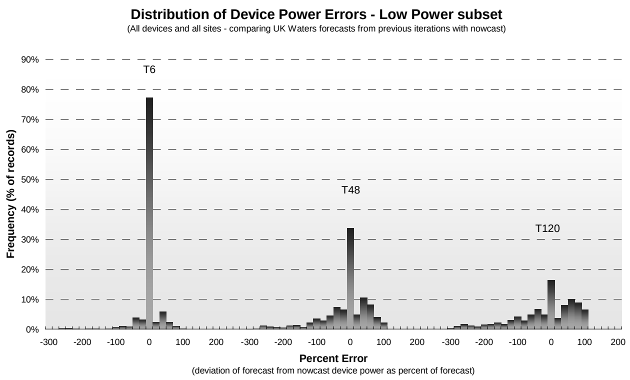
Error distributions

The median error in device power across all sites increases linearly from 0% at T0 to -20% at T120. Furthermore the importance of context in determining the consistency of a forecast is very evident by examining the median error of nowcast and forecast device powers. At low powers and long time horizons, the forecast can be as much as 50% below the eventual nowcast; however the high power errors are remarkably constant.



The detailed distributions of these errors show that the variability of error is much greater at low power conditions. Each power subset also skews in different directions at longer forecast horizons: e.g., at T120, the high power subset slightly over-estimates the eventual nowcast and the low power scenario underestimates it.





Implications for Wave Energy

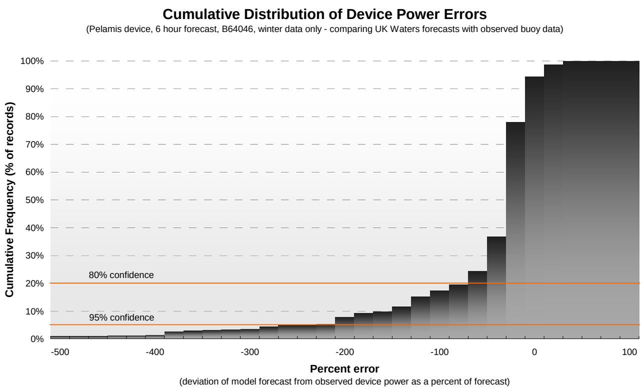
Overview

Although the UK Waters model may be useful to a number of different groups, its potential as a tool for the emerging UK wave energy industry is of particular interest. This section briefly examines how the results of this analysis might be used to increase the value of the model outputs for the operation of wave energy installations.

Dispatch plots

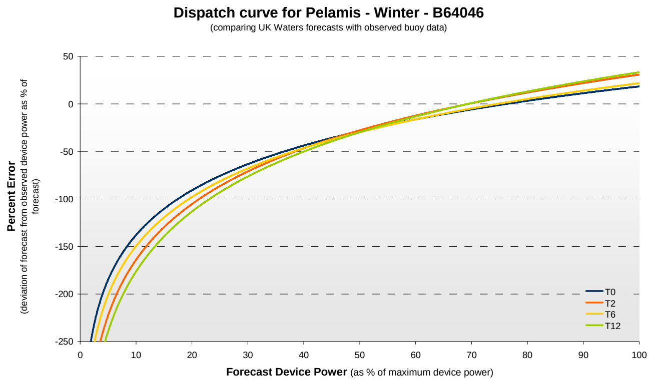
The error distributions presented previously are an important resource when trying to determine how to use the information provided by the UK Waters model. In this example, the objective is to determine the device output of a Pelamis wave energy device, installed at B64046, from a 6-hour winter forecast with a given level of confidence.

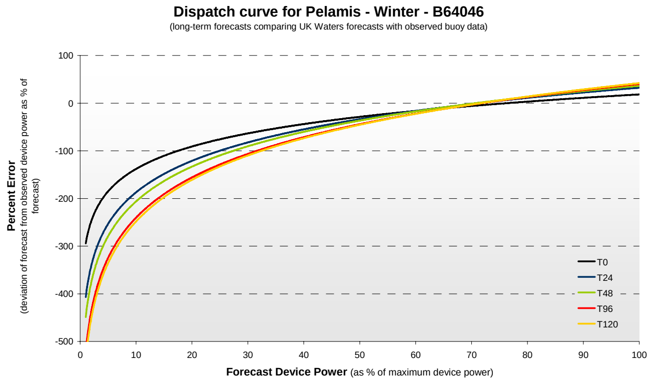
By plotting the cumulative distribution (below), the desired confidence level can be chosen and the corresponding error rate determined. For example, if a 95% confidence in output was selected, this corresponds to a device output of approximately 30 kW. At an 80% confidence level, an output of 110 kW can be achieved. Therefore depending on an operator’s risk tolerance and generator portfolio, a level of future electricity production can be considered “firm” with a known level of confidence.



More generally this relationship can be presented as “dispatch” plots, showing the relationship between percent error in the forecast with the level of device output. These curves are calculated at different forecast horizons, as shown above right.

The variability of model output at low power levels can also be seen clearly in these plots. Therefore one of the challenges for the wave energy industry is how to maximize this curve: that is, what levels of device output should be bid at various forecast horizons.





Conclusion

The wave power forecast analysis presented here suggests that the data provided by the UK Waters wave model is a valuable tool for in the UK wave energy industry. The model provides good quality estimates of observed wave and device powers across a range of forecast horizons. Although the error is the model is large overall, its performance in the high wave is superior to that at other times – this is important, as it associates greater forecast reliability with periods of higher electricity generation. Furthermore improvements in the resolution of the modelled and observed data may provide dramatic improvements, especially in low wave and inshore conditions.

The wealth of data created by the model is perhaps its greatest strength. In addition to being able to simulate locations where data collection may be too difficult or expensive, the model also enables those with an interest in wave energy to explore a range of scenarios, supported by detailed distributions of wave data in different sites and scenarios. This may encourage growth in the industry, be facilitating the creation of operational guidelines, siting criteria and other tools.

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