CHAPTER

# 13

# Determining Mean Annual Energy Production

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## 13.1 INTRODUCTION AND APPROPRIATE MODELLING TECHNIQUES

Estimation of the mean annual energy production (MAEP) of a wave energy converter (WEC) (or wave farm) is one of the fundamental objectives of numerical modelling. It is directly used in the calculation of the levelized cost of energy (LCOE), which is the primary economic determinant of the competitiveness of wave energy. The cost of energy is said to be levelized because the calculation is designed to assess energy technologies on a comparable basis and thus accounts for cost of the initial capital as well as the on-going cost of operations and maintenance. Thus, the LCOE is the cost at which energy would need to be generated to break even over the lifetime of the project.

It is reasonable to question why the MAEP is estimated and not the LCOE. However, the relatively simple definition of the LCOE disguises the fact that it is extremely difficult to calculate accurately. Even if the fabrication costs of the WEC could be estimated relatively accurately, the costs of maintenance and operation, which can represent a large proportion of the total annualized costs, are difficult to estimate. This is because not only are operation and maintenance costs naturally difficult to estimate, as they rely on understanding all the potential failure mechanisms and their probability of occurrence, but also because there is currently a lack of relevant knowledge and experience of full-scale WECs. Thus, there is generally a large uncertainty in the LCOE that is primarily associated with the cost estimate. The estimation of costs is considered to be outside of the scope of this book (as these could form the contents of a book on their own). Consequently, the estimation of the MAEP is considered independently, as it can be calculated significantly more accurately and subsequently can be used in an estimate of the LCOE. Further details regarding LCOE and cost estimations are given by Chozas et al. (2013) and Chozas et al. (2014).

All methods of estimating the MAEP involve a fundamentally relatively simple calculation.

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First, a set of sea-states that are considered to be a reasonable representation of the mean annual wave climate need to be identified. The power capture, $P_i$, in each of these sea-states is then estimated, either through direct simulation or interpolation, and multiplied by a representative duration, $f_i$, that equates to the frequency of occurrence of the sea-state (see Eq. 13.1)

$$MAEP = \frac{T}{N}\sum_{i=1}^{i=N} P_i \cdot f_i \tag{13.1}$$

where

$$\sum_{i=1}^{i=N} f_i = 1 \tag{13.2}$$

and $T$ is the average length of a year, which is 8766 h, following IEC/TS 62600-100 (2012).

In general, whatever method is used to estimate the MAEP, the accuracy of this estimate will increase with the number of sea-states used to represent the annual wave climate. However, the effort required to estimate the expected power capture for all of the sea-states also increases with the number of sea-states. Thus, there is always a balance between the effort required in generating an estimate of the MAEP and its accuracy. This balance extends into the numerical modelling technique, where a less accurate technique may be used to estimate the power capture if it allows a larger number of representative sea-states but with a net increase in the accuracy of the MAEP estimate.

It can be argued that any and all of the WEC modelling techniques described in Part A of this book may be suitable for the estimation of the MAEP, each technique having a unique combination of computational effort and accuracy. Table 13.1 contains a summary of the WEC modelling techniques available with reference to their computational effort and accuracy in estimating a particular sea-state's power capture. Further details on each technique can be found in the respective chapters.

The level of computing power typically available in a desktop computer now means that generally it is no longer necessary to use a frequency-domain model except during the very early stages of concept development, where a large number of configurations are being investigated or for large arrays. Unfortunately, except where a supercomputer is available, nonlinear potential flow and computational flow dynamics (CFD) methods are too computationally demanding to be used for the estimation of the MAEP. Consequently, the three generally suitable modelling techniques for the estimation of the MAEP are spectral-domain modelling, time-domain

**TABLE 13.1** Comparison of WEC Modelling Techniques for the Estimation of the MAEP

| Technique | Chapter | Computational Effort | Accuracy |
|---|---|---|---|
| Frequency-domain | 2 | Very low | Typically low, as nonlinearities are ignored in the model |
| Time-domain | 3 | Medium | Typically high, with appropriate parameterization of nonlinearities |
| Spectral-domain | 4 | Low | Can be high, but requires appropriate representations of nonlinearities |
| Nonlinear potential flow | 5 | High | Typically high, provided nonpotential flow nonlinearities are included |
| CFD | 6 | Very high | Can be high, but very dependent on the model formulation |
| System identification | 7 | Medium–low | Can be high, but dependent on the accuracy of the model used to identify the system |

modelling and system identification, with frequency-domain modelling potentially being suitable for large arrays although the accuracy limitations in these cases must be recognized. The different relationships between computational effort and accuracy for these modelling techniques means that each may be the most suitable depending on the particular circumstances.

The significance of the representative sea-states used to calculate the MAEP has already been noted. Thus, this chapter starts with a section detailing the different methods by which the wave climate can be represented for calculation of the MAEP. The next section details how the power capture may be determined for each of the representative sea-states and is followed by a section on the calculation of the MAEP, its interpretation and its uncertainty. The final main section discusses the current limitations associated with the estimation of the MAEP.

## 13.2 REPRESENTATION OF THE WAVE CLIMATE

For the calculation of the MAEP, the wave climate is considered to include all of the environmental factors that influence a WEC's power capture. Thus, it not only includes the sea-states, but also such factors as the water depth, the strength/direction of marine currents and the strength/direction of the wind. In addition, these factors are varying all of the time as the meteorological conditions change and so the wave climate also includes the temporal variations of these factors. Thus, characterization of the wave climate can be seen to be highly complex, which necessarily requires some parameterization so that it can be represented efficiently, whilst ensuring that the parameterization does not adversely limit accuracy.

Common to all wave climate representations, a sea-state is generally assumed to be statistically stationary over a period of a half to six hours and can be reasonably represented as the linear summation of uncorrelated sinusoidal wave components with different frequencies, amplitudes and directions. Although it is known that this is not strictly correct, as nonlinear coupling means that the wave components are not uncorrelated, it has been found to be a surprisingly accurate approximation and used almost universally to represent sea-states. Moreover, this representation is most accurate for nonextreme sea-states, which make the majority of the contribution to the MAEP. Thus, the waves in a sea-state can be generally represented using a two-dimensional directional-frequency surface variance spectrum (see Fig. 13.1), which provides all the information required to define the sea-state statistically.

From the directional-frequency spectrum a number of aggregate sea-state parameters can be defined and used to describe the particular sea-state. The vast majority of these aggregate sea-state parameters can be defined using spectral moments, where the $n$th moment, $m_n$, is defined by Eq. (13.3)

$$m_n = \sum_i f_i^n S_i \tag{13.3}$$

where $f_i$ is the wave frequency and $S_i$ is the surface elevation variance of the $i$th wave component. Using this definition, the spectral estimate of the significant wave height, $H_{m0}$, is defined by Eq. (13.4).

$$H_{m0} = 4\sqrt{m_0} \tag{13.4}$$

It is worth noting that this differs slightly from the significant wave height $H_s$, derived from time-domain analysis, as the average of the third highest waves, although the difference is typically not significant.

Other important sea-state parameters that can be estimated using spectral moments include the energy period ($T_e = m_{-1}/m_0$), the spectral estimate of the zero-crossing period $\left(T_{02} = \sqrt{m_0/m_2} \approx T_z\right)$ and the spectral bandwidth $\left(\epsilon_0 = \sqrt{m_0 m_{-2}/m_{-1}^2 - 1}\right)$. In traditional met-ocean data the peak period $T_p$ (the wave

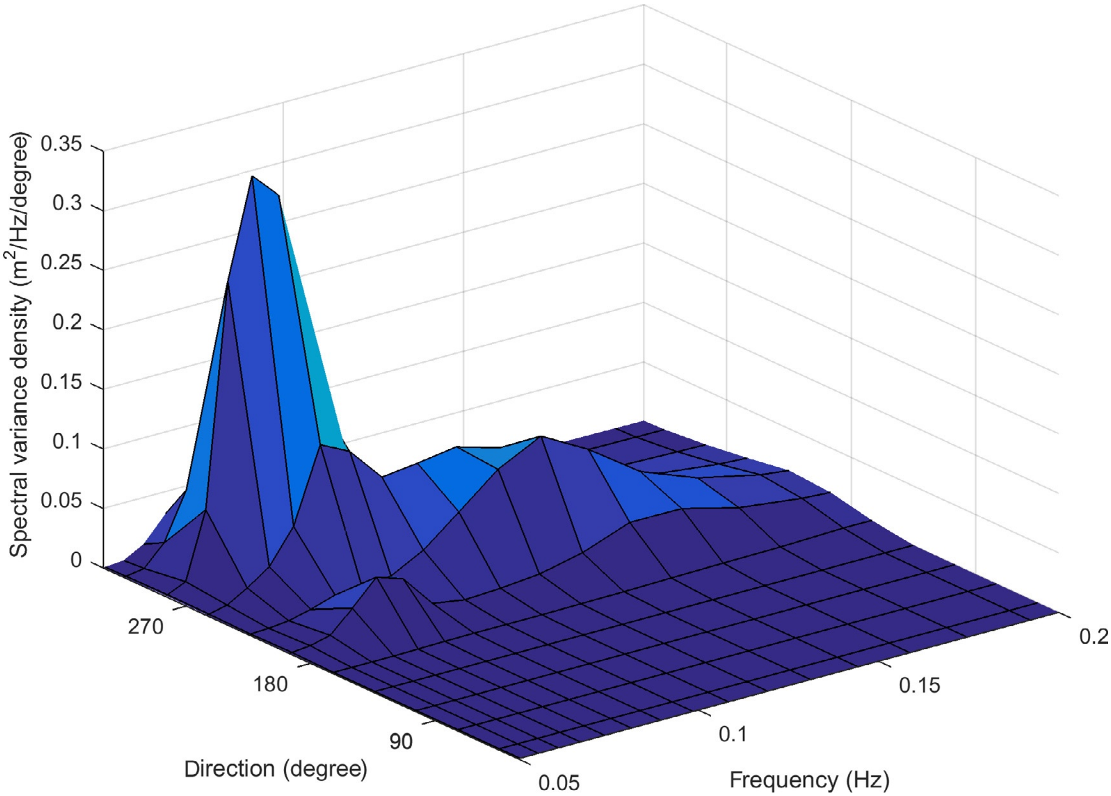


**FIG. 13.1** Example of a directional-frequency surface variance spectrum.

period at which the spectral value, ie, energy content, is maximum) is often used. However, the energy period is often considered a particularly relevant parameter for wave energy applications, because in deep water the wave power flux, $J$, is simply a function of $H_{m0}$ and $T_e$ as given by Eq. (13.5).

$$J = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \tag{13.5}$$

There are three fundamental ways in which the wave climate can be represented for calculation of the MAEP. The first way uses a further parameterization of the wave climate so that each sea-state is defined using a table of aggregated parameters such as $H_{m0}$ and $T_e$ (and possibly peak/mean wave direction); the second way uses the full time series of the sea-states; and the third way uses a refinement of aggregated parameters that retains as much of the key sea-state characteristics as possible. The formulation and analysis of each of these representations is discussed in detail in the following sections.

### 13.2.1 Traditional (Scatter Table) Representation

The traditional representation of wave climate is a two-dimensional table of the frequency of occurrence of sea-states defined by their significant wave height and a representative period, as shown in Fig. 13.2. This representation is generally called a scatter table (or scatter diagram). In some cases, this would be

| Significant wave height (m) \ Wave period (s) | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total | 0.1 | 0.5 | 7.1 | 19.5 | 33.1 | 27.9 | 8.4 | 2.3 | 1.0 | 0.2 | 100.0 |
| 6.0 | | | | | 0.2 | 0.1 | | | | | 0.3 |
| 5.5 | | | | 0.1 | 0.3 | 0.1 | | 0.2 | | | 0.7 |
| 5.0 | | | | 0.1 | 0.3 | 0.8 | 0.2 | 0.2 | 0.1 | | 1.6 |
| 4.5 | | | 0.1 | 0.7 | 0.2 | 0.7 | 0.5 | 0.2 | | | 2.4 |
| 4.0 | | | 0.5 | 0.8 | 1.6 | 0.8 | 0.8 | 0.1 | 0.1 | | 4.6 |
| 3.5 | | | 0.4 | 1.2 | 2.0 | 1.6 | 0.8 | 0.2 | | 0.1 | 6.3 |
| 3.0 | | 0.1 | 0.6 | 2.1 | 3.3 | 2.1 | 0.5 | 0.2 | 0.8 | 0.1 | 9.7 |
| 2.5 | | 0.3 | 1.5 | 2.5 | 7.4 | 8.2 | 1.7 | 0.8 | 0.1 | | 22.5 |
| 2.0 | 0.1 | 0.1 | 2.1 | 4.8 | 8.8 | 9.3 | 3.1 | 0.3 | | | 28.6 |
| 1.5 | | 0.1 | 1.9 | 7.1 | 9.0 | 4.2 | 0.6 | | | | 22.9 |
| 1.0 | | | | 0.1 | | 0.2 | 0.1 | | | | 0.4 |
| 0.5 | | | | | | | | | | | 0.0 |

**FIG. 13.2** Example of a scatter table.

expanded to a set of scatter tables with each containing data for a different sector of peak wave direction. A range of different representative wave periods has been used in the production of scatter tables, including the peak period, the zero-crossing period, the mean period, and the energy period. Because of the link with wave power density the typically preferred representative period for the calculation of the MAEP is the energy period $T_e$.

This representation using scatter tables was originally used for measured wave data, where limitations in data storage, battery capacity, transfer rates and analysis meant that it was not practicable to work with larger data sets that would contain the full time series of the directional-frequency spectrum (at half- to six-hour intervals). Specifically, there were insufficient memory storage or data transfer rates on older wave measuring instruments to save or report anything more than aggregated spectral parameters. Furthermore, it should be recognized that for many users of the wave climate data the aggregated spectral parameters were more than adequate. Still, these days battery capacity concerns can cause limitations on the level of details in the transmitted wave data.

For estimation of the MAEP, in many cases the wave climate from the nearest measurement point would be used, but as computing power increased it was possible to use wave transformation models to transform the wave climate from the measurement location to the proposed WEC deployment location. However, the accuracy of this wave climate at the deployment location was typically limited by the data available at the measurement location, which may only include a small number of aggregated wave parameters, such as significant wave height, zero-crossing period and peak wave direction, as well as the limitations of earlier wave transformation models that used an assumed spectral shape (viz. first/second generation spectral wave models). Consequently, the wave climate would essentially still be described using a scatter table, and it is the use of a scatter table that fundamentally defines the traditional representation of the wave climate.

It will be recognized that the traditional representation of the wave climate, using a scatter table, has an attractive simplicity, making it easy to see the typical wave heights and periods that may be expected. However, this simplicity hides a number of shortcomings that should be recognized if this representation is used. Essentially, the production of a scatter table involves the reduction of an enormous amount of data (a minimum of 10 years of data is recommended [IEC/TS 62600-100, 2012]), defined by a time series of the directional-frequency spectra, into a joint probability table containing a small number of bins defined by the significant wave height, a wave period and sometimes a wave direction. The set of representative sea-states used to define the wave climate is then reconstructed by assuming a standard spectral shape and directional spreading for each bin, although each bin is likely to contain a vast range of spectral shape and directional distributions.

An effect of this data reduction is that any variation in power capture with a parameter other than the significant wave height, the representative wave period and possibly peak direction cannot be accounted for because a standard spectral shape and directional distribution has to be used. However, it has been shown that the power capture of some WECs is highly sensitive to the spectral shape and/or directional distribution, which may result in a large error in the expected power capture. Other factors that could have a large impact on the power capture of a WEC, but are not distinguished in the traditional representation include water depth, marine currents and the wind.

Another issue with the traditional representation is that the bins in the scatter table have a finite size, which is typically 0.5 m for the significant wave height, 1.0 s for the representative wave period and 30 degree for the peak direction. Then, once a sea-state has been allocated to a bin, it is subsequently not possible to distinguish its actual parameters from all the other occupants of the bin. This could have a significant impact on power capture because the incident wave power density can vary significantly across a bin, especially for small significant wave heights. For example, consider the bin defined by a significant wave height of 0.5–1.0 m. In this case the incident wave power density is four times higher at the top of the bin ($H_s = 1.0$ m) than at the bottom of the bin ($H_s = 0.5$ m) with a potential similar degree of variation in the power capture. This is due to the nonlinear relation between the wave power flux $J$ and the significant wave height $H_{m0}$.

Finally, it is important to recognize that there remains a vast amount of wave climate data that is represented using scatter tables only. Thus, irrespective of the issues identified, the traditional representation is likely to be continued to be used for the estimation of the MAEP where no other representation of the wave climate is available.

### 13.2.2 Extensive Representation

An extensive representation of the wave climate consists of a time series that contains all the sea-states that have occurred during a specific period. The most complete extensive representation contains the directional-frequency spectrum, together with other relevant parameters. In this case, within the limitations of the assumption that the phases of the spectral wave components are uncorrelated, each sea-state is fully represented. This extensive representation of the wave climate has become possible as the data storage and processing capabilities of computers have improved; however, the number of individual sea-states is large. For example, if a distinct sea-state is defined every 3 h then 2920 sea-states are required for each year of wave climate data. It has been estimated that it may require 10 years of wave climate data to obtain a reasonable estimate of the wave resource, which means that records of approximately 30,000 sea-states would be required to produce an adequate estimate of the MAEP using an extensive representation.

An extensive representation of the wave climate is recommended by the IEC standards for wave resource assessment and characterization. It is anticipated by the IEC standards that the wave climate will be primarily defined using hindcast data produced using a wave propagation model, although the model should be validated using measured wave data. The reason for defining the wave climate using hindcast data is because measured wave data over a period of 10 years at a proposed location for a WEC is likely to be very rare. Furthermore, a key advantage of using hindcast data is that modern third generation spectral wave models, such as SWAN and Mike21SW, automatically produce a time series of the wave directional-frequency spectrum.

Although the directional-frequency spectrum is perhaps the most obvious parameterization of the sea-state, it requires a larger number of parameters (equal to the product of the number of frequency components and the number of directional components). However, these parameters, the directional-frequency spectral components, are not uncorrelated because although the spectral shapes are extremely variable they are still generally smooth functions. This suggests that the sea-states can be represented by a smaller number of parameters with a minimal loss in fidelity, where fidelity refers to the accuracy of the model using the sea-state parameters to estimate power capture.

One approach to the identification of a set of suitable sea-state parameters is to include those parameters that are found to have the largest influence on a WEC's power capture. This has the automatic effect of minimizing the loss of fidelity for a particular number of parameters. For example, for a directionally insensitive WEC a suitable parameterization of the sea-state could include the significant wave height, energy period and spectral bandwidth, which have been found by Saulnier et al. (2011) to have the largest influence on the power capture of an omnidirectional WEC.

An alternative approach to the identification of a suitable set of sea-state parameters is to assume that the sea-state is formed of a finite number of wave systems that can be linearly superimposed to create the actual sea-state observed. This approach focuses on accurately defining the sea-state and can provide an accurate estimate of the power capture because the sea-state is well defined. The advantage of this approach is that there is no dependence of the sea-state representation on the performance of the WEC and so it may be considered to be more versatile. An example of this type of approach has been developed by MacKay (2015), where a total of six parameters are used to represent a nondirectional wave climate.

A final approach is to use principal component analysis (PCA) to define a suitable set of sea-state parameters. PCA essentially involves projecting the current parameterization onto another set of parameters using the principle components. The method then retains the components that make the largest contributions to the representation of the sea-states. This approach has been used by Lavelle and Kofoed (2013) for the analysis of the nondirectional wave climate at Hanstholm, Denmark. It was found that for this site, 90% of the variation in the wave climate could be explained with only five parameters. A disadvantage of this approach is that there is a less obvious physical meaning to the sea-state parameters identified; however, the advantage is that it should provide a more accurate representation of the actual wave climate than the other approaches, which use more of a tangible parameterization.

### 13.2.3 Abridged Representation

An abridged representation of the wave climate consists of a reduced set of sea-states that provides a good representation of the sea-states that have occurred over the specified period. Thus, an abridged representation lies somewhere between the traditional and extensive representations of the wave climate. It is similar to a traditional representation because each sea-state is considered to be representative of a larger number of sea-states, but it differs from a traditional representation because the sea-states do not have a regular structure (as in a scatter table) and can be defined by multiple parameters. Conversely, it is similar to an extensive representation because the sea-states can be defined by multiple parameters, but it differs from an extensive representation because it does not contain all sea-states that would fully define the wave climate. The obvious attraction of an abridged representation of the wave climate is that it can ideally retain the best elements of the other representations, whilst eliminating the less desirable ones.

A range of different methods have been developed for the abridging, or downscaling, large data sets. Of these methods, those that have been applied to the representation of the wave climate can be classed as either clustering or selection algorithms (Camus et al., 2011). A clustering algorithm involves defining a set of sea-states, each of which is considered to characterize the surrounding sea-states, whilst a selection algorithm involves selecting a set of sea-states that are considered to be distributed evenly in the parameter space.

A fundamental component in the application of both clustering and separation algorithms is the definition of the separation between two sea-states; this is termed the criterion of similarity. There is no fundamental limit to the complexity of this criterion, but it is commonly defined by the Euclidean distance, $E$, in the normalized $k$-dimensional parameter space, $P$, between sea-state $i$ and sea-state $j$. To achieve this, the parameters are typically normalized based on their range so that the value of each parameter varies between 0 and 1, and then the Euclidean distance is given by Eq. (13.6).

$$E = \sqrt{\sum_k \left(P_i^k - P_j^k\right)^2} \tag{13.6}$$

Not surprisingly the use and application of this criterion of similarity differs for each algorithm. By way of illustration, an example of how this criterion has been used is provided for both a clustering algorithm and a selection algorithm.

The $k$-means algorithm (KMA) is a popular clustering algorithm that has been applied to the representation of the wave climate for the assessment of WECs (Lavelle and Kofoed, 2013). The KMA method starts by randomly selecting $M$ points in the parameter space, which will become the abridged representation of the wave climate. The Euclidean distance between these $M$ points and all of the sea-states is then calculated and each sea-state assigned to the nearest point (ie, the point to which it has the shortest Euclidean distance). The $M$ points are then redefined using the average parameter values of the sea-states assigned to the point. The Euclidean distances between these $M$ points and all of the sea-states are then recalculated and the process repeated until the points converge and the sea-state assigned to each point stabilizes.

The maximum distance algorithm (MDA) is a popular selection algorithm that has been applied to the representation of the wave climate for the assessment of WECs (de Andrés et al., 2013). The MDA method starts by selecting a single point, which is a sea-state in the wave climate. The choice of this point can vary, but de Andrés et al. (2013) used the sea-state with the largest sum of Euclidean distances to all the other sea-states in the wave climate. This sea-state is the first member of the abridged representation of the wave climate. The subsequent members are selected based on their being the most dissimilar to the current members. This process continues until the abridged representation of the wave climate contains the specified number of sea-states.

## 13.3 REPRESENTATION OF POWER PERFORMANCE

The most common representation of how the power capture of a WEC varies with sea-state is the power matrix, with an example power matrix shown in Fig. 13.3. Where this is generated from numerical modelling it is usual to assume a standard spectral shape, such as the Bretschneider or JONSWAP spectrum, as the input to the numerical model. However, it has already been noted that there can be a large variation in spectral shape for the significant wave height and representative wave period, which because the power performance is sensitive to spectral shape means that

| Significant wave height (m) \ Wave period (s) | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 6.0 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| 5.5 | 444 | 480 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| 5.0 | 378 | 408 | 436 | 463 | 488 | 500 | 500 | 500 | 500 | 500 |
| 4.5 | 316 | 341 | 365 | 387 | 408 | 428 | 447 | 465 | 483 | 499 |
| 4.0 | 259 | 279 | 299 | 317 | 334 | 350 | 366 | 381 | 395 | 409 |
| 3.5 | 206 | 223 | 238 | 252 | 266 | 279 | 291 | 303 | 315 | 326 |
| 3.0 | 159 | 171 | 183 | 194 | 205 | 215 | 224 | 233 | 242 | 251 |
| 2.5 | 116 | 126 | 134 | 142 | 150 | 157 | 164 | 171 | 178 | 184 |
| 2.0 | 80 | 86 | 92 | 97 | 103 | 108 | 113 | 117 | 122 | 126 |
| 1.5 | 49 | 53 | 56 | 60 | 63 | 66 | 69 | 72 | 75 | 77 |
| 1.0 | 24 | 26 | 28 | 30 | 32 | 33 | 35 | 36 | 37 | 39 |
| 0.5 | 8 | 8 | 9 | 9 | 10 | 10 | 11 | 11 | 12 | 12 |

FIG. 13.3 Example of a power matrix.

the power matrix could at best be considered to contain average power captures, but would be more accurately described as idealized power captures. Similar arguments would be made for other parameters such as wave direction and water depth. Of course, it would be possible to generate a multidimensional power matrix, where the additional dimensions could be parameters such as the spectral width or average direction, which would help to reduce the idealization. However, the number of required simulations would increase rapidly as each dimension is added, many of which would represent sea-states that never occur.

The alternative to the power matrix is to calculate the power performance of a specific set of sea-states that can be used either directly or indirectly in the calculation of the MAEP. Within this representation of the power performance there are two fundamental options: either the power captures in all sea-states are calculated, or the power captures in a subset of the sea-states are calculated. Mirroring the wave climate representation terminology, these are called the extensive power performance representation and the abridged power performance representation, respectively.

Although an appropriate set of the sea-states could be used to provide a reasonable set of data that defines the power performance of a WEC, it is worth noting that even if such a set of sea-states existed they would not illustrate the power performance of the WEC clearly. Thus, it is likely that, although a power matrix may not be required for the calculation of the MAEP, it is likely to still be required to provide an easy to view illustration of a WEC's power performance, albeit that the power captures illustrated are somewhat idealized.

## 13.4 ESTIMATION OF THE MAEP

By cross-indexing the wave climate and power performance representations, a range of different methods for estimating the MAEP can be seen to exist, as shown in Table 13.2. The combinations of wave climate and power performance representations that are incompatible are blocked out in this table, leaving six possible combinations, which are discussed in more detail in the sections shown in the table. In some cases the choice of method may be limited by the available representations of the wave climate and power performance; otherwise the choice will depend on the computational effort required to calculate the MAEP and the resultant accuracy of the estimate.

**TABLE 13.2** Methods for the Estimation of the MAEP

| | **Wave Climate Representation** | | |
|---|---|---|---|
| **Power Performance Representation** | **Scatter Table** | **Abridged** | **Extensive** |
| Power matrix | 13.4.1 | 13.4.2 | 13.4.2 |
| Abridged | | 13.4.3 | 13.4.4 |
| Extensive | | | 13.4.3 |

### 13.4.1 Power Matrix–Scatter Table

The sum of the bin-wise multiplication of the power matrix of the WEC and scatter table of the wave climate is perhaps the most commonly used method for the calculation of the MAEP, and is also the approach recommended by IEC/TS 62600-100 (2012). There is a simplicity to the method, which makes it attractive, and it clearly has to be used if only the power matrix and scatter table are available. However, the shortcomings and assumptions used in the scatter table and power matrix representations mean that there is likely to be a large error in the estimate of the MAEP calculated using this method.

The errors in the MAEP estimate when using this method arise from two fundamental sources. The first source of error is the condensing of the wave climate into a set of bins, which typically are indexed by just significant wave height and a representative wave period. However, within each bin there may be a large variation in power capture due to the significance of other parameters such as spectral shape. The second source of error is the representation of all the sea-states in the bin by the power capture of a single sea-state that is typically defined at the centre of the bin, which gives rise to a problem due to the nonlinear relation between wave power flux and significant wave height, especially for coarse resolution of the lower significant waves heights. Comparison with more accurate methods suggests that an error of up to 45% could be expected using this method, with the level of error depending on both the wave climate and WEC characteristics (de Andrés et al., 2015).

It will be seen that all the other methods can be expected to produce a more accurate estimate of the MAEP than the multiplication of the scatter table and power matrix, which suggests that this method should be used when only the scatter table and power matrix are available. Unfortunately, if only the scatter table and power matrix are available, it is not possible to calculate this error, but if it is used then the uncertainty in the estimate of the MAEP must be fully recognized.

### 13.4.2 Power Matrix–Extensive/Abridged Wave Climate

The calculation of the MAEP using a power matrix and an extensive or abridged set of sea-states involves interpolating the power matrix for each sea-state and summing the product of the estimated power capture and the annual average weighting associated with the particular sea-state. If an abridged wave climate is used then a clustering technique, such as the KMA, should be used as this should produce the most representative set of sea-states. By interpolating the power matrix, the error due to the variation in the power capture across a scatter table bin is reduced, which makes it more accurate than multiplication of the power matrix and scatter table, but a large source of error remains in the assumption of a standard spectral shape and/or directional distribution. In addition, if an abridged wave climate is used, then there will also be an error associated with using a subset of the sea-states in the wave climate.

The extent to which this method is an improvement over the power matrix–scatter table method depends on the accuracy of the interpolation method used. In general, the smaller the rate of change in a function's value over the parameter space the more accurate the interpolated value. Thus, a more accurate estimate of the MAEP can be achieved by first converting the power matrix into a capture length matrix before interpolation. The capture length typically has a smaller rate of change over the parameter space because a large proportion of the change in the power matrix is associated with the change in incident wave power density. Then, in calculating the MAEP the interpolated capture length for each sea-state is multiplied by the incident wave power of the sea-state (which typically has a low error) and the annual average weighting associated with the sea-state.

The method used for interpolation will also influence the accuracy of the MAEP estimate. This is especially the case if there are large rates of change in the capture length across the matrix. If the difference between the capture length values in adjacent bins of the matrix is relatively small, then a simple linear interpolation is likely to be adequate; however, larger differences are likely to benefit from more sophisticated interpolation. The radial basis functions (RBFs) method is a nonlinear interpolation technique that has been successfully used for the interpolation of a power matrix (de Andrés et al., 2015); however, some care is always required with nonlinear interpolation techniques to ensure that the interpolated values do not have insensible values due to overfitting of the interpolation function or otherwise.

### 13.4.3 Extensive/Abridged Power Performance–Extensive/Abridged Wave Climate

This method of calculating the MAEP involves simply summing the product of the power capture and the annual average weighting for each sea-state (where there is the necessary condition that the wave climate and power performance are represented using the same set of sea-states). If an extensive representation of the wave climate, defined by a complete parameter set is used, together with an estimate of the power capture that includes all the parametric dependencies, then the estimate of the MAEP will contain no errors due to the calculation of the MAEP. However, this is not equivalent to there being no error in the MAEP because errors may still exist in the calculation of the power capture for each sea-state, or in the parameters defining each sea-state. Alternatively, if an abridged wave climate is used then a clustering technique, such as the KMA, should be used as this should produce the most representative set of sea-states. In this case there will be some error in the estimate of the MAEP due to the use of a subset of sea-states in the wave climate. The other possible realization of this method is that the power performance and/or wave climate do not use a complete set of parameters but a limited set, for example the significant wave height, energy period and spectral bandwidth. In this case there would be an additional error in the estimate of the MAEP due to the parametric simplification.

### 13.4.4 Abridged Power Performance–Extensive Wave Climate

This method involves interpolating the power performance for each sea-state in the extensive wave climate and summing the product of the interpolated power capture and the annual average weighting associated for the sea-state. For this method to work effectively the abridged power performance representation should include sea-states of the extremes of the parameter space so that the power capture can be interpolated rather than extrapolated (which has much larger errors). Because the requirement is to include sea-states that cover the full extent of the parameter space, then the MDA is the most appropriate technique for identification of the sea-states used to generate the abridged power performance data.

As for the interpolation of the power matrix (see Section 13.4.2) it is generally preferable to interpolate a slowly changing function, which suggests that the capture length should be interpolated rather than the power capture. However, the MDA technique used to identify the members of the abridged power performance representation is likely to produce an unstructured, multidimensional data set that is not easily amenable to linear interpolation. This implies that a more sophisticated interpolation technique, such as the RBFs method, should be used. An example of this method is provided by de Andrés et al. (2013), where the power performance is defined by the significant wave height and peak period. In this case with 200 sea-states the MAEP was estimated to differ by only 10% from that based on an extensive representation of the wave climate. It may be expected that the accuracy of the method would increase if the bandwidth parameter were also included, although it is likely that this would also require an increase in the number of sea-states in the abridged representation of the power performance to guarantee this increase in accuracy.

## 13.5 LIMITATIONS AND CONSTRAINTS

In the absence of any computational limits then the best option is to use an extensive representation of the wave climate where the power capture in each sea-state is calculated with the most accurate numerical model available.

However, this luxury rarely exists. In reality, the efficient calculation of the MAEP requires a balance to be reached between the accuracy of the representation of the wave climate, the accuracy of the estimate of the power performance and the computational demands of the calculation. For example, a time-domain model may be expected to be more accurate than a spectral-domain model, but it is also expected to be more computationally demanding. Unfortunately, it is not possible to be proscriptive regarding the choice of numerical model, the number of parameters used to define the power performance and the number of sea-states used to define the wave climate, since the significance of all of these will depend on characteristics of both the WEC and the wave climate.

It will be noticed that the calculation of MAEP has been discussed without reference to the availability of the WEC. That is, it assumes that the WEC is capable of generating power 24 h a day, 365 days a year. Thus, the methods of estimation of the MAEP described in the chapter assume 100% availability and this should be explicitly noted where appropriate. Of course, in reality there will be times when the WEC is not able to generate power due to faults, either of its own or in the power supply network, which will reduce the MAEP. Unfortunately, calculation of the availability is extremely complex since it will not only depend on the operations and maintenance strategy adopted by the operators, but also on an analysis of the failure rates and required weather windows. This is considered to be outside of the scope of this book and the interested reader is directed to the relevant literature in this area (see, eg, Ambühl et al., 2015).

A further limitation on the estimation of the MAEP is that the wave climate must be estimated from a finite number of years of wave data. However, these years are only a sample of the long-term wave climate, which is what is typically required to estimate the MAEP. This results in an aleatory uncertainty, which is an uncertainty associated with the underlying variability of the data. Clearly, the larger number of years that are used to define the wave climate, the closer it is expected to be to the long-term average, which is why it is typically recommended that the wave climate be defined by at least 10 years of wave data. An analysis of the wave climate in the North Atlantic suggests that with 10 years of data the aleatory uncertainty is approximately 5% (MacKay et al., 2010). A final consideration that further complicates the accurate estimation of the expected MAEP is that in the expected deployment time-scales, climate change may be expected to have some effect on the wave climate, although it is not clear yet whether this would be an increase or decrease in the resultant MAEP.

## 13.6 SUMMARY

- The MAEP is equal to the sum of the product of a set of sea-states power capture and average annual occurrence.
- The numerical models currently most suitable for the calculation of the MAEP are time-domain models, spectral-domain models, and system identification models.
- There are three fundamental representations of the wave climate
  - Traditional—a scatter table indexed by the significant wave height and a representative period
  - Extensive—a time series of all the sea-states in the wave climate
  - Abridged—representative set of sea-states from the wave climate
- There are three fundamental representations of power performance
  - Power matrix—a table of power captures indexed by the significant wave height and a representative period
  - Extensive—a set of power captures defined for all the sea-states in the wave climate

  - Abridged—a set of power captures defined for a representative set of sea-states in the wave climate
- The different representations of the wave climate and power performance result in six different methods for the calculation of the MAEP.
- The most commonly used combination of the scatter table and power matrix results in the least accurate estimate of MAEP.
- The most accurate estimate of the MAEP is obtained from an extensive representation of the wave climate and power production, but this is also the most computationally demanding.
- The choice of method for estimating the MAEP requires a compromise between accuracy and computational demands.

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