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Output Characteristics of Tidal Current Power Stations

Clarke J A, Grant A D and Johnstone C M
Energy Systems Research Unit
Department of Mechanical Engineering
University of Strathclyde
Glasgow, UK

ABSTRACT

With increasing targets being set for renewable-derived electricity generation, wind power is currently the preferred technology. It is widely accepted that due to the stochastic nature of wind, there is an upper limit to the capacity that can be accommodated within the electricity network before power quality is impeded. This paper demonstrates the potential of tidal energy as a predictable renewable technologies that can be developed for base load power generation and thus minimise the risk of compromising future power quality.

KEYWORDS

Renewables, Tidal current, Base load power generation.

INTRODUCTION

Recent policy developments within the electricity supply industry have favoured the development of renewable technologies, as demonstrated by the UK Government's recent 'Energy White Paper' [UK Government, 2003] and the Scottish Executive's 'Securing a Renewable Future' publication [Scottish Executive, 2003]. These set aspirational targets of 20% and 40% respectively for the generation of electricity from renewable sources by 2020. Since the current economically viable renewable sources are stochastic in nature (e.g. wind power), achieving these targets will result in higher levels of vulnerability within the electrical supply network. This, in turn, will increase the levels of control and reserve plant required to prevent supply disruption. In an effort to address this undesirable situation, more predictable renewable energy technologies require to be developed. Tidal current technology has been identified as an important contributor because the energy yield and time of occurrence may be predicted in advance. Further, by arranging for the strategic location of tidal power generation systems at several locations, a continuous base load power supply should be achievable. This latter attribute is important, as sufficient base load supply is crucial to maintaining electrical network integrity. It is for these reasons that the UK Government is increasing its support for the development of tidal energy technology as a medium to long-term energy supply system.

DEVELOPMENT OF TIDAL TECHNOLOGY

Technology for the exploitation of marine currents is still in its infancy, being under development in the UK for only the last two decades. Work to date has shown the main research challenges to be associated with:

- the power capture device (rotor versus oscillating aerofoil);
- power take-off (hydraulic or mechanical transmission);
- device structural support (tensioned mooring or rigid structural piling); and
- connection of the generated power to the supply network.

At the present time two power capture devices are being investigated for commercial development: the oscillating aerofoil driving hydraulic accumulators [Trapp, 2002] and a horizontal axis turbine driving a mechanical shaft [Fraenkel, 2002]. The former device is a development of technology and principles emanating from the offshore marine industry, while the latter device is an evolution of the wind turbine in relation to the requirements of the sub-sea environment. In the case of the tidal turbine, although the fundamental fluid dynamic interactions between rotor and stream are the same as in wind energy conversion, there are certain differences that are likely to cause divergences in technological development. Some of these are obvious and will influence materials selection and structural design, e.g. the higher density of the fluid medium and the greater possibilities of surface fouling and corrosion. Some are less obvious and will have a profound impact on the take-up of marine power: the limited range of the current velocities at a given site, and the character of the turbulence regime. The latter is still the subject of debate, but the relatively constrained environment of tidal flow is likely to influence its nature.

The structural loading on wind turbines contains a large stochastic element, which arises from a combination of effects. These include wind shear (from the atmospheric boundary layer), misalignment of the rotor with the wind direction, interaction between the rotor and the supporting tower and, most significantly, the presence of turbulence in the approaching wind. This last effect manifests itself as short-term variations in both wind speed and direction. Directional changes caused by large-scale turbulent eddies have a particularly severe effect on dynamic loading. Another factor is the possibility of extreme winds, which requires statistical analysis to determine the 50-year or 100-year maxima to be used in structural design calculations. Wind turbines are of course shut down as a matter of routine under storm conditions.

Tidal current turbines will operate in a more predictable environment. Maximum current velocities can be predicted with reasonable accuracy and it should not be necessary to enforce turbine shut down except in an emergency. Dynamic loads may still occur as a result of velocity shear and misalignment, but these are also predictable. Incoming turbulence will generate fluctuating loads, although the range of excursions, particularly in the direction of flow, will be relatively small. Some stochastic inputs will also arise from the effect of storm surges, which may increase current velocities and introduce dynamic loading due to surface wave action. Most of the potential sites are in shallow water, and the rotor blade tips may approach within a few metres of the free surface, where agitation of the water beneath large waves may be significant. This clearly requires systematic investigation, but it may be that the effects are small. Sites will generally be close to land, and the fetches for surface wave development will be limited.

Research is continuing into determining the operational performance envelope of tidal stream rotors in real conditions [Engineering and Physical Science Research Council, 2003]. Eventually, it is probable that conditions will permit precise design solutions, tailored to specific sites.

DESIGN OPTIONS

It is impossible at this time to predict with confidence what the established design solutions to tidal stream energy conversion will be. Comparisons with wind energy are helpful, but may ultimately be misleading. For example vertical-axis turbines, which have found little favour in wind energy conversion, are being considered for tidal applications [Salter, 1998]. A major advantage is their omni-directional nature, eliminating the need for yawing mechanisms and associated bearings and seals, a considerable bonus in a marine environment. However, the two large prototypes presently deployed at sea are both of horizontal-axis configuration.

There are other ideas first suggested for wind energy, but found to be impractical, that could be considered for tidal streams: two which have surfaced recently are the creation of vortices to act as energy concentrators [Grant, 1998], and the adoption of contra-rotating rotors on the same horizontal axis [Clarke, 2003].

Even if the tidal stream turbine follows wind technology and adopts the horizontal-axis machine as the industry standard, questions remain about certain features of the design. For example, will mechanical control of the blade pitch angle be incorporated, as is the case for most large wind turbines? And will the rotors operate at fixed or variable speed? Here a divergence from wind energy practice is possible, given the growing support for high-voltage DC transmission for marine applications. This would suggest the adoption of variable-speed operation as standard for large tidal stream turbines.

All of these factors will influence the output characteristics of turbines, as expressed by the variation of power output over the duration of the tidal cycle. A major influence will also be exerted by the control algorithms employed. Here again, wind turbine practice may be taken as a starting point.

As for wind turbines, tidal stream machines are likely to have a cut-in stream velocity, giving rise to a period of enforced idleness at slack water. The velocity chosen will depend on site conditions and turbine design. Wind turbines also have a cut-out speed to avoid damage in storms, but for tidal streams this should not be necessary given the predictable nature of the flow regime. Shut-down procedures would of course be provided, but would only be executed in emergencies. For some locations, loads caused by wave action in stormy conditions might be severe enough to trigger shut-down.

The concept of a rated stream velocity, above which power is held more or less constant, is universal for large wind turbines. The reasoning behind this is essentially economic, and the value of rated velocity is chosen to minimise costs per unit of energy for the site in question. The same economic arguments are likely to apply to tidal stream machines, and the similarities in rotor fluid dynamics will allow the turbine to maintain constant power output above its rated velocity.

POWER OUTPUT CHARACTERISTICS

The instantaneous power P available to a single tidal stream turbine is given by the equation:

$$P = \tfrac{1}{2}\rho A V^3$$

where ρ is the fluid density, A the rotor swept area and V the velocity of the fluid stream. If the variation of V with time is assumed to be sinusoidal, P varies with time as shown in Figure 1, which covers a half-cycle of about 6h 12min.

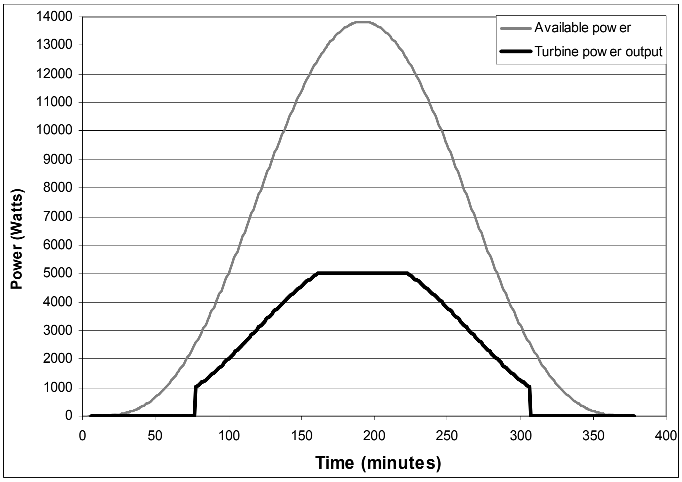

Figure 1: Turbine output relative to available power.

The power produced by the turbine depends upon its power coefficient, C_P, and on the control algorithms selected. Figure 1 shows the variation of power output with time, for arbitrarily chosen cut-in and rated stream velocities. In the run-up to rated power, the output is determined by the value of C_P, which in turn depends on the operating conditions: whether the rotor turns at fixed or variable speed, and whether the blade pitch angles may be adjusted. The curve in Figure 1 was obtained on the assumption that C_P could be maintained at a value of 0.4.

The situation presented here is of course a simplified example. In reality, the assumption of a sinusoidal variation in V may be inaccurate. Also, a series of half-cycles may exhibit changes in the value of peak velocity due to directional properties of the site, and due to the longer spring/neap tidal cycle. Variations in tidal range (and hence stream velocity) between spring and neap tides are very marked in some locations and almost negligible in others. This will impact upon choice of control algorithms, and reinforces the earlier suggestion that tidal turbine systems should be configured to suit the peculiarities of their particular site.

FIRM POWER

Tidal energy is unusual among renewables in that it offers ‘firm power’; the quantity and timing of power flows may be predicted with great accuracy. The only renewable source which gives a comparable security of supply is geothermal energy. Biomass and hydro power make use of stored energy and so provide a dependable resource, but the rate of replenishment of the store is uncertain.

Unlike the above sources, a tidal power station cannot supply a constant base load, as its output varies continually with the state of the tide and falls to zero at slack water. The capacity of output during the tidal fluctuations also varies as a result of lunar influences creating spring and neap tides. And the power delivery, though predictable, will not necessarily coincide with times of high consumer demand.

However, if a number of power stations suitably spaced around the coastline were linked into a grid system, the time-series power output could (while not being exactly constant) provide a substantial base load. This idea is not new [Bryden, 1994], but its implications for future resource planning do not seem to be fully appreciated. With large demands being placed on renewable energy to meet future electricity supplies, 40% by 2020 in Scotland, utilisation of tidal power to satisfy a proportion of base load demands will be crucial if stability of the electricity network is to be maintained.

To investigate whether the time delay between the occurrence of high water at the various sites can be used to produce a predictable consistent power output, a study was undertaken covering three geographically separated coastal sites:

- Cape Wrath on the north west corner of the Scottish mainland;
- Crinan, at the sound of Jura on the west coast of the Scottish mainland; and
- Sanda, off the Mull of Kintyre, a peninsula on the south-west of the Scottish mainland.

The distance separating Cape Wrath in the north from Sanda in the south is 237 miles.

Figure 2 illustrates the rise and fall in spring tides at the three locations, relative to some arbitrary datum level. It is clear that there are substantial differences in tidal range and, more significantly, in the timing of high and low water.

The bulk power delivery from tidal current turbines at the three sites is of course governed by the corresponding stream velocities. These were computed from published charts for the locations in question [D’Oliveira, 2002]. These charts contain hourly data and illustrate the variation of velocity over the tidal cycle. Figure 3 is a graph of stream velocities for the three sites over a 24h period, and for the same conditions as applied in Figure 2. It is interesting to note a clear departure form a sinusoidal curve in certain cases. Power is of course dependent on the cube of velocity.

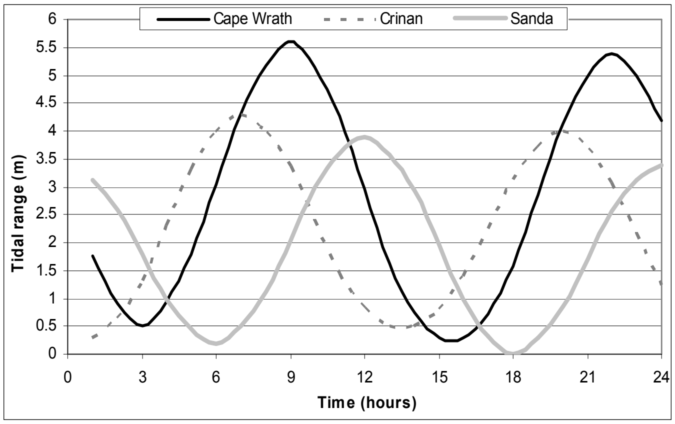

Figure 2: Spring tide range at three sites on the west coast of Scotland.

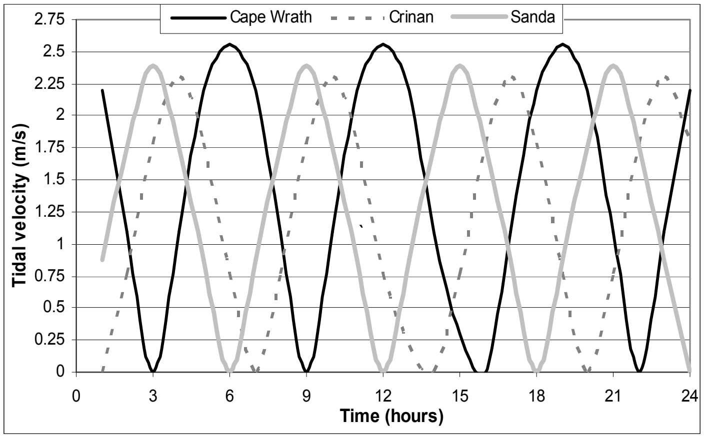

Figure 3: Spring tide velocities at three sites on the west coast of Scotland.

As a starting point, a single 10m diameter turbine is postulated at each site. Power characteristics were simplified from the model depicted in Figure 1: a constant power coefficient of 0.4 was applied throughout the speed range. The resulting power output curves are shown in Figure 4, for the three individual turbines, along with the summation of power output for the system as a whole, over a 24h period. It is clear that a significant base load is produced (over 100 kW in the example shown), amounting to about one-third of peak power output.

It is interesting to note that performance does not appear to be consistent over successive cycles, with much better smoothing of output towards the end of the period shown. It is thought that this might be due to the use of hourly data: where phase differences exist between component cycles, the summated energy output may jump from one hourly 'bin' to another, distorting the predicted performance of the system as a whole. Better temporal resolution should eliminate the problem, and an approach using interpolated data at 15-minute intervals was subsequently adopted.

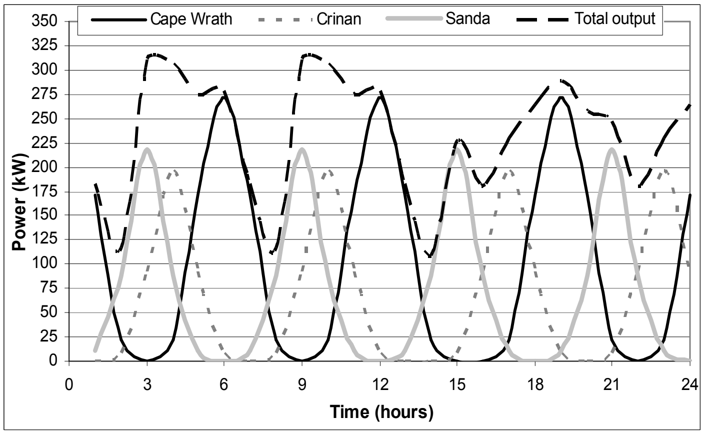

Figure 4: Site and total power output for a 10m diameter tidal turbine.

The results from this appear in Figure 5. In fact, there is very little difference between the summated power curves in the two figures, and the discrepancy in performance between early and late cycles in the 24h period remains. On further investigation, it appears that one of the sites (Sanda) is cycling at a higher frequency than the other two, a phenomenon which must of course reverse itself at some other point in the lunar cycle.

It is concluded that the summated output is sensitive to the characteristics of its component parts. Two further conclusions follow:

- Given the natural variations that are likely to occur between successive tidal cycles (under the influence of weather, or the longer cycle of spring and neap tides), this type of irregularity in summated outputs is likely to occur in practice.
- Accurate prediction of performance for systems of this kind may be problematic. What appear to be small uncertainties in the input data may produce a disproportionately large error in forecasts for the power output. This is not to say that the output is unpredictable, rather that very accurate data are needed to make the prediction.

From Figure 5 it can be seen that the specific locality of the tidal site is crucial to achieve optimum phasing of power delivery. The inclusion of a 4th site within this generation profile could compensate for the power dips occurring in hours 3, 28, 52 etc. and produce a more uniform power delivery. Preliminary studies suggest that such sites do exist, but the performance of a combined 4-site system has not been examined in detail.

A more general comment is that the assumed scenario of equal installed capacity at the three chosen sites is simplistic and will almost certainly not give an optimum performance. Variations in the mix of installed capacity will affect the ratio of base load to peak power output, and this is an obvious area for future investigation.

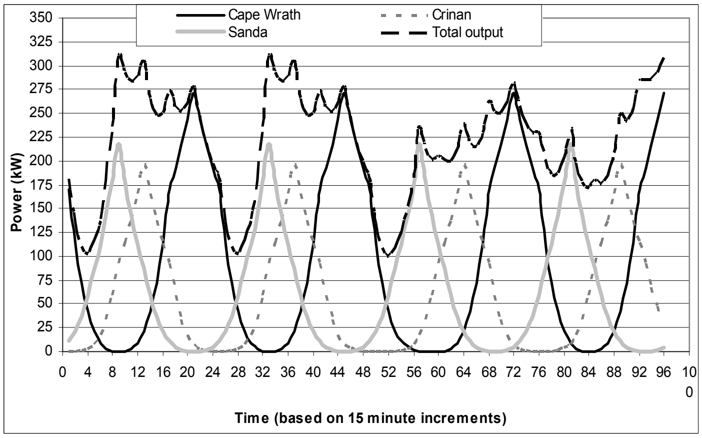

Figure 5 Site and total power output for a 10m diameter tidal turbine.

POWER SMOOTHING

Significant troughs occur in the system power output curve at approximately 6 hour intervals, and would probably be a feature of any system of this kind. If it were operated in parallel with hydraulic pumped storage, smoothing of the output could readily be achieved. Peak lopping and subsequent power inputs to supplement the tidal sources, for periods of reasonably short duration, are ideally suited to the characteristics of a hydraulic pumped storage scheme. For the system shown in Figure 5, a base load of over 200 kW would then be supported.

NEAP TIDES

All the calculations presented so far have been for spring tides. In neap tides, power levels are reduced and the way in which power fluctuates with time may vary. Figures 6, 7 and 8 present similar information to that contained in Figures 2, 3 and 4, but for neap rather than spring tides. Reductions in tidal range, current velocity and predicted power output are evident for all three sites, but not all sites are affected equally.

The impact of the transition from spring to neap tides results in a 56% reduction in tidal range at the north-west of Scotland, 74% at the west coast and a 54% at the south-west. This reduction in the tidal range and the correlated rate of change in tide height will directly influence the tidal velocities. As a result, 60%, 66% and 44% reductions in peak tidal stream velocities may be observed at the three sites respectively.

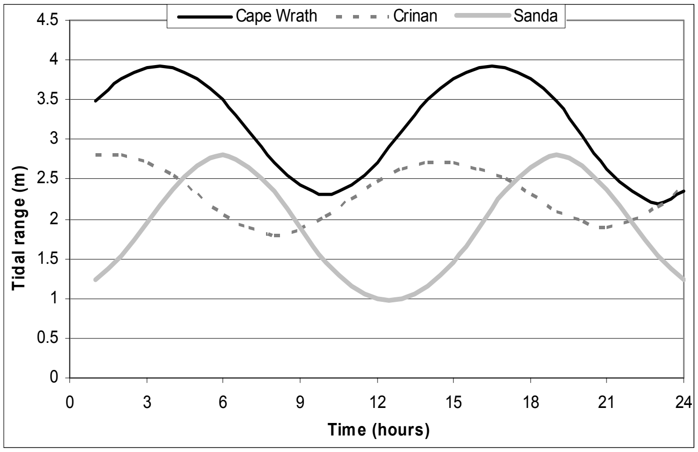

Figure 6: Neap tide range at three sites on the west coast of Scotland.

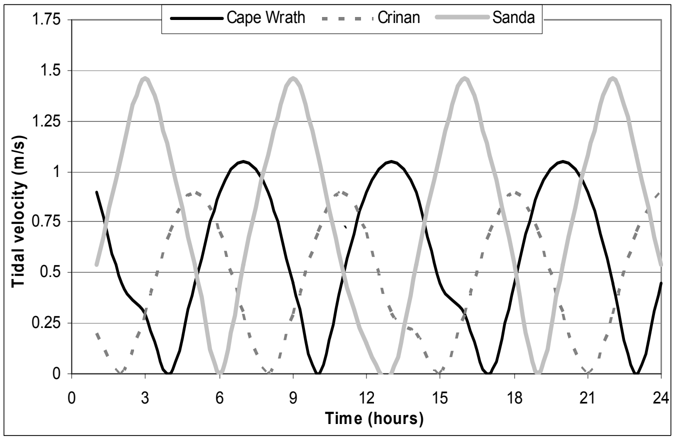

Figure 7: Neap tide velocities at three sites on the west coast of Scotland.

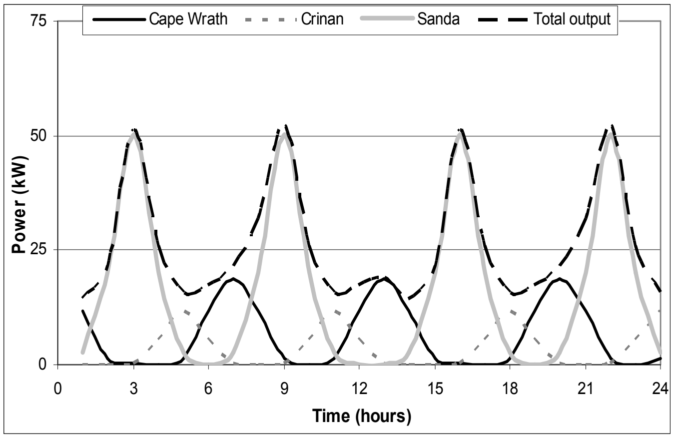

Figure 8: Site and total power output for a 10m diameter tidal turbine.

For the combined system, the ratio of base load to peak power output is reduced somewhat, because of near-zero outputs from turbines at certain times (Figure 8). However, the energy flows required to smooth the output curve (using hydraulic pumped storage) are relatively modest, much lower than for spring tides. So a reasonably steady base load could easily be achieved. But of course the level of base load available is comparatively low.

This disparity between spring and neap tide power production can be made clearer by adopting a longer time-scale. The effects of the longer, lunar cycle are illustrated in Figure 9, where power outputs for the hypothetical 3-site system are shown for a 28-day period. The dramatic variation in levels of power output is due to the cubic relationship between power and stream velocity: if velocities are halved, as is roughly the case here, power reduces by a factor of 8.

Some sites have a greater spring-to neap variation than others. This is evident for the three sites used in this study (Figures 3 and 7). In some cases the variation is close to zero, but unfortunately these tend to be sites where the tidal range is small anyway and the resource is correspondingly poor.

The timing of spring and neap tides is a planet-wide phenomenon, so the local phase shifts that occur in the shorter, twice-daily cycle are absent. The effects are experienced at all sites simultaneously, hence the output characteristics shown in Figure 9. As can be seen, the magnitudinal differences between total power output at spring and neap tides is considerable, differing by as much as 90%.

CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that the summation of outputs from a number of geographically remote tidal current power stations can provide a level of steady base load.

Much higher levels of base load could be obtained interfacing with conventional hydraulic pumped storage plant to smooth out short-term perturbations.

It was found that the form of the summated output was extremely sensitive to the characteristics of the individual power stations which formed the system. It follows that

- Accurate data are needed for the component sites, over the twice-daily and lunar cycles;
- The way in which sites are combined to form a system will have a critical impact on performance;
- Unpredictable phenomena such as storm surges may have a significant effect on the inter-relation of component sites.

Sites which offer a good potential resource seem to be strongly affected by the lunar cycle of spring and neap tides, resulting in substantial variations in the level of base load which can be provided.

Further investigation is required to assess the practical potential in Scottish waters, and how this might be most beneficially exploited. Fundamental study into how the performance of a multi-site system is affected by variations in installed capacity at the constituent sites is a key element in any future work.
Refinement of the hypothetical turbine output characteristics would give a more realistic picture of power delivery, and would enable investigation of the effects of changes in key parameters, such as rated current velocity.

Implications for the electrical supply network must also be examined: the levels of reinforcement required, and future security of supply.

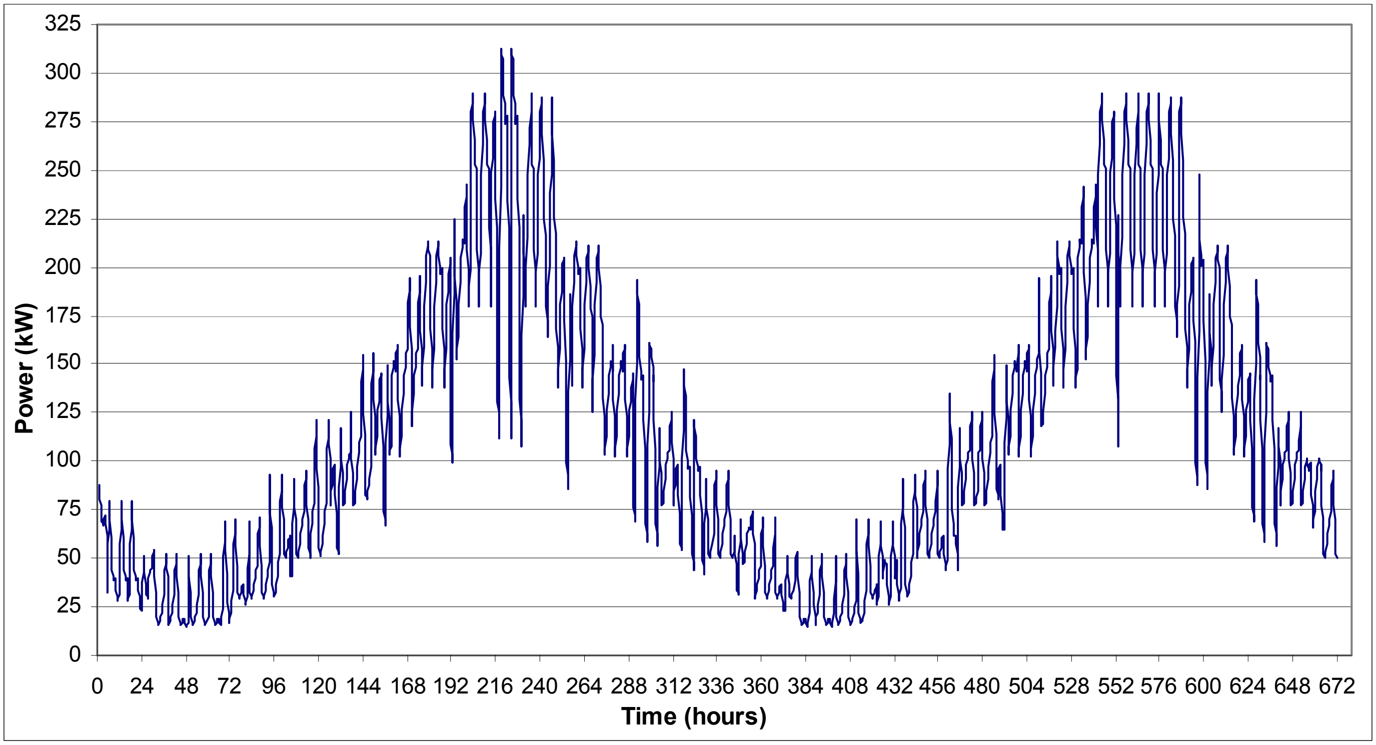

Figure 9: Fluctuations to power outputs between spring and neap tides.

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