The impact of limiting tidal turbine capacity on the output characteristics from three complimentary tidal sites in Scotland over the lunar cycle

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ABSTRACT
Recent Government policy has set specific targets for renewable energy technologies to contribute to the national electricity supply make up. Currently, wind power is the preferred technology. However, it is widely accepted that due to the stochastic nature of wind, planning restrictions and the finite availability of suitable sites there is an upper limit to the capacity that can be accommodated. This paper demonstrates the potential of tidal energy to provide firm power and shows that by limiting the capacity of the power generated, provides base load supply without compromising power quality. This increases the capacity factor of the installed system, thus improving the economic viability and commercial competitiveness of tidal farms.

KEYWORDS
Renewable energy, tidal current, base load generation, electricity supply.

INTRODUCTION
Recent energy policy developments in the UK have favoured the development of renewable technologies [1] [2]. Targets of 20% and 40% for the UK and Scotland respectively have been set for electricity generated from renewable sources by 2020. Present trends develop renewable technologies that are stochastic in nature, principally hydro and land based wind power initially, then offshore wind power in the medium to longer term; implying that target attainment will probably result in increased levels of vulnerability within the electrical supply network. This, in turn, will necessitate increased levels of energy storage, reserve plant and network control to prevent supply disruption and maintain power quality.

To minimise the risks associated with this, it would clearly be helpful if predictable renewable energy sources could be developed. By arranging for tidal power generation at favourably phased locations, a near-continuous base load power supply should be achievable, which will impact positively on the integrity of the electrical network.

DEVELOPMENT OF TIDAL TECHNOLOGY
Technology for the exploitation of marine currents is still in its infancy. At the present time two systems are being investigated for commercial development: the oscillating aerofoil driving hydraulic accumulators [3]; and horizontal axis turbines evolved from wind power technology, with two prototypes installed off the coasts of Norway and England [4]. Tidal current turbines operate in a more determinate environment than wind turbines. Maximum current velocities can be predicted with reasonable accuracy and the dynamic loading that may occur as a result of velocity shear and misalignment is largely predictable. That said, some stochastic inputs will arise from the effect of storm surges, bringing increased current velocities and introducing dynamic loading due to surface wave action. Although this requires systematic investigation, sites will generally be close to land so that the fetch for surface wave development will be limited. Incoming turbulence will also generate fluctuating loads, although the range of excursions, particularly in the direction of flow, will be relatively small.

For these and other reasons, research is continuing into determining the operational performance envelope of tidal stream rotors under real operating conditions [5]. Such research will lead to tools that enable precise design solutions to be tailored to specific site conditions.

DESIGN OPTIONS

It is impossible at this time to predict the optimal configuration of future tidal stream energy conversion devices. However, comparisons with wind energy give some useful pointers. Tidal stream devices are likely to have a cut-in stream velocity, with a period of enforced idleness at slack water. While wind turbines have a cut-out speed to avoid damage in storms, this should not be necessary for tidal turbines given the predictable nature of the flow regime. Shut-down procedures would only be executed in emergencies (e.g. 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, with the value of the rated velocity chosen to minimise the cost per unit of energy produced at the site in question. A similar economic argument is likely to apply to tidal stream machines, and the similarities in rotor fluid dynamics should allow the turbine to maintain constant power output above its rated velocity.

FIRM POWER

Tidal energy is unusual among renewable source technologies in that it offers 'firm' power whereby the quantity and timing of power flows may be precisely predicted. By phasing suitably located tidal energy power stations, the aggregate power output, although not exactly constant, could match a substantial portion of base load. While this idea is not new [6], the implications for future resource planning are only now being appreciated. With large demands being placed on renewable energy sources to meet future electricity supplies, the utilisation of tidal power where available will contribute to the maintenance of network stability.

To investigate further the firm power characteristic of tidal power, a study was undertaken covering three geographically separated but complementary Scottish coastal sites:

- Cape Wrath off the North-West coast;
- Crinan at the Sound of Jura off the West coast; and
- Sanda off the Mull of Kintyre, a peninsula to the South-West.

The distance separating Cape Wrath from Sanda is 237 miles.

The hourly stream velocities were determined from published charts for the three locations during both spring and neap tide conditions, which arise due to the gravitational interactions between the Sun, Earth and Moon [7].

To illustrate trends, a single 10m diameter turbine was postulated at each site. For simplicity, a constant power coefficient of 0.4 was applied throughout the speed range and no rated power limit was imposed. The resulting power output curves are shown in Figures 1 and 2 for the three individual turbines along with a summation for the system as a whole. For spring tides, a significant base load is produced, amounting to about one-third of peak power output. A similar trend is observed for neap tides but the outputs are much lower. Some changes between successive cycles are evident. On investigation, it appears that one of the sites (Sanda) is cycling at a higher frequency than the other two, a phenomenon that will reverse at some other point in the lunar cycle. Three main conclusions emerged from the study as follows.

- the aggregate power output is sensitive to the characteristics of its component parts;
- 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), some irregularity in aggregate power output is likely to occur in practice; and
- accurate prediction of performance for aggregated systems of this kind may be problematic (this is not to say that the output is unpredictable, but that accurate data are needed to make the prediction).

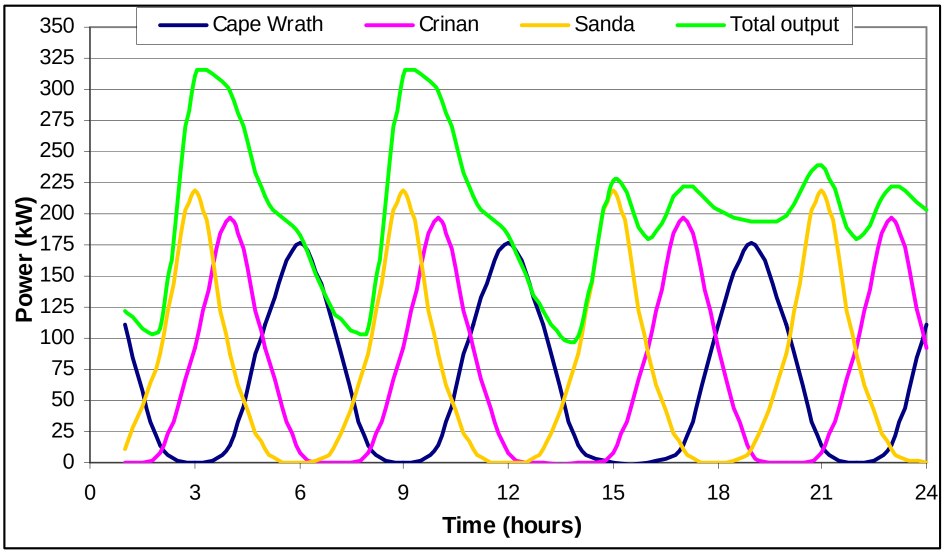

Figure 1: Site and aggregate power output for a 10m diameter tidal turbine with no limiting capacity in spring tides.

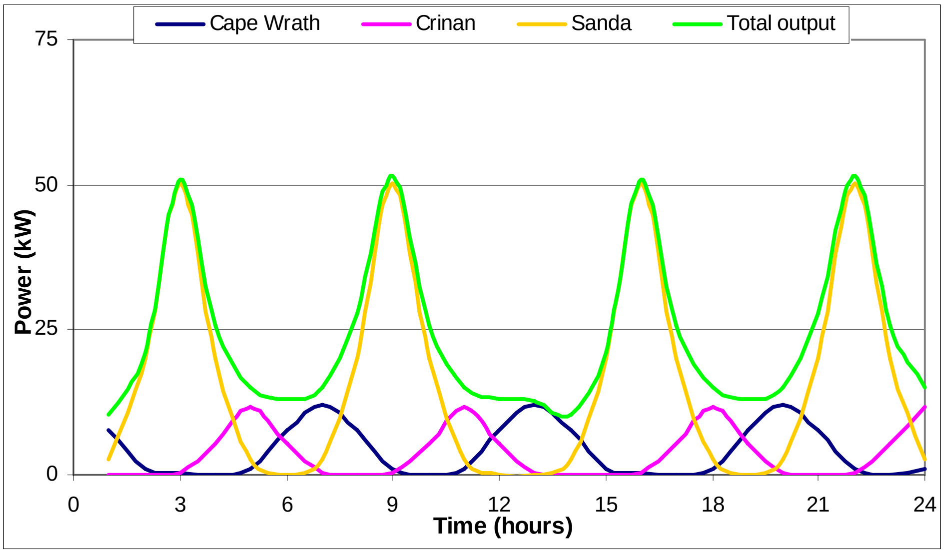

Figure 2: Site and aggregate power output for a 10m diameter tidal turbine with no limiting capacity in neap tides.

From Figure 1 it is seen that the maximum power delivered by a turbine during maximum spring tide velocities, and hence its rated capacity, needs to be 220kW, and the turbine would be operating at this capacity for approximately 10% of the time over the lunar cycle. This results in a large variation in peak power output between spring and neap tides, 220kW and 50kW for Sanda respectively. To limit these extremities in power output, the turbine's delivered power may be limited to a rated capacity. This may be achieved by designing the turbine so that the hydrofoil sections are either pitch or stall regulated above a specific tidal current velocity. In such cases, power delivered by the turbine is proportional to the speed of the tidal current until the limiting capacity is reached; beyond this power output is held constant even though the available power within the tidal stream continues to increase. Regulating/limiting the power delivered from a tidal turbine enables a lower capacity generator to be used thus saving in cost, and a higher capacity factor to be achieved as the turbine will operate at its rated capacity for longer periods of time, especially during spring tides (see Figure 3). This will improve the economics of power delivery from such systems.

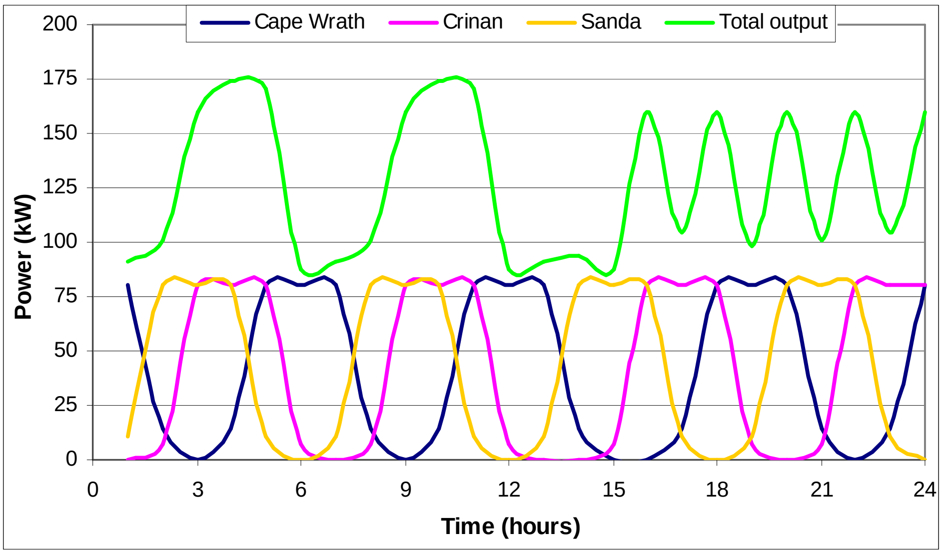

Figure 3: Site and aggregate power output for a 10m diameter tidal turbine with limiting capacity in spring tides.

The disparity between the total output from 80kW limited capacity tidal turbines and tidal turbines without limiting capacity located at the three sites during spring tides is depicted in Figure 4. Limiting the capacity of the turbines produces a more uniform power delivery with substantially reduced variation, thus facilitating the use of tidal energy for base load power supply. In the case of turbines without limiting capacity, the larger variation in power output level is due to the cubic relationship between power and stream velocity.

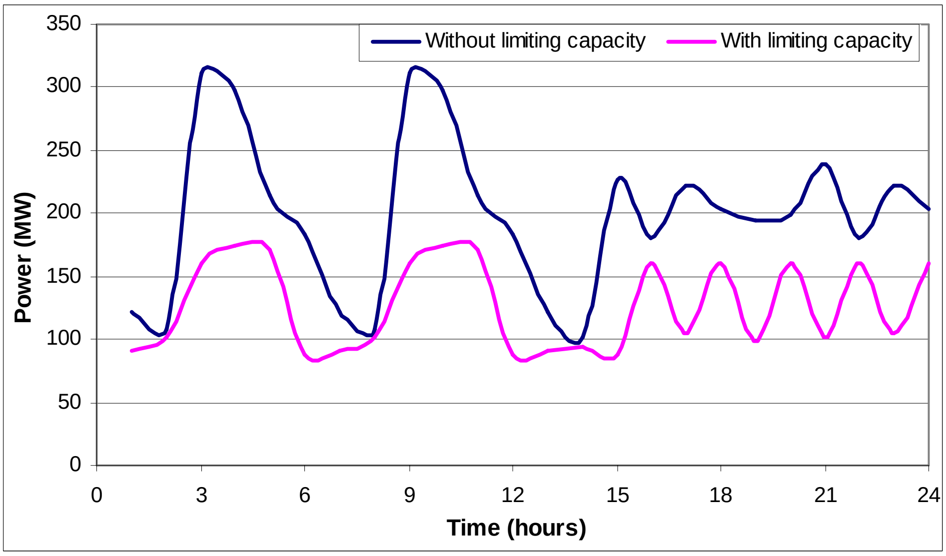

Figure 4: Variations in power output between a tidal turbine with and without limiting capacity during spring tides.

Since the components connecting the tidal turbine to an electrical network are sized and costed in accordance with the maximum capacity delivered, limiting the capacity reduces connection costs, gives a more uniform power delivery and reduces the payback period associated with system connection costs. This is due to the reduced capacity rating of the required hardware, and the higher capacity factors achieved because peak power is delivered for longer periods of time, especially during spring tides.

To demonstrate firm power of sufficient capacity, 100 tidal turbines were assessed at each of the three tidal sites. For the case where no limiting capacity is implemented, each turbine requires to be rated at 220kW giving an installed capacity of 66MW; the energy yield from this installation is 6.5GWh and the average capacity factor is 14.7% over a lunar cycle. Limiting the capacity of the turbines to 80kW to give an installed capacity of 24MW, reduces the energy yield to 5.25GWh and increases the average capacity factor to 32.5% over the lunar cycle. This demonstrates that an installation with 36% of the capacity rating of a non-limited installation will deliver 80% of the energy, give a better payback on the investment and result in a more uniform power supply to the electrical network. Figure 5 compares the power delivered from a 300 unit tidal farm for both 80kW and 220kW turbines. It is clear that limiting the capacity of the turbines limits the magnitude of the variation between spring and neap tidal cycles as well as resulting in more uniform power delivery.

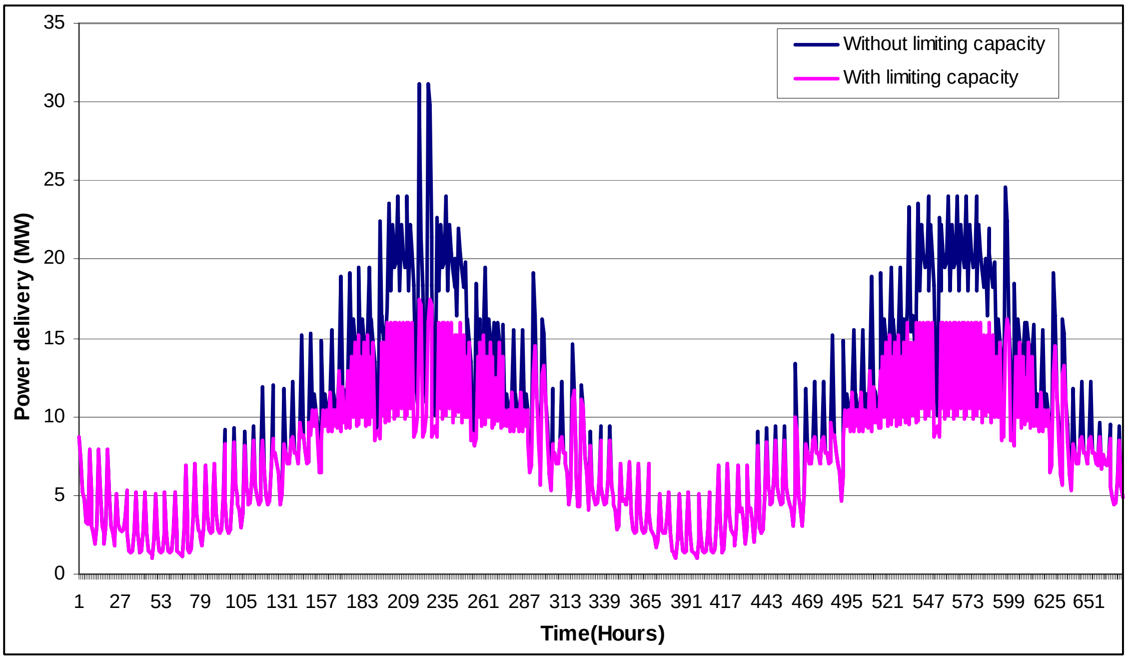

Figure 5: Fluctuations in power output between spring and neap tides for a tidal farm with and without limiting capacity.

When combining the power output from tidal farms located at three complementary sites, and where a continuous base load is required, the limiting capacity of the turbines may be determined by the tidal conditions experienced during neap tides. This however is unlikely to be the most cost effective way of exploiting the resource. Setting the limiting capacity at a higher value implies the need for an additional backup or storage facility. This issue is discussed below.

The analysis presented so far has focused solely on the power output characteristics of the turbines and no attempt has been made to match the number of turbines able to be installed and their installed capacities to the potentials of the sites chosen. Demand for electricity varies with time, and the notion of firm power must be viewed in this context. This work has shown that limiting the capacity of the turbines can substantially reduce the magnitude of the variation in the power supply. Doing so enables higher capacity factors to be achieved in the generation plant and electrical network, thus improving the commercial competitiveness of tidal power generation. In the Scottish context, the availability of three complementary tidal stream sites that are each grid access unconstrained presents a formidable problem. However, from Figures 1, 3 and 5 it is clear that (technically at least) some level of base load provision can be achieved. The twice-daily cycle could be further smoothed by the use of hydraulic pumped storage, or the phased operation of conventional hydro power plant, which could be especially useful in a local context.

The fluctuations in output due to the lunar cycle are more intractable as shown in Figures 1 and 2, as they affect all sites simultaneously. Here, the power output could be regulated so that the maximum rated output is that experienced during neap tides so that only a small proportion of the site's resource is utilised (a doubtful economic proposition). Alternatively, long term (e.g. weekly) energy storage could be introduced so that the excess capacity captured during spring tides can be stored for use during neap tides to maintain the capacity of delivered power. A third and most likely option during neap tides would be the introduction of other sources of energy to meet the shortfall.

CONCLUSIONS

The aggregate outputs from a number of dispersed tidal current power stations can provide a base load. The magnitude of the delivered power can readily be increased by using hydraulic pumped storage to smooth fluctuations in the twice-daily cycle. The lunar cycle of spring and neap tides causes long-period variations in power output of a magnitude that may be accommodated by complementary sources of energy, or by energy storage. The predictability of tidal power output may be regarded as a major asset in energy supply management.

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