A comparison of hydrokinetic turbines forming a vertical fence along the length of a river or tidal channel with a conventional rectangular turbine array

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ABSTRACT

We evaluate the engineering advantages and disadvantages of a hypothetical linear array of vertically oriented cross-flow turbines and oscillating hydrofoils aligned along the length of the river. In the case of cross-flow turbines, the array also includes static deflectors to divert the wake of upstream turbines away from downstream ones. The same result is achieved with oscillating hydrofoils through an asymmetric operation, which results in wake-vectoring. If the deflection can be structured to promote flow from one side of the array to the other, then it is possible that the energy could be replenished at such a rate as to make the trailing turbines extract energy at a level similar to the leading turbines, no matter how long the array is. The main advantages of these configurations are that they do not block the entire waterway, but allow shipping lanes to remain open on one or both sides of the array, while taking power from the entire flow field through deflection of energy across the plane between the turbines and the open flow field. We present a preliminary comparison of the performance of the array compared to that of the conventional arrangement of turbines in a rectangular array. We find that the linear array confers advantages of greater power production potential, shorter electrical cabling, dry onboard space, fewer mechanical drive-trains, and reduced underwater tasks. These advantages come at the cost of installing the deflectors for the cross-flow turbine array, and the structure needed to support the additional stress.

INTRODUCTION

A recent analysis has estimated about 1146 TW hr/yr (average power 130 GW) theoretical resource of renewable energy from in-stream river hydrokinetic sources in the contiguous lower 48 US states, of which 120 TW hr/yr (average 120 GW) is technically recoverable [1]. While the theoretical riverine hydrokinetic resource is a significant fraction of the US electricity consumption rate, a successful commercialization of river hydrokinetic power requires a technology that can realize or exceed the technically recoverable resource estimate, while satisfying the regulatory and economic constraints.

A key assumption that influences the technically recoverable resource is a limit on the number of the installed turbines. Since areas of fast flow are limited, the density of turbine determines their number. The turbines are conventionally assumed to be organized in a rectangular array [2, 3, 4]), as shown schematically in Figure 1. If rotary turbines are installed too close to one another, they suffer in their efficiency – the streamwise spacing between turbines needs to be 10 turbine diameters or more [2, 3] for the wake deficit to recover [5]. Furthermore, turbines may not interfere with other uses of the water, especially navigation [4]. This condition is usually satisfied by restricting the turbines to a layer near the river bed, and doing so imposes a severe constraint on the technically recoverable power

Furthermore, the difficulty in commercializing hydrokinetic power is not only in the technical feasibility of recovering the resource, but also in the cost of doing so. The cost of extracting hydrokinetic power depends on a myriad of design choices and parameters (e.g. see Refs. [2, 3]), which confound a clear comparison between different approaches.

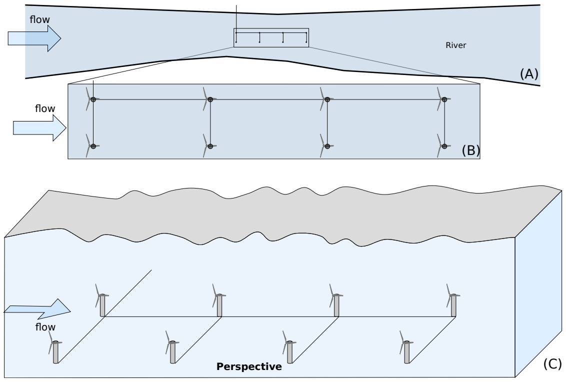

Figure 1: SCHEMATIC OF A CONVENTIONAL ARRAY. (A) ZOOMED OUT VIEW IN A RIVER. (B) ZOOMED IN PLAN VIEW OF THE TURBINES. (C) ZOOMED IN PERSPECTIVE.

Here we present a preliminary evaluation of an alternative configuration, a single row of turbines spanning almost all the depth of the water column installed along the length of the river. The wakes of turbines are deflected either by an asymmetric operation of the turbines themselves or by an interspersed row of deflector plates. In a recent work [6], a subset of the authors presented this configuration as an alternative to the conventional arrangement of turbines. They also presented the limits on performance of an idealized version of such an array. Their analysis may be thought as idealizing the hydrokinetic array as a generalized actuator disk, one capable of not only energy extraction analogous to the treatment of wind turbines in the Lanchester-Betz-Joukowsky analysis, but also flow deflection. Streamlines from the optimal flow that develops around such an array for a deflection angle of 20° are shown in Figure 2. The performance of the array was characterized in terms of a dimensionless array power density C_A defined as

$$C_A = \frac{\dot{W}}{\frac{1}{2}\rho U^3 LH}, \quad (1)$$

where $\dot{W}$ is the power generated by the array subject to the flow of a fluid of density ρ, speed U, and water depth H, and an array of length of L. Figure 3 shows the resulting C_A, as well as the dimensional array power density $\dot{W}/LH$, as a function of the flow deflection angle α through the array. For $\alpha = 20^\circ$, shown by the blue circle in Figure 3, $C_A = 0.17$. Here we extend the concept by presenting ideas for realization of such arrays, and presenting a preliminary analysis of the design.

Cross-flow turbines or oscillating hydrofoils oriented vertically, as shown in Figure 4, can be used for realizing such an array, but axial flow turbines are not practical when used for this purpose. We consider installation and maintenance of electrical and mechanical parts underwater as a cost driver. In particular, we consider factors that effect the cost of installation and maintenance of electrical and mechanical parts underwater, such as the number of turbines, distance between turbines, the availability of on-board dry space, and the number of underwater tasks.

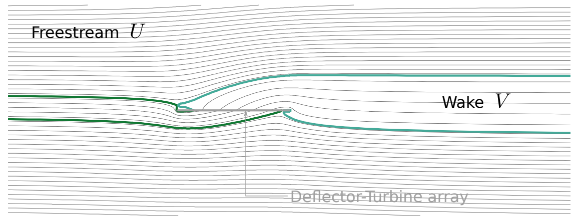

Figure 2: FLOW AROUND AN IDEALIZED DEFLECTOR-TURBINE ARRAY.

Through this comparison, we find that the linear array of turbines offer many advantages over the conventional configuration. The linear array of turbines occupies a smaller overall footprint and allows for a much closer spacing of turbines, while generating more power than the conventional array. Furthermore, while the turbines in the linear array span almost the entire water column depth, their mechanical and electrical parts can be installed above water, which reduces their installation and operating costs. The electrical interconnects between the turbines are not only shorter because of the close spacing of the turbines, but are also easily accessible for installation and maintenance because they are above the water depth. The linear array also benefits from the ease of water-proofing the dry equipment to survive flooding events, instead of designing it for submerged operation. These conclusions are reached despite conservatively overestimating the performance characteristics of the conventional array, while underestimating those of the alternative array.

These advantages are accompanied by the cost of the construction and maintenance of a structure capable of supporting the lift and drag forces on the hydrodynamic hardware. This preliminary analysis suggests that our alternative in-line turbine configuration offers many advantages and motivates more detailed analysis of the technical and economic feasibility of the newly proposed array configuration.

TECHNICAL PERFORMANCE

We start by calculating the characteristics of the conventional and the alternative turbine array, which forms the basis of our comparison. We assume a location in the river where the water depth is nominally H, and the flow speed is U. We further assume that, in the absence of the hydrokinetic array, the flow speed is maintained over a length L along the river. The width of the river with depth compared to H is assumed to be W.

The (conventional) rectangular array of turbines

Consider a rectangular array of turbines, each of diameter D with spacing $1.5D$ in the spanwise direction and $10D$ in the streamwise direction. Such an array may be comprised of turbines installed on the channel bed or on floating platforms. We only consider turbines installed on the channel bed because a floating electrical interconnect will render the river non-navigable, a scenario precluded by our assumptions. The diameter of the

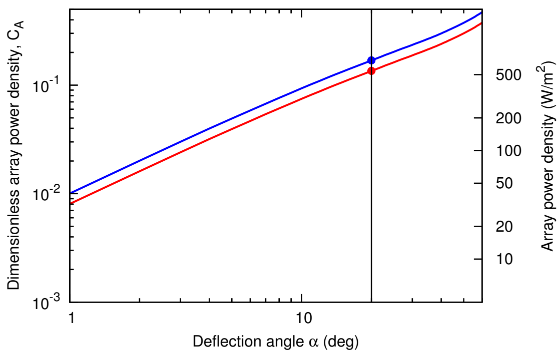

Figure 3: THE ARRAY POWER DENSITY AS A FUNCTION OF THE DEFLECTION ANGLE. THE LEFT AXIS SHOW THE ARRAY POWER DENSITY NON-DIMENSIONALIZED ACCORDING TO (1). THE RIGHT AXIS SHOWS THE DIMENSIONAL POWER DENSITY FOR A WATER FLOW SPEED OF 2 m/s. THE VERTICAL LINE CORRESPONDS TO A DEFLECTION ANGLE OF 20°.

bottom-mounted turbines is likely to be much smaller than the depth not only because of consideration of water level variations with the seasons [1] but also for navigation [2, 3]. In case of an array of cross-flow turbines, the diameter may be replaced by a characteristic scale of the turbine. Each turbine generates $\eta\frac{1}{2}\rho U^3\pi D^2/4$, where $\eta \approx 0.5$ is the turbine efficiency. The number of turbines in the array is the floor$(LW/15D^2)$. The total installed power is $\left[\ \text{floor}(LW/15D^2)\eta\frac{1}{2}\rho U^3\pi D^2/4\ \right]$. Ignoring the floor function, which further over-estimates the performance, the conventional array installed capacity is

$$\dot{W}_{\text{con}} \approx 1.3 \times 10^{-2}\rho U^3 LW. \quad (2)$$

Equation (2) for the technically recoverable power from a conventional array may be interpreted as corresponding to $C_A = 2.6 \times 10^{-2}$. This estimate is about a factor of 20 larger than the results from computational simulation of large (or infinite) wind turbine arrays modeled as actuator disks [7, 8] and within factor 2 of small experimentally realized arrays of horizontal and vertical axis turbines in air [9, 10] (see ref. [6] for details). In fact, increasing area density of turbines did not improve the total power generated by the computationally simulated array [8]. Based on these observations, we conclude that equation (2) is an upper bound on the performance of conventional arrays in general, and may be approached for small arrays.

The electrical cable length required to connect the array is the number of rows floor$(L/10D)$ times the length of each row W in addition to the cable of length L connecting the rows, which yields (ignoring the floor function) $\ell_{\text{con}} = 0.1LW/D + L$.

The (alternative) linear array of turbines

The linear array is formed by N turbines spread out over a distance L. The flow is diverted by an angle α to the freestream in order to deflect the wakes from the downstream turbines. The diversion is brought about by the static deflector plates or an asymmetric operation of the oscillating hydrofoils. In the case of oscillating hydrofoils, the phase of oscillations between neighboring foils can be tuned such that the vortices shed from the upstream foils interact favorably with downstream ones [11].

We have found through independent computational fluid dynamics analysis on flow deflected by standard NACA airfoils that a deflection angle of $\alpha = 20°$ is feasible. According to the results from ref. [6], reproduced as the blue curve in figure 3, the maximum value for C_A possible for $\alpha = 20°$ is 0.17. Any departures from the idealized analysis in ref. [6] is represented through a reduction in C_A by a factor of $\eta_{\text{ni}} = 0.8$, respresented by the red curve in figure 3, yielding an estimate of $C_A = 0.136$. Substituting in equation (1) yields an extracted power of

$$\dot{W}_{\text{lin}} = 6.8 \times 10^{-2}\rho U^3 LH. \quad (3)$$

These results may be rationalized from a different perspective as follows. The deflection angle of 20° is small enough that the deflected-flow through the turbine array may be estimated by the asymptotic expression $Q_0 = UL\tan\alpha$ (see Ref. [6] for details). The kinetic energy flux deflected through the array is $\frac{1}{2}\rho U^2 Q_0$. According to the analysis in ref. [6], at most a fraction given by $\eta_{\text{lin}} = 0.47$ of this deflected energy may be extracted by the turbine array. As before, to account for departures from ideal behavior analyzed in ref. [6], we assume an additional factor $\eta_{\text{ni}} = 0.8$ in the expression for this fraction. These assumptions yield an array power of $\eta_{\text{ni}}\eta_{\text{lin}}\tan\alpha\rho U^3 LH/2$, which upon substitution of η_{lin} and η_{ni} simplifies to equation (3).

Next we calculate the number of turbines in the array. We assume each turbine extracts energy from the local flow it experiences with the same efficiency $\eta = 0.5$ as we assumed for the turbines in the conventional array. The flow the turbines experience is approximately of speed U, but simply deflected to flow at an angle, and therefore a turbine of area $H \times D$ generates $\frac{\eta}{2}\rho U^3 HD$. The number of turbines is $0.272(L/D)$, spaced over a length L implies an inter-turbine spacing of $3.7D$.

We choose an aspect ratio AR, the ratio of height to horizontal extent, for the vertically oriented turbines, and consider $AR = 5$ as a typical value. Since each turbine spans the depth of the water column, $D = H/AR$. The turbine number and spacing written in terms of H and AR are $1.36L/H$ and $0.925H$ respectively.

The length of the electrical interconnect is simply the length of the array $\ell_{\text{lin}} = L$.

ENGINEERING ADVANTAGES

Apart from a favorable technical performance, the linear array also offers several engineering advantages conducive to lowering the cost of installation, operation, and maintenance. Next we describe our preliminary understanding of these advantages.

Example scenario

As an example, we consider a scenario typically encountered in a small river to demonstrate the advantages of

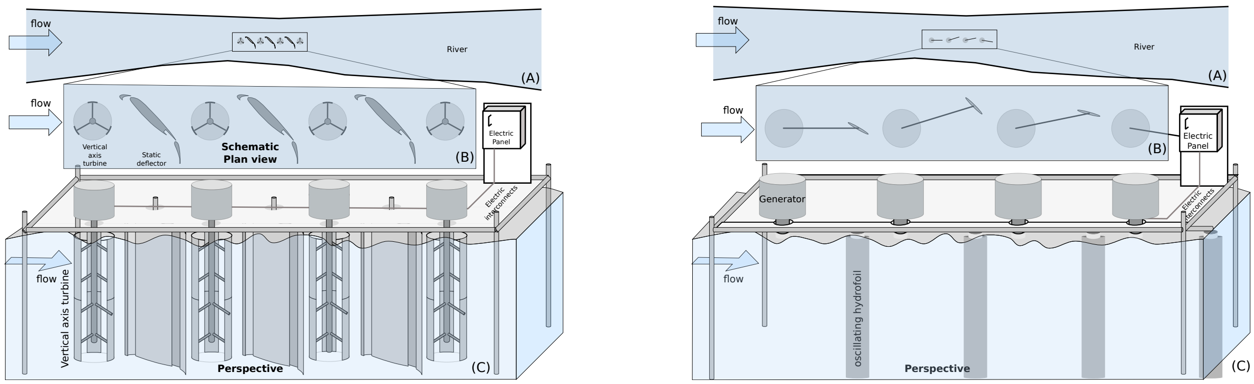

Figure 4: SCHEMATIC OF A LINEAR ARRAY OF VERTICAL AXIS TURBINES (LEFT) AND OSCILLATING HYDROFOILS (RIGHT). (A) ZOOMED OUT VIEW IN A RIVER. (B) ZOOMED IN PLAN VIEW OF THE TURBINES (AND DEFLECTORS). (C) ZOOMED IN PERSPECTIVE. THIS VIEW ALSO SHOWS THE SUPPORTING STRUCTURE AND THE ELECTRIC ROUTING.

Table 1: COMPARISON OF PERFORMANCE OF THE LINEAR AND THE RECTANGULAR ARRAY FOR A TYPICAL SCENARIO

	Rectangular	Linear
Power	187 kW	326 kW
No. of Turbines	30	8
Interconnect length	150 m	60 m

the linear array over the conventional array. The site under consideration in this example has depth $H = 10$ m, length $L = 60$ m, and width $W = 30$ m. We also assume a flow speed of $U = 2$ m/s. We also assume that the turbine height (and therefore diameter) is restricted to $D = 2$ m for the conventional array. The results are summarized in Table 1 We describe the results presented in this table in the rest of this section.

Technically recoverable power

For the example scenario, the conventional array produces 187 kW, while the linear array produces 326 kW. The ratio of the power generated by the linear array to that by the conventional array is

$$\frac{\dot{W}_{\text{lin}}}{\dot{W}_{\text{con}}} = 6\frac{W}{H}, \tag{4}$$

and therefore for any situation where $H < 6W$, the linear array is expected to have a greater technically recoverable power compared to the conventional array.

Smaller and efficient footprint

The linear array has a smaller footprint localized along the length of the channel. In our example scenario, the conventional array occupies an aggregate area of $LW = 1800$ m^2 (including space for cabling), while the linear array occupies an area of $LH/AR = 120$ m^2. This footprint allows for maintaining the navigation channels open, and continued use of the space for recreational and commercial purposes. Furthermore, the footprint area is indirectly related to the complexity of the installation and operation. We note that the size of the largest navigable vessel in the channel may be constrained by other considerations such as the presence of bridges crossing the river channel in the vicinity of the site.

Fewer turbines

In our example scenario, the conventional array has 30 turbines, while the linear array was comprised of only 8. The ratio of the number of turbines in the linear array to that in the conventional array is

$$\frac{N_{\text{lin}}}{N_{\text{con}}} = \frac{LW/15D^2}{0.272L/D} = \frac{W}{4.1\ D} \tag{5}$$

For locations where $W > 4.1D$, which is the typical case, the number of turbines in a linear array are fewer than those in the rectangular array. Since mechanical drive-trains are prime candidates for failure, having fewer of these increases reliability of the array.

Interconnecting length

For the example scenario, the length of the interconnect for the linear array is 60 m, while that for the conventional array is 150 m. The ratio of the length of the cable for the linear array to that of the conventional array is

$$\frac{\ell_{\text{lin}}}{\ell_{\text{con}}} = \frac{1}{1 + 0.1W/D}. \tag{6}$$

For sites where $W > 10D$, this ratio is less than 1/2. The interconnect is typically shorter for the linear array because W/D is expected to be greater than 10 for most sites. Furthermore, as we explain later, the cabling for the conventional array is expected to be underwater, while that for the linear array is expected to be above water, which is a serious advantage.

Supporting structure

The hydrodynamic forces on the vertical axis turbines or the oscillating hydrofoils are large. Civil structures are the natural candidates for providing support against the hydrodynamic loading. Integrating the linear array with construction and repair of bridges on the river may be a natural way to mitigate the difficulty with large hydrodynamic loads and provide a regular revenue from the civil construction.

Dry on-board space

The smaller footprint and the vertical profile of the array also facilitate incorporating dry on-board space above the water column (see Figure 4). If such an area is feasible, the mechanical drive-train and the electrical components of the array may be housed in this area. Critical equipment may be protected from flooding by installing tall barriers (not shown in Figure 4). Only the hydrodynamic elements (turbine blades or hydrofoils) need be submerged under water in this design. Doing so reduces the cost associated with marinization and sealing of these components.

Reduced underwater tasks

Since the only submerged parts of the turbines are the hydrodynamic elements, the number of underwater tasks during regular operations and maintenance, as compared to a rectangular array mounted on the channel bed, is greatly reduced. Access to the array does not require diving equipment. Only the installation of the supporting structure may need underwater operation.

Conclusion

We present an alternative hydrokinetic turbine array configuration, one in a linear form and possible augmented with static deflectors. The array deflects the wake away from downstream turbines in addition to extractign energy from the flow, and therefore has a greater power density than the conventional array. The array also occupies a small footprint in the water, and therefore interferes least with other activities in the water. A preliminary evaluation of this configuration in comparison with the conventional rectangular array of turbines highlights several advantages in terms of greater technically recoverable power potential, shorter electrical interconnect length, a smaller and more efficient footprint, fewer mechanical drive-trains, and the availability of dry on-board space with reduced underwater tasks. While our analysis is based on approximate performance measures, and qualitative considerations, the results suggest that a more thorough and detailed evaluation of the linear array bears merit.

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1. REFERENCES

[1] Jacobson, P., Ravens, T., Cunningham, K., and Scott, G., 2012. Assessment and mapping of the riverine hydrokinetic resource in the continental United States. Tech. Rep. 1026880, Electric Power Research Institute.

[2] Polagye, B., Previsic, M., Hagerman, G., and Bedard, R., 2006. System level design, performance, cost and economic assessment–Tacoma Narrows Washington tidal in-stream power plant. Tech. Rep. EPRI-TP-006-WA, Electric Power Research Institute.

[3] Previsic, M., Bedard, R., and Polagye, B., 2008. System level design, performance, cost and economic assessment–Alaska river in-stream power plants. Tech. Rep. EPRI RP 006 Alaska, Electric Power Research Institute.

[4] Vennell, R., Funke, S., Draper, S., Stevens, C., and Divett, T., 2015. "Designing large arrays of tidal turbines: A synthesis and review". *Renewable and Sustainable Energy Reviews,* ***41***, pp. 454–472.

[5] Jeffcoate, P., Trevor, W., and Elsaesser, B., 2016. "Field tests of multiple 1/10 scale tidal turbines in steady flows". *Renewable Energy,* ***87***(1), pp. 240–252.

[6] Mandre, S., and Mangan, N., 2016. " Framework and limits on power density in wind and hydrokinetic device arrays using systematic flow manipulation". *submitted*. arXiv:1601.05462 [physics.flu-dyn].

[7] Calaf, M., Meneveau, C., and Meyers, J., 2010. "Large eddy simulation study of fully developed wind-turbine array boundary layers". *Physics of Fluids,* ***22***(1), pp. 1–16.

[8] Miller, L., Brunsell, N., Mechem, D., Gans, F., Monaghan, A., Vautard, R., Keith, D., and Kleidon, A., 2015. "Two methods for estimating limits to large-scale wind power generation.". *Proceedings of the National Academy of Sciences of the United States of America,* ***112***(36), sep, pp. 11169–74.

[9] Kinzel, M., Mulligan, Q., and Dabiri, J., 2012. "Energy exchange in an array of vertical-axis wind turbines". *Journal of Turbulence,* ***13***(38), p. N38.

[10] Cal, R., Lebron, J., Castillo, L., Kang, H., and Meneveau, C., 2010. "Experimental study of the horizontally averaged flow structure in a model wind-turbine array boundary layer". *Journal of Renewable and Sustainable Energy,* ***2***(1), p. 013106.

[11] Kinsey, T., and Dumas, G., 2012. "Optimal tandem configuration for oscillating-foils hydrokinetic turbine". *Journal of fluids engineering,* ***134***(3), p. 031103.