

**THE TIDAL-STREAM ENERGY RESOURCE
IN PASSAMAQUODDY-COBSCOOK BAYS:
A FRESH LOOK AT AN OLD STORY**

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ABSTRACT

The Passamaquoddy- Cobscook Bay archipelago, located near the entrance to the Bay of Fundy where the mean tidal range is 5.7 m, has long been regarded a promising site for tidal-power development. Modern low-head turbines allow power extraction primarily from the kinetic energy of the tidal stream, rather than from the potential energy of an impounded basin, eliminating the need for expensive and elaborate systems of dams, locks and gates. Although the available power levels are much less in streaming applications, the resource may still be significant and accessible in areas with strong tidal flows, because the available power follows the *cube* of the current speed. The much lower costs per installed kilowatt and the relatively minor environmental impacts warrant a fresh look at the tidal-stream resource.

Circulation models indicate that the peak power resource in narrow straits such as Letete Passage and Lubec Narrows exceeds 10 kilowatts per square meter of installed turbine aperture. In those locations an installation with the surface “footprint” of a typical aquaculture site could produce peak power levels of 1-2 megawatts under mean tide conditions, and perhaps twice that during spring tides, using modern turbines. Lower power levels are available in deeper, less restricted regions such as Western and Head Harbor Passages. Regions between islands and near

headlands where flow speeds exceed about 2 m s^{-1} (about 4 knots) offer a modest tidal-power potential that could be tapped at relatively low cost and with minimal impact on the environment, fisheries and navigation.

Keywords: tidal power, Passamaquoddy Bay, Cobscook Bay, tidal-stream energy

1. Background

The Passamaquoddy-Cobscook Bay archipelago is located on the maritime border between the United States and Canada, in the eastern Gulf of Maine near the mouth of the Bay of Fundy, where the mean semi-diurnal tidal range is 5.7 m (Fig. 1). The solid contours show the tidal amplitude (half-range) increasing toward the head of the Bay of Fundy, where the range can exceed 15 m at spring tides; the Greenwich phases indicate a co-oscillating tide [1]. The unusually large range results from a near-resonance of the Bay of Fundy-Gulf of Maine system with the principal lunar semidiurnal (M-2) tide of the North Atlantic Ocean [2]. Passamaquoddy Bay, a rocky glacial basin with greatest depth about 115 m, lies mostly in Canada, whereas Cobscook Bay, a relatively shallow drowned river valley with greatest depth about 45 m, lies entirely in the U.S. (Fig. 2). The bays are connected to each other and to the Bay of Fundy by narrow passages and channels in which tidal currents can exceed 4 m s^{-1} [3].

Because of its large tidal range and nearly enclosed nature, the Passamaquoddy-Cobscook region, more compactly known as “Quoddy,” has obvious potential as a site for tidal power generation. Dexter P. Cooper, an experienced hydraulic engineer, first proposed a barrage-style tidal power scheme for the region after he visited Campobello Island in 1912. Throughout his

life, Cooper promoted an international tidal power project in which Passamaquoddy was to be the “high” pool and Cobscook the “low” pool, with a complex system of dams, locks and articulated gates operated to maintain a continuous one-way flow through a powerhouse between the two bays (see [4] for a summary description). The installed capacity of the original design was to be 300 MW, with room to expand to 500 MW. With updated turbines, the peak capacity was later estimated to be 1000 MW, comparable to a modern nuclear plant [5].

Cooper’s original plan was never constructed, partly because of concerns about detrimental impacts on the environment, fisheries and navigation, and also because of limitations of the electrical transmission grid at the time. In 1935, work began on a single-pool, U.S.-only version under the Works Progress Administration, but Federal funding for the project ceased the following year and construction halted abruptly. Since that time, there have been numerous studies and attempts to revive the project, but no further construction has resulted [6]. With modern power grids, the peaks from a tidal plant could be absorbed at any time, providing a ready market and eliminating the need for a separate firming facility, but the environmental impacts, changes in the tidal regime, and navigational complications remain compelling.

2. The kinetic energy resource.

Recent improvements in low-head turbine technology, as well as concerns about increasing levels of atmospheric carbon dioxide derived from burning fossil fuels, motivate a fresh look at the energy resource in flowing water such as tidal currents. Although the level of power available from kinetic-energy extraction schemes is generally much lower than from the potential energy of impounded basins, the former do not require construction, maintenance and operation of dams

and gates and therefore have much less environmental impact and much lower installation costs per kilowatt of capacity. In many ways, the opportunities for power development from tidal flows are analogous to wind-power development: both benefit from recent advances in technology, enlightened public policy, and the growing emphasis on renewable resources as an alternative to hydrocarbon fuels.

To illustrate the significant difference between the tidal-stream and tidal-barrage resource, consider a vertical section of area A in the ocean. The power available from the kinetic energy (P_{KE}) of water flowing through the section is proportional to the rate at which mass ρQ crosses the section times its velocity squared, or equivalently to the aperture area A times the *cube* of the velocity perpendicular to the section:

$$P_{KE} = \frac{1}{2} \rho Q V^2 = \frac{1}{2} \rho A |V|^3$$

Taking the water density ρ to be 1000 kg/m^3 for simplicity, the power available per unit aperture $(P/A)_{KE} = 500 \text{ w/m}^2$ for a flow speed of 1 m s^{-1} . Now imagine a dam or barrage to be constructed across the section, so that a height difference or “head” of 5 m is maintained from one side to the other, and arrange for the water to fall from the high to the low-water level through an aperture of area A , as before. The power available from the potential energy (P_{PE}) of the impounded water is proportional to the rate at which mass flows through the aperture, times its vertical drop η , further multiplied by the acceleration of gravity, g :

$$P_{PE} = \rho g Q \eta = \rho g A V \eta$$

For the same conditions as before, i.e. a flow speed $V=1 \text{ m s}^{-1}$, and taking $g \sim 10 \text{ m s}^{-2}$, the power available per unit aperture $(P/A)_{PE} = 5 \times 10^4 \text{ w/m}^2$, two orders of magnitude greater than the KE resource.

The simple example shows why tidal power schemes traditionally use dams and gates to trap water at high tide, allowing it to fall through turbines as the level outside the dam drops. In regions such as Quoddy, with a spring tidal range greater than 8 m, clearly the PE resource greatly exceeds the KE (streaming) resource. However, in constricted passages, tidal currents may considerably exceed 1 m s^{-1} , and since P_{KE} follows the cube of the flow speed a more careful look is warranted.

To aid the comparison, it is helpful to consider the peak power ratio $(P/A)_{PE:KE} = 2g\eta/V^2$, which varies directly with the tidal range but inversely as the square of the flow speed. The log of this ratio is shown in Figure 3 for tidal ranges from 1 m to 5 m and flow speeds up to 5 m s^{-1} . Stars on the figure indicate the ratio at three high-flow sites in the Quoddy region, based on estimates of flow speeds from model calculations, measurements or pilot information, discussed in a later section. For the locations shown (Fig. 2), the highest peak KE resource available is about one-tenth the PE resource. Equivalently, for a 5 m tidal range, a flow speed of slightly greater than 3 m s^{-1} (about 6 knots) is required for the streaming resource to rise to 10% of what would be available from a tidal barrage system (dashed line in Fig. 3). According to the NOAA Coast Pilot [3], currents can exceed this level in Lubec Narrows and Letete Passage.

Of course, in a tidal regime the flow reverses twice per tidal cycle, so the actual power available from the KE resource would show prominent peaks at times of maximum ebb and flow, or four times per lunar day in regions dominated by the semi-diurnal tide, such as Quoddy. There would also be monthly variations associated with the ellipticity of the moon's orbit, as well as

fortnightly spring-neap variations caused by the joint influence of the sun and the moon. In the Quoddy region, the monthly modulation of tidal range associated with the distance of the moon from the earth is greater than the spring-neap variation, a local anomaly. Furthermore, the diurnal tide is locally much smaller than the M-2 component, so that the diurnal inequality of successive highs and lows is relatively small. It is also important to note that modern low-head turbines have efficiencies of 30% or greater [7], so in practical terms about one-third of the available energy resource could be extracted.

2. Circulation models

To develop a better understanding of the distribution of the tidal-stream resource, a numerical circulation model known as ‘Mecca’ (Model for Estuarine and Coastal Circulation Assessment; [8]) was applied in the Quoddy region. The model calculates the velocity, temperature and salinity fields on a three-dimensional grid by integrating the finite-difference equations governing conservation of mass and momentum. The calculations were carried out on a rectangular grid with 120 x 80 cells providing 0.3 km resolution in the horizontal and a terrain-following (or “stretched”) vertical grid with ten levels that preserve vertical resolution over variable bottom depth. For reasons of numerical stability, intertidal regions in the model were not allowed to dry but were represented by thin (0.45 m) boundary layers.

The model runs were initialized with temperature and salinity values specified on the open boundary at the Bay of Fundy and at the mouths of five principal rivers in the domain; interior values were set by interpolation. Tidal forcing was applied at the open boundary by oscillating the sea level with the semi-diurnal period of 12.42 hrs and with elevation range 5.7 m,

corresponding to the principal lunar tidal component (M-2). Annual mean freshwater inflows were specified in the grid cells containing the river mouths. For these experiments, the influence of surface winds and surface heat fluxes were not considered.

The model equations and their finite-difference algorithms are developed in [8]. The vertical turbulent exchange coefficient includes mixing-length and Richardson number dependence, and the horizontal exchange coefficients depend on horizontal velocity shear. With the exception of a simplified turbulence parameterization, the formalism is similar to that given by [9], where the reader can find greater detail. An earlier version of the Mecca model was used to simulate the capacity and some of the environmental impacts of Cooper's original tidal power project [10].

3. The Quoddy resource

Figure 4 shows the tidal-stream power density per square meter of vertical aperture (P_{KE}), calculated from the vertically-averaged model currents, for most of the Quoddy region near the time of maximum flood in the narrow channels connecting the bays with offshore waters. The region shown covers the principal passages where tidal currents exceed 1 m s^{-1} (dashed box, Fig. 2). Figure 5 shows the power density in an expanded view of the Letete Passage region, with velocity vectors superimposed. In both figures, the power density is contoured on a log scale, with values from 10 to 10^4 w/m^2 shown; the contour interval for the gray-scale rendering is half-orders of magnitude [color versions of Figs 4-7 can be viewed in the on-line article; see <http://www.elsevier.com/xxx>]. Model output in the form of "movies" of the velocity fields and the pulsating power density can be viewed as animation sequences over multiple tidal cycles at

<http://cobscook.tamu.edu/review>. Examples of the circulation derived from a Cobscook-only application of a similar model are given by [11].

The highest model power densities on the flooding tide ($> 10 \text{ kw/m}^2$) are found in small areas within or very near Lubec Narrows and Letete Passage, where the maximum currents exceed 3 m s^{-1} . The power density exceeds 3.5 kw/m^2 in a surface area $> 2 \text{ km}^2$ near Letete Passage, compared to the same level in a surface area of about 0.1 km^2 near Lubec Narrows. At the same time, the power density is $> 1 \text{ kw/m}^2$ in small sub-regions of Head Harbor Passage, Western Passage and the outer arm of Cobscook Bay.

An embedded high-resolution ($\sim 60 \text{ m}$) model for the outer Cobscook region (dashed box in Fig. 4) shows the power density and the tidal currents in greater detail near the time of maximum flood (Fig. 6). The embedded model runs concurrently with and receives its boundary information from the coarser ($\sim 300 \text{ m}$) full-region model. To preserve readability, the vector velocities have been decimated by a factor of four in both directions; i.e., only one-sixteenth of the available vectors are shown in Fig. 6. The power density exceeds 0.1 kw/m^2 in most parts of the deep channel containing the principal tidal flow, and small regions where the density exceeds 1 kw/m^2 are evident. Densities $> 10 \text{ kw/m}^2$ are confined to the immediate region of Lubec Narrows. Full-resolution detail in the Narrows region at the time of maximum *ebb* (Fig. 7) indicates that the highest power densities occur on the U.S. side, because the flow at this time is mostly confined to the region west of the two small islands (Dudley and Treat Island) located just to the north of the channel opening. The maximum current speed in the Narrows (4.2 m s^{-1}) occurs on the ebbs, which are slightly stronger than the maximum flooding speeds (3.3 m s^{-1}) in the model simulations (the largest vectors are clipped at the boundary and thus are not visible in

Fig. 7). The Coast Pilot [3] also notes that ebbing currents are stronger than the floods in Lubec Narrows, with speeds greater than 8 knots (about 4 m s^{-1}) during spring tides.

A time series from a model grid cell near the center of Lubec Narrows clearly shows the peaky nature of the power density (Fig. 8), with considerably higher values at the ebbs ($\sim 16 \text{ kw/m}^2$) than at the floods ($\sim 8 \text{ kw/m}^2$). Under mean tidal conditions (M-2 range 5.7 m) and with a turbine efficiency of 33% [7], the model predicts an annual energy production potential of about $16 \times 10^3 \text{ kwh}$ per square meter of turbine aperture in Lubec Narrows. For an aperture of 600 m^2 , i.e. two model grid cells with low-tide depth 5 m (roughly the cross sectional area of the channel at low tide), this level of energy production would be about 10^4 mwh per year, sufficient to supply about 400 homes with typical consumption of 2,000 kwh per month.

A long-term observational buoy in outer Cobscook Bay (see <http://www.gomoos.org>) indicates peak current speeds of about 1.5 m s^{-1} , generally consistent with the model currents shown in Fig. 6. The buoy is moored near the center of the channel (location shown by the open circle in Fig. 6), just west of Broad Cove, close to the site of several floating aquaculture net-pens [11]. The model experiments indicate that the peak power density available near the buoy and in a larger area 2 km north of the buoy site is about 2 kw/m^2 under mean tide conditions. In these areas of relatively modest flow speeds, a moored power-generation installation comparable in surface footprint to a typical aquaculture operation could produce 0.3-0.5 MW at peaks during mean tide conditions. In the highest flow regions, such as Letete Passage and Lubec Narrows where the power densities are an order of magnitude larger, an installation of similar size could produce perhaps 3 MW during the four peak flow intervals in an average tidal day and twice that level during spring tides. Other possible installations in causeway openings or in swinging or lifting structures in narrow passages come easily to mind.

4. Concluding remarks

When considering the magnitude and distribution of the tidal-stream resource, it is important to remember that large tidal ranges are not necessarily required to provide current speeds in excess of 2 m s^{-1} in narrow channels connecting large water bodies. For example, on the east coast of the U.S., positive field tests of vertical-axis turbines recently have been conducted in Cape Cod Canal and in Long Island Sound [12]. NOAA tidal current tables and other sources [13] list many coastal inlets or inter-island passages that experience peak tidal current speeds exceeding 4 knots ($\sim 2 \text{ m s}^{-1}$), in some cases with tidal ranges less than 2 m. Non-tidal flows such as tailrace discharges from hydroelectric dams and freshwater reservoirs also offer potentially important (although less predictable) secondary resources.

Like wind power, the tidal-stream resource is diffuse and dispersed, and as such it is amenable to a wide range of applications and technological advances. For example, improvements in permanent-magnet alternators have helped revivify the wind power field, and the same technology can be appropriated for tidal-stream applications. In future decades, as the hydrogen economy grows [14], electricity generated from tidal, wind and other renewable sources may turn out to be well matched to hydrogen production by water electrolysis, using no hydrocarbons and producing no carbon dioxide.

Returning to the Quoddy region, model calculations and current observations show that the tidal-stream power resource is mainly concentrated in the passages linking the bays with the Bay of Fundy offshore, as one would expect. The highest values of power density are found in Lubec Narrows in the United States and Letete Passage in Canada, where the peak resource exceeds 10

kilowatts per square meter of turbine aperture. Less restricted areas with maximum current speeds $>2 \text{ m s}^{-1}$ (e.g. parts of Head Harbor, Western Passage, and Cobscook Bay) may hold practical promise for energy extraction at lower power density levels. In the highest flow regions, it appears that moored or anchored installations with spatial scales comparable to existing aquaculture sites could produce peak power levels of 1 MW or greater using modern, efficient turbines. In the near term, such installations, individually or grouped, would require connection to the local electric grid, which presumably could accept the tidal power peaks at any time.

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FIGURE CAPTIONS

Fig. 1. Map of the Gulf of Maine and Bay of Fundy, showing co-amplitude and co-phase lines for the M-2 (principal lunar semi-diurnal) tidal constituent (tidal data from Brown, 1984 [1]). The inset box identifies the Passamaquoddy-Cobscook region.

Fig. 2. Expanded view of of the Passamaquoddy-Cobscook Bays (inset, Fig. 1). The border between the U.S. and Canada is shown by the dash-dotted line. The solid inset box identifies Cobscook Bay. The dashed subregion refers to Fig. 4. Adapted from Brooks et al 1999 [11].

Fig. 3. A comparison of the peak power density from tidal-barrage (PE) versus tidal-stream (KE) systems. The base-10 log of the PE/KE ratio is shown for tidal ranges of 1-5 m and current speeds of 0-5 m s⁻¹. Stars show the ratios for several high-flow areas in the Quoddy region.

Fig. 4. Tidal-stream power density (log kw/m²) in the sub-region of the principal passages (dashed box in Fig. 2), from model calculation at the time of maximum flooding currents. The inset box refers to Fig. 6.

Fig. 5. Expanded view showing power density (log kw/m²) in and near Letete Passage at the time of maximum flood. Arrows show the vertically-averaged model currents. Note scale vector.

Fig. 6. Available power density (log kw/m²) in outer Cobscook Bay (inset box, Fig. 4) near the time of maximum flood in Lubec Narrows, from a high-resolution embedded model. Vectors

show the vertically-averaged tidal currents, decimated 16X for clarity. The open circle shows the location of a long-term observational buoy, referred to in Fig. 8.

Fig. 7. Full-resolution (60 m) current vectors and tidal-stream power density near Lubec Narrows at the time of maximum *ebb* currents. Maximum flow is 4.18 m s^{-1} . Vectors are clipped at the figure boundary.

Fig. 8. Time-series of available tidal-stream power density (kw/m^2) near the center of Lubec Narrows for a period of 4.5 days. The peaky nature of the resource is apparent, with larger values on the ebb than the flood.















