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Gross Hydrokinetic Power Potential of the Florida Current

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Summary: The overall gross power potential of the Florida Current in the Straits of Florida is estimated, and different approaches to the problem are discussed. Although it is unlikely to be realized, a total gross potential of some 200 GW is shown to be consistent with published methods. Limitations and implications are also discussed in this brief note



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1. Introduction

As the economic and environmental costs of fossil fuels continue to escalate, and as demand for energy climbs, the development of new clean and renewable energy resources takes on added urgency. Most renewable energy resources are inherently regional in nature, and so the concept of a diversified portfolio of energy for the future emerges (e.g., Hanson, 2009). One resource that is relatively new to the portfolio is marine renewable energy (MRE), the potential of waves, tidal and open-ocean currents, and the thermal structure of the oceans.

The Florida Current—the reach of the Gulf Stream that flows through the Straits of Florida (Fig. 1)—offers a source of clean and renewable base-load power for the Southeast Florida metropolitan area and beyond. This was recognized as long as 40 years ago when, during the oil embargo by the Organization of Petroleum Exporting Countries, philanthropist J.D. MacArthur convened a meeting of ocean scientists and engineers to discuss the matter (see Stewart, 1974b, for a workshop summary.) One outcome of that meeting was an estimate that

“there is a large energy resource available in the kinetic energy of the flowing Florida Current portion of the Gulf Stream System equivalent to that of about 25 one-thousand-megawatt power plants”

with the qualification that

“the amount of energy that could be extracted with practical systems, however, might not be more than the output of two one-thousand-megawatt power plants.” (Stewart, 1974a)

This 25 GW gross estimate has persisted in various published contributions through the years. It was not until a decade after the MacArthur Conference that the National Oceanic and Atmospheric Administration’s Sub-tropical Atlantic Climate Studies (STACS) program provided data to allow calculation of a gross power estimate, and this was done only recently (Hanson, *et al.*, 2010). In any case, the amount of power extractable depends on a variety of factors including the strength of the resource itself, the technology available for deployment, and social

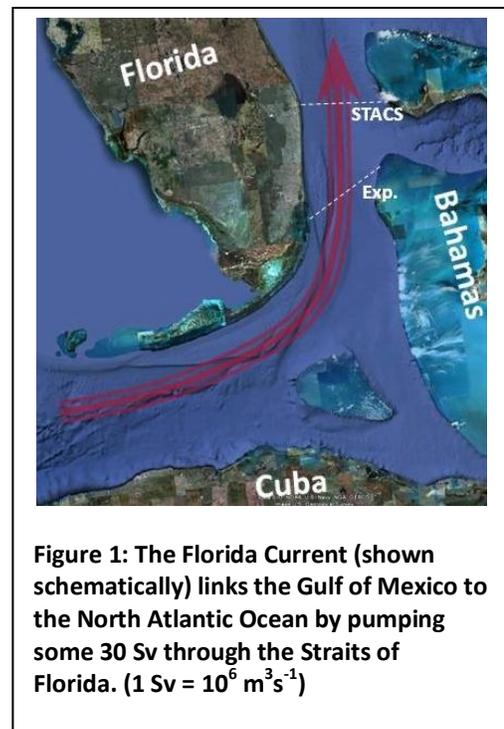
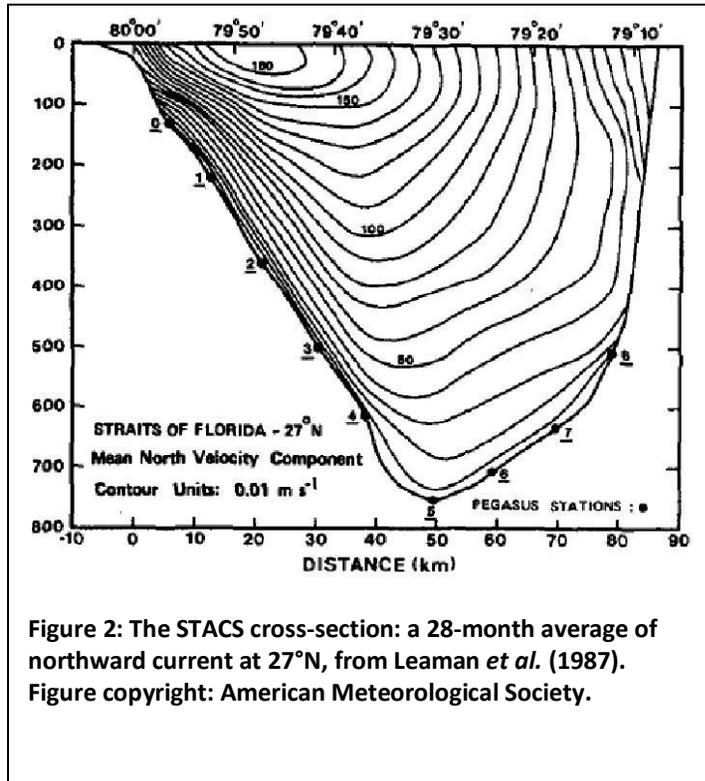


Figure 1: The Florida Current (shown schematically) links the Gulf of Mexico to the North Atlantic Ocean by pumping some 30 Sv through the Straits of Florida. (1 Sv = $10^6 \text{ m}^3 \text{ s}^{-1}$)

restrictions on that deployment. This note is concerned with the first of these, what has been called the *gross potential* power (e.g., DOE, 2012, p.1).

2. The STACS Cross-Section



STACS (e.g., Molinari, 1989) was a long-term oceanographic research program that initially focused on the behavior of the Florida Current, and much of today’s physical oceanography knowledge base concerning the flow through the Straits of Florida can be traced to it. One important set of current observations was obtained from 1982-1984 on cruises across 27°N (Fig. 1), between about West Palm Beach, Florida and West End, Bahamas. Pegasus floats were used to profile the strength of the current, and Leaman *et al.* (1987) discussed the results. Figure 2 is the figure from that paper showing the averaged northward current in the cross-section.

The total power of a fluid flow can be described in terms of its *power density*, the power per unit area orthogonal to the flow direction:

$$\Phi = \frac{1}{2} \rho v^3$$

where ρ is the fluid’s density and v its speed. For a cross-section such as that of Fig. 2, then, the power density Φ integrated over the cross-sectional area gives the total power available in the fluid flow. Hanson *et al.* (2010) showed that the total power in Fig. 2 is approximately 20 GW, and, further, that the power is a strong function of flow speed. Because generating systems—turbines—have a *cut-in speed* below which they do not operate, it is useful to depict power integrated upward from a particular cut-in speed, because that shows what a given turbine design has available to it (Fig. 3, top curve). For example, turbines with a 1.5-kt (0.75 m s⁻¹) cut-in speed have somewhat more than 17 GW available while those with twice that cut-in speed have less than 8 GW available. (Below, turbine systems will be discussed in terms of their cut-in speed in nautical miles per hour—kt—while the flow will be described using SI units. For illustration purposes, 1.5-kt and 3-kt systems will be used.)

This power availability, however, is not what is truly extractable. For one thing, no turbine system is 100% efficient—indeed, Betz’ Law shows them to be less than 60% efficient under the best of conditions. Therefore, the power produced by an individual turbine is

$$P = A_E \Phi$$

where the *effective area* A_E of the turbine is the product of ϵ , the system’s efficiency (which will be taken as 40% here, two-thirds of the theoretical maximum) and A , the swept area of the rotor, for conventional axial-flow systems such as familiar wind turbines.

For another, it would not be feasible to deploy turbines in such a way as to fill the entire cross-sectional area at and above the systems’ cut-in speed. Thus, “extractable” power is some fraction of the total power. This has been illustrated by the bottom curve in Fig. 3 with a hypothetical deployment of 40%-efficient turbines that, all together, occupy half the area available, meaning that the top curve is simply multiplied by 0.2. Note that the two example designs of a 1.5-kt system and a 3-kt system can now extract about 3.5 GW and 1.5 GW, respectively.

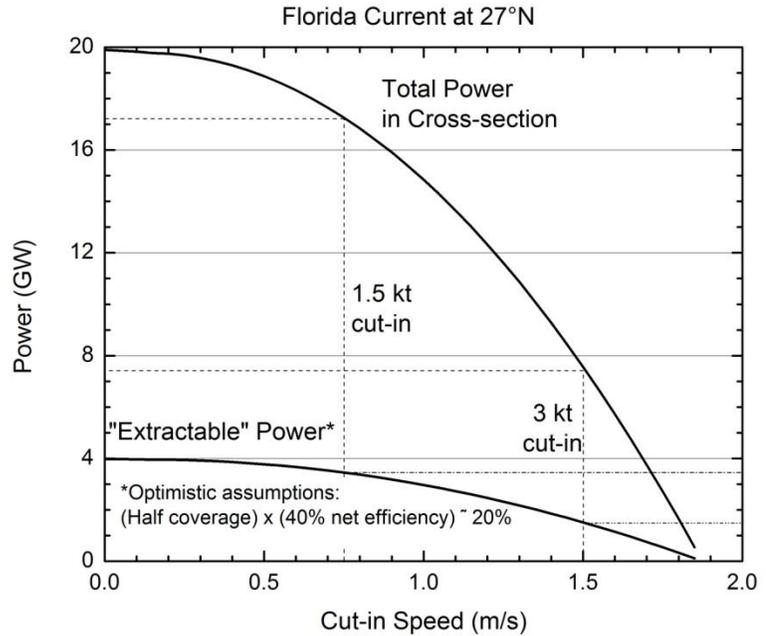


Figure 3: Total and “extractable” power as a function of cut-in speed for STACS cross-section, after Hanson (2011).

Although these numbers bracket the 2 GW “practical” limit of the MacArthur Report (with these assumptions, the report’s 2 GW could be extracted by a half-coverage array of 2.8-kt systems), it is probably coincidence, as there was no discussion in that report of deployment strategies such as the one used here for illustration.

An array of identical systems will, of course, produce power in different amounts, depending on where in the flow a particular unit is placed, because the current speed varies so much. Given the cross-section and its integral that resulted in Fig. 3, however, it is possible to calculate an equivalent averaged current speed \bar{v}_e for a given cut-in speed’s total power as

$$\bar{v}_e^3 = \frac{1}{A} \int_A v^3 dA \text{ for } v \geq v_{\text{cut-in}}$$

For the two cases here, these averaged current speeds are $\bar{v}_e=1.22 \text{ m s}^{-1}$ and $\bar{v}_e=1.65 \text{ m s}^{-1}$ for the 1.5-kt and 3-kt system examples, respectively. Thus, the averaged power densities Φ available to the units in an array is, respectively, 931 W m^{-2} and $2,302 \text{ W m}^{-2}$. Table I shows system power (taking into account the 40% efficiency, and neglecting hub diameter so that rotor diameter is simply twice the blade length) for systems of various sizes at these two current speeds.

Blade Length (m)	Rotor Area (m ²)	1.5-kt system Power (kW)	3-kt system Power (kW)
5	78.5	31	72
10	314	117	289
15	707	263	530
20	1,257	468	1,158
25	1,963	731	1,808
30	2,827	1,053	2,603

Table I: Per-unit power for 40% efficient systems of various sizes, using assumptions in examples discussed in text.

Table I also illustrates a paradoxical trade-off: in a comparison such as this, “better” systems—meaning those with lower cut-in speeds—will always produce less power per unit on average, because they will be deployed in slower flows, on average. Of course, they also have more potential power available. As an example, to deploy systems with 20-m blades and recover the “extractable” power available from the Fig. 3 would require 7,478 1.5-kt systems to extract 3.5 GW or 1,295 3-kt systems to extract 1.5 GW. How to balance this trade-off in terms of the economics of power extraction provides a challenge for developers. To complicate the challenge, it is important to note that the STACS cross-section is a time average, and the actual current exhibits significant variability in both space and time (e.g., Hanson *et al.*, 2011).

To this point, the discussion has focused exclusively on the single STACS cross-section. This obviously begs the question of whether additional deployments up- or downstream, in additional cross-sections, are possible and how much additional power could be extracted—a question to which there yet is no good answer. It can be approached, however, from another perspective.

3. Offshore wind

Open-ocean current power has much in common with offshore wind power. There is a tendency for a prevailing direction of the flow, with variability superimposed; flows are generally not confined to narrow geographic regions, such as inlets to embayments in the ocean (in which tidal power can be significant) or, in the atmosphere, gaps between topographic features. Because extraction of ocean-current power is similar in principal to extraction of wind power, it is useful to make an assessment of the oceanic resource from the wind-power perspective.

The U.S. Department of Energy estimates the power potential of offshore wind using a method developed at the National Renewable Energy Laboratory (Musial *et al.*, 2004; 2006;

2010; Schwartz *et al.*, 2010—this will be called the “NREL Method” here). Power estimates using this method have been labeled “gross potential” power (e.g., DOE, 2012).

The NREL Method has two parts. First, it uses wind climatologies to map out areas over which the average wind speed at wind-turbine hub height is above a threshold of 7 m s^{-1} (excluding environmentally sensitive areas), which implies a power density threshold of $\Phi_t \gtrsim 210 \text{ W m}^{-2}$ (recall that this area is orthogonal to the flow). Then, based on an assumed generating capacity in such conditions of 5 MW km^{-2} of ocean surface, it sums over those areas to find a total potential. Although the results are discussed in terms of “classes” of wind, categorized by wind speed, there is no indication that the actual power potential includes these variations.

The assumed generating capacity of 5 MW km^{-2} carries interesting implications. For wind systems of 40% net efficiency, one (5 MW) system per km^2 means a system with $\sim 140 \text{ m}$ blades (at the 7 m s^{-1} threshold), or a 280 m rotor diameter – thus they would be spaced less than four diameters apart. For similarly efficient 1.25 MW systems, four per km^2 implies 500-m spacing of systems half the single-system size, the same fractional spacing. In this context, it is important to note that downwind effects on system performance in arrays are not considered in the NREL Method resource assessment, nor are implications of the cross-flow torques imposed on these large rotors by vertical wind shear on the same scale as the rotors.

Can the NREL Method be applied to the Florida Current? Several factors are involved in answering this question.

In terms of power density, a 7 m s^{-1} wind, with a power density $\Phi \approx 210 \text{ W m}^{-2}$, is the equivalent of a current threshold of $v_t \approx 0.75 \text{ m s}^{-1}$ (or 1.5-kt—which is why such a system is used as an example here), because the cube root of the density ratio (water/air) is just less than 10. Therefore, each square kilometer of the Florida Current inside the 0.75 m s^{-1} isotach in Fig. 2 along the stream-wise length of the Florida Straits becomes a candidate for the offshore wind assessment method.

To extract at least 5 MW from each square kilometer of ocean surface would require exactly the same configuration of equipment as it would in the atmosphere—a single 5 MW system with a 280-m rotor, four 1.25 MW systems half that size, or more, smaller systems. Of course, logistics would prevent identical deployments—aside from the challenges of salt water, for example, much of the Straits of Florida are over 400 m deep, making bottom-mounted deployment on towers all but impossible. And forces in the ocean, including torques, scale as a factor of ten higher than in the atmosphere (Hanson *et al.*, 2010), while the shear profile of the current occurs on much smaller scales than in the atmosphere. Consequently, very large rotors are not feasible. It therefore remains to determine how equipment could be deployed to fulfill the NREL Method’s assumption of 5 MW km^{-2} .

Consider the 40% efficient, 20-m blade, 1.5-kt systems shown in **boldface** in Table I. At $v_t = 0.75 \text{ m s}^{-1}$ of current, these produce only 109 kW each (recall that the computation for Table I

used a current speed of $\bar{v}_e=1.22 \text{ m s}^{-1}$). Generating 5 MW would therefore require some 46 such systems. One possible design for open-ocean current energy conversion systems uses twin, counter-rotating rotors on a hydrodynamic hull with control surfaces. The question then becomes whether 23 such twin-rotor systems could reasonably be deployed in a square kilometer.

To simplify the discussion, consider an array designed on a 3x3x3 grid, as shown in Fig. 4. Removing four units (labeled i or ii) on the bottom layer would yield 23 systems, each with two rotors, capable of some 5 MW altogether in a $v_t = 0.75 \text{ m s}^{-1}$ flow. In a square kilometer, the distance between the stacks of three systems would be 333 m, or more than 8 rotor diameters compared to the 3.5 or so in the atmospheric case; as in the atmosphere, staggering placement of stacks in successive rows would then minimize downstream interactions. And although the depth of the stacks of systems would be more than 120 m (three rotor diameters), the $v_t = 0.75 \text{ m s}^{-1}$ isotach is much deeper in most of Fig. 2. For example, at 200 m, the E-W width of the 0.75 m s^{-1} or greater flow is approximately 45 km. Deploying each stack of three units between, say, 40 m (below surface shipping) and 200 m would leave room for vertical space between the units. Note that, in each $1 \text{ km}^2 \times 200 \text{ m}$ deep column of water (moving at 0.75 m s^{-1} or faster), only about a third of the cross-sectional area would be occupied by turbines, significantly less than the half assumed above in the discussion of the STACS cross-section.

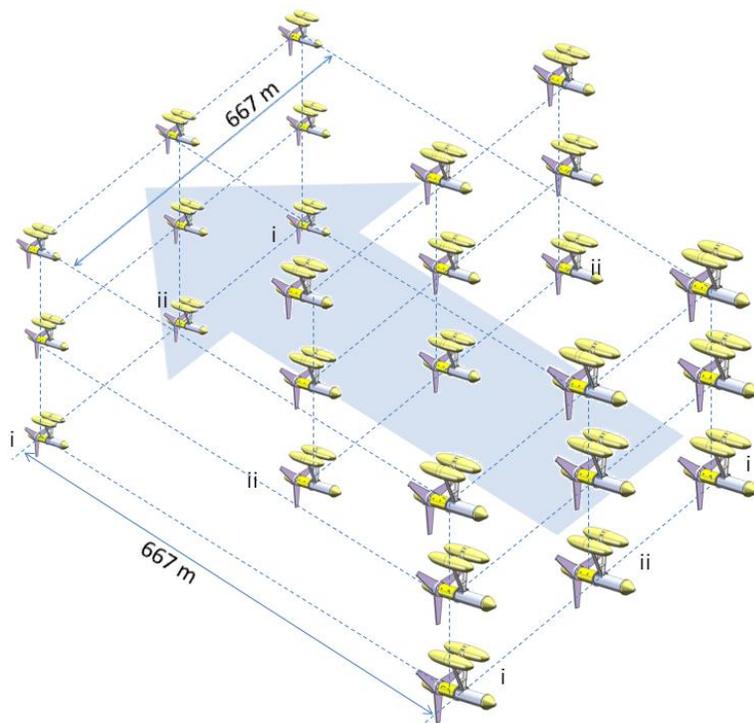


Figure 4: 3x3x3 array of turbines (vertical scale exaggerated) with offset middle row. Flow is in direction of large arrow. Removal of either (i) or (ii) labeled units results in 23 units per km^2 . Note that single-rotor systems are depicted here, purely to simplify the illustration; dual-rotor systems are discussed in the text.

Now, the surface expression of the $v_t = 0.75 \text{ m s}^{-2}$ isotach in the STACS cross-section is some 60 km wide. A careful analysis of the STACS cross-section suggests that the equivalent averaged depth of this isotach across a 60-km wide swath is 280 m, more than enough to deploy the 3x3x3 arrangement of 1.5-kt units in Fig. 4.

Consequently, at least at 27°N , the NREL Method of assuming a 5 MW km^{-2} power potential for flows with power densities greater than 210 W m^{-2} (or flow speeds greater than 0.75 m s^{-1}) can be applied to the Florida Current's surface signature.

It remains to ask whether the 27°N conditions of the STACS

cross-section apply elsewhere in the Straits of Florida. The only other published cross-section of the Florida Current was obtained using ship-board acoustic measurements at $\sim 26^\circ\text{N}$, along the weekly track of the cruise ship *Explorer of the Seas* (the “Exp.” dashed line in Fig. 1—see Beal *et al.*, 2008). When corrected for the ship’s ENE heading, the surface expression of the 0.75 m s^{-1} isotach in that cross-section is also 60 km wide, and the vertical structure below is also quite similar if bathymetry is taken into account. More generally, there are variations of the Florida Current’s structure during its passage through the Straits of Florida, but there is also evidence that it retains a remarkable self-similarity (e.g., Bosc *et al.* 2010; Hanson *et al.*, 2011).

The 27°N cross-section, then, would seem to provide a useful template at least to first order. Given this, it is straightforward to produce an overall power estimate: The distance along the core of the Florida Current from the Dry Tortugas, west of Key West, to a section offshore Port St. Lucie, at the north end of the Little Bahama Bank where the Straits of Florida effectively terminate, is somewhat over 650 km, meaning that there are some $40,000 \text{ km}^2$ of the ocean surface above 280-m average-depth water columns that are moving northward at speeds at or above the 0.75 m s^{-1} threshold for applying the NREL Method. At 5 MW km^{-2} , this means that there is a total gross hydrokinetic power potential of some 200 GW in the Straits of Florida.

4. Discussion: Implications & Limitations

How reasonable is this 200 GW estimate?

As noted in Section 2, current speeds higher than the 0.75 m s^{-1} cut-in threshold occur throughout much of the water column, and Fig. 3 shows that they are responsible for just over 17 GW of the 20 GW total in the 27°N cross-section of Fig. 2 and for about 3.5 GW of “extractable” power under the assumptions used here (Fig. 3). This means that the power from about 57 such cross-sections, spaced a bit over about 11 km apart, can account for the 200 GW total. (If, as in Section 3, only a third of the cross-sectional area is occupied by turbines, these numbers become 87 cross-sections at 7.5 km spacing.) If these are the dual-rotor units discussed in Section 3, a total of 213,675 units would be required, 2,456 in each of the 87 cross-sections. While these numbers are daunting, it should be noted that the NREL Method applied to the U.S. coastal economic zone offshore results in some 4,000 GW of total gross potential power (Musial *et al.*, 2004; 2006; 2010; Schwartz *et al.*, 2010), for which 1.6 million 2.5 MW units would be required. In each case, the point of the NREL Method is not to suggest a strategy for extracting the power levels obtained; rather, it provides a total gross potential, an absolute upper bound.

Although the scenario discussed here provides a rationale for application of the NREL Method to the Florida Current and consistency for these estimates of the potential hydrokinetic power in the Straits of Florida, it seems overly ambitious. A more useful approach would work against the 200 GW total potential from the perspective of existing generation capacity. In this regard, by way of comparison, the total electrical generating capacity of all power stations in Florida is in the neighborhood of 60 GW (EIA, 2011); in the U.S. it is about 1,000 GW (EIA,

2010). In 2009, the Nation's electricity usage was the equivalent of about 440 GW continuous EIA (2010) (of course, usage is not continuous, so capacity must be much higher to handle peak loads).

Closer to the resource, the FPL Turkey Point Generating Station south of Miami is currently rated at 3.3 GW of capacity; there are plans to expand that to 5.6 GW (FPL, 2011) over the next few years. When the upgrade is finished, something just under 3% of the total gross hydrokinetic resource in the Straits of Florida will be generated by a combined set of nuclear and gas-fired units at this site.

Could this amount of power be extracted reasonably from the ocean?

Note that 5.6 GW represents 1.6 times the 3.5 GW “extractable” power in the 27°N cross-section at speeds above the 1.5-kt cut-in threshold. Generating this much power from the 40-m diameter, dual-rotor systems used in the examples here would require slightly less than 6,000 of them (using the \bar{v}_e power levels). Spreading extraction of this amount of power over three cross-sections, 2,000 per cross-section, would occupy 30% of the $v_t = 0.75 \text{ m s}^{-1}$ water in each. (Alternatively, additional cross-sections occupied less fully could be used.) From the technology perspective, these numbers seem far more reasonable. Nor is 5.6 GW a necessary limit. Four cross-sections each producing 2.5 GW, and using 5% of the Florida Current's 200 GW potential, would produce 10 GW and make a significant impact on South Florida's hunger for electricity.

But what about economics?

At a current (estimated) wholesale rate for electricity of \$0.05 per kW-hr, 5.6 GW generation would gross \$49 billion in revenue over a 20-year life cycle (or \$8.2 million per unit). Economic feasibility, of course, depends costs of fabrication and deployment, operations and maintenance, and the return on investment requirements, all of which are unknown, particularly given economies of scale associated with a 6000-unit installation compared to prototype development.

In addition to these unknowns, impacts of such installations on both the physical and biological environments of the Straits of Florida are as yet unknown—although some early studies are beginning to provide the insight that perhaps only a few percent of the gross potential power may be prudently extractable. Beyond the environmental studies, however, is the murky and unpredictable area of social acceptance of all this technology in the ocean. That is likely to be the biggest hurdle in tapping into this source of energy for the future.

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