TIDAL ENERGY: THE CASE OF EURIPUS' STRAITS

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Abstract

The tidal energy potential of low current tidal and marine currents is investigated in this work. Existing data on the current velocity and sea level at the Euripus' strait in Evia, Greece, is used to compute the energy yield based on contemporary turbine designs. Requirements, limitations and opportunities concerning the exploitation of low velocity tidal streams are discussed. The exploitation of tidal energy technology in conjunction with RES microgrids is proposed for coastal areas with abundance of sun and wind such as the Mediterranean islands.

Keywords: Tidal Turbines, Tidal streams, Tidal Energy, Energy assessment

Introduction

Tidal energy is being studied as a potential Renewable Energy Source (RES) over the last two decades, especially in the Northern European countries where pilot energy plants are harnessing the energy of the Atlantic Ocean tides. Tidal technology is not as mature, as wind or solar energy, but has the significant advantage of predictability, facilitating demand side energy management, the new paradigm in the smart grid and the emerging electric power markets (M.J. Khan, G. Bhuyan, M.T. Iqbal & J.E. Quaicoe, 2009; Greene, 2000). Currently, manufacturers are focused on the exploitation of the strong tides of the big oceans, deploying tidal farms from hundreds of kW reaching up to several MW, tied to the grid (Melton, 2012; Ray 2000; Hagerman and Polagye, 2006; Denny, 2009; Triton 2002). On the other hand, little to no attention has been given to the weaker tides of smaller seas, eg the Mediterranean, or to the sea currents observed in straits.

The trend in electrical energy generation is distributed generation (Pepermans, 2005) along with demand side management and smart grid technologies (Buchholz, 2008, Strachan, 2002). Microgrids are an emerging technology for on location power generation and distribution, and minimized transmission costs. Microgrids (Kojima, 2009) are employing RES along with energy storage technologies with some backup generation facility.

Small island communities or communities along the coastline of the Mediterranean basin are often used as summer vacation destinations, leading to high power demand peaks in the summer months, often several times higher than those in the wintertime. As their connection to the main grid is not always possible or cost effective, they have to generate their own power using expensive and environmentally harmful diesel and, as of lately, supplement it with, wind and solar energy. 'Green islands' (ISET, 2008; Degner, 2004; Tselepis, 2003) whose energy supply will solely rely on Renewable Energy Systems (RES) have been studied and promoted over the last two decades in conjunction with EU's guidelines and goals for 2020 and 2050. However, sun and wind, which exist in abundance in such destinations, especially in the summer months, are highly unpredictable. Intermittency is a problem for wind and solar power. These sources of renewable energy require backup from traditional forms of power generation. The inherent predictability of tidal power is highly attractive for grid management, removing the need for back-up plants powered by fossil fuels. Tidal energy, when integrated in such a Renewable Energy Sources (RES) microgrid, can facilitate the optimum design and control of such a microgrid.

So far, tidal turbines have not been seen as part of a RES microgrid but rather as a plant in themselves tied to the main power grid. In this work, we use available data to explore the tidal energy potential of Euripos' Gulf in Evia, Greece, with respect to the state-of-the art in tidal energy generators. The potential and limirations of tidal turbines, optimized for low velocity currents, in conjunction with RES microgrids, consisting of photovoltaics (PV) and wind generators, often encountered in Southern Europe, is discussed.

Tides and Tidal Energy

Oceans and their currents are driven by the gravitational forces between our planet, the Sun and the Moon creating the periodic rise and fall of the sea's level, known as the tide. The Moon, being closer to our planet, contributes approximately twice as much to the tides observed on Earth.

Tides are classified according to their:

a) Tidal range: spring/high tides and neap/low tides
b) Periodicity: daily tides with tidal period of 24 hours and 50 minutes, semi-diurnal tides with tidal period of 12 hours and 25 minutes and mixed tides.

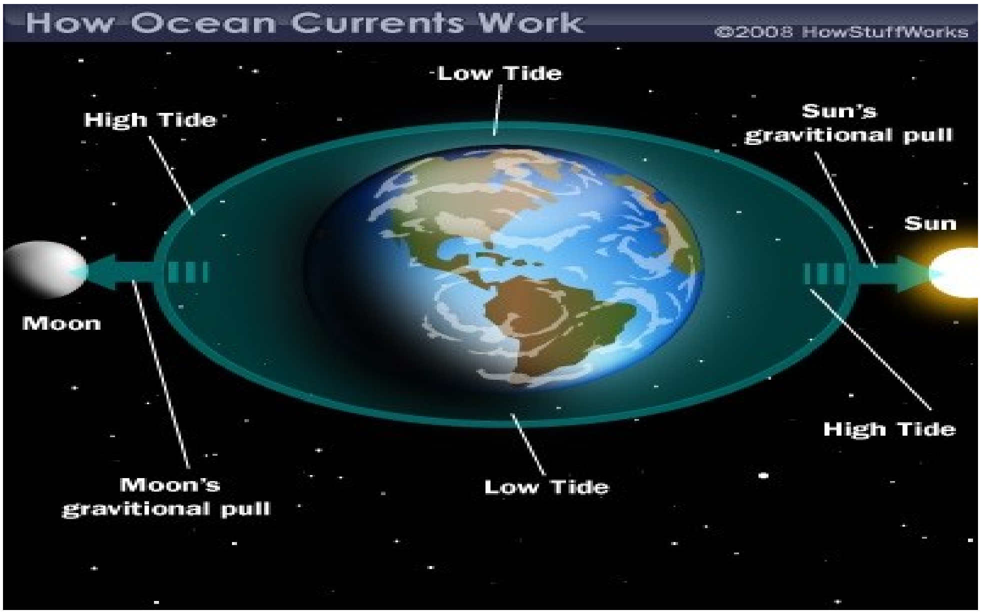


Figure 1: Contribution of Moon and Sun to the creation of the High and Low tides on Earth (Lemonis, 2004)

Tidal period is defined as the time between the appearance of high and low tide and tidal range is defined as the height difference between the highest and the lowest value of sea level (Lemonis, 2004). Tidal energy can be harnessed both in the potential and kinetic form. In the first case the difference in the water level between high and low tide is used to drive turbines in structures like dams, called tidal barrages (La Rance, France), similar to the hydroelectric barrages. In tidal stream systems instead, turbines are submerged to exploit the kinetic energy of tidal currents, with a working principle similar to that of wind generators (Figure 2).

These tidal generators can be deployed in arrays, in tidal farms, and are usually characterized by lower environmental impact and construction costs than tidal barrages. The average power density (APD) of such a turbine is estimated in a manner similar to that of the wind generators and is proportional to the cube of the flow velocity of the stream, U in m/s, and the sea water density,□□ which is approximately 1027 kg/m^3, three orders of magnitude greater than air's (Horton):

$$APD = \frac{1}{2} \times \rho \times U^3 \qquad (1)$$

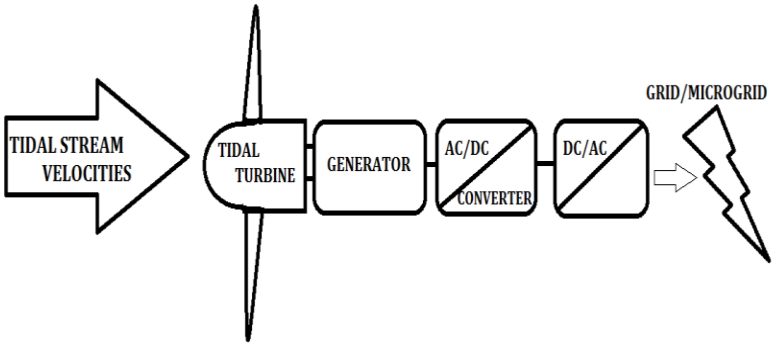


Figure 2: Tidal turbine block diagram.

APD varies with the cube of the velocity of the stream which means that the APD of a wind generator operating at 10m/s wind velocity corresponds to a tidal stream velocity of a mere 1m/s.

The tidal energy system is extremely site specific since its efficiency depends heavily on the stream velocity as well as the physical characteristics of the deployment location, bathymetry and morphology. Generally speaking, better conditions will be found in zones such as estuaries, straits or wherever the local morphology causes the water section to suddenly narrow down leading to bigger head or higher current speed. The useful channel section is though limited by the upper and lower depth bounds: turbines must be deployed below 5m for the small boat traffic and below 20m for all boat traffic. The lower limit is determined by the benthic layer of the channel which is typically 1/10 of the mean minimum channel depth (Hagerman and Polagye, 2006).

Because the tidal current velocity varies with time (Figs 3-5), the Root-Mean-Square (RMS) velocity, U_{rms}, as follows from the velocity distribution (Fig. 9), is used to compute APD in (1):

$$APD = \frac{1}{2}\rho \sum_{i=1}^{NB} \left(U_i^3 f(U_i) \right) = \frac{1}{2}\rho U_{rms}^3 \qquad (2)$$

where U_i the center of every velocity interval, NB the number of velocity intervals, $f(U_i)$ the probability of the i-th velocity interval.

Tidal turbines are divided into two main categories, the horizontal axis (Figure 2) and vertical axis (Figure 3).

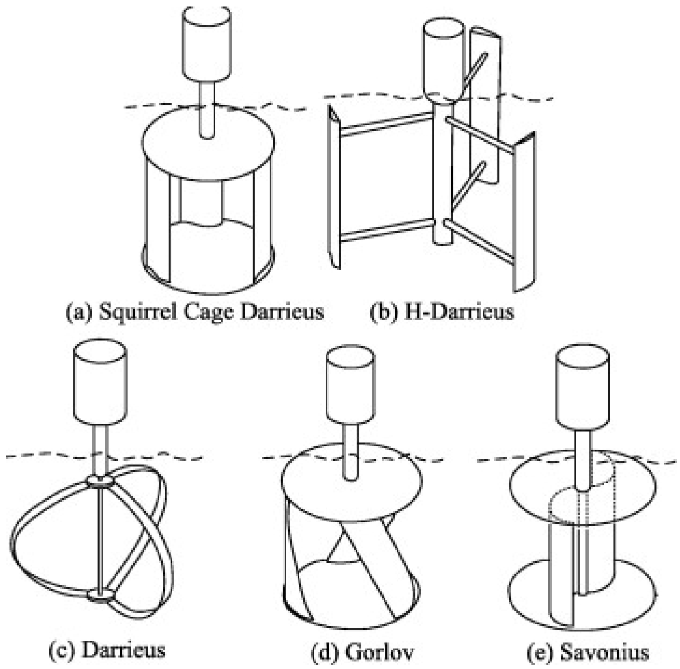


Figure 3: Vertical axis tidal turbines

Horizontal turbines typically consist of three or two wing blades that operate vertically with respect to the sea bed, spanning a circular cross sectional area. Horizontal axis turbines are usually installed in areas where the tidal effect is stronger. For lower stream velocities, their operation may be Venturi-enhanced. Vertical axis turbines don't have a specific number of blades and operate horizontally with respect to the seabed. Their cross sectional area is square and suffers from lower turbulence at the edge of the blades.

Ultimately, the power extracted, P, depends on the cross sectional area of the turbine's blades, A in m^2, and the overall efficiency of the turbine given by the dimensionless performance coefficient C_p:

$$P = \frac{1}{2}\rho A U^3 C_p \qquad (3)$$

C_p is the product of the performance coefficients of all subsystems, *i.e.* turbine, generator, power conditioning. and is typically lower than 45%.

Reports (Melton, 2012) indicate that with the existing technology less than 20% of the current's kinetic energy is harnessed.

Due to the high sea water density, the tidal generators may result in smaller constructions than the wind generators, for the same output power P, as long as the velocities are high enough to overcome the inertia of the given design. However for low stream velocities, the area swept by the blades, A, needs to be increased leading to significant up scaling in the geometric characteristics of the turbine. Furthermore, tidal generator designs must take into account the harsh sea operating environment. Therefore, the optimal tidal turbine design is a technological object yet to be overcome.

Existing tidal plants are found mainly in Northern Europe, *e.g.* Northern Ireland, Scotland, Norway or the Netherlands. In Southern Europe and the Mediterranean Sea, tides are smaller because of the Gibraltar straits. However, the Mediterranean basin offers several sites where tidal currents are non-negligible as well as marine currents. Strong local currents are encountered in straits all over the Mediterranean Sea, with the most characteristic example being the Straits of Gibraltar, the Otranto, Messina and Sicily straits etc. Strong local sea currents can also be identified in island complexes, such as the Cyclades complex, Greece, the region south of the Cape of Kafireas, or the Mykonos-Tinos straits. One of the most characteristic tidal currents in Greece is the one observed in Euripus' Strait separating the island of Evia from mainland Greece. The tidal current spans the whole length of the channel from North to South but it is strongest at its narrower part, near the city of Chalkida, where the Old and New Bridge connecting Evia Island and mainland are located. The Old Bridge is at the narrowest part of the strait and it is where the phenomenon is significantly stronger.

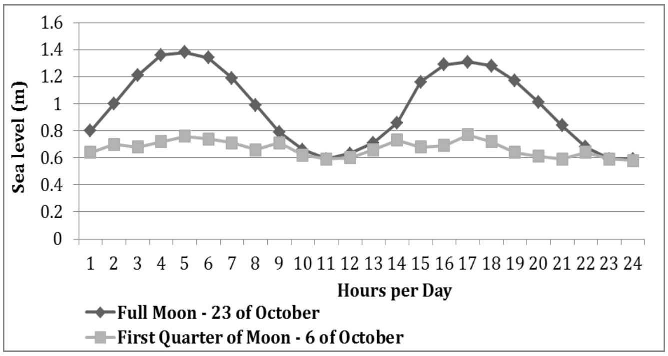


Figure 4: Sea level height at the North port of Chalkida, Greece, recorded during a full moon (high tide) and first quarter (low tide) day in October

The Euripus' strait tidal cycle is semi-diurnal, characterized by two peaks every 24 hours. Data on the Euripus' tidal current is rare. The Hellenic Navy Hydrographic Service (HNHS) has been systematically recording the sea level at the North and South end of the port of Chalkida where the Old Bridge is. Data on the months October – December 2010 has been kindly made available to us. The peak height which varies with the moon phase ranges from approximately 0.70m to 1.40m for a high tide (upper curve, Fig 4), and 0,60 to 0.75 for a low tide (lower curve, Fig.4), during a day.

A thorough profiling of the Euripus' current has been carried out by the Hellenic Centre for Maritime Research (HCMR). The data has been kindly made accessible to the authors for this work. The data consists of velocity time series recorded along the channel at the New Bridge location for May and July 2010 and profiling of the current by magnitude and direction which was carried out at cross sections, along the depth and width of the channel in three different locations, namely the Old Bridge, New Bridge and North side of the port – Lighthouse on four different dates from May till September 2010. Based on these measurements, HCMR estimated APD to be 13.46 W/m^2, 1105.87 W/m^2 and 13.46 W/m^2 at the New Bridge, Old Bridge and North Side respectively.

A comparison between the data from HNHS and HCMR was carried out to determine whether the energy potential could be inferred from sea level data, such as the HNHS time series, which are easier to obtain and usually more readily available for several locations in the Mediterranean Sea.

The sea level data (Figs 4 and 6) shows clearly the high tide coinciding with the full and new moon and low tide occurring at the quarter phases. The sea level variation at the North side is significantly stronger while at the South side it is small and quite unruly. This is in line with the weak but turbulent flow observed and the basin's morphology there. Fig. 5 shows the maximum and minimum values recorded during the month of November 2010. The maximum values typically range from 1.20m to 1.40m and the minimum values from 0.65 to 1.00m.

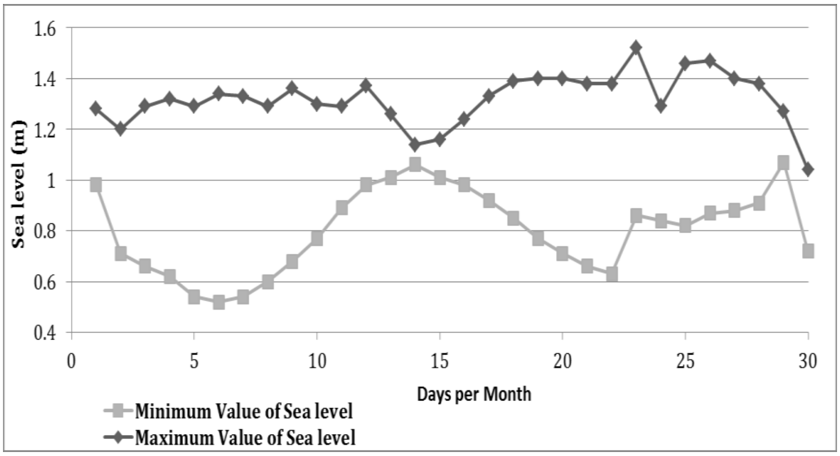


Figure 5: Maximum (top) and minimum (bottom) values of sea level for the month of November 2010 at the North side

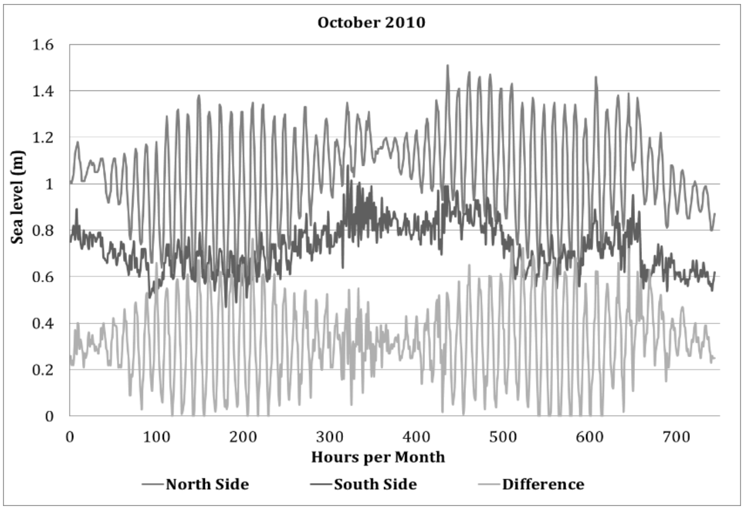


Figure 6: The sea level as recorded on an hourly basis at the North (top) and South side (middle) and their difference (bottom) for the month of October 2010

To assess the energy potential using sea level measurements, the Bernoulli's equation for uniform non-viscous flow relating height difference, Δh, and velocity U is used:

$$U = \sqrt{2 * g * \Delta h} \quad (4)$$

where g is the gravitational acceleration. (4) does not take into account the channel and seabed profile so it yields a rough approximation of U which is typically overestimated.

After the velocity time series based on HNHS data is calculated using (4) the probability density of the velocity and the cumulative distribution for the months October – December 2010 (Fig. 7) are constructed. The distributions are hardly discernible from month to month which is a manifestation of the periodicity and the predictability of the tidal phenomenon.

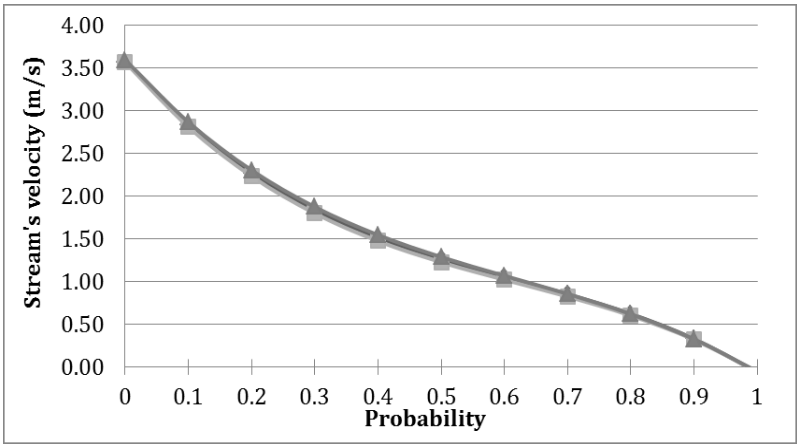


Figure 7: Calculated velocity distributions for October - December 2010

According to the calculations, the probability of velocities over 1m/s is higher than 50% and velocities over 2m/s, which is the minimum operating velocity for existing tidal turbine designs, have a probability of approximately 26%.

In order to compare our calculated velocity distributions based on the HNHS sea level measurements for the period October – December 2010 with the measured HCMR velocity distribution for the period May-June 2010, and test the hypothesis that sea level time series data can be used for the assessment of the tidal current energy potential, we need to calculate the velocity distribution for the months of May-June 2010 based on the sea level data.

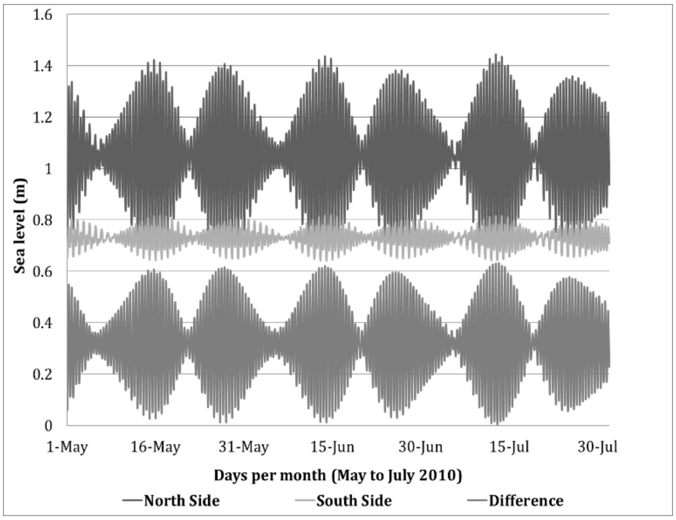


Figure 8: Estimated value of the sea level for the North (top), South (middle) side and their difference (bottom) for May - July 2010.

Harmonic Analysis Method of Least Squares (HAMELS) method (Boon, 2007) was used to construct sea level time series for the period of May-July 2010 and from that calculate the velocity distribution. HAMELS performs harmonic analysis on data, expressing tidal height differences as the summation of harmonic sinusoidal terms, which in our case are the tidal components. The major tidal constituents contributing to the astronomical tide are: M2 - Principal lunar semidiurnal constituent, S2 – Principal solar semidiurnal constituent, N2 - Larger Lunar elliptic semidiurnal constituent, K1 - Luni-solar declinational diurnal constituent, O1 - Lunar declinational diurnal constituent, M4 - First overtide of M2 constituent, M6 - Second overtide of M2 constituent, S4 - First overtide of S2 constituent and MS4 - A compound tide of M2 and S2. An estimate of these constituents can be obtained by HAMELS. Using this method, a set of water level or current observations is processed in order to determine the amplitude and phase of the main tidal constituents of the place under consideration. The complete constituents set is used as a model and is made to “fit” the data according to the least squares criterion, i.e. picking the combination that causes the sum of the squared differences between observed and model-predicted water levels or currents to be as small as possible. The resulting constituents set can then be used to predict the tide at a different time period.

To compute the harmonic components, we use the time series of the maximum and minimum sea level values and their difference. Then, we use these harmonics to estimate the sea level at a different time period, such as May - July 2010 (Fig. 8).

Based on the comparison between sea level, estimated for the same time period, and measured velocity current (Fig. 9), the Euripus’ tidal current seems to be a hydraulic current, in the sense that the current is created by the difference in height of the tides at two locations joined by a waterway (http://co-ops.nos.noaa.gov/faq4.html).

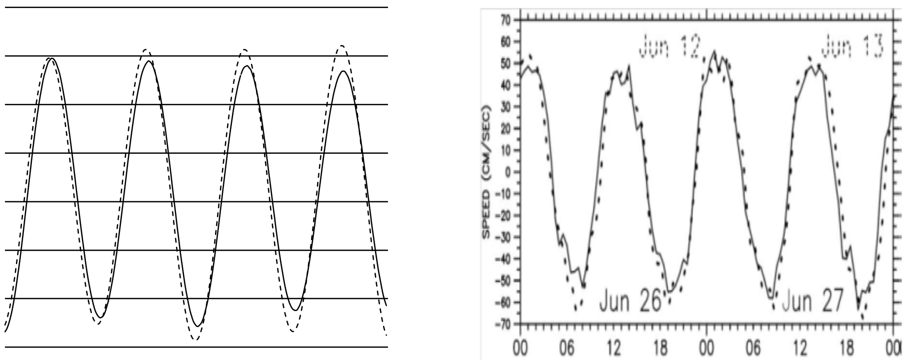


Figure 9: Estimated height differences and measured speed currents and between north and south ports of Evripos bay during June 12-13, 2010 (solid line) and June 26-27, 2010 (dashed line)

Next, we use (4) to compute the current velocity for May – July 2010, extract the velocity distribution for these months and compare it with the measured distribution by HCMR at the North side (Fig. 10). The calculated data are qualitatively comparable with the measured ones but they are shifted towards higher velocities due to the undelying assumptions in (4).

The estimated velocity distribution was used to compute the energy yield of a commercial turbine in Euripus’ channel. The Tocardo BV T2 model was chosen for the calculations because it can operate at velocities as low as 0.25m/s while the span of its blades is appropriate for the size of Euripus’ channel. The specifications of T2 are shown on Fig. 11 and summarized on Table I. Note that according to (3), the lower the stream velocity the higher the cross-sectional area needed and therefore the longer the blades. The turbine is bidirectional which means that it operates for both stream directions and has an optimal operational range between 1.50 and 2.50m/s.

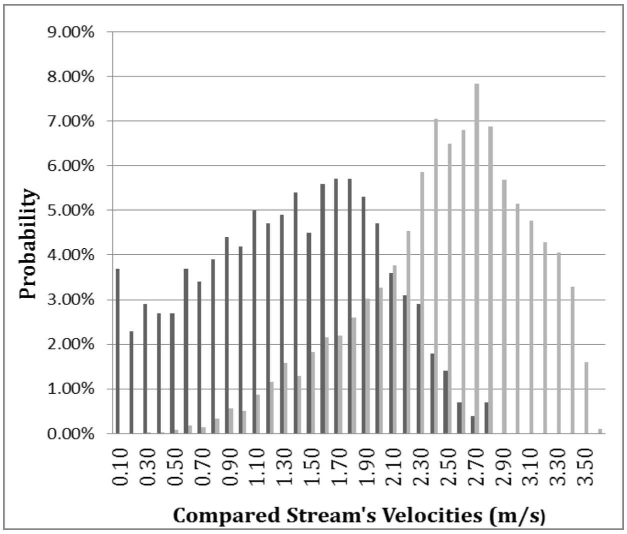


Figure 10: Comparison between recorded (left histogram) and calculated (right histogram) data of the current velocity

The results shown below (Fig. 12 -13) take into consideration the measured velocity distribution for the period May to July 2010 at the Old Bridge location and the data of T2. Fig. 12 shows the output power distribution using T2 at the Old Bridge based on the measured velocities U1…k. For velocities less than 0.25 m/s the T2 model cannot operate and the turbine's output is zero.

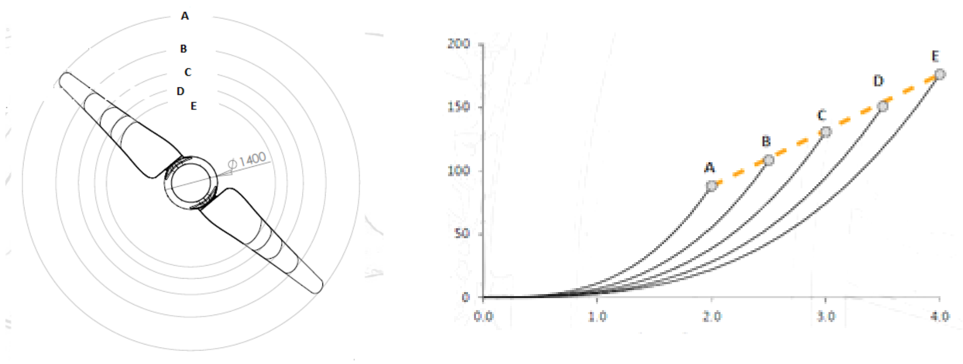
To calculate the energy yield at the Old Bridge using T2, we multiply the output power P as given by the T2 datasheets using the measured velocities with the number of operating hours, t:

$$E_{yield} = \sum_{i=1}^{k} Pt \qquad (5)$$

The expected energy yield exceeds an impressive 90000kWh per year for just one T2 turbine. However, the location at the Old Bridge is one of the narrowest areas of the Gulf, approximately 8 meters wide, which means that is unsafe to install even one T2 turbine which needs at least 7 meters for its optimal operation, even in the case of the smallest blade span (Fig.11) . Such an installation would also create problems to the boat traffic that goes on on a regular basis there. However, in the other locations, the yield is almost 60 times smaller, e.g. at the New Bridge the maximum calculated energy yield is 1475kWh per year because of the smaller velocity of this site. Taking into account that the average consumption of a Greek household, according to the Hellenic Statistical Agency, amounted to 3750kWh for 2012, deploying a T2 turbine at the New Bridge, where the current velocities are low would cover less than 50% of the household's energy demand. However such a turbine could be combined with a RES microgrid, featuring solar panels or wind generators, to enhance the microgrid potential and stable operation given the predictability of the tidal energy. Nevertheless, for such an innovative approach to harnessing tidal energy, new generator low cost designs are needed which will be optimized for operation at lower current velocities.

Table I Tidal turbine T2 data
(http://web.vims.edu/physical/research/TCTutorial/tideanalysis.htm)

POWER OUTPUT	87-200 kW
NUMBER OF BLADES	2
DIAMETER OF BLADES	4.5-9.0 m
CROSS SECTIONAL AREA	15.8-63.7 m^2
ROTATIONAL SPEED	22-45 rpm
ROTATIONAL TYPE	Bidirectional



T200 Blade diameter (m)	A	B	C	D	E
	9,2	7,3	6,1	5,2	4,6

Figure 11: BV T2 specifications

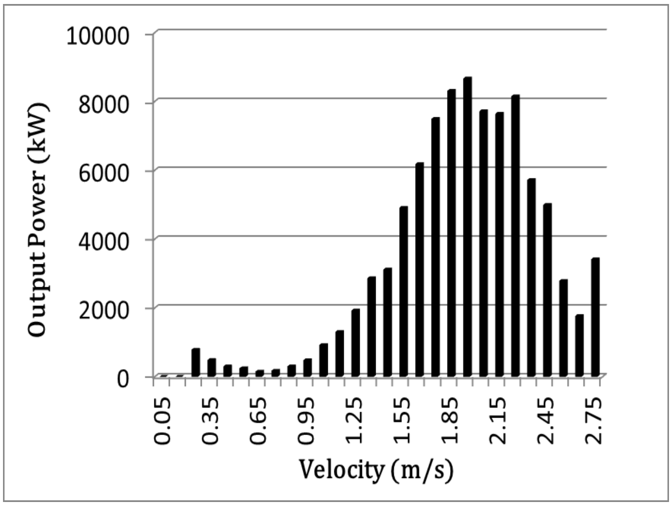


Figure 12: Estimated power production from T2 tidal turbine at the Old Bridge

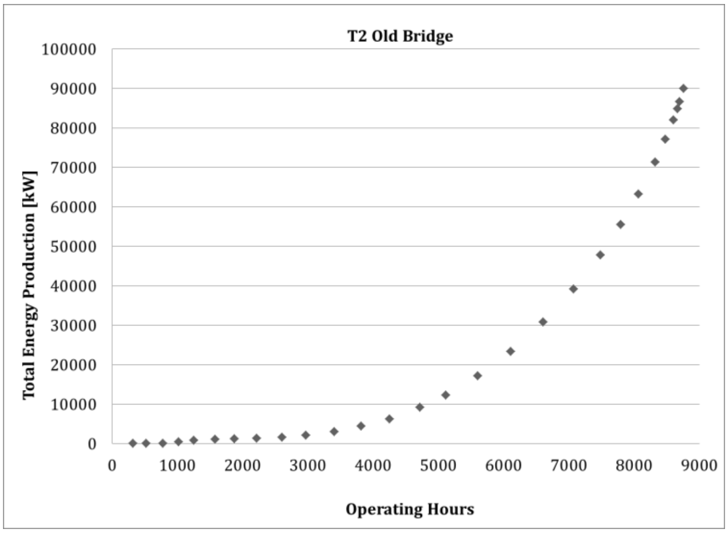


Figure 13: Yearly energy production from one T2 tidal turbine installed at the Old Bridge region

Conclusion

The Euripus's channel tidal energy potential was explored based on existing current velocity and sea level data for three locations near Chalkida, Greece and a commercial tidal turbine design. A harmonic analysis method was used to extract current velocity information from sea level measurements, as the latter are more common in existing databases. It is possible to extract useful information from such an analysis based on existing sea level time series. However, alternative and more accurate methods must be used to convert sea level to stream velocity. The highest energy potential lies, as expected, at the Old Bridge location where installation of a tidal turbine is not possible due to morphological issues and shipping use of the channel there. A small but not insignificant potential exists in other sites, such as the New Bridge. To tap this energy potential, new turbine designs, optimized for operation at velocities around 1 m/s, are desirable. Such a novel design should allow for integration in RES microgrid to exploit fully greatest advantage of the tidal energy, its predictability.

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