A modelling approach for a cost-based evaluation of the energy produced by a marine energy farm

Nicolas Maslov*, Jean-Frédéric Charpentier*, Christophe Claramunt*

Naval Academy Research Institute, 29240 Brest Cedex 9, France

Abstract

The research presented in this paper is part of a project whose aim is to develop a flexible system to help industrials to efficiently install marine energy farms in a suitable area. We introduce a methodology and a decision-aid system for marine farm design. The developed framework will help, for a given marine area, to find the most relevant sites and marine technologies using multi-criteria analysis. The approach is oriented toward marine current energy but this methodology can be extended to others marine energies. Amongst the criteria involved in the decision process, a model is developed to evaluate the quantity of electrical energy produced by the farm, and the cost of the system during its entire lifetime. These two parameters allow us to derive the cost of the produced energy, which is one of the more important criteria to evaluate the economic feasibility of a marine energy project. The energy produced is evaluated taking into account both technological possibilities (turbines technology, generator type, underwater cables, offshore substation etc.) and site characteristics. The cost is estimated thanks to a specific cost model of each component and the farm layout, and also includes a first order evaluation of the installation/dismantling and maintenance costs.

Keywords: Marine energy, Energy cost, Site evaluation, Multi-criteria analysis, Decision tools, GIS

1. Introduction

Oceans constitute an important source of renewable energy which remains today largely untapped. In order to face the increasing demand for energy and the public desire to produce energy with low environmental impact, and also to reduce dependence on fossil energies, the exploitation of marine resources generates a growing interest. In particular, it has been observed that marine renewable energy could make a significant contribution to electricity production [1]. Several kinds of marine converters have been so far proposed for extracting marine energy from wave, tidal current, wind or exploiting thermal and salinity gradient. However, the choice of the best site and technological options for marine energy converters is a complex decision process involving several spatial and technical dimensions which interact to each other. First, the spatial component is closely related to the search of the best implantation site. Sites are chosen principally for their energetic potential and characteristics to accommodate a specific type of systems. Secondly, the selected technologies must also be designed for an optimal exploitation of the available resources, while respecting the constraints of the environment. These constraints come

*Corresponding author
Email address: nicolas.maslov@ecole-navale.fr (Nicolas Maslov)

from different domains and may be contradictory to each other. Therefore, the decision process should integrate these different parameters in a integrated fashion. Accordingly, a decision-aid software might be an appropriate solution to present a set of options and to facilitate expertise between stakeholders (i.e., evaluation of optimal locations, best technology choice and design, farm dimension configuration).

This paper focuses on marine current but can be extended with some minor adaptations to wind turbines. The objective is to present a model for cost and energy which, aggregated to other criteria, will allow us to find an optimal location for a marine converter farm, and to choose the harnessing systems in terms of technology choice, size, power rating and number of machines.

On the one hand, identifying the best location to implement an offshore energy farm can be treated as a geographical problem, Geographic Information Systems (GIS) have been especially designed to solve this kind of problem [2]. On the other hand, constraints coming from the technology side provide quantitative and qualitative inputs and outputs (particularly societal aspects). The combination of GIS and multi-criteria analysis should help the users to evaluate various alternatives taking into account multiple and conflicting criteria and objectives [3]. The objective is to establish a methodology to elaborate such a reasoning framework. Overall, the approach will provide a complete decision-aid process (Figure 1). The first step of the approach presented in this paper is to introduce the two criteria used to estimate energy costs. These two criteria are integrated in a complex decision process tool which includes geographical constraints [4]. In the present paper, the focus is drawn to the methodology rather than consideration of all technologies, this being limited regarding the availability of tidal turbine data. The developed system should be modular. The energy-and cost-based model derived suggested in the next sections considers the most relevant parameters, but the final user will be free to adjust, remove or to add additional parameters. The marine converter farm planning approach is taken up at a "macro-level" view, this is the reason behind the choice of an accuracy degree the most suitable.

The reminder of the paper is organised as follow. Section 2 presents the methodology and a brief presentation of the criteria used for the marine converter farm planning decision-aid tool. Section 3 develops the models used for estimating: 1) the energy produced for given time periods and locations according to the converter type (design and technical solutions), and 2) the global cost of the project including the farm cost and the cost of installation/dismantling and maintenance operation. These estimation models integrate different components from current research. The different measures used are adapted to our global approach [5–7]. A case study will finally illustrate the energy model and the way it can be applied to different technologies in section 4. Finally section 5 summarizes our work and outlines further work.

2. Methodology

Many works have been developed so far for wind and tidal turbine technological choice, design and optimization [8–11]. These works mainly address the problem of extracting the maximum energy available and the reduction of global losses. Solving this problem leads to optimize the design of each part of the energy chain, and also to evaluate the impacts of the technologies used. Many technological options can be applied to the design an energy chain. For tidal energy (as wind energy), two types of turbines can be used: horizontal or vertical axis systems. The number of blades [12], blade shape [13, 14] and the presence of pitch and yaw systems are possible options for turbine design. Regarding the drive train, the use of gearbox or the use of direct driven systems are possible choices. For the generator, induction (squirrel cage or double fed) or synchronous generator (PM or wound rotor) can be used. There are also several possible options in terms of power electronic and variable speed control [15]. The combination of the possible technology choices in the different parts of the whole energy chain increases the number

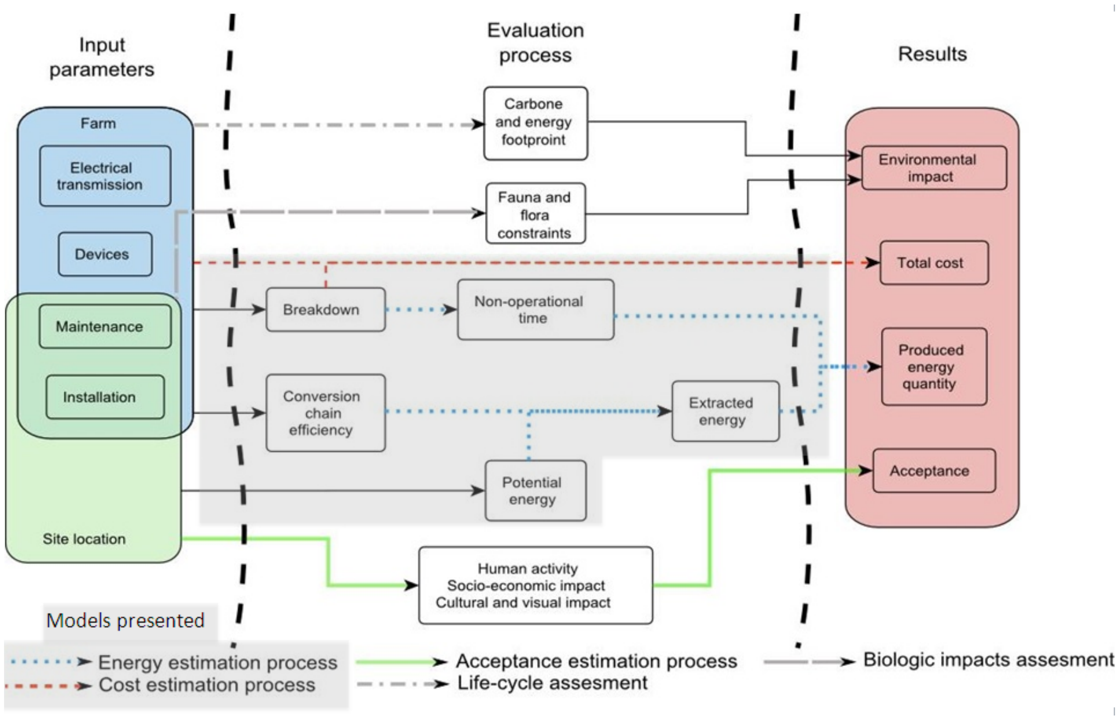

Figure 1: Global Multicriteria approach where the models will be inserted

of technological possibilities. It can be noticed that all these combinations are not possible (as an example it is practically not possible to design a system associating an induction generator without a gearbox). Hence, various models of optimization have been proposed [16–18] for wind turbine in order to optimize the design of the systems in terms of compromise between investment cost and energy production. An important issue in energetic project planning is the cost of the energy (CoE), it can be calculated as adapted from [5]:

$$CoE = \frac{TC}{\sum_{i=1}^{n_y} AEP_{net}} \tag{1}$$

where AEP_{net} is the Annual Energy Production, TC is the total cost including converters, installation\dismanteling and annual operating expenses (maintenance, land lease cost, etc.), i denotes to the number of years (commonly life-span of $n_y = 20$ years is considered for wind turbine).

Two models have been developed to determine the cost of energy (CoE), one for energy assessment and one for cost estimation. The evaluation of the produced energy is derived from a resource model (that depends on the site location), a performance model (performance of each component of the conversion chain) and an estimation of the operational time of the system (based on the downtime statistical rates of each component). On the other side, the estimation of the global cost of the project includes two kinds of expenses. The first one is related to the farm cost. This cost evaluation is specific to the devices (technology used, number of machines, converter design, electrical transmission). The second one is related to the farm geographic location (installation/dismantling and maintenance operations costs) which depends on several parameters such as depth, nature of seafloor, distance from ports and networks). The number and nature of maintenance operations also depend on a statistically evaluated failure data of the components. These two models are developed in the next sections.

3. Produced energy by a marine current turbine

The process that estimates the amount of produced electricity depends on three components: the available resources, performance of the extracting system (which depends on technology and control) and running time of the system. Regarding these technical performances, the principal components taken into account are the turbine, gearbox (which is not used in direct drive systems), generator, associated power converter and the transmission elements (substation-line, etc.) (Figure 2).

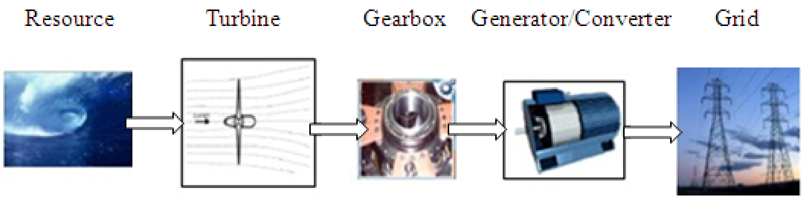

Figure 2: Marine converter global schema

The evaluation of the total extracted energy, E_{te}, follows the model described by the scheme illustrated in Figure 3. This section is organised according to the different steps of this process:

1. Evaluation of the potentially harnessed resource (box 1 in Figure 2): the resources distribution (direction and velocity) is based on a tidal coefficient model developed by the SHOM (French National Hydrography and Oceanographic Service) which is used to estimate the amount of energy that can be extracted in a given area. This model allows us to predict the number of hours corresponding to each amplitude and direction of the tidal current for the whole lifetime of the turbine.

2. The model takes into account the turbine fluid mechanics model. It integrates the turbine characteristics (box 2,3 and 4 in Figure 2) as follows:
   - effect of yaw in hydrodynamic performance: an attenuation coefficient is introduced to take into account the difference of orientation between the turbine axis and the fluid direction for each considered elementary period (for fixed orientation turbines).
   - control strategy which depends on the fluid velocity and the turbine components characteristics

3. The components behaviour influences the harnessed mechanical energy. The components behaviour is characterized by (box 5 in Figure 2):
   - a statistical downtime rate (which allows to have an estimation of the system operating time)
   - their efficiency (which allows to derive the global efficiency of the system)

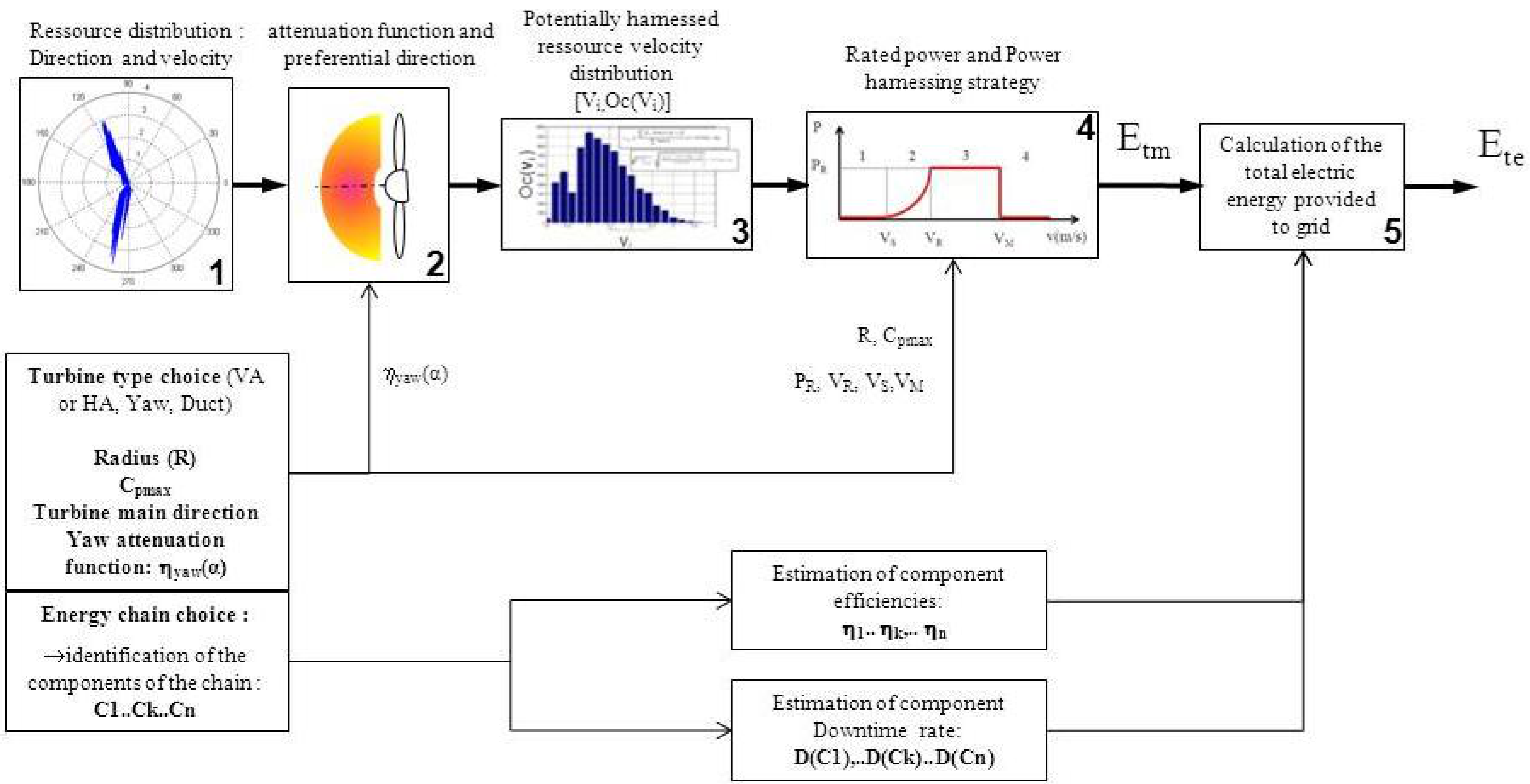

Figure 3: General scheme of the electrical energy calculation model

3.1. Potentially harnessed resource (box 1 of Figure 2)

Thanks to their astronomical origin, tidal current velocities are predictable with an accuracy of 98% for decades at first order (without considering the possible perturbation related to sea states). The resource model used is the one proposed by the SHOM in [19], a model that has been developed for the specific case of the Atlantic French coast. It has been used in [20] to predict the performance of a marine turbine. The current velocity vector, $\boldsymbol{V_{tide}(h)}$ can be determined for each tidal hour of each tidal cycle characterized by a tidal coefficient, C. The value and direction at each time can be interpolated. This interpolation is based on the known values of tidal current velocities vectors for each tidal hour, h, for the average tidal coefficient for spring tides ($C = 95$), $\boldsymbol{V_{st}(h)}$, and for the average coefficient for neap tides ($C = 45$), $\boldsymbol{V_{nt}(h)}$. The values of $\boldsymbol{V_{nt}}$ and $\boldsymbol{V_{st}}$ are given in tidal current charts for each location. Overall, the vector corresponding to a given tidal cycle coefficient, C, for the tidal hour, h, can be calculated as follows:

$$\boldsymbol{V_{tide}(h)} = \boldsymbol{V_{nt}(h)} + \frac{(C-45)(\boldsymbol{V_{st}(h)} - \boldsymbol{V_{nt}(h)})}{95-45} \tag{2}$$

Equation (2) derives the fluid and direction velocity in one place for any hour. As an example Figure 4 from [20, 21] shows the evolution of the current speed value during one month and one year in a location situated in Raz de Sein in North West France.

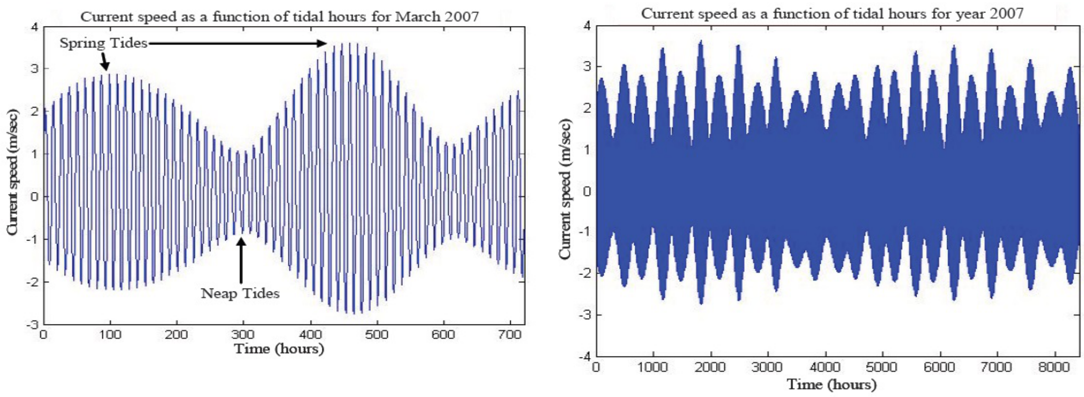

Figure 4: Tidal velocity in the Raz de Sein (Brittany-France) for March 2007 and along the year 2007

For each location, assuming flow velocity (at neap and spring tides) and a tidal coefficient, it is also possible to represent the current ellipse representing the directions of current velocities for each tide hour. The current direction is important to qualify the capacity of some devices to harness the kinetic energy. In fact, if currents are not always oriented along the turbine axis, the extraction of energy may be sometimes limited. In a marine turbine context, horizontal axis turbines are often used without yaw systems to limit maintenance operations [22]. Therefore, they cannot extract efficiently the energy when the current is oriented with a too large difference of direction regarding to the turbine axis. Moreover, one can remark that some blades profile used in turbines can have a different power coefficient depending of the way the stream goes through the turbine (asymmetric blades). Overall, this kind of turbine has a preferred direction to extract the energy.

In some cases, horizontal axis marine current turbines can be surrounded by a duct. Here, the stream is accelerated so a turbine with a smaller diameter can be used for a given power, or otherwise, and for a given diameter, a larger amount of power can be extracted by the turbine. In this case, the level of power is dictated by the duct entrance diameter [22]. Furthermore, with an optimized design, the duct extracts efficiently the energy from the stream with a deviation depending on the duct aperture.

On the other hand, vertical axis turbines can receive the kinetic energy of the water perpendicular to its rotation axis. However, these turbines have lower power coefficients than horizontal axis turbines. In a location where the current directions are strongly disaligned with a main direction, their lower power coefficient can be compensated by the fact that these turbines can extract efficiently energy from all directions of currents. Depending on the location, the current can statically deviate more or less from a main direction. This means that some machines are therefore more suitable than others to capture the energy as a function of the site location.

Using the model previously introduced in eq(2), one can calculate the distribution of the equivalent velocity in time along a given orientation (this includes a yaw attenuation which depends on technology choice). This statistical distribution corresponds to the resource which can be practically harnessed by a healthy given system. Figure 5 gives an example of the current velocity distribution along a preferential direction in the Raz de Sein in Brittany for a 703 days period.

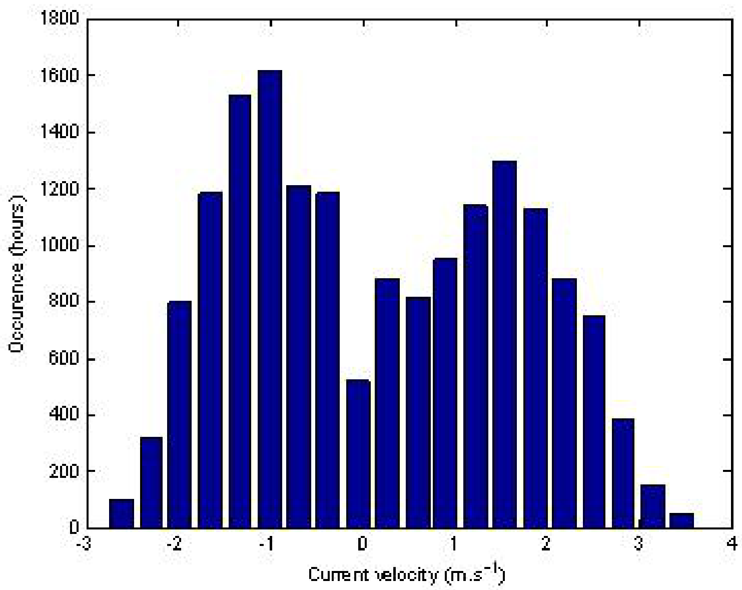

Figure 5: Current distribution

3.2. Turbine fluid mechanics model

3.2.1. Global hydrodynamic behaviour (box 2, 3 and 4)

As for wind, the tidal current turbine kinetic power density in one place and at one time can be calculated from the kinetic power density of fluid mass moving through an elementary section (1 m^2), and it is given by:

$$p = \frac{1}{2}\rho {V_f}^3 \tag{3}$$

where ρ denotes the fluid mass density (kg.m^{-3}), V_f the velocity of the fluid (m.s^{-1}). This power density is given by surface section unit and can be expressed in W/m^2

Whatever the type of turbine used, the power extracted is a part of the kinetic power which crosses the area, A (m^2) swept by the turbine blades and that can be calculated as follows:

$$P_t = \frac{1}{2}\rho A C_p {V_f}^3 \tag{4}$$

where C_p is the power coefficient of the turbine.

C_p values depend of the design of the turbine (horizontal or vertical axis, and the number of blades, blades shapes). C_p curves can be established using several simulations or tests at various fluid speeds and various rotating speeds [23]. For a given turbine design, the C_p function depends mainly on two parameters: β, the pitch angle and λ, the tip speed ratio (TSR) defined by:

$$\lambda = \frac{\Omega_t R}{V_f} \tag{5}$$

Figure 6 gives an example of C_p curves as a function of the TSR and the pitch angle for a given horizontal axis tidal turbine [20].

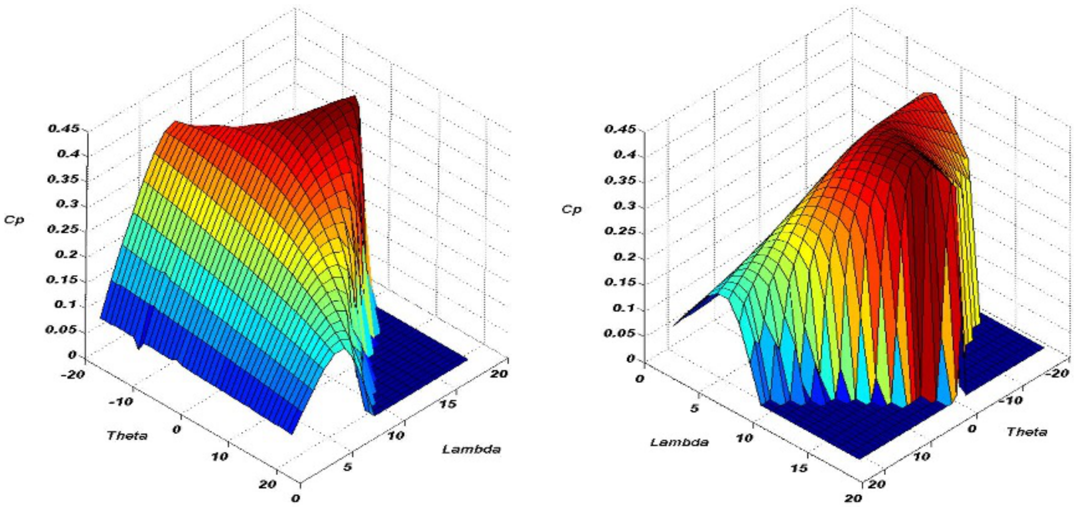

Figure 6: Power coefficient functions [20]

The maximal value of C_p is theoretically limited by the Betz Law to 16/27≈0.59. In a practical case, the maximal value of C_p for a given turbine geometry is often in the [0.4, 0.5] range depending of the turbine technology and design. For example, the horizontal axis turbine has a better C_p (typical maximal value around 0.5) than vertical axis Darrieus Turbine with a maximal value around 0.4, [24]. Table 1 presents a summary of the different technologies that can be used and the corresponding ranges of maximal value of C_p (according to [12]), C_{pmax}, and yaw attenuation.

Table 1: Cp and capture angle values proposed for different turbine technologies

	Turbine			
	Horizontal axis			Vertical axis
	With Yaw	Without yaw		
		No ducted	Ducted	
yaw attenuation	no attenuation	attenuation	attenuation up to duct aperture	no attenuation
C_{pmax}	0.46	0.46	0.5	0.40

3.2.2. Effect of yaw in hydrodynamic performance (yaw attenuation, box 2)

In an horizontal axis systems, the yaw angle (deviation between the flow and axis directions) has also a strong effect on rotor performance as shown in figure 7 from [25]. In order to model this effect a coefficient of attenuation, $\eta_{yaw}(\alpha)$, can be introduced in the calculated power, depending on the yaw angle. This attenuation function can be modelled as suggested in [6]:

$$P = \frac{1}{2}\rho\ \eta_{yaw} A C_p {V_f}^3 \text{ with } \eta_{yaw} = cos^3(\alpha) \tag{6}$$

This attenuation in terms of power corresponds to an equivalent fluid velocity, V_{eq}, along the turbine axis.

$$V_{eq} = V_f cos(\alpha) \tag{7}$$

This attenuation will be used for tidal turbines with a fixed orientation.

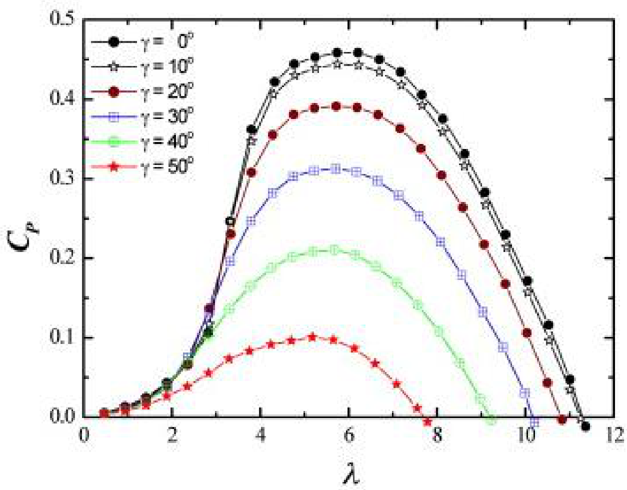

Figure 7: Yaw angle effect on the power coefficient of an horizontal axis turbine from [25]

3.2.3. Operating curve (box 4)

The typical operating curve of a wind or current turbine is shown by Figure 8. This curve can be divided in four sections [26]. The design of the tidal turbine energy chain is mainly defined for a nominal fluid speed V_R.

- Zone 1: the fluid speed is below the starting speed of the fluid V_S. The turbine does not work because the turbine does not produce sufficient energy to compensate the system losses.

- Zone 2: the fluid speed is between the speed V_S and rated speed V_R. Accordingly, the extracted power is maximized controlling the speed (torque), using the generator power electronics drive, and eventually pitch control. These controls are used to maintain the system in its maximal power point (which corresponds to the maximal value of C_{pmax}). This control strategy is called Maximal Power Point Tracking Strategy (MPPT). Therefore, the energy model developed in this paper considers that the mechanical power extracted by the turbine in this area is given by:

$$P = \frac{1}{2}\rho C_{pmax} A V^3 \tag{8}$$

- Zone 3: the fluid velocity reaches the value, V_R, corresponding to the system power rating in the MPPT strategy, P_R. Beyond this rated fluid speed, the cost of the extra sizing of the generator and structure would not be recovered by a production increase. The C_p value must be controlled to limit the mechanical power. Two types of regulation can be used [27]. The C_p value can be adjusted by a control of the turbine speed or a pitch control or by a combination of the two control systems. The pitch control is the preferred option for large wind turbines. However, in the case of marine turbines, pitch control is sometimes eliminated to reduce the maintenance constraints and to increase robustness. Accordingly, the power should be limited using speed control only [28]. For the developed energy model, let us consider that the extracted mechanical power is equal to $P = P_R$ when the value of the fluid velocity is greater than V_R.

- Zone 4: this corresponds to the area where the fluid speed exceeds the maximum speed permissible by the system. Above this speed, it is preferable to stop the turbine to reduce the risk of damage and the turbine does not produce energy.

Regarding the operating conditions corresponding to zone 2 and zone 3, a variable speed system is needed. Power electronic drives are used for variable speed turbine control in both tidal and wind systems. They allow the adjustment of the generator electrical frequency and voltage to the grid. The advantage of using power electronics is to harness the optimal energy and to control precisely the extracted power and the turbine speed. However, extra costs and additional losses are associated to these electronics drives [27].

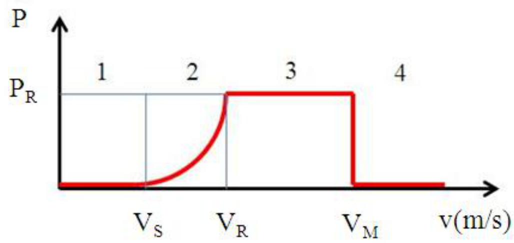

Figure 8: Power curve model

3.3. System technical characteristics (box 4 and 5)

The estimation of the total extracted energy, E_{te}, is based on the knowledge of the behaviour and efficiencies and the downtime statistical rates of each component and the available resource data. Two inputs can be observed. The first one is the statistical fluid velocity data (values and direction) and the second one is the chosen technological options.

System sizing is characterized by a technology choice (turbine/generator/converter type) which allows to determine the corresponding value of C_{pmax}, a geometrical sizing of the turbine (which allows to determine the cross area, A), and a power sizing of the converter and generator set (which allows to determine V_R, V_M and corresponding power P_R).

Regarding the power curve model (box 4), it appears that the values C_{pmax}, V_S, V_R, V_M and P_R are sufficient to determine the extracted power, $P_m(V_i)$, which can be mechanically extracted by an healthy turbine for each value of the fluid velocity, V_i, in the identified potentially harnessed resource distribution range. V_i is the corrected value of the fluid velocity taking into account the yaw effect(yaw attenuation in case of fixed orientation turbine)

Considering this potentially harnessed resource distribution (i.e. the number of hours corresponding to each velocity in the lifetime of the system, $Oc(V_i)$), it is possible to evaluate the total amount of mechanical energy, E_{tm}, which can be extracted by an healthy given turbine in a given site:

$$E_{tm} = \sum_{i=1}^{n} Pm(Vi).Oc(Vi) \tag{9}$$

This energy is given in Watt.hour (W.h).

In order to evaluate the real electrical energy, E_{te}, provided to the grid it is necessary to integrate, in this equation, for each of the different component, C_i with $i \in [1, k]$, of the energy chain, an efficiency estimation $\eta(C_i)$ and the relative downtime rate $D(C_i)$ (downtime relative time reported to the life time of the system). This statistical failure rate depends on the considered component technology and the accessibility of the system (capacity of maintenance intervention in situ). The efficiencies are related to the specific behaviour of each component.

$$E_{te} = \left(1 - \sum_{i=1}^{k} D_i(C_i)\right) \Pi_{i=1}^{k} \eta_i(Ci) E_{tm} \tag{10}$$

3.4. Downtime rate evaluation

The failure rate is calculated by a statistic analysis of each component during several years of operation. This evaluation is essential to estimate the operational time of the turbine in order to estimate the annual produced energy. As an example, table 2 from [29] presents the statistic downtimes related to each component of classical onshore wind turbines. The value of $D(C_k)$ can be extracted from such statistical data. The failure rate varies from a country to another, and the rates tend to increase with the size of the turbine and the access difficulties. Two parameters are relevant for each component for downtime estimation: the number of failures during the life cycle and the downtime to repair or replace each component after its failure (including repair delays, spare-holding and component availability).

These statistics show that eliminating components as gearbox, yaw or pitch systems generate significant reductions of global system downtime, and an increase of the extracted energy.

Table 2: Downtimes and failure frequencies for components in Swedish wind power plants 2000-2004 from [29]

Composant	Average number of failures per year per turbine	Average downtime per failure in hours	Non-operational time per year per turbine (h)
Structure	0.006	104.1	0.6246
Yaw system	0.026	259.4	6.7444
Hydraulics	0.061	43.2	2.6352
Mechanical brakes	0.005	125.4	0.6270
Gears	0.045	256.7	11.5515
Sensors	0.054	49.4	2.6676
Drive train	0.004	291.4	1.1656
Control system	0.050	184.6	9.23
Electric system	0.067	106.6	7.1422
Generator	0.021	210.7	4.4247
Blade/pitch	0.052	91.6	4.7632
Hub	0.001	12.5	0.0125
Total			51.5885
No gear PMSG	0.001	100	0.1
Total			40.137

Moreover, the gearbox has been identified has one of the most critical component due to its high rate of failure and the time needed to repair it (this component is responsible of 22.4% of the total downtime in the case of Swedish onshore wind farms) [30]. This explains the interest of using direct drive technologies to minimize the number of interventions in an offshore and tidal context.

3.5. Efficiency estimation of each component

The efficiency of each component, as a function of the operating point, can be found in technical data sheets of the component builders. The main components that take part in the global efficiency of the conversion chain are the gearbox, generator, converters, transformers, and cables. The knowledge of the components efficiencies allow the computation of the produced energy. The gearbox and the generator are the principal components influencing the drive train possible configuration. When considering the case of the Double Fed Induction Generator (DFIG) and the Permanent Magnet Synchronous Generator (PMSG), this leads to three different solutions and then to three drive train efficiencies. The consideration of the pitch system in the energy extraction strategy broadens the set of solution to the four configurations, which are considered in our study. Indeed, other associations can be found as DFIG with one stage gearbox for instance but in our methodology the configurations included depend on the availability of data which have been found in the literature.

The studied configuration with a pitch system are as follows:

- Configuration 1: 3-stage gearbox + DFIG,
- Configuration 2: 1-stage gearbox + PMSG,
- Configuration 3: Direct Drive + PMSG.

Configuration without a pitch system are as follows:

Table 3: Drive train efficiency components from [32]

Rated power(%)	Baseline generator Efficiency	DD generator (PM) Efficiency	Power Converter Efficiency	Baseline Gear Efficiency	Single Stage Gear Efficiency
100	94.8	94.9	96.8	97.5	98.6
75	94.9	95.8	97.0	97.2	98.4
50	**93.7**	**96.5**	**97.3**	**97.0**	**98.2**
20	90.5	96.3	97.1	96.1	97.4
6	85.0	93	90.8	88.7	91.3

Table 4: Drive train comparaison from [**?**]

Generator	DFIG 3GB	PMSG 1GB	PMSG DD
Mass	+	+	-
Cost	++	+	-
EYR	-	-	++

EYR: Energy Yield and Reliability
+ Advantage; - Disadvantage

- Configuration 4: Direct Drive + PMSG.

The drive train efficiency can be estimated using the main components listed in Table 3. In the particular case of the DFIG design; the power converter efficiency affects only 33% of the extracted power. Indeed, we consider an operating point where around 1/3 of the power comes through the converter and the 2/3 remaining is transmitted directly by the generator to the electric grid (the converter need only to be rated at around 1/3 of full rated power as explained in [31]). It can be also noticed that this model considers that the efficiency of each component does not vary with the operating conditions in a first approximation and correspond to a point at 50% of the rated power. These efficiencies values are given in bold in Table 3.

In a context of maximization of the produced energy, the direct drive PMSG solution is clearly a relevant compromise in term of reliability and efficiency comparing to the geared configurations. However, DFIG is the most lightweight and low cost solution. Concerning the PMSG with 1-stage gearbox, this solution presents one of the best ratios of the annual energy yield cost [33]. A qualitative comparison of the different drive train configurations is shown in Table 4.

4. Marine farm system cost

4.1. Initial cost

An offshore tidal turbine farm should include the following elements: a set of wind turbines and their foundations, a transformer station located at sea or on land (depending on the distance to the coast and the total power of the farm), a network of submarine inter-turbines cables (buried or not depending on the seafloor type), a network of submarine cables for transmitting energy from the offshore substation to the shore station and a connection cable to the electric distribution grid (Figure 9). This configuration is similar to an offshore wind turbine farm.

The global cost of the system is characterized by two models, the first one is the farm cost and the second deals with maintenance operations. The cost evaluation is not an easy problem because the price of each component depends on manufacturers and fluctuates with the

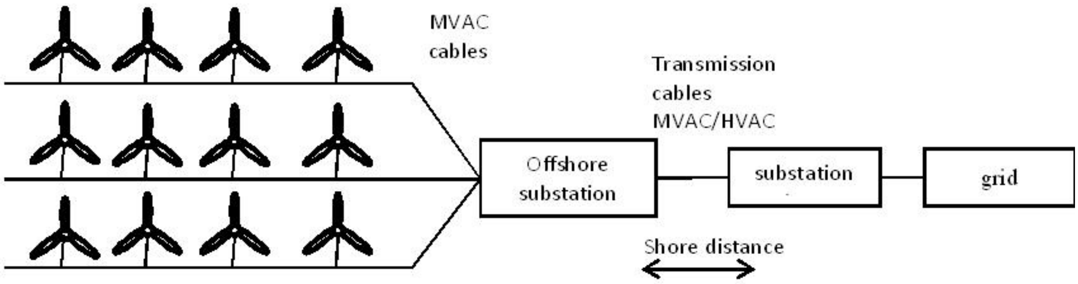

Figure 9: Wind turbine farm layout

market economy. The cost of the farm includes turbines, (blades, generators, converters...), inter-turbines and underwater cables (this cost, C_{cable}, depend on the farm configuration and the distance to the network), offshore substations rating (based on total farm capacity) and installation.

The cost of the global farm including n turbines can be therefore approximated roughly as follows:

$$C_{farm} = n.C_{turbine} + n.C_{foundation} + C_{installation}(n, P_R) + C_{cable}(n, P_R) + C_{offshoresubstation}(n, P_R) \tag{11}$$

4.1.1. Turbine cost

The turbine cost can be, for example, estimated through a component model such as the one presented in [5]. This kind of estimation can be performed using the systems component type and characteristics. A preliminary calculation of the cost of each component according to their mass, power rating or volumes can be evaluated.

Then, if a turbine is composed by k component the turbine cost, $C_{turbine}$ can be determined as follows:

$$C_{turbine} = n \sum_{i=1}^{k} C^i_{component} \tag{12}$$

4.1.2. Foundation cost

The cost of the foundations (construction and installation) represents from 20% to 25% of an offshore wind turbine project cost [34]. The water depth has a strong impact on the foundation type structure and the geology also affects the choice of the foundation. In the first instance, each depth range can be associated roughly to a respective foundation type. Gravity or monopole is for example used for shallow water, tripod or jacket structure for intermediate water and floating structure for high depth. An estimation of the cost including the water depth in main input parameter can be done in first order. These foundation costs can be approximated as in [35] for wind turbines:

- 0-30 m $Cost_{foundation}/MW = 0.15 + 10^{-5}\ depth^3$

- 30-60 m $Cost_{foundation}/MW = 0.35 + 4\ 10^{-5}\ depth^3$
- >60 m m $Cost_{foundation}/MW = 0.15 + 0.016\ depth$

These costs are given in billion euros per installed MW.

However, experiences derived from the offshore oil industry clearly show that the foundation cost is conditioned by many other factors such as oceanographic and meteorological conditions, local geology, proximity to industrial harbours, and availability of the specific logistic necessary installation. Some of these factors are taken into consideration in the next section, that is, the installation and extrapolations that have been performed for the marine current turbine case.

4.2. Installation/Dismantling cost

As mentioned previously, several factors such as the proximity of equipped harbours affect the cost of the project. The installation cost mainly depends on the necessary time needed to realize the implementation of all turbines in the farm. This cost depends on the harbour distance but also on transportation means and their storage capacity which influences the installation time. A preliminary evaluation methodology of this cost integrating the location parameter, distance to port D_{port}, and the type of transport is given by [35] for wind turbines wind farms and will be used for tidal turbine farms as follows:

$$C_{transport\&installation} = \frac{N_{WT}}{N_{WT/Vessel}} \left(\frac{2\ D_{port}}{V_{vessel}} + t_{load} \right) C_t + N_{WT} \left(t_i + t_{prep} \right) C_i + C_{vessel} C_{mob} \quad (13)$$

With N_{WT}, N_{Vessel} and $N_{WT/Nvessel}$ denote respectively the number of turbines, number of vessels used for transportation, and vessel capacity (in number of transported turbines). C_t, C_i and C_{mob} denote respectively the daily cost of transport and installation and the mobilization cost of each vessel. t_{load}, t_i and t_{prep} denote respectively the loading time of each structure, installation time and preparation time for the installation.

Weather conditions can strongly impact installation and maintenance operations. These operating conditions depend on the state and wind level, and accessibility to the system. Offshore operations are typically not carried beyond to a wind speed of 12 m/s and a wave height of 2 m [7]. The decommissioning operations of marine energy systems are other sources of expenses to be taken into consideration. Indeed, the question of the end life of a farm is a constraint to integrate from legal and technical points of view. The dismantling operation may be considered as an inverse process of the the installation operations and will be subject of similar constraints [36]. In our current work, the decommissioning cost is calculated as in [37] where it is estimated at roughly half of installation costs.

4.3. Maintenance operation (box 5)

Maintenance operations can be divided in two categories: preventive maintenance and corrective maintenance [38]. Preventive maintenance includes the planned operation due to the specificity of the elements of the system (fatigue, wear, corrosion, and erosion). This kind of maintenance is principally fixed to decrease the probability of failure or to provide necessary operations. It may also include the following operations: inspection, adjustments, lubrication, etc. The preventive maintenance cost (C_{pm}) can be calculated as follows:

$$C_{pm} = n_m.C_m \tag{14}$$

where n_m is the number of planned maintenance during the life time and C_m the cost of each intervention.

Basically, for the preventive maintenance of the drive train of a wind turbine, a two-person crew performing twice 8-hour per day is scheduled twice a year [39]. The cost of these operations depends on the access capabilities to the machine which is a key feature in offshore and underwater systems. This is why some projects propose some specific systems to facilitate maintenance operations particularly in marine turbine contexts. For example, MCT Seagen Technology proposes a system to raise the turbine over the water surface [40]. Accordingly, the majority of maintenance can be carried out of the water and the cost of maintenance operations are probably of the same order than in the case of an offshore wind turbine.

Conversely, corrective maintenance refers to non-scheduled interventions. The main purpose is to repair failed items. This kind of maintenance operations can be also an opportunity to carry out preventive maintenance on other systems. In order to estimate the cost of corrective maintenance (C_{cm}), the knowledge of the probability of failure of each component should be considered. This probabilistic data is not easy to evaluate due to the non-disclosure of manufacturer data. It can also be noticed that these data depend on the environment (temperature, corrosion, etc.) and also of the preventive maintenance frequency for each component.

The cost of the interventions can be estimated according to the failure importance. The interventions for repairing the damaged material is divided into four categories according to the failure importance:

- 1^{st} category: total replacement of a bulky piece as the rotor and the generator container, need of external crane or specific high power winch (for current turbine),
- 2^{nd} category: replacement of large piece, need of internal crane or winch,
- 3^{rd} category: medium reparation,
- 4^{th} category: small repair and general maintenance.

$$C_{cm} = \sum_{i=1}^{2} \left(\sum_{k=1}^{n_{comp}} Pf(k).C(i,k) + C_r(k) \right) + \sum_{i=3}^{4} \left(\sum_{k=1}^{n_{comp}} (Pf(k,i).C(i,k) \right) \tag{15}$$

In order to estimate the corrective maintenance, a probability of failure rate and needed intervention level is assigned to each component failure. The failure probability of the component k of needing an level i intervention, $Pf(k,i)$, is an average failure rate in the system life derived from statistical data. A cost corresponding to each failure category is estimated considering the average time to repair, associated parts, labour cost and logistical equipment to use. In the case of a replacement of the component, the extra cost of the new component, $C_r(k)$ is added (case 1 and case 2). For the time being, data related to intervention constraints and durations can be found only for offshore wind turbine context. In the case of marine turbines where systems are less easy to access these data have to be adjusted to the corresponding technology and environment constraints. For a wind turbine context, the first and second categories (cases of the most serious failures) represent around 1% of interventions in which heavy logistical means are necessary (crane, barge, high power winches ...). For these two first cases the estimated repair time is about 40 hours with the presence of four technicians. The third and fourth categories represent 34% and 65% of interventions, respectively. This requires conventional logistical means (ship or helicopter). The intervention duration is about ten hours for the third category and three hours for the fourth category with the presence of only two technicians in both cases [7].

5. Energy calculation case study

In order to illustrate the pertinence of our approach, let us introduce the case study. The marine energy production potential is determined for two sites in "Raz de Sein" area in Brittany France. This area and the location of the sites are presented in Figure 10. The energy potential of these two sites is derived as a function of the technology. The "Raz de Sein" is is a well-known area for its strong tidal currents. This area is considered as one of the most promising places for marine current turbine implantation. The two chosen experimental sites are characterized by two different current configurations (Figure 11). In these two sites, the methodology previously established to estimate the energy produced is applied for two types of turbine (an horizontal axis turbine without yaw and without duct and a vertical axis Darrieus type turbine).

Figure 10: Raz de Sein area and locations where current velocity is > 1 $m.s^{-1}$ for 30%, 40%, 50% and 60% of the time

Figure 11 shows the ellipse current of the two sites during a full year. The first site presents a bigger current ellipse asymmetry than the second one. For the two sites, the amount of energy collected, and the corresponding average power is calculated for vertical axis turbine (VA) and horizontal axis turbine (HA) cases. Firstly, a theoretical ideal turbine (C_p=0.59, operating at Betz limit) in all the directions)is considered as a reference. In this theoretical case, the asymmetric flow site has a potential energy of 1.33 10^7 W h/year/m^2 and the second site 1.18 10^7 W h/year/m^2. More details on the both site energetic potential can be found in Table 5. Note that power at flood and ebb are significant in both cases. Therefore, a reversible turbine seems relevant in this case.

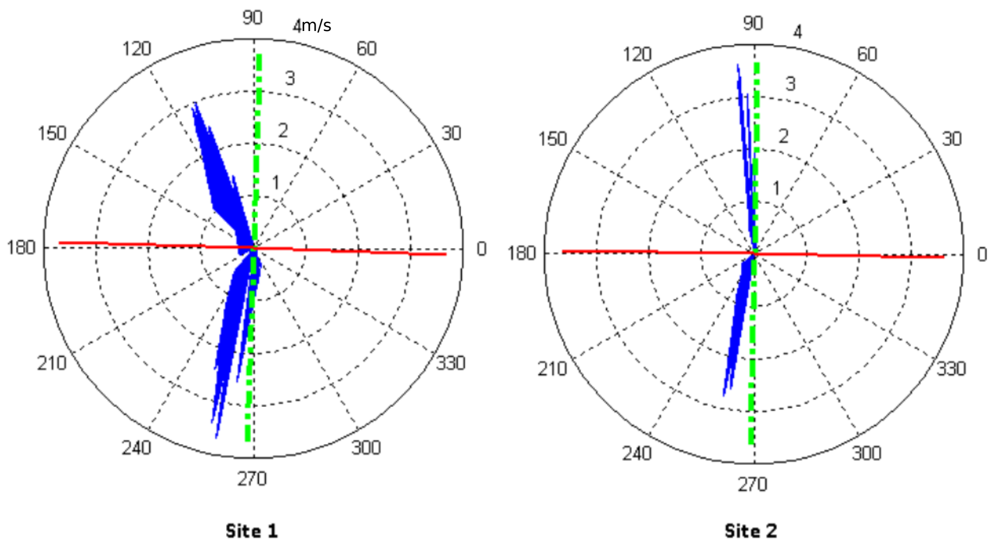

Figure 11: Current ellipses and HA preferred orientation for two Raz de Sein sites (1 year velocity vectors)

Table 5: Energetic potential of two Raz de Sein sites by m^2 (C_p=0.59)

	Site 1	Site 2
P_{mean} (W)	1.57 10^3	1.40 10^3
P_{max} (W)	1.53 10^4	1.47 10^4
E_{flood} (W.h/year)	5.86 10^6	8.30 10^6
E_{ebb} (W.h/year)	7.39 10^6	3.47 10^6
Total (W.h/year)	13.25 10^6	11.77 10^6

In order to exploit the potential of both sites, 500 kW marine current turbines with a swept area of 113.1 m^2 are considered(this area corresponds for example to a 12 m diameter HA turbine or a VA turbine with 10 diameter and 11.31 m length). Two kinds of turbine with the same section are tested at both sites, one with an horizontal axis and the other one with an vertical axis. The specific parameters used for these turbines are illustrated in Table 1. Table 6 shows the characteristics and the energy produced for both sites and the two turbines during one year. In both cases, the HA turbine with a fixed orientation produces more energy than the VA turbine (around 11% and 13% high for the site 1 and 2 respectively). These results show why the industrial projects are now mainly focus on HA turbine technologies. However, in the case of an higher asymmetrical or a more circular distribution a VA turbine could produce more energy. Regarding site 1, it has been also observed that if the turbine swept area decreases (for example if the depth limits the turbine radius), the VA turbine will be more efficient than the HA one. With a five-meters diameter HA turbine and an equivalent surface VA turbine, a VA turbine produces around 11% more than an HA turbine (Table 7). In this particular case where the depth is a restrictive constraint, the VA might be appropriate.

Table 6: Energy produced in two Raz de Sein sites according to VA or HA (11 m diameter) turbines

Site 1	HA	VA
C_p	0.46	0.40
Orientation of the axis	88°	all
Energy (W.h/year)	1.03 10^9	9.7 10^8
Site 2	HA	VA
Cp	0.46	0.40
Orientation	89°	all
Energy (W.h/year)	1.09 10^9	8.6 10^8

Table 7: Energy produced in site 1 according to VA or HA (5 m diameter) turbines

Site 1	HA	VA
C_p	0.46	0.40
Orientation of the axis	93°	all
Energy (W.h/year)	1.66 10^8	1.76 10^8

Let us now have a rough estimation of the installation cost of such marine turbine in this area. The different cost parts are relative to the elements presented in Table 8. While approximated, these data nevertheless constitute the majority of expenses and allow us to introduce some geographical parameters. The cost of kWh for the best alternative is evaluated to 0.229 Euro/kWh for a single marine turbine with a 20 years lifetime. For a wind turbine as in Europe in 2010, the cost ranges is between 0.11 to 0.15 euros/kWh [41]. Therefore, the energy cost for a marine current turbine is significantly higher than for a wind turbine. However, increasing the number of turbines will reduce this cost. Indeed, the cost of an electric system (line, transformer, etc) used for a farm is not proportional to the number of turbines. This is why the installation cost may be reduced if a farm with a large number of turbines is considered. The calculation of energy cost is based on the analogies with wind turbine component model. For some components, these models do not totally match with the marine current turbine application. The cost of these components are underestimated and, in some cases, removed from this application.

Based on a single criterion (i.e. the energy produced), an horizontal axis turbine for both studied sites is preferable for the considered technical configuration. Even with a site with an asymmetric (not extreme) distribution current, the HA turbine proves its efficiency and why it is widely used. However, this example shows also that considering both resource characteristics and the technology choice is crucial in order to fully assess the economic interest of a marine energy site. This also shows that it is necessary to combine several concepts depending on the mechanics and energy conversion choices. These concepts should be taken into account by the spatio-temporal analysis in order to establish an efficient decision-aid tool for a marine energy systems implantation.

In order to validate if such sites as potentially exploitable, future works have still to be performed. In particular, the developed model should also integrate the environmental constraints within the decision process. In particular, it will be necessary to insert additional natural constraints such as biologic parameters like possible impacts on the natural marine sediment, marine habitats, migration zones and the maritime flora. Another aspect for quantifying the environmental impact is to include the system life cycle assessment. Four parts have to be considered in the case of a marine converter farm [42]: production, transport, maintenance, dismantling. The benefits on the environment should be also evaluated with the carbon and energy footprint.

The social acceptance constitutes another important criterion to take into account in the approach. The introduction of a new activity at sea is source of conflict with sea users. Human activity at sea includes many forms (e.g. navigation, fishing, drilling, cable, fish farming, leisure, natural areas, telecom, military activities, etc.). On land, public acceptance goes through the cultural and visual impacts, the landscape modification is a parameter to take into consideration as well as the social and economic impacts in term of tourism and employments.

Table 8: Cost estimation for one turbine

	Parameters used	Cost (k€)
foundation	depth: 30 m	242
installation	distance to harbour: 45 km (Brest)	1,840
dismantling	distance to harbour: 45 km (Brest)	920
maintenance	distance to harbour: 45 km (Brest)	460
electric System	distance to network: 5 km	1,000
generator	PMSG direct drive	124
miscellaneous	hub, nacelle, blade, electronic,blade, warranty	172
Total		4.758 k€

6. Conclusion

This paper presents a preliminary global methodology for building a decision aid-tool for selecting a marine converter farm site and farm design. The evaluation of the energy cost is one of the main criteria taken into account. We introduced a methodology that estimates the cost of the energy production and the produced energy. This method takes into account the site resource characteristics and several technology options for the main encountered technologies for marine current turbine. This methodology can be extended to other technologies, and particularly to wind turbine. These suggested models constitute a first set of criteria involved in the decision process. They are developed in order to include several parameters depending on the location of the farm. In the decision aid-tool, the parameters included in these models can be modified by the user by taking into account the specific feature of a particular system in a modular way. This methodology is briefly illustrated by a case study that concerns the energy production of a marine current turbine in the Raz de Sein in Brittany in North West France. This case study shows also that taking into account several technological possible choices and site characteristics(current, depth, location) are necessary to estimate the economic interest of a marine energy site and to identify a relevant technological choice.

As farm planning is not limited to energy cost energy, this decision-aid system has also to include in further work additional constraints for environmental and social acceptance assessment. Indeed, the insertion of an offshore turbine farm must be integrated into several sustainable development dimensions: economic, technological, social and environmental [4, 43]. However, the proposed methodology is modular and many other criteria can be taken into account with some adaptations.

In further works, all criteria taken into consideration will be aggregated using a multi-criteria analysis method. The aim of such method will be to present a set of options and to facilitate stakeholders' expertise (i.e., evaluation of optimal locations, best technology choices and design, farm dimension configuration). Moreover, the approach will be integrated within GIS where the decision-aided system developed will face two kinds of problem: (1) to suggest the best converter choice and configuration for a given site, and (2) suggest the most appropriate site for a given category of converter.

[1] B. Multon, Marine renewable energy handbook, Wiley-ISTE, 2013.

[2] A. Nobre, M. Pacheco, R. Jorge, M. Lopes, L. Gato, Geo-spatial multi-criteria analysis for wave energy conversion system deployment, Renewable Energy 34 (2009) 97–111.

[3] S. Carver, Integrating multi-criteria evaluation with geographical information systems, International Journal of Geographical Information System 5 (1991) 321–339.

[4] N. Maslov, D. Brosset, C. Claramunt, J.-F. Charpentier, A geographical-based multi-criteria approach for marine energy farm planning, ISPRS International Journal of Geo-Information 3 (2014) 781–799.

[5] L. Fingersh, M. Hand, A. Laxson, Wind turbine design cost and scaling model, National Renewable Energy Laboratory Golden, CO, 2006.

[6] M. Suzuki, Numerical analysis of horizontal-axis wind turbine characteristics in yawed conditions, Open Journal of Fluid Dynamics 2 (2012) 331–336.

[7] L. Rademakers, H. Braam, M. Zaaijer, G. Van Bussel, Assessment and optimisation of operation and maintenance of offshore wind turbines, in: Proceedings of the European Wind Energy Conference, Madrid, Spain.

[8] R. Baños, F. Manzano-Agugliaro, F. Montoya, C. Gil, A. Alcayde, J. Gómez, Optimization methods applied to renewable and sustainable energy: A review, Renewable and Sustainable Energy Reviews 15 (2011) 1753–1766.

[9] F. Vieira, H. M. Ramos, Optimization of operational planning for wind/hydro hybrid water supply systems, Renewable Energy 34 (2009) 928–936.

[10] K. Nigim, P. Parker, Heuristic and probabilistic wind power availability estimation procedures: Improved tools for technology and site selection, Renewable Energy 32 (2007) 638–648.

[11] W. Batten, A. Bahaj, A. Molland, J. Chaplin, Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines, Ocean Engineering 34 (2007) 1013–1020.

[12] E. Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer, 2006.

[13] P. Fuglsang, H. Madsen, Optimization method for wind turbine rotors, Journal of Wind Engineering and Industrial Aerodynamics 80 (1999) 191–206.

[14] M. Jureczko, M. Pawlak, A. Mężyk, Optimisation of wind turbine blades, Journal of Materials Processing Technology 167 (2005) 463–471.

[15] S. Ceballos, E. Robles, Power electronics for generator control in ocean energy converters, in Electrical Design for Ocean Wave and Tidal Energy Systems, IET, 2013.

[16] T. Diveux, P. Sebastian, D. Bernard, J. Puiggali, J. Grandidier, Horizontal axis wind turbine systems: optimization using genetic algorithms, Wind Energy 4 (2001) 151–171.

[17] H. Li, Z. Chen, Design optimization and evaluation of different wind generator systems, in: Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on, IEEE, pp. 2396–2401.

[18] P. Fuglsang, C. Bak, J. Schepers, B. Bulder, T. Cockerill, P. Claiden, A. Olesen, R. van Rossen, Site-specific design optimization of wind turbines, Wind Energy 5 (2002) 261–279.

[19] S. Benelghali, M. Benbouzid, J. Charpentier, Comparison of pmsg and dfig for marine current turbine applications, in: Electrical Machines (ICEM), 2010 XIX International Conference on, IEEE, pp. 1–6.

[20] S. Benelghali, R. Balme, K. Le Saux, M. Benbouzid, J. Charpentier, F. Hauville, A simulation model for the evaluation of the electrical power potential harnessed by a marine current turbine, Oceanic Engineering, IEEE Journal of 32 (2007) 786–797.

[21] S. Benelghali, On multiphysics modeling and control of marine current turbine systems, Ph.D. thesis, Université de Bretagne Occidentale, 2010.

[22] S. Benelghali, M. Benbouzid, J. Charpentier, Marine tidal current electric power generation technology: State of the art and current status, in: Electric Machines & Drives Conference, 2007. IEMDC'07. IEEE International, volume 2, IEEE, pp. 1407–1412.

[23] J. Thongam, P. Bouchard, H. Ezzaidi, M. Ouhrouche, Wind speed sensorless maximum power point tracking control of variable speed wind energy conversion systems, in: Electric Machines and Drives Conference, 2009. IEMDC'09. IEEE International, IEEE, pp. 1832–1837.

[24] S. Eriksson, H. Bernhoff, M. Leijon, Evaluation of different turbine concepts for wind power, Renewable and Sustainable Energy Reviews 12 (2008) 1419–1434.

[25] M. Adaramola, P.-Å. Krogstad, Experimental investigation of wake effects on wind turbine performance, Renewable Energy 36 (2011) 2078–2086.

[26] S. Benelghali, M. Benbouzid, J. Charpentier, Implications of control schemes for electrical system design in tidal energy converters, in Electrical Design for Ocean Wave and Tidal Energy Systems, IET, 2013.

[27] T. Ackermann, et al., Wind power in power systems, volume 140, Wiley Online Library, 2005.

[28] Z. Zhou, F. Scuiller, J. F. Charpentier, M. Benbouzid, T. Tang, Power limitation control for a pmsg-based marine current turbine at high tidal speed and strong sea state, in: Electric Machines & Drives Conference (IEMDC), 2013 IEEE International, IEEE, pp. 75–80.

[29] J. Ribrant, L. Bertling, Survey of failures in wind power systems with focus on swedish wind power plants during 1997-2005, in: Power Engineering Society General Meeting, 2007. IEEE, IEEE, pp. 1–8.

[30] J. Ribrant, Reliability performance and maintenance-a survey of failures in wind power systems, Doctoral dissertation, XR-EE-EEK (2006). Available at: `http://faculty.mu.edu.sa/public/uploads/1337955836.6401XR-EE-EEK_2006_009.pdf` [accessed 15.01.2014].

[31] P. Jamieson, Innovation in wind turbine design, John Wiley & Sons, 2011.

[32] G. Bywaters, V. John, J. Lynch, P. Mattila, G. Norton, J. Stowell, M. Salata, O. Labath, A. Chertok, D. Hablanian, Northern power systems windpact drive train alternative design study report, NREL, Golden, Colorado, Report no. NREL/SR-500-35524 (2004).

[33] D. Bang, H. Polinder, G. Shrestha, J. A. Ferreira, Review of generator systems for direct-drive wind turbines, in: European Wind Energy Conference 2008, Belgium, pp. 1–11.

[34] P. Nielsen, Offshore wind energy projects, feasibility study guidelines, SEAWIND-Altener project-Feasibility Study Guidelines (EMD) (2003).

[35] J. Serrano Gonzalez, M. Burgos Payan, J. Riquelme Santos, An improved evolutive algorithm for large offshore wind farm optimum turbines layout, in: PowerTech, 2011 IEEE Trondheim, IEEE, pp. 1–6.

[36] M. Kaiser, B. Snyder, Modeling the decommissioning cost of offshore wind development on the us outer continental shelf, Marine Policy 36 (2012) 153–164.

[37] M. J. Kaiser, B. Snyder, Offshore wind energy installation and decommissioning cost estimation in the us outer continental shelf, US Dept. of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement, Herndon, VA TA&R 648 (2010).

[38] A. Rausand, Mand Høyland, System reliability theory: models, statistical methods, and applications, volume 396, Wiley-Interscience, 2003.

[39] R. Poore, T. Lettenmaier, Alternative design study report: Windpact advanced wind turbine drive train designs study; november 1, 2000–february 28, 2002, 2003.

[40] P. Fraenkel, Marine current turbines: pioneering the development of marine kinetic energy converters, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 221 (2007) 159–169.

[41] IRENA, Renewable energy technologies: Cost analysis series - volume 1: Power sector, 2012.

[42] Life cycle assessment of offshore and onshore sited wind farms, 2004. Available at: `http://www.vestas.com/~/media/vestas/about/sustainability/pdfs/lca_v80_2004_uk.ashx` [accessed 15.01.2014].

[43] H. Doukas, B. M. Andreas, J. E. Psarras, Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables, European Journal of Operational Research 182 (2007) 844–855.