Multi-criteria analysis to evaluate tidal energy potential in France

F. Castillo, M. Ikhennicheu, and J C. Gilloteaux

Abstract—**This study presents a holistic multi-criteria analysis based on open-source database to compare nearshore, run-of-river, and estuary sites for potential tidal turbine implementation. Metropolitan France is taken as a case study. Retained criteria for the analysis cover several aspects including: technical characteristics, ecological and regulatory aspects, usage conflict, and socio-economic criteria, making the proposed methodology applicable to other countries and renewable sources. The present paper includes the presentation of the multi-criteria approach with a specific focus on two methodologies to assess respectively: the production capacity and the number of full-time equivalent employments. Additionally an exhaustive list of sources is presented. The approach is used to compare 10 sites. The potential of installation capacity for the French territory is 3.7GW, which is in line with the usual values found in the literature. The study reveals that with the proposed approach the most suitable site for tidal implementation is the Raz-de-Sein in Brittany with a grade of 72.4 out of 100. It is underlined that with the actual grading system, nearshore locations tend to be more suitable than run-of-river and assimilated sites. The Alderney race, the most powerful French site with 1.8 GW, arrived in third position with a grade of 69.4, validating the need to include not only technical aspects during site pre-screening phase but also XXX aspects. The inclusion of further criteria, that would give advantage to smaller or isolated sites is also discussed.**

Keywords*—*France, multicriteria analysis, tidal turbine, tidal potential assessment.

I. Introduction

To achieve its target of 32% of renewable energies in the energy mix by 2028 [1], France can rely on the second largest exclusive economic zone in the world [2], and the longest inland waterways in Europe [3]. With such capacity, marine renewables can play a significant role. Tidal energy, extracting energy from moving mass of water, induced by tide, run of river, or tidal estuaries might be part of the solution. Indeed, with about 3GW, France has the second largest exploitable tidal potential in Europe, and one of the largest in the world [4]. In addition, the country benefits from a strong industrial network to support the value chain, with developers (e.g. Sabella [5], HydroQuest [6], Guinard energies [7]) working closely with academic partners involved in this area ([8], [9], [10]). This positive environment starts to materialize with the creation of different test sites and installation of several tidal turbine prototypes ([5] and [6]).

Most of the public research focuses on the most energetic sites, mainly located nearshore such as the Atlantic and Channel waters [11] and the Ouessant (Ushant) Island [12]. Several studies relate to the Alderney race, the most powerful site in France ([13] and [14]). However, the literature lacks early-stage studies allowing sites comparisons covering nearshore, estuaries and run-of-rivers sites. In most cases, scarce data can be found on the latest. For instance, no public studies were found highlighting the potential in Etel, the Adour river or Rhone river where tidal turbines are installed nonetheless ([7], [15] and [16]).

In addition, when publicly available, most studies mainly focus on assessing tidal resource. However, when selecting the most appropriate site for an energy systems implementation, other aspects such as environmental restrictions or potential usage conflicts, should be accounted for. This multi-criteria analysis aims at integrating such aspects and facilitating the decision-making process. A literature review of multi-criteria analyses in renewable energies [17] illustrates how common this approach could be in the renewable energy sector. To assess the best sites for wave energy implementation in France, some publications use multi-criteria analysis relying on parameters such as wave energy, bathymetry, distance to coastline and ports or seabed [18]. Regarding tidal energy, rather few papers using multi-criteria analysis are available. One of the rare studies on the topic investigates potential sites for tidal energy in Australia [19]. Their approach relies on various

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815180.

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Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-478

factors including electrical grid proximity, water depth or protected areas. They include a sensitivity analysis on the weighting factor, to reduce confirmation bias. However, their study focuses on offshore locations only.

In addition, one missing aspect of those multi-criteria analysis is usually the various socioeconomic criteria such as local content, which is key for local communities [20].

In this paper, it is proposed to use a multi-criteria approach to assess the tidal energy potential of 10 pre-selected sites in metropolitan France for both, nearshore and run-of-rivers/estuary sites. This holistic approach relies on several aspects including technical, environmental or usage conflict criteria but also socio-economical ones. The assessment relies exclusively on open-source databases. This constraint imposes to derive information from publicly available data that have impacts on a targeted parameter, instead of focusing directly on it.

The proposed method enables comparison between sites and significant project cost reduction thanks to open-source databases. It is easily reproductible for any country and any renewable energy source by national actors interested in assessing renewable potential.

This study is realized as part of the Horizon 2020 ELEMENT project. This project aims at reducing operational overheads, maximize energy outputs from arrays by introducing intelligent control systems and finding better ways of capturing data on tidal stream dynamics [21], and at assessing French and European tidal potential.

II. Methodology

A. Multicriteria analysis

The following sections described the multi-criteria analysis developed to perform site comparison.

1) Methodology

The multicriteria analysis relies on the attribution of score to different criteria. To discriminate sites, 3 grades – from 1 to 3 - per criterion are defined.

Criteria are also weighted to reflect their importance to the success of a project. Criteria, ranges, and weights, are selected for this project following workshops with ELEMENT project participants, which includes relevant academic and industrial stakeholders [21]. The final site score, obtained by using equation (1), can go from 0 – unsuitable site for tidal implementation, to 100 – suitable site for tidal turbine.

$$X = \frac{1}{2}\left(\left(\sum_{n} w_i g_i\right) - 100\right) \quad (1)$$

In this equation, n is the number of criteria, w_i is the weight of ith criterion, g_i the grade of the ith criterion and X is the final score. The sum term being between 100 and 300, the global score is brought back to 0 to 100 by subtracting 100 and dividing by 2.

This final score can be highly dependent on weight factor attributed and a sensitivity analysis might be required to prove robustness of the model, as shown in [19]. However, as this study includes some socio-economic indicators, that will be affected by local policies, this robustness assessment is out of the scope.

The criteria and their weights are defined in section 2 and in tables 1 and 2. The grading systems for each of the criterion is detailed in section 3.

2) Criteria presentation

28 criteria are used in the proposed methodology, grouped in 5 categories: technical criteria, socio-economic criteria, regulatory criteria, human activities and ecological criteria. Those criteria are detailed in Table 1 and Table 2, along with the associated weights.. Weight have been defined following a workshop with ELEMENT project partners. A weight of 5 is attributed to criteria of high importance (as they can lead to potential site exclusion), a weight of 4 to essential criteria, 3 for criteria having significant impacts but that are not driving decision, 2 for criteria that should not impact projects and 1 for criteria that can be overlooked.

3) Grading system

As explained above, final score is defined using a grading system between 1 and 3 for each criterion (see Table 1 and Table 2). For ease of reading, units are specified at the end of each criterion. Some clarification are detailed in the tables for criteria requiring them.

Two criteria directly refer to the potential: the highest speed current and the installed capacity. The latest aims at including space available for tidal farm implementation. Details are given in section B regarding the methodology applied for its calculation and in section F for some information regarding the case study.

For the local content assessment, methodology is described in section C. In addition, it is explained is section G why in this study the results is only proportional to the installed capacity.

TABLE 1
INSTALLED POWER CALCULATION PARAMETERS

Criteria	Description	Weight	Grading system	Details
TECHNICAL CRITERIA				
High speed current	Maximum sea surface current velocity during mean spring tide	5	3: $u \geq 2.5$, 2: $2.5 > u \geq 1.5$, 1: $u < 1.5\ m.s^{-1}$	Ranges are defined following perspectives proposed in [22][22] and [23]
Technical potential (MW installed)	Technical potential (MW) calculated following methodology described in section 5.2	4	3: $P \geq 500$, 2: $500 > u \geq 5$, 1: $u < 5MW$	Ranges defined to include small capacities - that would be installed in insulate locations, where electricity is usually produced with diesel engines making tidal energy competitive - and larger sites.
Turbulence	Turbulence intensity (%) estimated based on site configuration	3	3: low turbulence probability 2: medium turbulence probability 1: high turbulence probability.	Evaluated using the topography of the site, as a rough soil, with strong bathymetry variations or with visible boils at the sea surface, is more likely to produce intense turbulence intensity.
Depth	Minimum depth for a mean spring tide	5	3: $d \geq 10$, 2: $10 > d \geq 5$, 1: $d < 5m$	Ranges derived from turbines diameters increased by a minimum sea surface clearance.
Tidal range	Maximum tidal range at the specified location	3	3: $Range < 3$, 2: $3 \leq Range < 10$, 1: $Range \geq 10m$	Ranges selected following discussions with ELEMENT project participants.
Soil conditions	Type of soil at the specified location (sand, mud, rocks, etc.)	4	3: smooth rock and other smooth seabed 2: rough soil but stable 1: Rough and unstable	Soils conditions would mainly impact by installation and stability perspectives.
Navigation area	Presence of a navigation route	3	3: site is out of navigation route 1: if not	
Servitude	Distance to a servitude such as gas pipeline or power cable	4	3: no servitude, 2: servitudes at more than 250m, 1: servitude within 250m	250m is selected to reflect good practice regarding marine operations, anchor radius and allow cable routing.
Accessibility	Evaluation of site accessibility by road or boat	3	3: high accessibility, 2: medium, 1: low	Aim at reflecting difficulties (water depth, obstacles, etc.) that would further reduce options during installation and O&M phases.
Access to electrical connection	Distance to a connection point (without power restriction)	4	3: Connection point < 1km, 2: Connection point between 1 and 3km, 1: Connection point > 3km	Ranges defined by taking existing and future tidal farm projects to identify typical values.
SOCIO-ECONOMIC CRITERIA				
Local content	Project economic impact (jobs).	5	3: $P \geq 500$, 2: $500 > u \geq 5$, 1: $u < 5MW$	Hypothesis retained for this study make the number of jobs directly proportional to the installed capacity, explaining why the same intervals are used (see section G). This criterion is removed for the case study.
Regional strategy for offshore renewables	Regional help to support offshore renewables (R&D projects, subsidies, etc).	3	3: Well-developed strategy 2: Existing but incomplete strategy 1: No or limited strategy	Assessed following policies in place at a regional level. The assessment is validated by interviews performed with relevant stakeholders.
Active SME in the sector	Existing companies with capacities for offshore renewables in the region.	1	3: high number of SME dedicated to offshore renewables (ORE) 2: medium number of SME 1:low number of SME	Assessed by looking at different entities (cluster, trade association) summarizing information at a regional level
Possible synergies with current offshore activities	Other offshore renewables activities or projects close to the studied location. "Possible synergies" means potential cost reductions by sharing infrastructures, workers, etc.	3	3: if synergies are strong 2: if synergies are small 1:if synergies are impossible	Evaluated at local level by evaluating the number of tests sites, existing project etc.
Relevant academic stakeholders.	Presence of academic stakeholders in the region of the studied location. They could create synergies with industrial partners, develop R&D projects, revenues, etc.	3	3: strong presence 2: moderate presence 1:weak presence	Assessed at a regional level by identifying entities involved in marine renewable energies.

TABLE 2
INSTALLED POWER CALCULATION PARAMETERS

Criteria	Description	Weight	Grading system	Details
		Regulatory criteria		
Natura 2000	Special European protection areas for fauna and flora	3	3: if site is out of zone, 1: if site is in zone	
Listed site	Protected area (zone of interest for architecture, arts, etc.)	4	3: if site is out of zone, 2 if electrical connection would be in zone, 1: if site is in zone	
ZNIEFF I and II (birds)	Special protection areas for fauna and flora.	4	3: if site is out of zone, 1: if site is in zone	
Loi littoral (coastline regulation)	Regulation aiming at protecting the coastline to avoid erosion and flooding	4	3: if site is out of zone, 1: if site is in zone	
RCFS[1]	Special protection areas for animals	2	3: if site is out of zone, 1: if site is in zone	
		HUMAN ACTIVITIES CRITERIA		
Fishery	Evaluation of fishery activities	3	3: if no fishery, 2: if usual fishery zone, 1: if dedicated zone	Dedicated zone refire to specific recognized area (e.g. scallops in Normandie)
Port activity	Evaluation of port activities	5	3: if nearby port available for tidal project activity (<10km), 2: if nearest available within 10-50km and/or all nearby ports lacking required capacity or fully occupied with other activities, 1: if no nearby port (<50km) and/or all nearby ports fully occupied with other activities or lacking required capacity	Defined following workshop with ELEMENT project partners and internal knowledge.
Shipwrecks	Presence of shipwrecks	3	3: if absence, 1: if presence	
UXO	Presence of UXO	4	3: if low risk, 2: if medium risk, 1: if high risk	
Tourism-recreational boating	Level of recreational boating	2	3: if Low, 2: if medium, 1: if high	Assessed if site is known for this aspect (e.g. Bassin d'Arcachon in France).
Military zone	Presence of a military zone	5	3: if out of zone, 1: if in zone	
		ECOLOGICAL CRITERIA		
Migratory fish	Presence of migratory fishes	3	Presence of migratory fishes	
Habitats (mudflats, seabed)& inventory zone (roselières, vasières)	Presence of habitats or inventory zone. Habitats are areas important for fauna/flora preservation. Inventory zone are areas used to assess environmental state of a site	3	Presence of habitats or inventory zone. Habitats refer to areas important for fauna and flora preservation, while inventory zone are areas used to assess environmental state of a site	

[1] RCFS Réserve de Chasse et de Faune Sauvage (Hunting and Wild life Reserve)

B. Potential evaluation

The installed capacity is directly calculated using equation (2), where ρ is the water density, U is the current velocity, C_p is the power coefficient, D the turbine diameter, A is the site area, and α and β represent respectively a lateral and a downstream minimum spacing between turbines.

$$P = \frac{1}{2}\rho\pi\frac{D^2}{4}C_p U^3\left(\frac{A}{\alpha D \beta D}\right) \quad (2)$$

In this study, 4 virtual turbines are considered, with respectively a nominal power of 20kW, 50kW, 70kW and 100kW. For each site, only one tidal turbine type (the largest possible one) is selected based on available water depth to ensure enough sea surface clearance above the blade tip. The water depth, lateral and downstream spacing as well as power coefficient are determined following discussions with NOVA Innovation, the turbine supplier of the ELEMENT project. Table 3 below summarizes the values used to calculate the potential for each site. The available area A for farm deployment is determined by finding space where both the minimum water depth and a minimum current speed of 1.5 m/s (maximum value during mean spring tide) are respected.

TABLE 3
INSTALLED POWER CALCULATION PARAMETERS

Parameter	Value	Unit
minimum depth for 20kW turbine	6.3	m
minimum depth for 50kW turbine	11	m
minimum depth for 70kW turbine	14	m
minimum depth for 100kW turbine	19	m
Lateral spacing α between turbines	3.5	-
Downstream spacing β between turbines	11	-
Power coefficient C_p	0.4	-

C. Local content assessment

The second methodology used in this study is the local content assessment. It relies on the expenditure and so-called input/output economical matrices. It represents the economical flux between different economic sectors, due to the exchange of good and services. This approach is well-documented and applicable to different sectors. A description of the methodology can be found in [51] and its application to an offshore wind farm can be found in [54]. It allows to obtain the number of created jobs (direct, indirect and induced) by considering the increase of revenues generated by the farm creation.

The first step of the methodology is to define the capital and operational expenditures (respectively CAPEX in €/kW and OPEX in €/kW/year), along with a CAPEX/OPEX breakdown. Hence, each step of the projects (e.g. design, installation, rotor construction, etc.) can be associated to a NACE (*Nomenclature des Activités Econominques*, economic activity nomenclature) code [53], defined in the statistical classification of economic activities in the European community. This code allows to associate a component (e.g. turbine, foundation, etc). to an economic sector (i.e. to a company), and therefore to future employments. Each company in Europe is registered following this classification.. A national share is defined because: only national employment is accounted for and the renewable energy component will be partially built locally. This share is determined based on discussions with ELEMENT project partners. Using socioeconomic indicators such as the number of employments per gross value added (GVA), the number of FTE (full time employment) jobs that will be created by the installation of a tidal farm can be calculated. The methodology is summarized in Fig.1.

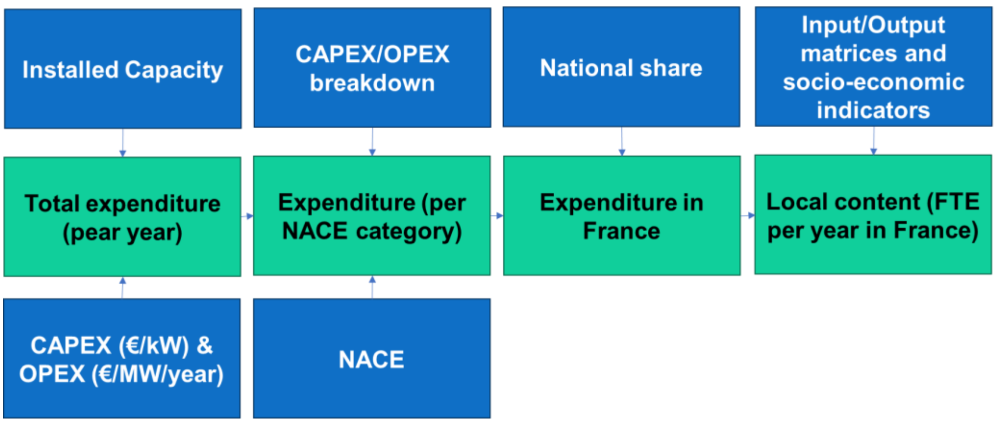

Fig. 1. Local content methodology description

III. CASE STUDY

D. Site selection

The present study focuses on 10 sites in Metropolitan France, selected after a pre-screening analysis. This pre-screening phase is realized using a minimum water of 3m, to reflect use of both bottom-fixed and floating tidal turbines, and a minimum surface current speed of 1.5 m/s. The maximum velocity during a spring tide is used as reference following perspective proposed by industrials [22]. At first, 23 locations are identified using this methodology. Finally, 10 sites are chosen based on availability of data and to ensure a balance between

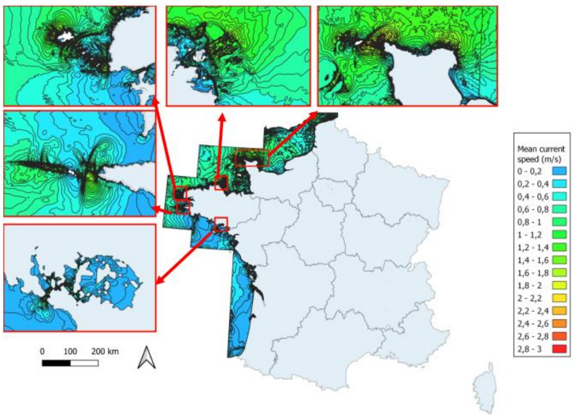

Fig. 3. Offshore locations.

nearshore and run-of-river/estuaries sites as expected by the ELEMENT project.

Table 4 presents the 10 studied sites. Each site is identified by an index, reported in Fig.2. for localization.

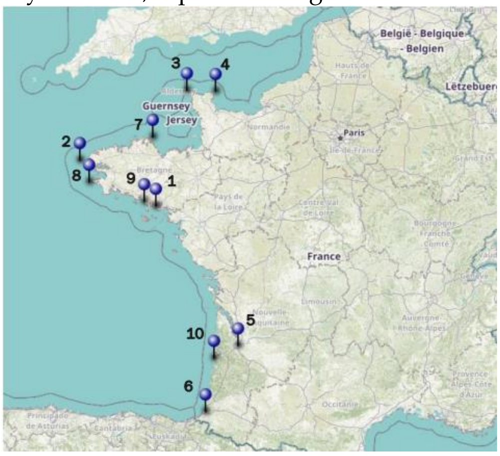

Fig. 2. 10 selected sites geographical location

TABLE 4
10 SITES SELECTED FOR POTENTIAL ASSESSMENT

Site Name	Type of site	Geographical information[1] (Département[2])	Index
Ria d'Etel	Estuary (Aber)	Etel (Morbihan)	1
Fromveur passage	Nearshore	Atlantique (Finistère)	2
Alderney Race	Nearshore	British Channel (La Manche)	3
Raz-Barfleur	Nearshore	British Channel (La Manche)	4
Pont de Pierre	Estuary	La Garonne (Gironde)	5
Adour	Estuary	L'Adour (Pyrénées-Atlantiques)	6
Paimpol-Brehat	Nearshore	British Channel (Côtes d'Armor)	7
Ras-de-Sein	Nearshore	Atlantique (Finistère)	8
Passage de la Jument	Estuary (Gulf)	Golfe du Morbihan (Morbihan)	9
Arcachon Bay	Estuary	Bassin d'Arcachon (Gironde)	10

[1] Ocean, sea, estuary or river.
[a] French administrative division.

E. Database sources

As this study relies on several criteria with technical and socio-economic data, several data sources types must be used. In addition, the proposed approach relies on open-source data to allow project developers or decision-makers to perform a pre-screening analysis before buying any detailed data for a specific site. This section aims at presenting the different sources used in this case study., When possible, it also details the spatial and temporal resolution of the source.

The maximum current surface velocity during spring tide for nearshore locations is assessed using Shom data [24]. The model developed by the Shom has a spatial resolution of 2km, down to few meter for some regions. Some local current generated by specific topography are not covered by this model. The last update is from 2005. For Adour and Pont de Pierre site, data rely on a study performed for the Aquitaine region [25]. The mesh used to compute the current has a size of 5m. Only mean current value are computed, but trends can be estimated for maximum value and then compared to other sources [26]. For Etel, a maximum current speed between 2.6 m/s and 4.0 m/s is given in [27] for a French tidal coefficient of 120 (spring tide 93-97). Using this value and based on discussions with Guinard energies, a maximum value of 2 m/s is used as a reference. For the calculation of the potential for nearshore locations, more precise current speeds are used. They are given by MARS2D model developed by IFREMER [28]. The spatial resolution is 250m and the time resolution 15 min.

The turbulence intensity being hard to obtain without in-situ data acquisition, it is decided to analyse bathymetry, soil type and visual analysis using different sources such as Shom [24], Navionics [29], and Google Earth [30]. For the Alderney race a dedicated study is used [31]. The water depth, the tidal range, soil conditions, servitudes and accessibility are evaluated based on the same references. For the depth, the Shom spatial resolution is 111m [24], and for soil conditions, it is 5 arcminutes [24]. Navionics [29] is used to assess the navigation routes.

For electrical connections, database from the French DSO Enedis is used [32].

Protected sites such as: Natura 2000, listed site, ZNIEFF I and II and RCFS zone are evaluated using the geoportail database ([33], [34], [35]). For the coastline regulation, a tool published by the Observatoire des Territoires is used [36]. This tool directly provides cities under regulation. Several sources are used for assessing fishery activities, including a state of the art of the professional fisheries, studies, and dedicated research covering press articles on each locations [37], [38], [25]. The port activity is assessed using various references, including articles, port website, and discussion with relevant stakeholders such as the Grand Port Maritime de Bordeaux ([39], [40], [41]). Shipwrecks can be extracted from Shom and Navionics data ([24], [29]). As explained the UXO (Unexploded Ordonnance) is assessed by defining their probability of presence. This is performed by analysing world war II bombings [42], press articles [43] and dedicated studies [44]. It is also assumed that presence of strong activities (trawlers, existing farms) tends to reduce the probability of UXO presence. Recreational boating is evaluated using tourism activity. It is done by assessing the number of marinas using specialized websites such as [45] or dedicated studies ([25], [38]). The same two studies are used to assess presence of military zone. Navionics and Google Maps are also used to analyse uncover zones or ammunition depots. Eventually, migratory fishes, habitats, inventory zones are assessed by analysing data coming from the PLAGEPOMI project from the French organization DREAL [46] and national agency websites ([47], [48], [49], [50]).

Some of those open-access databases are solely for the French territory, whereas some of them are also available for Europe or the rest of the worlds.

F. *Potential assessment – case study*

As explained in Section B, the minimum current velocity was set to 1.5 m/s (maximum current speed during spring tide). However, for the Adour location (Bayonne) an average value above 1m/s is given, with a maximum value below 1.5 m/s. the site was kept to be representative of small and isolated locations despite its low value.

For nearshore sites, the potential is calculated using the average current velocity for spring tides of the year 2015. This year is used as a reference following the methodology proposed in [11]. This year is characterized by 37 spring tides (French tide coefficient 93-97). Offshore locations potential is represented on Fig.3. For Bayonne and Bordeaux the maximum current velocity is from [25]. For Etel river, data are derived from discussion with Guinard energy, that installed a turbine prototype in the Etel river in 2019.

G. *Local content – study case*

This section provides more details about the values and hypotheses used in this case study regarding local content assessment. A CAPEX of 7580 €/kW and an OPEX of 505 €/kW/year are used [52]. The CAPEX and OPEX breakdowns, providing directly NACE categories [53], are respectively presented in Table 5. The design phase and construction phase are assumed to last for 1 year in this study and the operational phase for 20 year. This is a strong hypothesis as it leads to a high number of FTE the first year.

Therefore, in this study, the number of jobs is created directly proportional to the installed capacity. In reality, CAPEX and OPEX rely on the scale of the project, the scale of the turbine, the nature of the project (nearshore vs in-land for instance), etc. However, for a preliminary large scale analysis, this level of precision is dispensable.

As the local content is redundant with the potential, it is not accounted for in the site grading as it would have no impact on the final grade. However the calculation is carried through to give a quantitative order of magnitude in terms of local content.

TABLE 5
INSTALLED CAPACITY

CAPEX breakdown		OPEX breakdown	
NACE Code	Share	NACE Code	Share
M71	14	C33	50
C28	28	H50	49
C27	14	D35	1
C25	14		
H50	16		
F42	5		
K64	8		
D35	1		

H. *Uncertainties*

Categories boundaries are designed to reduce the uncertainties effect on the ranking. It means that the sites ranking should not be impacted by uncertainty. The main uncertainties in this study comes from the current, the potential assessment, and the local content analysis.

For the current speed, the uncertainty is mainly related the spatial resolution of the model used. As stated in section E, the mesh spatial resolution is 5m for the Adour and Pont de Pierre sites. Any local behaviour occurring at a lower scale (e.g. local acceleration, physical obstacle) will not be captured. For Etel, the spatial resolution is unknown, but the velocity has been verified against measurements. The uncertainty is therefore linked to the measurement equipment. For the other sites, the spatial resolution is 250m. The potential is proportional to the cubic power of the current speed and is therefore impact by the spatial resolution. In a lower extent, the available area is a source of uncertainty as it does not take into account any obstacle that can reduce the usable surface, in the calculation of the site potential. The time resolution has limited impact in this study as it will mainly impact current gust velocity. It has little to no impact on the site's category. Uncertainty on other data type (depth, soil conditions) are also linked to the spatial resolution stated in E.

For local content calculation , the main sources of uncertainty are the national shares and the CAPEX/OPEX breakdowns. For the national share, Innosea has estimated the uncertainty of approximately 10% using an internal database. For the CAPEX breakdown, the uncertainty can also be estimated to 10% thanks to industry information and discussion with developers. The uncertainty linked to economic data by themselves (I/O table, salaries, etc.) was not found in the literature.

It is reminded that this study is a scoring exercise, and boundaries are selected so that uncertainty do not impact ranking.

IV. RESULTS

I. *Potential installed capacity*

Using the methodology presented above, the potential capacity was calculated for each location except the Adour site, Pont de Pierre and Etel, where ranges are extracted from [25] and discussions with Guinard energy. Table 6 summarizes the calculated potential. It is to be noted that this approach leads to a production capacity of approximately 3.7 GW. This value is in line with [4].

TABLE 6
INSTALLED CAPACITY

Site	Potential (MW)	Grade
Ria d'Etel	≤ 5	1
Fromveur passage	282	2
Alderney race	1830	3
Raz-Barfleur	1057	3
Pont de Pierre	≤ 5	1
Adour	≤ 0.5	1
Paimpol-Bréhat	246	2
Raz-de-Sein	266	2
Passage de la Jument	6.1	2
Arcachon Bay	2.3	1

J. *Local content results*

Even though the local content is eventually not included (see section G), results are provided here. The methodology developed leads to 18 FTE direct jobs per MW installed in France during the design, construction and installation phase. This value is relatively high compared to values that can be found in the literature (3 FTE/MW [55]). As explained above, it is mainly driven by the hypothesis of 1 year for construction and design phase lifespan, that would be different in a real project. The results is also strongly dependent on the CAPEX and OPEX value. With alternative values from [52] the number of jobs drops to 9.2 FTE/MW. For the OPEX, it leads to 2.5 FTE per MW installed (direct and indirect) while 0.65 FTE/MW are obtained in other studies [55].

K. *Multicriteria analysis results*

Table 7 provides the global score obtained for each site using multi-criteria methodology presented in this paper.

TABLE 7
GLOBAL SCORE MULTICRITERIA ANALYSIS

Site	Score
Raz de Sein	72,4
Paimpol-Bréhat	71,9
Alderney Race	69,4
Passage du Fromveur	68,9
Raz-Barfleur	67,3
Passage de la Jument	59,7
Point de Pierre	59,7
Etel	58,2
Adour	46,9
Arcachon bay	42,3

With this approach, it can be seen that the most suitable site for tidal turbines implementation is not necessarily the most energetic one, the Alderney race reaching the third place. However, results show that nearshore locations are clearly more suitable for tidal implementations than run-of-river/estuary sites, as those sites are at the top of the ranking with almost 10 points ahead. Some explanations regarding this trend are given below. Estuary and run-of-river sites can then be split between two groups: above and below 50. Table 8 describes values for each site and each category of criteria.

First, it can be seen that run-of-river sites and assimilated obtain rather low grades in regulation and ecological diagnostics because of the presence of coastline regulations, habitats or migratory fishes. Nearshore locations are less sensitive to those criteria. It is also observed the large dispersion in the socio-economic grade (local content excluded) . Indeed, Point de Pierre, Arcachon bay and Adour river are negatively impacted by a lesser developed environment for tidal energy (regional strategy, academic supports, etc.). Technical criteria are also less favourable to those sites, as they usually have less suitable conditions (available area, low water depth leading to smaller turbines, etc). As part of the ELEMENT project, interviews were conducted with different stakeholders. It confirmed this trend and the adequacy between multi-criteria site ranking and industrial perspective on tidal development in France.

TABLE 8
GLOBAL SCORE MULTICRITERIA ANALYSIS

Site	Technical	Socioeconomic	Regulation	Human activities	Ecolo-gical
Raz de Sein	63,2	63,3	70,6	88,6	100
Paimpol-Bréhat	69,7	73,3	70,6	81,8	50
Alderney Race	68,4	76,7	70,6	70,5	50
Passage du Fromveur	68,4	73,3	58,8	65,9	100
Raz-Barfleur	68,4	76,7	58,8	70,5	50
Passage de la Jument	65,8	63,3	47,1	72,7	0
Point de Pierre	56,6	23,3	82,4	88,6	0
Etel	60,5	46,7	58,8	77,3	0
Adour	44,7	23,3	35,3	88,6	0
Arcachon bay	50	23,3	35,3	59,1	0

V. CONCLUSION AND DISCUSSION

In this study, a multicriteria analysis is developed and applied to compare 10 pre-selected potential sites for tidal turbines implementation, including offshore, nearshore and run-of-river/estuary site in France. A holistic approach is developed, including technical criteria, environmental criteria, usage conflicts, but also socio-economic criteria. The study relies on open-access data only, allowing this methodology to be transposable to any other renewable energy and for any country (providing that the data is available).

The site potential is calculated, and results show good agreement with literature with values between 3GW and 5 GW. The most powerful sites are nearshores, with the Alderney race being the most promising one.

When including other criteria, it is interesting to notice that ranking changes. Though nearshores locations are still scoring amongst the highest, the most suitable site appear to be the fourth most powerful one (Raz de Sein). This site is driven by other criteria such as human activities and ecological criteria. As expected, small sites such as Adour and Arcachon bay are at the end of the ranking.

The study includes the development of an expenditure based methodology to estimate the number of jobs created by the project. The hypotheses used, such as CAPEX spreads over 1 year, or the use of the same CAPEX and OPEX values whatever the farm capacity, lead to quite high results compared to literature values. In addition, it leads to results directly proportional to the installed capacity, regardless of the nominal capacity considered. Therefore, this criterion is not included for the case study presented.

This study also highlighted the lack of open-access data, making comparison complicated for a larger number of sites. Hence, potential suitable sites could have been overlooked because of the lack of general knowledge.

Further work should focus on refining some of the criteria used. As already discussed, by refining FTE jobs assessment methodology (by considering different CAPEX and OPEX or different phase lifetime), it is expected that discrimination between sites would increase. In addition, further criteria could be added. As an example a levelized costs of energy (LCOE) estimation could be included. This approach would allow small isolated sites, where energy production is usually expensive, to become more competitive from an industrial perspective. Life cycle assessment (LCA) could also be included, as it can allow to target site having the largest environmental impact improvement. That can further help isolated sites to be competitive since the electricity is usually produced through fossil fuels. However, those criteria might be complicated to gather based on open-access data only, as it usually requires to know some advanced project details.

ACKNOWLEDGMENT

Authors want to thanks ELEMENT project partners for their kind supports and interesting remarks, with a special thanks to IDETA and NOVA Innovation. We also thank our colleagues Claire Baron and Félix Gorintin for their help.

REFERENCES

[1] Ministère de la transition énergétique, "Stratégie française pour l'énergie et le climat, programmation pluriannuelle de l'énergie", 2019.

[2] J. Claudet, C. Loiseau and A. Pebayle "Critical gaps in the protection of the second largest exclusive economic zone in the world", *Marine Policies*, vol. 124, 2020. DOI: 10.1016/j.marpol.2020.104379.

[3] Ministère de la transition énergétique, Available: https://www.ecologie.gouv.fr/generalites-sur-transport-et-reseau-fluvial-en-france#scroll-nav__3

[4] CVA, "Etude stratégique de la filière hydrolien marin", 2018
[5] Sabella, Available: https://www.sabella.bzh/
[6] Hydroquest, Available: https://www.hydroquest.fr/
[7] Guinard energies, Available: https://www.guinard-energies.bzh/fr/guinard-energies/
[8] Ifremer, Available: https://www.ifremer.fr/fr/infrastructures-de-recherche/le-bassin-houle-et-courant-de-boulogne-sur-mer
[9] IRDL, Available: https://www.irdl.fr/poles-thematiques-de-recherche/
[10] Lheea, Available: https://lheea.ec-nantes.fr/
[11] R. Campbell, A. Martinez, C. Letetrel and A. Rio, "Methodology for estimating the French tidal current energy resource", *Int. Jour. Of Marine Energy"*, vol. 19, pp. 256-271, 2017
[12] T. E. Tawil, J. F. Charpentier and M. Benbouzid, "Tidal energy site characterization for marine turbine optimal installation: Case of the Ouessant Island in France", *Int. Jour. Of Marine Energy"*, vol. 18, pp. 57-64, 2017
[13] A. Sentchev, J. Thiébot, A. C. Bennis and M. Piggott, "New insights on tidal dynamics and tidal energy harvesting in the Alderney Race". *Phil. Trans. R. Soc. A*. vol. 378 Issue 2178, 2020, DOI: 10.1098/rsta.2019.0490
[14] J. Thiébot, S. Guillou and E. Droniou, "Influence of the 18.6-year lunar nodal cycle on the tidal resource of the Alderney Race, France", 2020, *Applied Ocean Research,* vol 97.
[15] Available: https://www.citedelocean.com/fr/urabaila-une-hydrolienne-innovante-dans-l-estuaire-de-l-adour/
[16] Available: https://france.representation.ec.europa.eu/projects/des-hydroliennes-sur-le-rhone-une-premiere-mondiale_fr
[17] R. A. Taha and T. Daim, "Multi-criteria Applications in Renewable energy Analysis: A literature review" in *Research and Technology Management in the Electricity Industry*. Green Energy and Technology, Springer, 2013.
[18] A. Martinez, Z. B. Mustapha, R. Campbell and T. Bouragba, "A Multi-criteria Methodology to Select the Best Wave Energy Sites" in WCST, UK, 2016.
[19] P. Marsh, I. Penesis, J. R. Nader and R. Cossu, "Multi-criteria evaluation of potential Australian tidal energy sites", *Renew. Energ,* vol 175, pp. 453-496, 2021.
[20] S. Lalancette, P. LE Floc'h and B. Le Gallic, "Les énergies marines renouvelables répondent-elles au modèle d'économie de la fonctionnalité ? ", *Les nouv. Chantiers de la justice envir.*, vol 19, no 1, 2019.
[21] Available: https://element-project.eu/partners/
[22] Available: https://www.geolittoral.developpement-durable.gouv.fr/IMG/pdf/potentiel_courant_moyen_terme_manche_manche.pdf
[23] Available: https://www.geolittoral.developpement-durable.gouv.fr/IMG/pdf/potentiel_courant_court_terme_manche_manche.pdf
[24] Available: https://data.shom.fr
[25] V. Mazeiraud, T. Guerin and Y. Mensencal, "Etude regionale d'evaluation du gisement d'energies en mer de la façade aquitaine", Artelia, 2012.
[26] Available: https://seeneoh.com/sites/bordeaux/
[27] "Document d'objectifs Site Natura 2000 Ria d'Etel," Syndicat Mixte de la Ria d'Etel, 2021
[28] Available: https://marc.ifremer.fr/comment_ca_marche/modeles_mars2d
[29] Available: https://webapp.navionics.com/?lang=fr#boating@6&key=kcnhGzz~G
[30] Available: https://earth.google.com
[31] M. Thiébaut and al. "Characterization of the vertical evolution of the three-dimensional turbulence for fatigue design of tidal turbines", *Philo. Transactions of the Roy. Soc. A: Math. Phy and Eng. Sci.,* vol 378, issue 2178.
[32] Enedis, Available: https://data.enedis.fr/pages/accueil/?id=dataviz-lignes-et-postes
[33] Geoportail, Available: https://www.geoportail.gouv.fr/carte.
[34] IGN. Available: https://www.ign.fr/.
[35] BRGM. Available: https://www.brgm.fr/fr.
[36] Observatoire. des territoires Available: https://www.observatoire-des-territoires.gouv.fr/classement-des-communes-en-loi-littoral.
[37] A. Le Meur, "Rapport d'information déposé en application de l'article 145 du Règlement par la commission des affaires économiques sur la pêche", 2019
[38] "Determination du potentiel hydrolien en Basse-Normandie," 2012, Artelia.
[39] Port de Brest, Available: http://www.brest.port.bzh/fr/?option=com_content&view=article&id=186:hydrolienneopenhydro-en-route-pour-paimpol-brehat&catid=39:actualite.
[40] La Presse de la Manche, Available: https://actu.fr/normandie/cherbourg-encotentin_50129/50-hectares-du-port-de-cherbourg-seront-alloues-aux-energies-marinesrenouvelables_34318820.html.
[41] https://www.bordeaux-port.fr/
[42] S. Genevois. Available: https://dlozeve.github.io/ww2-bombings/
[43] La presse de la Manche, Available : https://actu.fr/normandie/saint-vaast-la-hougue_50562/au-large-cotentin-chalutier-remonte-une-bombe-dans-filets_5273823.html
[44] Robin des Bois, Available: https://robindesbois.org/inventaire-desdechets-de-guerre-regions-atlantique-manche/. [Accessed 07 05 2021].
[45] Cotentin unique par nature, Available: https://www.encotentin.fr/aventure/plaisance/port-mouillage/
[46] DREAL, "Plans de gestion des poissons migrateurs (PLAGEPOMI)," Available: http://www.nouvelle-aquitaine.developpement-durable.gouv.fr/plans-de-gestion-despoissons-migrateurs-plagepomi-a1240.html.
[47] Institution. Adour, Available: https://www.institution-adour.fr/.
[48] Observatoir de l'environnement en Bretagne, Available : https://bretagne-environnement.fr/.
[49] Inventaire National du Patrimoine Naturel, Available: https://inpn.mnhn.fr/accueil/index
[50] Geobretagne Available: https://cms.geobretagne.fr/
[51] J. D'Hernoncourt ,M. Cordier and D. Hadley, "Input-Output Multipliers – Specification sheet and supporting material",*Spicosa project report*, 2011
[52] OES, "International levelised cost of energy for ocean energy technologies", 2015
[53] Available: https://ec.europa.eu/eurostat/fr/web/products-manuals-and-guidelines/-/ks-ra-07-015
[54] S.Kahouli, and J.C Martin, "Assessment of regional economic impacts of an offshore wind project: a French case study", Amure Publications, Working Papers Series D-38-2015, 62p.
[55] H. Boye, E. Caquot, P. Clement, L. de La Cochetiere, J.-M. NATAF and S. Philippe, "Rapport de la mission d'étude sur les énergies marines renouvelables," 2013.