Standard methodology for tidal array project optimisation: An idealized study of the Minas Passage

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***Abstract*—This proceeding describes the principles as well as an idealised application of a standard methodology designed for tidal array project optimisation. In essence, this iterative method defines, in a systematic fashion, how to design the most adapted optimisation strategy to a particular project. This coupled optimisation system accounts for both hydrodynamic and techno-economic aspects and has lead to an improvement of 63% of the internal rate of return compared to a non-optimised scenario. This proceeding also investigates comprehensive metrics and benchmarks for tidal array optimisation based on both environmental and socio-economic aspects of the project site by investigating the sensitivity of a set of optimisation levers and analysing array-induced hydrodynamic-impacts. Future work will involve accounting for additional constraints based on limiting environmental impacts.**

***Index Terms*—Tidal array optimisation, numerical modelling, resource assessment, environmental impacts, standard methodology**

I. Introduction

To date, some 190 tidal power sites have been identified off Canada's coasts with a total estimated capacity of 42,000 MW, which is equivalent to more than 63 percent of the country's annual total consumption. Tidal Energy Converters (TECs) deployed in arrays are one of the most promising solution to efficiently capture this carbon neutral energy resource. Indeed, in contrast to tidal barrages, TEC arrays permit a higher concentration of devices without entirely blocking the tidal flow and thus avoid drastic changes in the hydrodynamics of the site while minimizing the overall cost, by allowing for shared maintenance and grid connection expenses. Whilst the tidal energy industry grows and commercial-scale TEC array projects emerge, the optimisation of TEC arrays becomes prudent to improve financial viability and limit environmental impacts.

Unfortunately, the most efficient solution of such a multi-objective complex problem is rarely the obvious one. TEC arrays must be optimised in order to achieve maximum performance. This optimisation may encompass a number of different aspects such as device placement, control system design, deployment strategy, structure and foundation types, operation and maintenance costs, power generation and connection, and electricity tariffs. All of these parameters are interconnected through the hydrodynamics governing the flow surrounding the considered array and requires cutting-edge numerical methods in order to be appropriately addressed and optimised. A collaboration between the authors has enabled this study to move one step forward by numerically simulating the presence of such underwater power-plants, assessing both their potential hydrodynamic impacts and financial viability and also generating alternative array layouts of enhanced power generation.

As the industry grows, the need to standardise methods and metrics becomes crucial in order to increase resource and impact assessment accuracy, improve business models, reduce investment risks and, thus, successfully develop sustainable tidal energy projects. Several industrial and research collaborations have put substantial efforts and led ambitious projects addressing this need in past ten years or so. Examples of such collaborations include the Internal Electrotechnical Commission, the National Renewable Energy Laboratory, Equimar, and France Energy Marine. Yet the process of standardisation has left out an important piece of any commercial-scale project: optimisation. Due to its complexity and project-specific nature, it appears almost impossible to propose a standard set of optimisation metrics and benchmarks which would be applicable and relevant for every tidal energy project. Nonetheless, in a effort to engage this standardisation process, rather than standardised metrics, the present document lay the founding principles of a standardised optimisation approach.

The proposed approach assumes that accurate resource assessment have been carried out beforehand. This also implies a high level of confidence in the hydrodynamic model, thus, the access to a solid in-situ measurement database as well as model verification and validation. Similarly, by this stage, the appraisals of the local economic factors and supply chain should have been conducted. Although originally applied to computer science, Donald Knuths famous quote also applies here, Premature optimisation is the root of all evil [1]. The proposed methodology can be summarised in seven steps:

1) Definition & evaluation of the baseline
2) Definition of constraints
3) Definition of aims
4) Definition of levers
5) Configuration and execution of the optimisation system
6) Evaluation of the optimum scenario
7) Return to step-2 if needed

This optimisation methodology is semi-automatic in the sense that some steps can be automated, for instance the execution of step 5, while other steps require manual intervention and expertise knowledge, for instance the environmental impact definition of step 2. These manual decisions need to be re-evaluated after each iteration.

II. Background

The optimisation of industry-scale tidal farms arrays is a challenging problem due to the large number of design variables (at a minimum the number of turbines and their position), and because the turbine performance is very sensitive to the speed of the flow [2]. In addition, the hydrodynamics in the farm, and potentially even far outside the farm, are substantially affected by the installation of tidal turbines. Hence, the feedback of the farm on the flow cannot be neglected, resulting in an optimisation problem that is coupled to the hydrodynamic equations.

Different approaches have been used for the tidal farm optimisation problem. Simplified, analytical models provide a first estimate for the potential of a tidal resource, and how the farm performance depends on its configuration [3], [4]. Numerical models that solve the three-dimensional or depth-averaged Navier-Stokes equations combined with a turbine model predict the farm performance more accurately than the simplified models. However, due to the computational cost of these models, typically a handful of farm configurations are selected and compared in practice [5]–[10]. Due to the large number of farm design parameters, such a manual approach is not feasible for finding the optimal farm configuration. This limitation can be overcome by combining efficient derivative-based optimisation methods with the hydrodynamic model and its adjoint version. This idea was first implemented in [11] and has subsequently been extended to include costs such as cabling [12], and to a coarser scale optimisation in which a spatially varying turbine density function is optimised instead of the position of each turbine [13].

Limited work has been done to study environmental impact due to limitations in modeling capability, devices in the water to study, and funding. A proposed metric for generalizing the overall impact of a turbine farm is the Significant Impact Factor (SIF) [14]. The SIF is used as a rough approximation of the percent of energy in a system that can be removed via power production without severe environmental and economic impact. The SIF ranges in value from a low 10%, representing more sensitive areas, to a more generous 50%. This metric is a useful straight-forward approximation to the level of extractable energy in an area of interest, but it does not take into account the detailed local characteristics in a region nor does it account for any particular impacts to the system. It is used to give a range in possible outcomes for the extractable energy (e.g. [15]).

Modeling of particular sites has lead to more information about potential impacts of tidal farms on the surrounding areas. Results from one-dimensional, time-dependent channel models of an idealized [16] and realistic [17] estuary system showed a reduction in tidal flux and range, as well as energy, the level of which heavily depended on the amount of energy removed from the systems, where the energy was removed from (and at how many places), and the geometry and energy in the system. A two-dimensional model showed potential major impacts to tidal range in the Bay of Fundy with major extraction due to nudging the nearly-resonant system closer to resonance [18]. Another study used a two-dimensional model to investigate the risk of flooding due to a tidal farm [19].

Numerous studies have aimed to quantify and model the interdependencies and impacts that technological choices have on the economics of tidal energy projects [20], [21]. Ultimately, these techno-economic studies permit the identification of the main drivers involved in the pricing of tidal energy. Nonetheless, in order to sustainably and accurately drive the cost of tidal energy down and thus compete with other, more mature renewable energy technologies, optimisation must encompass simultaneously economic, technological, hydrodynamic, and environmental aspects. An economically viable project is a project that can generate power with the best performance and within acceptable environmental impacts. The following section will address these aspects in turn.

III. Methodology

A. Hydrodynamic optimisation

The farm optimisation problem is solved as a coupled optimisation problem following [13] and [11]. A turbine farm is represented by a turbine density function $d : \Omega \to \mathbb{R}$ over the two-dimensional horizontal domain Ω. This density function describes the number of turbines per square meter, hence areas with high d values represent an area with densely packed turbines, while areas with $d = 0$ are turbine-free areas.

The main objective of the optimisation is to find the turbine density function d which maximises

$$\max_{d:\Omega\to\mathbb{R}} \text{Revenue}(d) - \text{Cost}(d) - \text{EnvImpact}(d).$$

This objective consists of three competing targets: the farm's revenue over its lifetime, its total costs, and its environmental impact. To be consistent, all targets must be converted into the same unit, typically a currency. The details of the environmental impact objective will be discussed in section III-B. The revenue and cost objectives are defined as

$$\begin{aligned}
\text{Revenue}(d) &= Ik\text{Power}(d)\mathrm{d}x,\\
\text{Power}(d) &= \frac{1}{2}\rho C_T A_T \int_0^L \int_\Omega d\|\mathbf{u}\|^3 \mathrm{d}x\mathrm{d}t,\\
\text{Cost}(d) &= C\int_\Omega d\mathrm{d}x.
\end{aligned}$$

Here, I is the income per energy unit, k is a energy loss factor due to mechanical and electrical losses, ρ is the density of water, C_T is the turbine's thrust coefficient, A_T is the turbines's cross section area, L is the farm's lifetime, $\mathbf{u}$ is the depth-averaged water velocity, and C denotes the cost per turbine (note that $\int_\Omega d\mathrm{d}x$ is the total number of turbines in the farm).

Both the farm's revenue and the environmental impact depend on the water velocity $\mathbf{u}$. Since the farm has a significant impact on the hydrodynamics, this dependency must be implicitly taken into account by solving the non-linear shallow water equations

$$\begin{aligned} \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} - \nu\nabla^2\mathbf{u} + g\nabla\eta + \frac{c_b + \frac{1}{2}C_T A_T d}{H}\|\mathbf{u}\|\mathbf{u} &= 0, \\ \frac{\partial \eta}{\partial t} + \nabla\cdot(H\mathbf{u}) &= 0, \end{aligned} \tag{1}$$

with appropriate boundary conditions. Here, $\mathbf{u}$ is the depth averaged velocity, ν is a kinematic viscosity, g is the gravitational acceleration, η is the free-surface displacement, $H = h + \eta$ is the total water depth, and c_b is the natural bottom friction coefficient. The effects of the turbine farm are incorporated as an additional bottom friction term in the momentum equation.

In summary, the farm optimisation problem can be formulated as a maximisation problem

$$\max_{d:\Omega\to\mathbb{R}} \text{Revenue}(d, \mathbf{u}) - \text{Cost}(d) - \text{EnvImpact}(d, \mathbf{u}),$$

where $\mathbf{u}$ is the solution to the shallow water equations (1). In addition, we enforce that the turbine density satisfies the constraints

$$\begin{aligned} 0 \le d \le \bar{d} \qquad & \text{in } \Omega_{\text{farm}}, \\ d = 0 \qquad & \text{in } \Omega \setminus \Omega_{\text{farm}}. \end{aligned}$$

That is, turbines may be only installed in the farm area and the maximum turbine density is limited by a turbine-specific value $\bar{d}$.

We find the solution of this optimisation problem with an iterative procedure. Each iteration consists of three steps:

1) solve the shallow water equations for the latest (or an initial) turbine density d and compute the objective value;
2) solve the adjoint equations to compute the sensitivity of the objective with respect to changes in d;
3) apply the L-BFGS-B optimisation method [22] to obtain an improved turbine density d.

This approach is implemented in the open-source package OpenTidalFarm and the finite-element library FEniCS [23]. For more details on this optimisation approach we refer to [11] and [13].

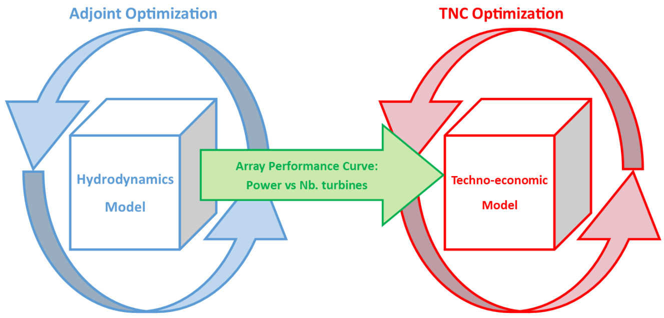

Fig. 1. Optimisation system

B. Environmental impact metrics

While producing enough electricity at a low enough cost for economic viability is ultimately necessary for a tidal farm to be employed, environmental impacts should also be considered in turbine farm deployment. A range of environmental impacts are possible, including changes to sediment transport, marine mammal and fish behavior, flow fields, and many more. In this work, a small subset of the wide range of possible environmental impact metrics are considered: changes due to tidal farms to the free surface, flow fields, and vertical vorticity, where the vorticity is defined as $\partial\mathbf{u}_y/\partial x - \partial\mathbf{u}_x/\partial y$. The metrics were chosen due both to availability in our two-dimensional model approach and to their basic relevance to turbine siting. These changes can be expected to be seen in both space and time, but will be viewed primarily as averages over a tidal cycle. Changes to the free surface elevation can be important in particular domains, such as the Bay of Fundy, in which the tidal signal is close to resonance [18]. The speed is expected to be reduced since the turbines extract energy from the kinetic energy available in the system; however, the pattern of this reduction may be important, and may need to be limited to a particular value. Changes in the vorticity might be usable as a proxy for transport changes to the system, and could potentially effect where material travels downstream of a turbine farm. Investigating these representations of environmental impacts and, eventually, incorporating them as constraints into the optimisation system, will mitigate detrimental effects from the farms while preserving power production and economic viability.

C. Techno-economic (T.E.) model

1) T.E. Model description: This numerical model is a suite of functions written in Python that gather a multitude of cost factors, financial parameters, and deployment strategy options leading to the calculation of economic markers and thus the assessment of the techno-economic viability of a given tidal array project and site. Only the relevant functions and economic metrics embedded in the T.E. model are presently detailed; table I gathers all the input parameters of the T.E. model as well as their acronyms and related project's sector. Unfortunately, some baseline values cannot be shared due to non-disclosure agreements.

Acronym	Definition	Baseline value	Sector
Nt	Number of turbines	320.0	
Diam	Turbine Diameter (m)	17.0	Turbine design
Cutin	Cut-in speed (m/s)	1.0	
Cutout	Cut-out speed (m/s)	3.0	
Cp	Power coefficient	0.4275	
Ct	Thrust coefficient	0.86	
Q	Array perf.: number of turbine vs capacity	N.A.	N.A.
TE	Transmission efficiency (%)	90.0	Grid connection
CC	Cable cost + installation per km (k$/km)	N.D.	
OS	Onshore Substation (k$)	N.D.	
GC	Inter-array connection per unit (k$/Unit)	N.D.	
Cable	Cable length (km)	20.0	
SRC	"Small repair" (SR) cost (k$)	N.D.	O & M
SPC	"Small part replacement" (SP) cost (k$)	N.D.	
LPC	"Large part replacement" (LP) cost (k$)	N.D.	
SRF	SR annual frequency per unit (1/y/unit)	2.75	
SPF	SP annual frequency per unit (1/y/unit	2.0	
LPF	LP annual frequency per unit (1/y/unit)	0.25	
SRDR	SR work boat daily rate (k$/days)	N.D.	
SPDR	SP support vessel daily rate (k$/day)	N.D.	
LPDR	LP Jack-up barge daily rate (k$/day)	N.D.	
SRTT	SR boat transit time (day/km)	0.00083	
SPTT	SP vessel transit time (day/km)	0.0017	
LPTT	LP barge transit time (day/km)	0.0028	
TECA	% of TEC availability	85.0	
Port	Distance from maintenance port (km)	50.0	
IND	Needed days for installation per unit	80.0	
OMC	Monitoring & control annual cost (k$/y)	N.D.	
MC	Management cost (k$/y)	N.D.	
IC	Insurance annual cost (k$/y)	N.D.	
OMC	Monitoring & control annual cost (k$/y)	N.D.	Installation
DND	Needed days for decommission per unit	30.0	
IDDR	Installation/Decommission vessel daily rate (k$/day)	N.D.	
DC	Decommissioning cost per turbine per km (k$/Unit)	N.D.	
IVTT	installation/decommission vessel transit time (day/km)	0.0032	
InstPort	Distance from installation/manufacturing port (km)	200.0	
SC	Structure cost per unit (k$/Unit)	N.D.	Individual turbine cost
FC	Foundation cost per unit (k$/Unit)	N.D.	
CSC	Control system cost per unit (k$/Unit)	N.D.	
PTOC	PTO cost per unit (k$/Unit)	N.D.	
SSC	Site surveys cost per km2 (k$/km2)	200.0	
PLT	Project life time (years)	25.0	Deployment strategy
UIY	Units installed per year	5.0	
YFD	Year of first deployment (year)	2.0	
Berth	Berth area (km2)	1.6	
LR	Learning rate (%)	11.0	
G	Grants (k$)	1000.0	Financing
CoC	Commissioning cost (k$)	N.D.	
SV	Salvage value as % of CAPEX (%)	20.0	
DTR	Discounted Tax rate (%)	11.0	
ET	Electricity tariffs post-FIT ($/MWh)	200.0	

TABLE I
PARAMETERS OF THE T.E. MODEL AND THEIR BASELINE VALUES. N.A. DENOTES "NOT APPLICABLE" AND N.D. DENOTES "NOT DISCLOSED"

The capital costs are calculated on a yearly basis as the summation of the fixed costs due to the development of the project site itself (i.e. commissioning, site studies, grid connection) plus the cost of each installed turbine (i.e. device cost plus installation cost). The former is spend between Year 0 of the project and the Year of First Deployment (YFD); the latter cumulatively increases with the number of Units Installed per Year (UIY).

The Operation and Maintenance (O&M) costs are also calculated on a yearly basis and account for the price of small repairs, small and large part replacements (i.e. SRC, SPC, LPC), their frequencies and process periods (i.e. SRF, SPF, LPF) and logistic costs (daily rates and speed) for different-sized boats. All these O&M parameters are functions of the distance to the maintenance port (Port). Monitoring and control costs (OMC) are also accounted for in the O&M balance.

In this model, the grid connection aspects have been substantially simplified. The cable cost and its installation (CC) is a function of the cable length (Cable) whereas the inter-array connection (GC) is a function of the number of turbine installed. The overall costs also accounts for the price of an onshore substation (OS).

The concepts of "learning curve" and "cost reduction by learning" play an important role in this model. They rely on the idea that as tidal turbines are being installed around the world and the supply chain is being established, the manufacturing and operating costs of such technology decrease thanks to the experience gained by the industry [24]. In the present study the cost reduction CR due to learning is calculated with

$$CR(t) = (1 - LR)^{\log_2(\frac{ICFns(t)+ICFww(t)+ICp(t)}{50.0})}.$$

Here LR is the learning rate, $ICFns$ the installed capacity forecast in Nova Scotia, $ICFww$ the installed capacity forecast worldwide, $ICFp$ the installed capacity forecast in the current project, t the time in years and 50.0 being the increment value in MW. One should notice that this learning curve is thus very dependent of the tidal energy production forecast [25].

This T.E. model has been made particular to the Bay of Fundy by integrating in its revenue stream function Nova Scotia's feed-in tariffs (FIT). It is assumed in the present study that the "developmental" FIT applies. This highly ambitious scheme aims to boost the entire industry growth and experience by guaranteeing a tariff of $530 per megawatt hour for the first 16,560 megawatt hours produced in a year and $420 per megawatt hour for any energy produced above 16,560 megawatt hours per year for the first 15 years of the project[1]. Note that the generated power itself is impacted by transmission efficiency (TE) and turbine availability (TECA).

From a financial point of view, one can also notice the integration of grants (G), salvage value (SV), discounted tax rate (DTR), and an electricity tariff post-feed-in-tariff (ET). The T.E. model also permits try and/or optimise array deployment strategies by using the total number of turbine (Nt) in the array, the project life time (PLT), YFD, and UIY as input variables.

Among all the different economical benchmarks available in this T.E. model, three will be used in this study, namely the Internal Rate of Return (IRR), the Levelized Cost Of Energy (LCOE) and the Overall Benefit (OB). The IRR defines the "average" periodically compounded rate of return that gives a net present value PV of 0.0 [26] and in capital budgeting to measure and compare the profitability of investments. The LCOE is usually used to assess a projects financial feasibility and if calculated as usually done by Utilities [24]:

$$LCOE = \frac{PV(Cc + Dc + AOMc)}{PV(EPOLP)} \tag{2}$$

where Cc represents the capital cost, Dc the decommissioning cost, $AOMc$ the annualized O&M costs and $EPOLP$ the Energy produced over life of project. Finally, the Overall Benefit (OB) represents the cumulative balance of the costs minus the revenue (i.e. including salvage value) over the entire life time of the project hereafter expressed in M$.

[1] http://fundyforce.ca/fee/

Water density	$\rho =$	1000 kgm^{-3}
Gravitational acceleration	$g =$	9.81 ms^{-2}
Bottom friction	$c_b =$	0.0025
Turbine thrust coefficient	$C_T =$	0.86
Turbine cross section	$A_T =$	219 m^2
Water depth at rest	$h =$	40 m
Kinematic viscosity	$\nu =$	40 m^2s^{-1}
Minimal distance between two turbines		48 m
Maximum turbine density	$\bar{d} =$	$4.34 \cdot 10^{-4}$ m^{-2}

TABLE II

SETTINGS USED FOR THE NUMERICAL EXPERIMENTS

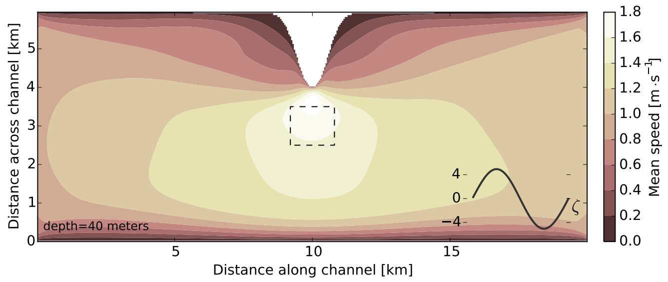

Fig. 2. The base case simulation with no turbines: an east-west channel with a headland protruding from the north wall. The channel is 40 m deep and the simulations are all analysed for a single M_2 tidal cycle after one cycle of ramp up time. The dashed box indicates the lease and potential deployment area for turbines in subsequent simulations. Color indicates the speed averaged over one tidal cycle.

2) Sensitivity analysis methodology: Gardner et al (2015) [27] apply a simple finite-difference approach to study the effects of the T.E. model output with respect to changes to its inputs. It consists of moving one input variable in the model, keeping others at their baseline (nominal) values, assessing the impact of this change on the outputs, then, returning the variable to its nominal value and then repeating for each of the other inputs in the same way [28]. Additionally, the same relative change (i.e. 10%) has been applied to each input. This permits one to quantify the importance, or "weight", of each input relative to one another as regards to their impact on the outputs. This sensitivity analysis approach has a drawback however as its outcomes are fully dependent on the chosen baseline values and thus is entirely case, or project, specific.

3) T.E. optimisation scheme: The optimisation scheme applied to the T.E. model is referred as "TNC" method. This constrained optimisation uses a truncated Newton algorithm (also known as Newton conjugate-gradient method) [29], to minimize a function with variables subject to bounds. This algorithm uses gradient information, which are obtained using finite differencing.

IV. RESULTS & ANALYSIS

We use an idealised simulation to illustrate the proposed methodology. We ran a two-dimensional simulation using OpenTidalFarm [11], with a channel that is 20 km long, 6 km across, and 40 m deep (see figure 2). The horizontal resolution ranges from 50 m within the lease site near the headland to 100 m at the inlets of the channel; the rectangular, 1.6 km (along-channel) by 1 km, lease site is gridded with structured triangles (right triangles) and outside of the lease site with unstructured triangles. This simulation is intended to be an idealized representation of Minas Passage in the Bay of Fundy, Canada, an area of interest for tidal energy development. The depth for the channel was chosen by averaging the bathymetry in the corresponding area in and around Minas Passage (figure 3). The M_2 tide is the dominant tidal constituent in the Minas Passage and is used to force the headland simulation with a realistic amplitude of 5 m [18]. The free surface is forced at the west boundary with a sine wave of M_2 frequency and at the east boundary with the same form but with a phase difference approximated assuming a propagating wave down the channel. The shallow water equations are spatially discretised using the finite element method with the P2-P1 element pair. In time, we applied a θ-timestepping scheme with $\theta = 0.6$. The remaining model settings are listed in table II. In the resulting simulation, the peak speed is near 3 ms^{-1} with average speed near the headland approximately 1.7 ms^{-1} (figure 2), and the vertical vorticity reaches a maximum of about 0.01 s^{-1}.

Then, we applied the 7 steps of the proposed methodology.

1) Definition & evaluation of the baseline
   This step consists in defining, through educated guesses, a non-optimised case which will be used as a baseline and comparison benchmark for the rest of the optimisation. In particular, this step should focus on defining the hydrodynamic and environmental metrics and limit levels to monitor.
   To start our framework, we ran an initial non-optimised farm deployment which simulated turbines homogeneously in the lease area and which was otherwise identical to the base case described previously and shown in figure 2. As in the base case, this simulation is two-dimensional in x and y. The friction level chosen for the homogeneous case approximately represents a uniformly-deployed farm of 320 turbines. This non-optimised scenario will be used as hydrodynamic and array performance baseline in the next steps of the standard optimisation methodology.
   The turbines affect all flow fields calculated by OpenTidalFarm. The free surface is, on average, only marginally impacted, with an average increase of up to about 2.5 cm near the headland tip and less to the sides of the headland, and a small decrease of less than 1 cm on the side of the farm opposite the headland (not shown). The speed is decreased within the farm area and downstream (figure 4), and vertical vorticity is generated by the presence of the farm (figure 5).
   Changes due to the turbine farm can be better seen in comparisons of averages over the tidal cycle. The speed is decreased due to the farm within the farm and downstream on both cycles (represented by blue), but increased in a smaller area between the farm and the headland (figure 6). The vorticity is increased on the south end of the farm (represented by orange) since it is

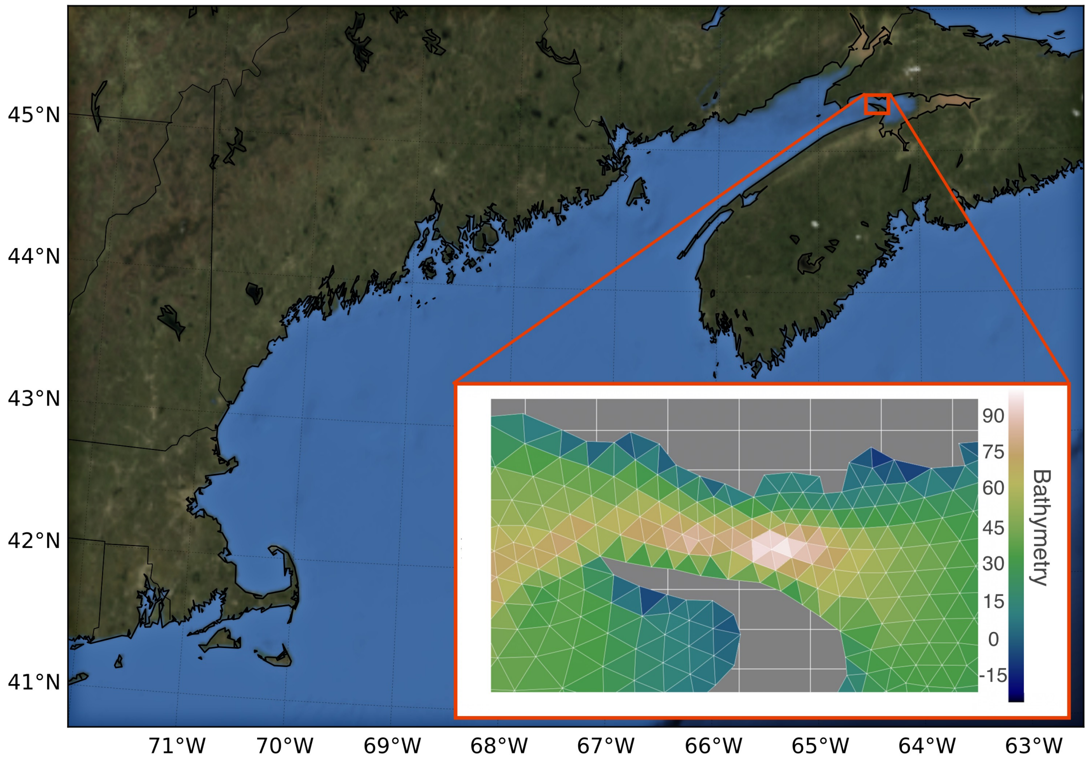

Fig. 3. Bathymetry and the coastline of Minas Passage, Bay of Fundy, Canada from a simulation of the Gulf of Maine run in FVCOM [30].

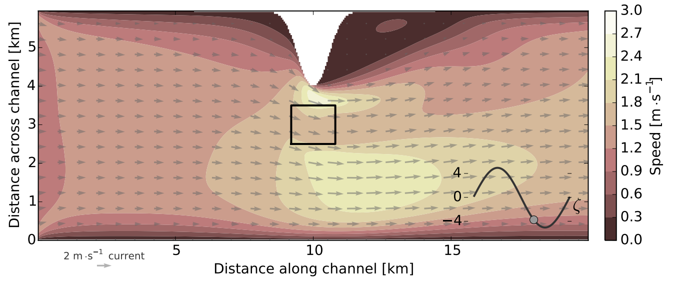

Fig. 4. The non-optimised example scenario with a homogeneous turbine farm near the headland tip (black box). Simulated speed at one particular time near peak flood tide is shown in shades of pink with overlaid arrows indicating the corresponding velocity field. A subplot in the lower right indicates the time in the tidal cycle shown on the free surface elevation, ζ.

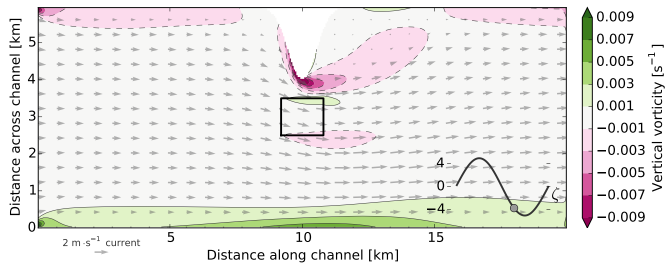

Fig. 5. Vertical vorticity for the non-optimised scenario. The same time and details are shown as in figure 4.

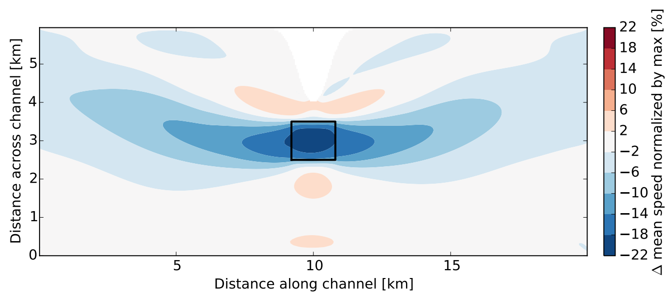

Fig. 6. The mean speed for the non-optimised scenario minus the mean speed for the base case, normalized by the maximum base case speed, presented as a percent. Positive (red) indicates an increase due to the turbine farm and negative (blue) indicates a decrease.

generated by the farm itself (figure 7). It is also generated on the north end, but this effect is not seen in the overall change in average vorticity since the placement of the farm also decreases the vorticity generated by the headland near the north end of the farm. Overall, these two effects are seen as a decrease in the vorticity due to the turbine farm.

The capital investment balance of the non-optimized case is described by figure 8.

2) Constraints

There can be many constraints to a project and they can span over different areas of expertise. For example,

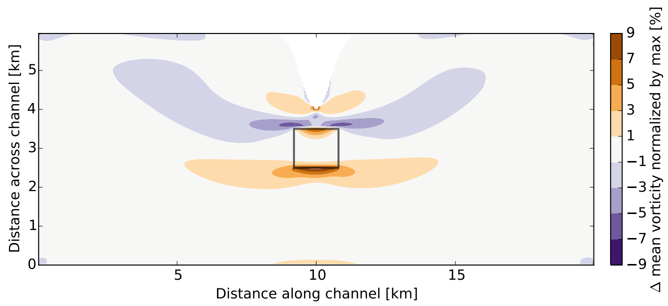

Fig. 7. The mean absolute value of the vorticity for the non-optimised scenario minus the mean absolute value of the vorticity for the base case, normalized by the maximum base case vorticity, presented as a percent. Positive (orange) indicates an increase due to the turbine farm and negative (purple) indicates a decrease.

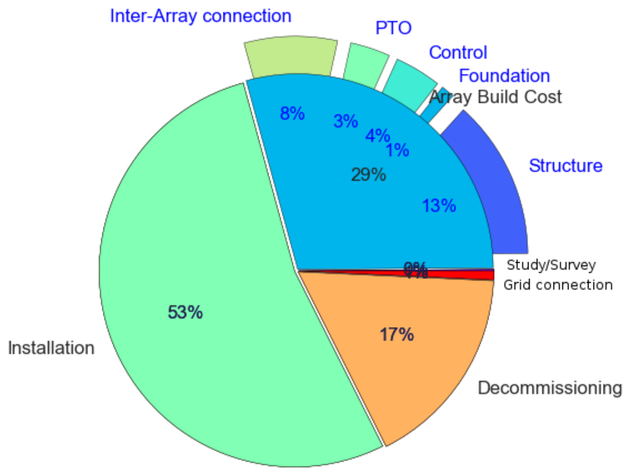

Fig. 8. Capital investment balance for non-optimized scenario. notes: Study/Survey = 0.2% and Grid Connection = 0.8%

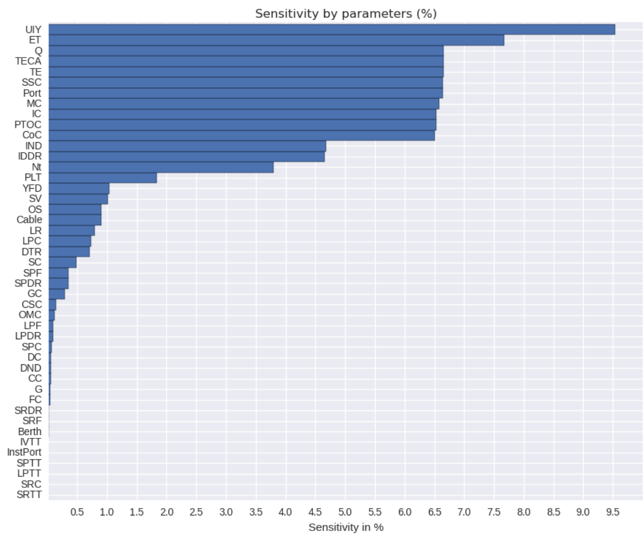

Fig. 9. Sensitivity by T.E. model's parameters

engineering constraints may encompass bathymetric gradients, sea bed geophysics, grid capacity, device operating window, sea users, etc. Environmental constraints can be related to marine life, sedimentation, tidal wave propagation, fisheries, etc. Economic and strategic constraints such as local tax policies, investors requirements, supply chain, port logistics and facilities, etc, could also defined. In essence the constraints are project-specific. They are also very important in the optimisation approach as they cap the magnitude range and/or define the static value of the optimisation variables.

Due to the assumptions inherent in idealised cases, the set of constraints has been greatly simplified here. It is considered that only one type of device technology and design is available. Grid, cable, O&M and installation logistics and facilities are also considered as imposed. Similarly, the project life time and financial aspects are considered fixed.

3) Aims

While the constraints are project specific, aims can be better seen as stakeholder-specific. Depending on one's involvement and progress into a project, the chosen set of aims may vary. One can easily conceive that, although partners of a same project, an investor, a policy-maker and a device developer would have very different goals and agendas. The optimisation tool that would be used must therefore be adapted to one's aims. Nonetheless, in most cases, these aims will involve multiple benchmarks and economic markers.

In the present case, the stake of the site developer shall be optimised. Three economic markers shall be used as optimisation target, namely minimum LCOE, maximum IRR and maximum OB. For the sake of the exercise and associated findings, these three makers will be optimisation separately rather than in conjunction.

4) Levers

Taking out out constraints and aims from the set of variables, one is only left with potential optimisation inputs, hereafter called levers. Yet levers are not equal in regard to their impact on the previously defined aims. Additionally, depending on one's models, sets of levers might be grouped around common strategies and optimisation schemes. Sensitivity analysis appears as the most relevant method to address this step of the standard optimisation methodology. Rather than working out which variables have the most impact on the defined aims, this analysis identifies where in the model accuracy is the most needed and thus where the risks due to misassessment are the highest. Optimisation efforts should then be focused in these areas for efficiency. Furthermore, by using more advanced sensitivity methods such as regression analysis [31] or variance-based methods [32], relationships between variables and aims could be simplified and thus decrease the model's computational cost where high accuracy is not needed.

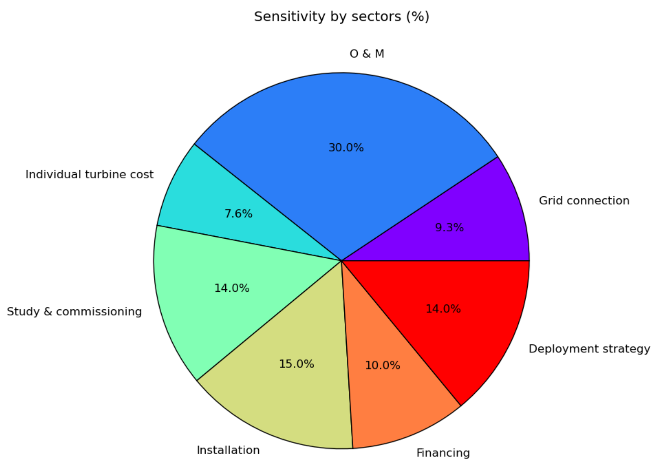

Fig. 10. Sensitivity by project's sectors

Figure 9 gathers the results of a finite-difference sensitivity analysis (section III-C2) conducted on the T.E. model (section III-C3). It clearly shows that some parameters have more impact on the aims than others. Scanning through the first parameters with the highest influence, some of them seems obvious, and others do not. While the electricity tariff post-FIT (ET), the array performance (Q), transmission efficiency (TE) and the turbine availability (TECA) were expected to have important influence on the LCOE, IRR and OB, parameters such as the number of units installed per year (UIY), the number of days for installation per turbine (IND) or the distance to the maintenance port (Port) may not have been considered as important *a priori*. Once again, the present analysis is only relevant for this project and greatly dependent on the chosen baseline values.

In figure 10, all the parameters' sensitivity have been regrouped and normalized per sector. This representation permits assessment of which aspects of the project are worth optimising. However, this sensitivity representation has to be treated with caution as it is also dependent on the level of complexity and the number of parameters used to formulate each sector's behaviour. Here "O&M" may appear as an obvious choice for strategy optimisation whereas "grid connection" optimisation may be less important. In the case of the latter, it is believed to be artificially induced by the simplifications used in the T.E. model. Nevertheless, accordingly to the assumed constraints in step-2 of the standard optimisation methodology, only the "deployment strategy" will be subject to optimisation. Consequently, the optimisation levers will be the number of turbine (Nt), the the number of units installed per year (UIY), the year of first deployment (YFD) and the array performance (Q). The ranges of magnitude applied in this case are defined as follows:

Lever	Range of magnitude
Nt	(10 - 600) turbines
UIY	(1 - 30) deployed turbines per year
YFD	(1 - 10) year
Q	(10 - 600) deployed turbines

5) Optimisation System
Once the constraints, aims and levers are defined, one has all the required elements to build the most relevant optimisation system. As for the above, this crucial step is project-specific and the means used for it are totally dependent on the user's aims. Most importantly, the so-built optimisation system has to cover necessary techno-economic aspects and site hydrodynamics relevant to the addressed problem. Additionally, numerical implementation complexity and related computational cost should be spent only where needed in order to obtain the most efficient and least time-consuming optimisation process. One can imagine, for instance, a case where an investor wants to know what is the minimum installed capacity required to make a profitable business model. In this particular scenario, the power generation becomes an aim rather than a lever, the hydrodynamic aspects could be totally neglected, and thus the optimisation system would be designed and adapted for focusing on the rest of the problem. In the present case, both tidal array hydrodynamics and techno-economic strategies have to be modelled and optimised to achieve our aims. The proposed optimisation system is illustrated in figure 1. In this figure, the looping arrows represent the local optimisation, the cubes represent the models used and the straight arrow the information exchange between optimising models. The hydrodynamic model and optimisation is detailed in section III-A whereas the techno-economic model and optimisation is described in section III-C. From the lever point of view, Nt, UIY and YFD shall be optimised by the T.E. model whereas Q shall be optimised in the hydrodynamic model. This one-way system with successive optimisation can be qualified as "weak" coupling. This optimisation system does, however, meet the requirements defined by step-5 of the standard optimisation methodology discussed in section I.

6) Optimum scenario evaluation
The last step of the proposed standard optimisation methodology is the evaluation of the so-obtained optimum scenario. This step consists of performing a comparison with the baseline case (step-1) in order to assess the level of optimisation achieved on the aims but also monitor the hydrodynamic metrics and limit levels previously defined. In the possible eventuality that this level of optimisation is negligible, one should go back to step-2 and go through all the steps again in order to revise the optimisation strategy and eventually find the strategy that is best adapted to the project. As mentioned earlier, in the present study, three separate optimisations have been performed, each targeting different aims, namely LCOE,

No. turbines	Avg. power production (MW) non-optimised	optimised	Improvement (%)
19	10.5	12.1	15.3
45	23.4	25.4	8.8
88	41.3	44.0	6.5
152	62.1	64.7	4.3
249	84.0	87.5	4.2
365	100.6	105.0	4.4

TABLE III

FARM POWER PRODUCTIONS WITH A NON-OPTIMISED LAYOUT (REGULAR DEPLOYMENT), AND THE OPTIMISED LAYOUT FROM THE HYDRODYNAMIC OPTIMISATION.

Aim	Optimized levers			Optimisation (%)		
	Nt	UIY	YFD	Tech.-Eco.	Hydro.	Both
LCOE	20.0	1.0	1.0	11.1	5.7	22.2
IRR	120.0	11.5	6.0	35.6	28.6	63.0
OB	155.0	14.5	3	185.0	35.0	223.8

TABLE IV

OPTIMISED LEVERS AND RESULTS FOR STANDALONE TECHNO-ECONOMIC, STANDALONE HYDRODYNAMIC AND JOINT OPTIMISATIONS

IRR and OB. Although expected, the optimum values for each lever differs a lot depending on the targeted aim (table IV).

Example snapshots, from the same time as shown in figures 4 and 5, for the optimised scenario are shown in figures 11 and 12. The turbine field is no longer homogeneous and has more turbines closer to the headland. This leads to a smaller impact to the speed (figure 11), as compared with the non-optimised case shown in figure 4, as well as to the vorticity (figure 12), as compared with figure 5. Accordingly, the difference in mean speed (figure 13) and mean vorticity (figure 14) between this optimised case and the no-turbine case is smaller than in the non-optimised case.

The results of the hydrodynamic optimisation are summarised in table III. As a general rule, it appears that using an adapted optimisation system, and thus performing joint optimisations, leads to higher improvement than using standalone optimisations. This proves the importance and benefit of step-5 of the standard methodology. The improvement of the overall benefit (OB) seems dubiously high. This can be explained by the lack of capital investment constraint and the fact that the baseline case shows poor results in terms of OB. Another interpretation could be that OB is not a relevant benchmark or marker for such optimisation and that cost/benefit ratio would be more appropriate. One should note that the optimised number of turbines installed is always a lot smaller than the number of turbines installed in the non-optimised case. This is mostly due to the fact that the turbines used in this study were designed for faster flow leading to a mismatch between their costs and generated power.

V. CONCLUSIONS & FUTURE WORK

Although its means of application are case specific, the proposed standard methodology for tidal array project has shown itself to be a thought process, relevant and applicable to any given project. This approach helps the design of a holistic optimisation system leading to better improvements than standalone optimisation.

Nonetheless, in regard to its application in the present study, a few limitations are worth noting. The hydrodynamic behaviours taking place within the tidal array have a great impact on the entire system, from resource and impact assessment to the device design and failure rate. Therefore, the accuracy of the turbine representation in the hydrodynamic model could be examined and improved. Similarly, some sector of the project, such as the grid connection or the installation

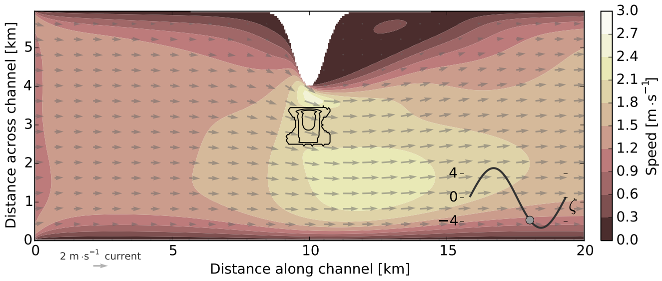

Fig. 11. The optimised example scenario with a nonhomogeneous turbine farm near the headland tip (black contours — more contours indicate more friction and therefore more turbines). Simulated speed at one particular time near peak flood tide is shown in shades of pink with overlaid arrows indicating the corresponding velocity field. A subplot in the lower right indicates the time in the tidal cycle shown on the free surface elevation, ζ.

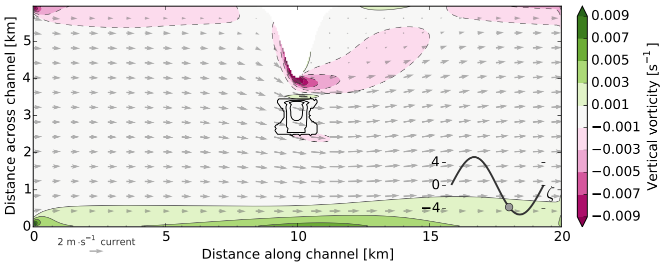

Fig. 12. Vertical vorticity for the optimised scenario. The same time and details are shown as in figure 11.

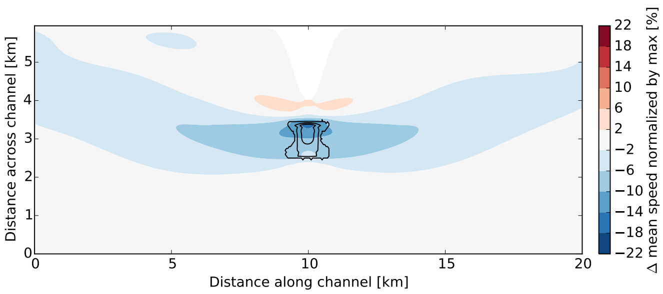

Fig. 13. The mean speed for the optimised scenario minus the mean speed for the base case, normalized by the maximum base case speed, presented as a percent. Positive (red) indicates an increase due to the turbine farm and negative (blue) indicates a decrease.

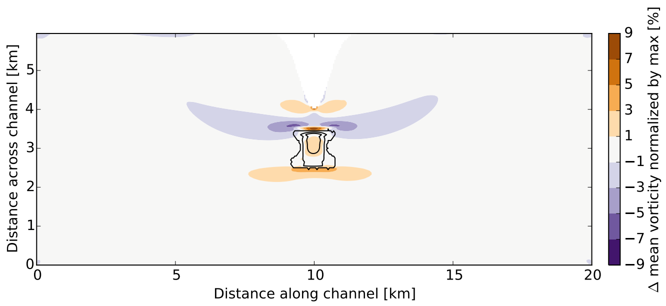

Fig. 14. The mean absolute value of the vorticity for the optimised scenario minus the mean absolute value of the vorticity for the base case, normalized by the maximum base case vorticity, presented as a percent. Positive (orange) indicates an increase due to the turbine farm and negative (purple) indicates a decrease.

strategies, shall have their modelling improved in the T.E. model. Additionally, from the numerical implementation point of view, the implementation of a "hard" or "nested" coupling in the optimisation system would improve both results and computational performance. The T.E. optimisation scheme could also be improved by using multi-objective methods thus permitting optimisation against several different aims at once.

As for the results themselves, one should note the choice of relevant metrics for the optimisation aim formulation is primordial and that some of them, such as the overall benefits, are indissociable of some constraints. Finally, in future work, environmental impacts will be implemented as optimisation constraints rather than simply monitored in order to ensure the sustainable character and long-term economic-viability of tidal array projects.

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