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An integrated model for estimating energy cost of a tidal current turbine farm

Ye Li [a,*], Barbara J. Lence [b], Sander M. Calisal [a,c]

[a] Naval Architecture and Offshore Engineering Laboratory, Department of Mechanical Engineering, The University of British Columbia, 1051-6250 Applied Science Lane, Vancouver, BC, Canada V6T1Z4

[b] Department of Civil Engineering, The University of British Columbia, 2002-6250 Applied Science Lane, Vancouver, BC, Canada V6T1Z4

[c] Piri Reis University Turkey, 34940 Tuzla Istanbul, Turkey

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ABSTRACT

A tidal current turbine is a device for harnessing energy from tidal currents and functions in a manner similar to a wind turbine. A tidal current turbine farm consists of a group of tidal current turbines distributed in a site where high-speed current is available. The accurate prediction of energy cost of a tidal current turbine farm is important to the justification of planning and constructing such a farm. However, the existing approaches used to predict energy cost of tidal current turbine farms oversimplify the hydrodynamic interactions between turbines in energy prediction and oversimplify the operation and maintenance strategies involved in cost estimation as well as related fees. In this paper, we develop a model, which integrates a marine hydrodynamic model with high accuracy for predicting energy output and a comprehensive cost-effective operation and maintenance model for estimating the cost that may be incurred in producing the energy, to predict energy cost from a tidal current turbine farm. This model is expected to be able to simulate more complicated cases and generate more accurate results than existing models. As there is no real tidal current turbine farm, we validate this model with offshore wind studies. Finally, case studies about Vancouver are conducted with a scenario-based analysis. We minimize the energy cost by minimizing the total cost and maximizing the total power output under constraints related to the local conditions (e.g., geological and labor information) and the turbine specifications. The results suggest that tidal current energy is about ready to penetrate the electricity market in some major cities in North America if learning curve for the operational and maintenance is minimum.

1. Introduction

The depletion of traditional energy resources (e.g., fossil fuels) and the degradation of the environment as a result of the fossil fuels consumption urge the global community to seek alternative energy resources, especially renewable resources. A variety of renewable energy resources, such as wind, sun (solar energy), ocean wave and tidal current, are being explored in different countries [1–5]. Particularly, tidal current is regarded as one of the most promising resources [6,7]. The devices used to harness tidal current energy are tidal current turbines, and they function in a manner similar to offshore wind turbines. Similar to a wind turbine farm, a tidal current turbine farm consists of a group of tidal current turbines distributed in a site where high-speed current is available. The development of tidal current turbine farms is marching into the pre-commercial stage.

The construction of a commercial tidal current turbine farm is expected to require substantial investment. Expected energy cost is one of the important factors for the justification of constructing such a farm. The energy cost is defined as the ratio of the total cost to the total energy output over the lifetime of a farm. Mathematically, the energy cost can be estimated by using:

$$c_{energy} = \frac{\sum_i \sum_j levco_{i,j}}{\sum_i \sum_j Energy_{i,j}} \tag{1}$$

where $levco_{i,j}$ and $Energy_{i,j}$ denote levelized cost (present value of the total cost of building and operating a power plant over its economic life time) and energy output of turbine i in the year j, respectively.

Estimating energy cost requires the information on the expected energy output from a tidal current turbine farm and the cost which is the sum of capital cost, fees (e.g., permitting and license) and operation and maintenance (O&M) cost that might be incurred (see Section 2.2 for details). However, it is not practical to conduct experiments to estimate unit cost by building and operating a fairly large scale tidal current turbine farm to obtain information on energy output and total cost. Normally, designers turn

* Corresponding author. Present address: US National Wind Technology Center, National Renewable Energy Lab. 1617 Cole Blvd., Golden, CO 80401, USA. Tel.: +1 303 384 6988.

E-mail address: ye.li@nrel.gov (Y. Li).

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to modeling the farm system to obtain this information. A few models have been proposed for estimating potential energy output from (e.g., [8–10]) and energy cost of (e.g., [9,10]) a tidal current turbine farm. The former papers, which proposed models for estimating energy output from a tidal current turbine farm, all use the efficiency of a stand-alone turbine to represent the efficiency of individual turbines in the farm and neglect the hydrodynamic interactions between turbines. The hydrodynamic interactions between turbines may have significant impact on turbine's efficiency and thus power output and reliability from a tidal current turbine farm [11,12]. The latter papers, which estimated the energy cost, all assume that the O&M cost is equal to a fixed percentage of the capital cost of the tidal current turbine farm. Moreover, the cost associated with licensing and permitting fees were not discussed either, although they are quite noticeable at some extension [13,14]. For example, the licensing fee can be close to the cost of a quarter of the turbine [15]. The permitting and siting fees highly depend on the location of the site. In short, the results based on these simplifications and assumptions are not convincing to investors [16], which is considered as one of the major barriers to the industrialization of tidal current turbine farms [17,18].

In order to improve the accuracy in estimating the energy cost of a tidal current farm, the University of British Columbia (UBC) tidal current energy group have tentatively proposed an approach [19] to calculate energy output and total cost. Specifically, it calculates the energy output by using the method suggested by Li and Calisal [20] which assume that the hydrodynamic interaction between turbines is proportional to the vortex decay rate with respect to the distance and calculates the O&M cost by using a quasi linear method developed by Li and Florig [21]. The generated result is expected to be more accurate than those obtained with the previous approaches, but this approach still has some practical limitation and is rough approximation so that the results may not always convince the investors. Specifically, the method to calculate the energy output and the hydrodynamic interaction [20] cannot accurately predict the energy outputs of farms with some distributions for it treats a turbine as a block, the method for estimating O&M cost [21] cannot accurately handle those nonlinear conditions in the O&M process which may sometimes happen, and necessary fees are not included as well. In this paper, we include the calculation of fees, and use more accurate methods to approximate hydrodynamic interactions between turbines and the O&M cost of the farm and then estimate energy cost with a cost-effectiveness analysis. Cost-effectiveness analysis is a typical analytical approach for comparing the relative expenditure (costs) and outcomes (effects) of two or more courses of action. Specifically, we minimize the energy cost by strategically planning the turbine distribution in a farm with full consideration of the hydrodynamic interactions between turbines (to maximize the energy output from the farm) and strategically selecting O&M plans (to minimize the total cost).

After stating the assumptions that we have made in formulating the model for estimating energy cost in the next section, we then introduce the integrated model (including an integrating module, a hydrodynamic module and an O&M module) that we use to estimate the energy cost. We explain the hydrodynamic module, which is used to calculate power output for a given set of turbines and turbine configuration, after which we present the O&M module with different O&M strategies. As there is neither a real operational tidal current farm nor an existing convincing cost model, we choose to validate our model with published offshore wind farm cost studies. Finally, we apply the integrated model to estimate the energy cost for an example turbine farm, as a case study. We find that, in some areas, the tidal current energy may penetrate the market if the learning curve is minimum and the O&M strategies is optimized.

2. Main structure of the model

The integrated tidal current turbine farm system model consists of three sub-modules, which are the hydrodynamic module, the O&M module, and the integrating module, as shown in Fig. 1. In this model, we use a scenario-based cost-effectiveness analysis to identify the minimum energy cost. The hydrodynamic module calculates hydrodynamic power outputs, P_{hydro}, for the different scenarios, which are combinations of turbine configuration, total number of turbines, and turbine distribution in a farm and identifies the one that achieves the maximum power output. The O&M module calculates the O&M cost for the different scenarios, which are combinations of weather conditions, farm specifications, labor cost, other facility cost (e.g., transportation vehicle cost and maintenance equipment cost) and O&M strategies, and identifies the one that achieves the minimum O&M cost. The integrating module is used firstly to convert the total hydrodynamic power calculated by using the hydrodynamic module to total energy output, then to calculate the total cost by adding the capital cost, the O&M cost and fees together, and finally to estimate energy cost and identify the scenario that achieves the minimum energy cost. In formulating the integrated model for estimating the energy cost, we make the following assumptions:

- Energy losses that are increased from year to year due to equipment degradation are offset by energy gains from improved management strategies and monitoring technologies.
- No electricity transmission cable is shared by two or more turbines. That is to say, one turbine is assigned to one cable.
- Two components on one turbine will not fail at the same time.
- Turbines, during their life time, will not be replaced with turbines having higher efficiency, which may be available in the market due to technological developments, which means that turbine efficiency will not increase over time.
- The traveling distance of maintenance vessels and helicopters from turbine to turbine for routine maintenance is neglected.
- Routine maintenance frequency and its effect on emergency maintenance are assumed constant over time.
- The labor and maintenance materials costs are functions of the farm information (e.g., the size of the farm, and offshore distance of the farm). For example, the larger the farm size is, the cheaper the unit cost of the maintenance material is.
- The time needed to acquire replacement parts is assumed to be constant. That is, logistics will not be affected by weather and types of failures.
- The performance of maintenance vessels, helicopters and labor force are assumed perfect so that there are no additional costs due to vessel failures and labor behavior.

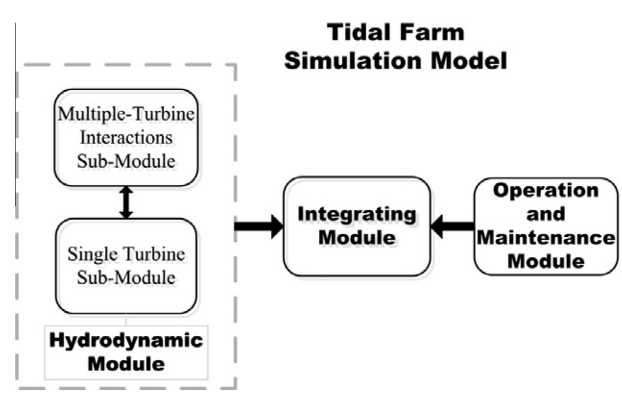

Fig. 1. Tidal turbine farm system model.

2.1. Energy output

The energy output here refers to the amount of energy in the load center which is ready to be delivered to the existing electricity grid. Total energy output from a tidal current turbine farm can be expressed as follows,

$$Energy = g(P_{out}(t), T) \tag{2}$$

where P_{out} denotes the final electrical power output from the farm, given the total number of turbines and turbine distribution, t denotes instant time, and T denotes the lifetime of the farm.

The power generation and transmission process can be modeled using three systems, including: (1) hydrodynamic system, which generates hydrodynamic power from tidal current using turbines, (2) mechanical system, which converts hydrodynamic power to mechanical power using a generator (e.g., a gearbox and flywheel), and (3) electrical system, which converts mechanical power to electrical power and then transmits the electrical power to local load center(s).

2.1.1. Electrical system

For a given farm, the power output, P_{out}, from the electrical system can be expressed as follows,

$$P_{out} = f(P_e) \approx f_t P_e \tag{3}$$

$$P_e = f(P_m) \approx f_e P_m \tag{4}$$

where f_t, P_e, f_e, and P_m denote the electrical power transmission efficiency, the total electrical power, the electrical power conversion efficiency, and the total mechanical power of the farm, respectively.

By substituting P_e in Eq. (3) with Eq. (4), we can summarize the final power output as follows,

$$P_{out} \approx f_t f_e P_m \tag{5}$$

Technically, turbine configuration and turbine distribution in a farm have little influence on the conversion efficiency, f_e, and the transmission efficiency, f_t. Thus, we focus on mechanical power output, P_m, instead of electrical power output, P_{out}.

2.1.2. Mechanical system

The mechanical power is converted from hydrodynamic power and it can be expressed as follows,

$$P_m = f_m P_{hydro} \tag{6}$$

where f_m and P_{hydro} denote mechanical power conversion efficiency and hydrodynamic power from a farm, respectively. Similar to f_e and f_t, f_m is not determined by the turbine distribution and O&M strategies. Thus, we focus on hydrodynamic power output, P_{hydro}, instead of mechanical power output, P_m.

2.1.3. Hydrodynamic system

Hydrodynamic power, P_{hydro}, can be estimated by using:

$$P_{hydro} = \sum_{i=1}^{N} \eta_i P_{ideal-s} \tag{7}$$

where η_i, N, and $P_{ideal-s}$ denote the hydrodynamic power efficiency of turbine i, the total number of turbines in the farm, and the ideal hydrodynamic power that a stand-alone turbine can generate, respectively. The ideal hydrodynamic power from a stand-alone turbine can be expressed as follows [22],

$$P_{ideal-s} = \frac{1}{2}\rho A U_\infty^3 \tag{8}$$

where ρ, A, and U_∞ denote density of sea water, turbine frontal area, and free stream incoming flow velocity, respectively.

2.1.4. Total energy output

Considering the operation of the turbines, the total energy output from a farm over its life time (as shown in Eq. (2)), can be expressed as follows,

$$Energy = \int_0^T P_{out}\, dt = E_{ideal} - E_{down} \tag{9}$$

where E_{down} denotes the downtime energy loss during the maintenance when the turbines are shutdown, which is affected by maintenance strategies and weather only, and E_{ideal} denotes the energy output from a tidal current turbine farm when no maintenance is needed (i.e., there is no energy loss due to downtime). The ideal energy output can be expressed as follows,

$$E_{ideal} = \bar{P}_{out} T \tag{10}$$

where $\bar{P}_{out}$ denotes the average final power output over time.

To simplify the relationship among variables in Eq. (9), we define a tidal coefficient, f_{tidal}, as the ratio of the average final power output to the final electrical power output as follows,

$$f_{tidal} = \frac{\bar{P}_{out}}{P_{out}} \tag{11}$$

Additionally, we define the downtime coefficient, f_{down}, as the ratio of the downtime energy loss to the ideal energy output as follows,

$$f_{down} = \frac{E_{down}}{E_{ideal}} \tag{12}$$

f_{tidal} can be obtained by analyzing local tidal constituents in a potential site, and f_{down} is determined by the maintenance strategies. By substituting Eqs. (10)–(12) in Eq. (9), the equation for estimating the total energy output can be rewritten as follows,

$$Energy = P_{out} f_{tidal}(1 - f_{down})T \tag{13}$$

Based on the relationship among the set of variables in Eqs. (5)–(8), we can rewrite Eq. (3) as follows,

$$P_{out} \approx f_t f_e f_c \frac{1}{2}\rho A U_\infty^3 \sum_{i=1}^{N} \eta_i \tag{14}$$

Then, by substituting Eqs. (6)–(9) into Eq. (14), the total energy output can be rewritten as follows,

$$Energy \approx f_e f_t f_c f_{tidal}(1 - f_{down})T \sum_{i=1}^{N} \eta_i P_{ideal-s} \tag{15}$$

The electrical efficiency coefficient, f_e, the conversion coefficient, f_m, the transmission efficiency coefficient, f_t, and the downtime coefficient, f_{down}, are not affected by the turbine distribution and turbine configuration, and the tidal coefficient, f_{tidal}, can be treated as a constant [23]. Thus, we define a new coefficient, F, to account for all the non-hydrodynamic energy losses as follows,

$$F = f_e f_t f_m f_{tidal}(1 - f_{down}) \tag{16}$$

Finally, by substituting Eq. (16) into Eq. (15), the total energy output can be rewritten as follows,

$$Energy = FTP_{ideal-s} \sum_{i=1}^{N} \eta_i \tag{17}$$

F and $P_{ideal-s}$ are all deterministic and fixed values, and only the total hydrodynamic efficiency and the life expectancy of the farm are variables. Thus, when we use a scenario-based analysis to maximize the total energy output, we focus on the total hydrodynamic efficiency and farm life expectancy. Specifically, the total hydrodynamic efficiency is affected by the turbine distribution which can be obtained by using the hydrodynamic module presented in Section 3. The life expectancy of a farm is affected by the materials of turbine components, weather, and O&M strategies, which all are discussed in Section 4.

2.2. Total cost

In order to calculate the energy cost from a tidal current turbine farm, besides the total energy output from the farm, we also calculate the total cost of the farm. The total cost is the sum of the capital cost, the O&M cost and fees, so that the levelized cost in Eq. (1) can be calculated by summing these two components as follows,

$$levco_{i,j} = cap_{i,j} + fee_{i,j} + \mathrm{O\&M}_{i,j} \tag{18}$$

where $cap_{i,j}$, $fee_{i,j}$ and $\mathrm{O\&M}_{i,j}$ denote levelized capital cost and levelized fee and levelized O&M cost of turbine i in the year j, respectively. The capital cost here refers to the cost in purchasing the turbines and constructing the farm. In this study, the life time capital cost of a farm is estimated by multiplying the unit capital cost, which is the sum of the cost in purchasing one turbine and the cable for electricity transmission and the cost in installing and decommissioning the turbine and cable, with the total number of turbines in the farm as follows,

$$cap_{life} = \sum_{i} \sum_{j} cap_{i,j} = N \cdot cap_{unit} \tag{19}$$

$$cap_{unit} = cap_{turbine-u} + D_{offshore} \cdot cable_{unit} \tag{20}$$

where cap_{unit} denotes unit capital cost, $cap_{turbine-u}$ denotes the capital cost of one turbine including the cost of manufacturing, installing, and decommissioning a turbine, $D_{offshore}$ denotes the offshore distance from the farm to the local load center, and $cable_{unit}$ denotes the unit cable cost which is the sum of the per meter cost of manufacturing, installing, and decommissioning a cable. The fee is similar to the capital cost; it is assumed to be a onetime cost. It mainly includes the costs of permitting, licensing, certification and siting. In this study, we assume the turbine developer is also the farm operator. Thus the licensing and certification fees are avoided. Besides the permitting and siting fees, the rest two do not depend on number of turbine. Thus, for a company that will develop many farms, only permitting and siting costs count and it highly depends on the policy of related agencies such as US Federal Energy Regulatory Commission. In term of permitting fee and siting fee, they are highly site dependent. We adapted the treatment from recent consultation with a group of offshore engineering experts [24] by assuming the permitting and siting fee is around 37 times the capacity of the generator in the unit of dollar. For example, if a farm is 100 MW, the permitting and siting fee is $3.7 M.

The O&M cost includes all the costs except those incurred in purchasing turbines and constructing the turbine farm. The capital cost and the fees are a deterministic and fixed value, while the O&M cost of an offshore structure is uncertain and variable because of the unexpected factors such as weather and sea states which may lead to uncertain O&M needs. For example, Hurricane Katrina led to unexpected O&M needs, which are responsible for more than a billion US dollars in losses incurred in the offshore industry [25]. Surprisingly, little attention has been paid to the unexpected factors in offshore turbine farm industry. Given the similarity between offshore wind turbine farms and on-land wind turbine farms, the system modeling of offshore wind turbine farms focused on modeling the entire system (e.g., planning, manufacturing, and integrating electricity) following the experience from on-land wind turbine farm research e.g., [26–31]. While, the failures happened in offshore wind farms were mainly caused by the lack of knowledge related to maintenance vessel transportation and offshore weather [32]. Then, in order to accurately predict energy cost, research on modeling offshore wind turbine farms shifted from modeling the cost of the entire system towards giving special attention to different O&M strategies [33,34].

Given the documented experience of modeling the cost of offshore wind farms, when estimating total cost of a tidal current turbine farm here, we would not focus on the capital cost and fees. Instead, we give special attention to the systematical analysis of its O&M cost which is shown in Section 4.

3. Hydrodynamic module

The hydrodynamic module is designed to estimate the hydrodynamic power output from a tidal current turbine farm. In the past decades, many numerical methods were proposed to estimate the hydrodynamic power output of tidal current turbines, such as streamtube method [35], finite element method [36], two-dimensional panel method [37] and discrete vortex method [23], and a comprehensive review can be found in [38]. Among these methods, the newly developed discrete vortex method [23], i.e., DVM-UBC shows an excellent cost-effectiveness. Thus, we decided to use this method to develop the hydrodynamic module and we use the power prediction procedure suggested by Li [38] to calculate the power output. The hydrodynamic formulations in the module are rather complicated, given that the focus of this paper is on energy management and integrated modeling of the energy cost of a farm, we only briefly synthesize DVM-UBC and the power calculation procedure. For those who are interested in hydrodynamic discussion, Refs. [11,23,38] are recommended.

DVM-UBC is a discrete vortex method with free wake structure to describe underwater structures and an unsteady flow around. It uses a group of vortices to represent the tidal current turbines, and uses a group a free vortices and uniform to represent the unsteady wake. By using DVM-UBC, we develop a numerical model to predict power output of a stand-alone turbine according to turbine configuration (e.g., turbine height, turbine radius, and blade geometry) [23], and a numerical model to predict the power output of two turbine systems according to the system configuration (e.g., relative rotating direction and relative distance) [11], respectively. Good agreements are obtained between numerical results and experimental test results [11,23]. Moreover, we extend this DVM-UBC and developed a model to estimate the power output of an N-turbine system, i.e., a tidal current turbine farm, according to the turbine distribution of the farm with an emphasis on hydrodynamic interaction between turbines, and it is, then used to estimate the energy output of the farm [38].

One worth noting point that we found during the formulation of DVM-UBC is about the interaction between turbines as detailed in [11]. We found that hydrodynamic interaction between turbines can post constructive impacts on the power output of the turbines when the configuration and the operation condition of the turbines are optimally designed. Here, "constructive impacts" means that the power output of the turbines with optimal design can be more than that of the turbines which are located far away from each others, i.e., there is no hydrodynamic interaction between turbines. The main reason is that the wake interaction will change the distribution of the vortices. For the turbines with constructive impacts from hydrodynamic interaction, the induced velocity and the lift on the blade will increase so that the power output increase. On the other hand, for turbines with destructive hydrodynamic interaction, the induced velocity and the lift on the blade will decrease so that the power output decrease.

Fig. 2 depicts the basic structure of the hydrodynamic module. The inputs of the module are turbine configuration and turbine distribution. The output of the module is the hydrodynamic power of a farm based on Eqs. (7)–(9). Given a specification of turbine con-

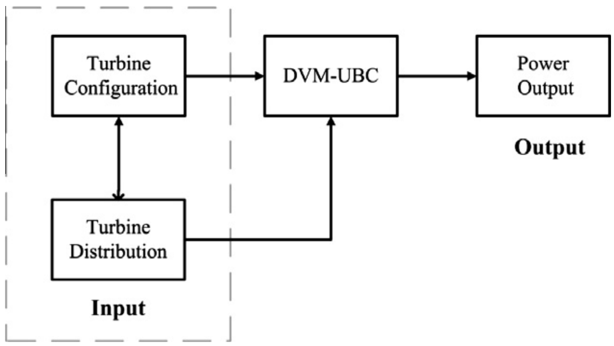

Fig. 2. The structure of the hydrodynamic module.

figuration and turbine distribution, the power output of each turbine in the farm According to the turbine distribution, the effects of hydrodynamic interactions between turbines on power output of each individual turbine is evaluated. That is to say, the hydrodynamic module can predict the power output of a tidal current farm with turbines close to each other (i.e., the farm with hydrodynamic interactions between turbines) more precisely than existing methods.

4. Operation and maintenance module

The O&M module calculates the O&M cost for a combination inputs of the farm attributes (e.g., turbine distribution and turbine configuration), local condition and maintenance strategy. The main structure of the O&M module is shown on the left hand side of Fig. 3 which includes an emergency maintenance cost sub-module, a routine maintenance cost sub-module, a service sub-module, and a farm attribute sub-module. The inputs of the O&M module are services and farm attributes information from the service sub-module and the farm attribute sub-module, respectively. Specifically, the service and the farm attribute sub-modules provide inputs for the emergency and routine maintenance sub-modules. The output of the O&M module (i.e., the O&M cost) can be obtained by summing the routine maintenance cost and the emergency maintenance cost which are calculated in the routine and emergency maintenance sub-modules. That is to say, the levelized O&M cost can be obtained by using:

$$\mathrm{O\&M}_{i,j} = EC_{i,j} + RC_{i,j} \tag{21}$$

where $EC_{i,j}$ and $RC_{i,j}$ denote the levelized emergency maintenance cost and routine maintenance cost of turbine i in the year j, respectively.

4.1. Emergency maintenance cost

The emergency maintenance cost is the sum of the material, equipment, transportation, and labor cost for emergency maintenance, and these costs are related in a way as shown on the right hand side of Fig. 3, which can be written as follows mathematically,

$$EC_{i,j} = ELC_{i,j} + ETC_{i,j} + EEC_{i,j} + EMC_{i,j} \tag{22}$$

where $ELC_{i,j}$, $ETC_{i,j}$, $EEC_{i,j}$ and $EMC_{i,j}$ denote levelized emergency labor, transportation, equipment, and material costs incurred for the emergency maintenance of turbine i in the year j, respectively.

The structure of the emergency maintenance sub-module is the most complicated one among all the four sub-modules because the preparedness of emergency situation and the optimization of the emergency operation are complicated. Emergency maintenance entails fixing an existing or pending failure of one or more devices. The major components affecting the emergency maintenance cost are the failure rates, the replacement cost for the broken components, and the turbine downtime. The type of equipments needed for the emergency maintenance affects both the equipment cost and the transportation cost. Larger equipments such as cranes might be required for some emergency maintenance depending on the level of failure severity (e.g., minimal, mid-level or severe), and these equipments require special vessels. Labor cost as well as the type and cost of the materials used in maintenance also depend on the level of the failure severity. The labor, equipment and transportation costs are proportional to the required maintenance time, and some emergency maintenance requires the turbine to be shut down for a relatively long time depending on the failure situation, accessibility of the turbine and availability of the materials.

4.2. Routine maintenance cost

Fig. 4 shows the structure of the routine maintenance sub-module and Eq. (23) shows the mathematical expression for estimating the routine maintenance cost. Similar to the emergency maintenance

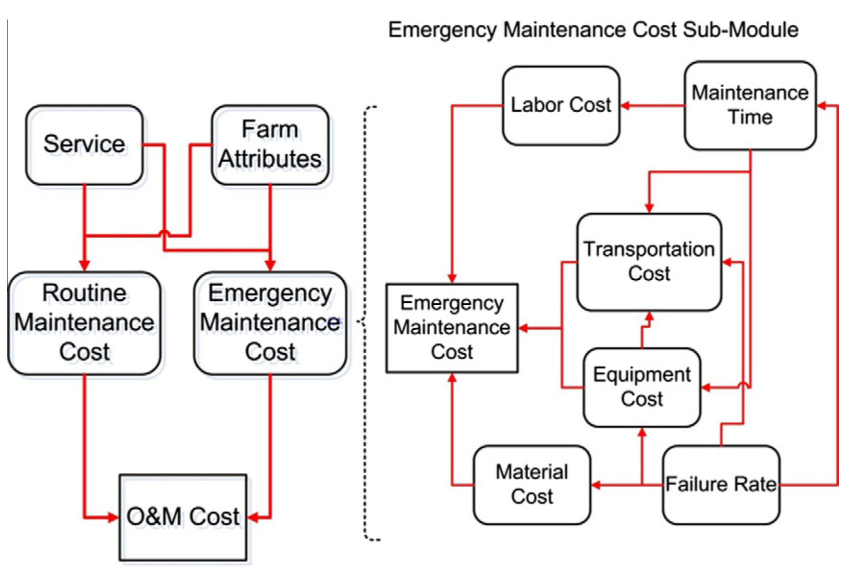

Fig. 3. The structure of the O&M module (Left) and an expansion of the emergency maintenance sub-module (Right).

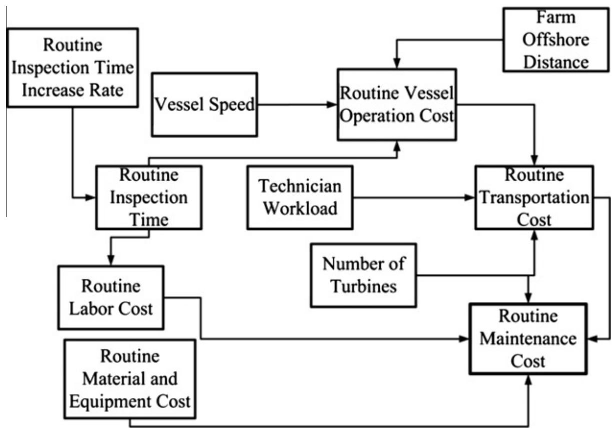

Fig. 4. The routine maintenance sub-module.

cost, the routine maintenance cost also consists of material, equipment, transportation, and labor costs.

$$RC_{i,j} = RLC_{i,j} + RTC_{i,j} + REC_{i,j} + RMC_{i,j} \tag{23}$$

where $RLC_{i,j}$, $RTC_{i,j}$, $REC_{i,j}$ and $RMC_{i,j}$ denotes levelized routine local, transportation, equipment, and labor costs of turbine i in the year j, respectively.

Routine maintenance is conducted once or twice a year [39]. Routine maintenance includes both maintenance and monitoring. Some tasks can only be performed on site such as device vibration tests and seal checks; while some other tasks, such as connection and stability test, can be self-checked, and the results are sent to the control center remotely via data cable and can be accessed online [40]. Factors affecting the costs of routine maintenance include the number of turbines, the magnitude of labor-hours per turbine that are needed to perform a maintenance operation (i.e., routine inspection time), labor skill, transport cost, and the cost of diagnostic equipments. The duration of the routine maintenance each year will increase as the life of the farm increases because older turbines need more attention, and the increment of the duration is determined by the routine inspection time increase rate (see Fig. 4). Onsite routine maintenance only needs vessels (mainly tugs), and the vessel operation cost is determined by vessel speed and farm offshore distance. In addition, a few routine maintenance procedures require the turbines be temporarily taken off-line although most procedures are conducted when the turbine is shut down when the current speed is very low. The mathematical relationships between these factors are given in the Appendix in detail.

4.3. Service sub-module and farm attribute sub-module

Service sub-module and farm attribute sub-module are relatively simpler than the two maintenance sub-modules. There are no lower level module (e.g., a sub-sub-module) in these two sub-modules. The inputs of the service sub-module are all the information related to service such as labor performance, unit material cost, material reliability, and facility availability, and the inputs of the farm attribute sub-module are the information related to the farm such as turbine geometry, weather, geological condition and flow velocity. The outputs of these two sub-modules are the inputs of those two maintenance sub-modules. The basic function of these two modules is to transform their inputs into outputs by using different transformation techniques. For example, the weather data and material reliability data are transformed from discrete formats (the inputs) to continued probability functions (the outputs) or from time domain to frequency domain.

Particularly, compared with the inputs of previous energy cost prediction models, the inputs here are treated in greater details via the service sub-module and the farm attribute sub-module. For example, in previous models, researchers discuss turbine fatigue by considering a turbine as one component; in this study, a turbine is decomposed into several components (e.g., brake, blade, shaft and belt) when the fatigue is concerned in the farm attribute sub-module.

5. Computational procedure of the farm system model

In Sections 2–4, we presented the assumptions, the structure and the main formulations of the model for estimating energy cost of a tidal current turbine farm. We name the model Tidal Energy-UBC (TE-UBC). Fig. 5 shows the flow chart of the computational procedure of TE-UBC. This numerical program starts with the inputs as given in Table 1. As a scenario-based analysis model, the program firstly checks whether a given scenario is a "reasonable" scenario according to certain criteria (e.g., whether the number of turbines or current velocity is within a certain range). For example, in this study, we suggest that as long as the maximum current velocity is between 2 m/s and 6 m/s, the scenario is a reasonable scenario due to economic concerns[1]. If the scenario is reasonable, the program starts the simulation. By using the hydrodynamic module, the power output from the turbine farm is obtained. By using the O&M module, the O&M cost is obtained. Then, in the integrating module, with the power output calculated in the hydrodynamic module, the energy output can be calculated by using the relationship between power output and the energy output, i.e., Eq. (17). On the other hand, the capital cost of the farm is calculated by using Eqs. (19) and (20). Then, by adding the capital cost, the O&M cost and the fees together following Eq. (18), the total cost (i.e., the sum of the levelized costs) can be obtained. The energy cost can be calculated as the ratio of the total cost to the total energy output, Eq. (1). The program ends if there are no more scenarios to be simulated. Otherwise, the program will check whether a new scenario is reasonable again and repeat the procedure. This forms a loop and the program continually saves the lowest cost scenario. Finally, the program will identify the scenario which achieves the minimum energy cost.

5.1. Validation

Before we use this new model to predict the energy cost of tidal current turbines, we shall validate the model first. However, because there is no operational tidal current turbine farm, and all previous simulations have some deficiencies as stated in Section 1, we decide to validate this model with offshore wind farms considering that the principle and the operational condition of the offshore wind farm is similar to the tidal current turbine farm; we compare the energy cost obtained with this model and published offshore wind farm results. Particularly, we validate our model with the recent offshore wind energy studies [41,42]. As offshore wind is already commercialized but not mature yet, one important topic is the relationship between the experience and O&M cost. In another word, learning curve of the technology will reduce the O&M cost (Fig. 6a). Another validation is a typical concern, perhaps for all the new energy technologies, the relationship between the energy cost and the lifetime of the technology. Apparently, the energy cost will significantly reduce when the lifetime of the turbines gets longer. It is noted that good agreement is obtained between the results obtained with TE-UBC and Lemmings et al. [41] and

[1] When the current velocity is too low (e.g., lower than 2 m/s), the energy output is low while the operation cost is not low; when the current velocity is too high (e.g., higher than 6 m/s), the turbine may have a significant reliability issue. Of course, for different turbine design, the feasible current velocity will be various.

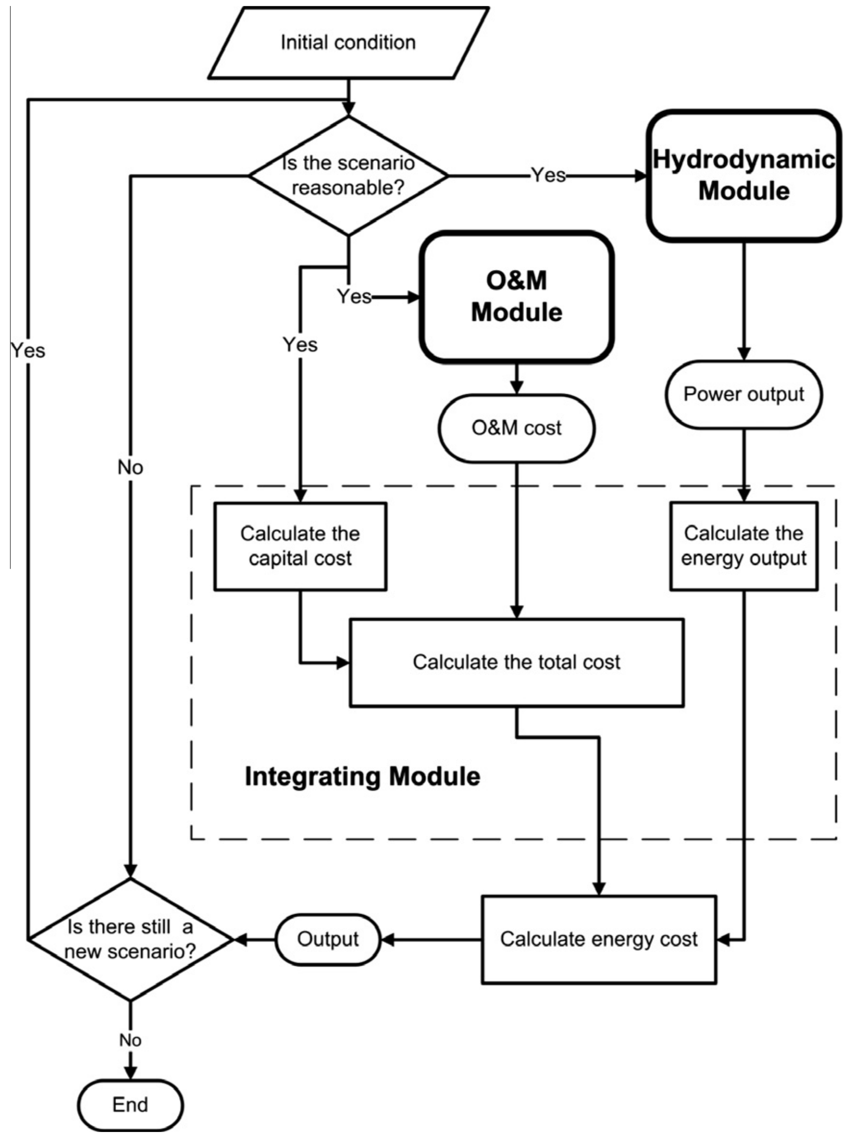

Fig. 5. The flowchart of the computational procedure of the farm system model (TE-UBC).

Table 1
Farm specifications.

Parameter	Value
Labor cost (technician salary $/h)	80
Labor (technician) workload(h/day)	10
Vessel speed (kn)	12
Foggy time offshore (day/year)[a]	5
Extreme wind and wave condition offshore (day/year)	8
Offshore distance (km)	0.5
Current velocity (m/s)	2
Capital cost including installation ($/turbine)	150,000
Permitting fee ($/kW)	37
Routine maintenance frequency (time/year)	2

[a] Technician working time and vessel travel time will be doubled during the foggy day.

Engels et al. [42]. The difference between the results predicted by TE-UBC and the published results may be caused by the difference between the O&M strategies as well as the description of aerodynamics for the wind turbines and the hydrodynamics for the tidal current turbines. Also, one may note that the optimization function in the hydrodynamic module is turned off during the calculation as above two offshore wind farms are not aerodynamically optimized in terms of the turbine distribution. Perhaps an aerodynamic version of TE-UBC shall be developed for planning offshore wind farm in future, although this is not the focus of this study. Overall, one can conclude that TE-UBC is a cost effective numerical model with acceptable accuracy.

6. Planning of tidal current turbine farms in the Quatsino Narrow – a case study

Using data for a potential farm site near Vancouver, BC, Canada, we demonstrate the use of the TE-UBC for finding the minimum energy cost with a scenario-based analysis. The site is in Quatsino Narrows, Vancouver, BC, Canada, where the average current velocity is 2 m/s; the detailed hydrographic data are obtained from Canadian Hydrographic Service. Cost and material information (e.g., manufacturing, labor, maintenance material costs, and device fatigue information) are adapted from BBV [39] and Rademakers [33]. Weather information, e.g., fog and wind, is obtained from Environmental Canada. Major farm specifications from the references mentioned above are summarized in Table 1. Basic turbine

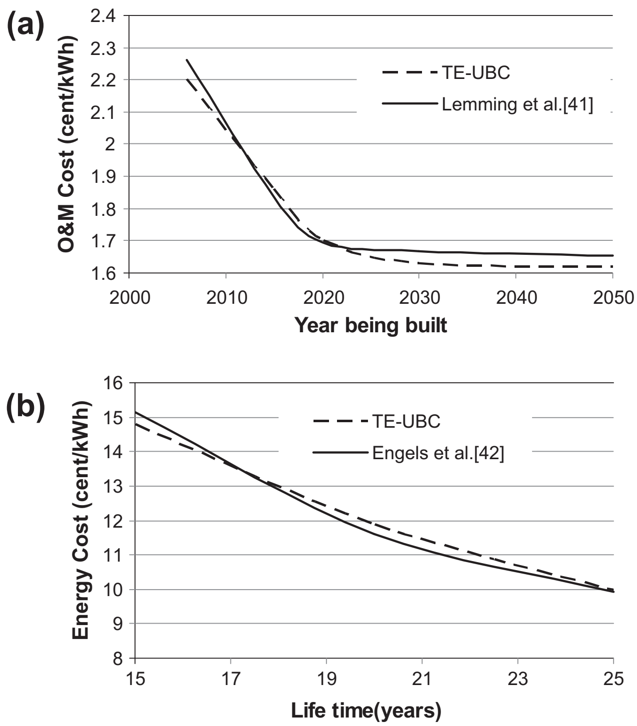

Fig. 6. Validation of TE-UBC: (a) comparison with Lemming et al. [41]; and (b) comparison with Engel et al. [42].

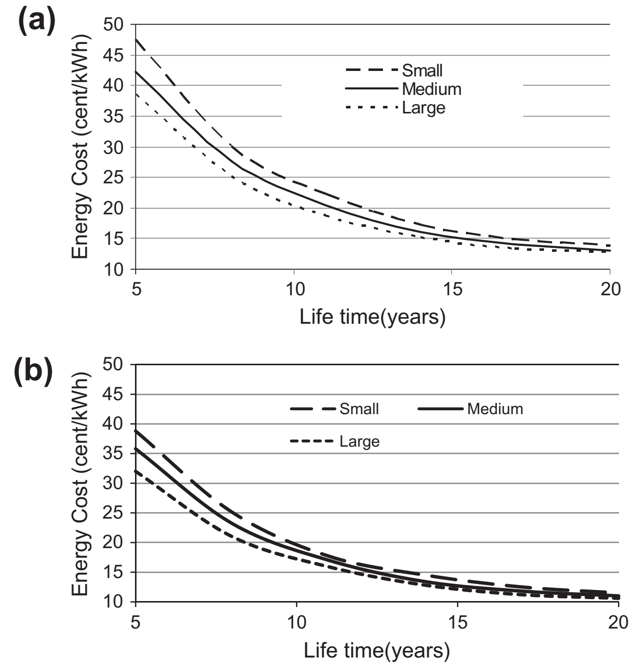

Fig. 7. Energy cost of tidal current turbine farm: (a) no hydrodynamic interaction; (b) with constructive hydrodynamic interactions.

specifications include that the turbine blades are NACA0015, the number of turbine blade is three, turbine height is 12.5 m, turbine radius is 5 m, and the solidity is 0.375. The engineering characteristics of this turbine is extensively discussed in Li and Calisal [43,44].

As a comprehensive integrated model, TE-UBC is able to handle various scenarios. To find the true minimum energy cost, one has to do an exhaustive search of all the possible scenarios for farm information (e.g., number of turbines, and distribution of turbines) and the O&M strategies, which require advance search techniques. The development and utilization of advanced search techniques are beyond the scope of this research which is the modeling process. Hence, for illustration purpose, we only investigate several scenarios with different turbine distribution, different farm size (number of turbines) and different turbine lifetimes. Fig. 7 shows the relationship between the energy cost and the farm size as well as the lifetime of the turbines of two farms with different turbine distributions (i.e., one farm without hydrodynamic interaction between turbines and the other with constructive hydrodynamic interactions between turbines). Three different farm sizes are investigated: small (10 turbines), medium (30 turbines), and large (100 turbines). The lifetime of the turbines are made varying from 5 to 20 years. The maximum lifetime of a turbine farm, i.e., 20 years, is extrapolated from that of offshore platforms, which typically extends to 25 years or so [25]. Designers of tidal current turbines in the UK and Canada have projected a 30-year lifetime for their designs [45]. Although the actual operational lifetime of tidal current turbines will not be available until more experiences is gained from sea tests on full-scale devices, some causes for optimism lie in the fact that pre-commercial testing of near-shore turbines has resulted in turbines operating without failure over a 5-year period [40], despite the lack of a systematic maintenance program.

The results suggest that the energy cost reduces significantly when the farm lifetime increases. However, the lifetime of the device will significantly affect the O&M cost because older equipment requires more attention. Given the lifetime of the turbines, the larger the farm size is, the lower the energy cost will be, which is mainly due to the difference in O&M cost for farms of different sizes, but not due to the difference in capital cost (i.e., no economies of scale). Additionally, for two farms of the same size and with the same lifetime and maintenance strategies, the one in Fig. 7b (the farm with constructive hydrodynamic interaction) is more economically competitive than the one in Fig. 7a (the farm without hydrodynamic interaction). This is mainly because the energy output from the farm with constructive hydrodynamic interaction is more than that from the farm without hydrodynamic interaction while the total costs of both farms are similar.

7. Discussion and conclusions

7.1. Discussion

The integrated model presented here includes many aspects of a tidal current turbine farm. Because tidal current turbine is still a new technology, some assumptions we made are rather conservative which may slightly over predict the energy cost. Firstly, we assume that the O&M transportation cost in routine maintenance per turbine is quasi inversely proportional to the total number of turbines in a farm, which means that the larger the farm is, the lower the routine transportation cost per turbine is. In detail, a routine maintenance is conducted on one trip from the harbor to the farm site, no matter how many turbines are at the site. Thus, a farm with a larger number of turbines will result in a smaller routine transportation cost per turbine. Secondly, we assume the unit capital cost of turbines does not change with the size of turbine farm. In fact, it is understood that the unit manufacturing cost should significantly decrease when the number of manufactured turbines increases. As a new product without too much experience, we suggest, however, using the same capital cost per turbine no matter how many turbines are manufactured (see Eq. (19)).

Additionally, the results show that the energy cost tends to be constant if the lifetime of a farm is more than eighteen. Thus, the

Table 2
2008 Electricity price in major coastal cities in North America [46].

Customer city	Residential	Small commercial	Big commercial	Industrial
Vancouver, BC	6.98	7.63	5.33	4.23
San Francisco, CA	18.08	15.23	12.23	8.33
New York, NY	21.27	21.68	18.11	15.16
Boston, MA	19.12	20.08	17.11	14.76

farm owner may take the energy cost at this condition as the cost to penetrate the local electricity market. Here, we compare the energy cost of when the lifetime of the farm is 20-year with the electricity price in major cities in North America in four different demand sectors, which are residential, small commercial, medium commercial and industrial sectors (Table 2). It is noted that the energy costs are higher than the maximum market price in Vancouver which is the price for small commercial usage, 7.63 cents/KW h, although it is lower than that in some cities such as Boston, New York and San Francisco. Such a comparison suggests that the tidal current energy generated in BC is almost ready to penetrate into the local market in Vancouver if some governmental credits can be granted. Notwithstanding, one shall note that the predicted results here are obtained under the conditions where the learning curve is minimum and no extremely unexpected issue happens.

7.2. Conclusions

Planning a tidal current turbine farm and modeling its operation are complicated problem due to the lack of detailed analysis and understanding of the turbine working principle and the complexity of the ocean natural environment. Given the present knowledge of tides, principles of turbine analysis and computational ability, this paper presents a systematic framework and an integrated model (TE-UBC) for estimating the energy cost of tidal current turbine farms which integrates different research disciplines and new approaches such as DVM-UBC. TE-UBC can be used to estimate the energy cost based on a given turbine configuration and local conditions. Based on the validation, one can say that TE-UBC is a cost-effective model with acceptable accuracy. The results in the case study suggest that by utilizing constructive hydrodynamic interactions, the energy cost can be reduced by about 15% compared with the case where the hydrodynamic interaction is avoided. The results show that the minimum energy cost for a large farm (100 turbines) with a 20-year life in offshore BC can be about 8 cents/KW h and it is only a little bit higher than the local market price. Additionally, TE-UBC does not only provide a more accurate result than previous model but also provide a comprehensive framework for conducting sensitivity analysis. The results show that, besides tidal flow velocity, the two most important control variables for energy cost are farm size and turbine relative distance (i.e., turbine distribution in the farm).

7.3. Future work

Considering the scope of the work, the analysis of grid interconnection is not conducted in this study. Although there are many references in electricity dispatch but they are all based on other generation technologies. Future work is required to integrate the electricity distribution and integration based on the special characteristic of tidal current energy in details. Additionally, fees are not precisely included in this study because they are yet to be determined by governmental agencies. They should be included in future models when they are known, perhaps within next decade or so.

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Appendix A

In Section 5, we present the basic structure of the O&M module of TE-UBC. Here, we show more details about this module for those who are interested in the formulation. In order to simplify the discussion, we use cost variables without subscripts to replace those with subscripts in the following description because most cost variables are levelized over the lifetime of a tidal current turbine farm. For example, we use ELC to represent $ELC_{i,j}$ (emergency labor cost of turbine i in the year j, see Eq. (22)).

A.1. Emergency maintenance sub-module

The emergency maintenance cost is the sum of emergency transportation, labor, equipment and material cost. Here we explain how these four components are estimated. The simplest one is the emergency material cost (EMC), which is determined by the level of failure severity and the types of failed components. Emergency transportation cost (ETC) can be expressed as either the emergency vessel cost ($ETVC$, when the failure severity is minimal and mid-level) or the sum of the emergency vessel and helicopter cost ($ETVC$ and $ETHC$, when the failure is severe), as shown with the following equations:

$$ETC = \begin{cases} ETVC & \text{when the level of failure severity is minimal and mid-level} \\ ETVC + ETHC & \text{when the level of failure severity is severe} \end{cases} \tag{24}$$

$$ETVC = (ODist/VS \times 2 + (DTime + EWTime) \cdot ETNum) \times EVC \tag{25}$$

$$ETHC = (ODist/HS \times 2 + (DTime + EWTime) \cdot ETNum) \times HC \tag{26}$$

where $ODist$, VS, HS, $DTime$, $ETNum$, EVC and HC denote the offshore distance of the farm, vessel speed, helicopter speed, delay time due to weather and related reasons and labor waiting cost, number of turbines that need emergency maintenance, the emergency vessel cost per day, and the emergency helicopter cost per hours. $ETNum$ is determined by component failure rate in regular condition (Table 3) and such rates are affected by the conditions of weather and sea state. $DTime$ is determined by the type of the failure component and the level of the failure severity.

The emergency labor cost (ELC) can be estimated as follows,

$$ELC = TechS \times ETNum \times ELNum \times EMT + DTime \times LWC \tag{27}$$

where $TechS$, $ELNum$, EMT and LWC denote the technician's salary, number of technicians required during this emergency maintenance, time required for this maintenance, and labor waiting cost respectively. In this study, technician salary and their waiting costs are constants. $ELNum$ and EMT are both functions of the severity of the failures that an average turbine experiences.

The emergency equipment cost (EEC) can be written as follows,

$$EEC = (DTime \times EWaC + EWoC \times EWTime) \times ETNum \tag{28}$$

Table 3
Component failure rate in regular condition (times per turbine per year).[a]

	Minimal	Mid-level	Severe
Shaft	0.002	0.007	0.001
Brake	0.0153	0.0325	0.0025
Generator	0.065	0.0545	0.0065
Electrical system (including cable)	0.225	0.09247	0.000002
Blade	0.042	0.0273	0.00007
Gearbox	0.2125	0.0325	0.0005
Control system	0.1	0.1	0.0001
Others	0.03	0.0299	0.00006

[a] Adapted from Rademakers [32].

where *EWaC*, *EWoC* and *EWTime* denote the equipment waiting cost, equipment working cost and equipment working time, respectively. They all are determined by the type of failed component and failure severity level.

A.2. Routine maintenance sub-module

Similar to the emergency maintenance cost, the routine maintenance cost is also the sum of four components, which are the routine labor, transportation, equipment and material costs. Similar to the emergency material cost, the routine material cost is also the simplest one among four routine maintenance costs, and it is determined by the type of the turbine components. The routine labor cost (*RLC*) can be obtained as follows,

$$RLC = RITime \cdot TechS \times N \times LDisc \tag{29}$$

where *RITime* and *LDisc* denote the routine inspection time per turbine and the labor discount rate (i.e., the larger the size of the turbine farm is, the lower the discount rate is. The default value of the discount rate is set as 1).

The routine transportation cost (*RTC*) and routine equipment cost (*REC*) can be estimated as follows,

$$RTC = (ODist/VS \times 2 + RITime \cdot N) \times RVC \tag{30}$$

$$REC = RITime \cdot N \times EWoC \tag{31}$$

where *RVC* denotes the routine vessel cost.

The technician workload is set as eight hours per day. That is to say, the vessel returns to the harbor and goes to the farm again the next day if the routine inspection cannot be finished in one day. Thus, the program will minimize the routine maintenance cost by choosing the optimal combination of the number of vessels and the number of technicians.

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