Levelized Cost of Electricity for Hydrokinetic Turbines

Matheus Montenegro Nunes, Rafael Castilho Faria Mendes Sergio Frontin Taygoara Felamingo de Oliveira , Rudi Henri van Els and Antonio Cesar Pinho Brasil Junior

***Abstract*—Hydrokinetic turbines are an emerging technology capable of generating electricity through a renewable energy source. Due to the novelty, there is a lack of knowledge in this area, especially in the context of expenditures. In this way, the main goal of the present work is to develop a methodology to compute the costs and risks associated with this technology. The results are presented for two real turbines, manufactured by the Laboratory of Environment and Energy at the University of Brasilia and tested at two different sites. All expenditures are described, and the Levelized Cost of Electricity is analyzed for both turbines.**

***Index Terms*—hydrokinetic turbines, Levelized Cost of Electricity, renewable energy, annual energy production.**

I. Introduction

Hydrokinetic energy conversion technology is currently a major focus of global research and development (R&D) projects. Recent analyses have examined its potential as a renewable energy source for generating electricity [1]. However, several challenges must be addressed to enhance hydrokinetic turbines' technological and commercial maturity. These challenges include improving onboard systems, optimizing the technology for fluvial environments [2], and reducing costs [3].

The choice of technology options that can reduce costs and maintain systemic reliability should be influenced by the evolutionary trajectory of energy costs. Economic analysis plays a crucial role in determining the viability of an energy source. In this context, several initiatives have been undertaken to estimate the cost of hydrokinetic systems. For instance, Kusakana and Vermaak [4], in 2013, analyzed the theoretical costs for a South African case; Punys et al. [5], in 2015, simulated the total energy cost using a hydraulic model in Lithuania; and Costa et al. [6], in 2021, theoretically computed the potential costs in the Amazon region. However, the lack of reports on actual case costs prevents a reliable estimate for project implementation and assessment of associated risks. Consequently, it is currently unfeasible to demonstrate this technology's technical, economic, and environmental benefits compared to other electrification options [7].

Following the energy context, the Levelized Cost of Electricity is a basis for comparing various energy sources. In addition, this parameter helps estimate the economic viability of the technology. The Levelized Cost of Electricity determines how much it costs to generate one kilowatt-hour of energy with a given technology [8]. As a baseline reference, the cost of a kilowatt-hour of solar photovoltaic and wind power is currently approximately US\$ 0.03-0.041 and US\$ 0.026-0.050, respectively [9], [10], and was estimated to be US\$0.42-US\$1.47 for [11] for theoretical hydrokinetic turbine models. s.

The Levelized Cost of Electricity considers the ratio between all the energy produced during the lifetime of the installation and all the expenses incurred during that time. The idea of this indicator is to correct both the cash flow and the energy converted to present values. In this sense, the calculation is defined as

$$LCOE = \frac{CAPEX + OPEX}{AEP}, \tag{1}$$

where

- LCOE is the Levelized Cost of Electricity;
- CAPEX is the Capital Expenditure;
- OPEX is the Operational Expenditure;
- AEP is the Annual Energy Production.

The CAPEX and OPEX expenditures can be broken down into several sub-items, as shown in Figure 1. To determine the Levelized Cost of Electricity, we must account for each item for the reference installation. Finally, we evaluate the energy produced over the turbine's lifespan at the reference site for the operating conditions.

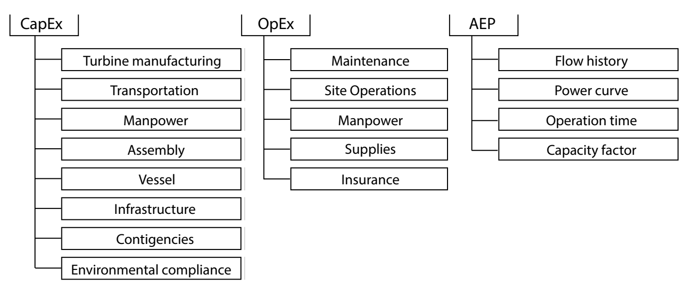

Fig. 1. Hydrokinetic turbines cost.

In this regard, the main objective of the present work is to estimate the reference cost values for the development of river hydrokinetic turbines based on actual field experiments in the Brazilian context.

II. Methods

For the levelized energy cost analysis, one must consider the costs of the reference technology and the site where it is installed. Each installation platform will have a reference

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cost depending on the type of equipment employed, the reference site, and its scale. As the technology matures, the reference cost begins to be defined based on the most efficient installations evaluated. Those may be a more efficient design or improvements on the original concept bringing in new technologies [12].

Two reference models will be evaluated: the Generation 2 turbine, rated at 2 kW, and the Hydro-K platform, rated at 30 kW. Both models were produced by the University of Brasilia (UnB) and are illustrated in the sections III and IV.

A. Installation Site Analysis

The first point of analysis of the installation site is to investigate the topology of the terrain. The topology is essential to determine the costs related to transportation, accessibility of the site, and how the installation is to be done. Another critical point is the bathymetry of the river, which is used to determine possible anchor points and the depth of the installation site. Finally, an assessment must be made of the flow velocity in the river cross-sections [13]. This velocity assessment should be representative of an annual flow velocity distribution.

B. Annual Energy Production - AEP

To estimate the annual energy production, we must first know the turbine's power coefficient. This value represents the ratio between the mechanical shaft power of the turbine and the power available in its operating area, and it is collected through experiments or numerical analysis.

The power coefficient is used together with the velocity distribution previously defined in the site analysis to find the average shaft power, P_m, of the turbine for that operating site

$$P_m = \frac{1}{2}\rho U^3 A C_p, \tag{2}$$

where ρ is the specific mass of the flow, U is the velocity of the flow, A is the cross section of the rotor, and C_p is the power coefficient.

The average shaft power is then used to calculate the average turbine operating power, P_t,

$$P_t = \eta_m \eta_T \eta_e P_m, \tag{3}$$

where η_m is the bearing efficiency, η_T is the transmission efficiency, and η_e is the generator efficiency.

The annual energy production is then estimated as

$$AEP_n = P_t t, \tag{4}$$

applying the total annual turbine operating time, t, and the average turbine operating power.

The value of total energy production over the entire life of the turbine is an estimate of the future cost of annual energy production. In this case, it is important to consider the discount rate, d, equivalent to 11.75% [1], applied to the energy production of each year of operation,

$$AEP = \sum_{n}^{N} \frac{AEP_n}{(1+d)^n}, \tag{5}$$

[1]Based on the Brazilian official interest rate (SELIC) [14] on March 16, 2022.

where n represents the year of operation and N is the installation's lifetime.

C. CAPEX

Initial capital expenditures consider the expenses incurred during the equipment development and installation time. These are the expenses that precede the platform's operation and power generation. The main capital expenditures are illustrated in Figure 2.

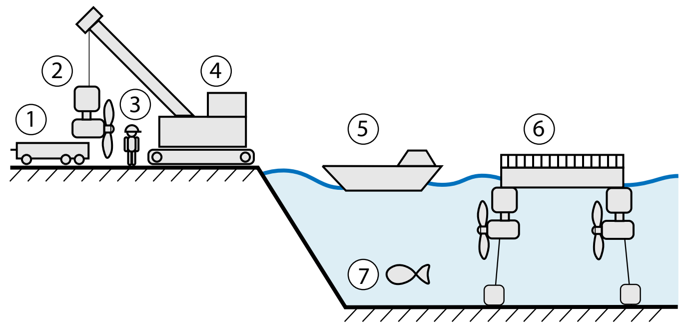

Fig. 2. Main initial capital expenditures organized during the installation of the platform: 1 - Transportation, 2 - Turbine, 3 - Manpower, 4 - Assembly, 5 - Vessel, 6 - Platform, 7 - Environmental compliance.

River hydrokinetic technology is often used in isolated communities that are difficult to access. Transportation and assembly costs should consider this impediment when estimating based on standard values. If estimates are required, manufacturing-related expenses should assume using off-the-shelf marketable components (generator) and standard materials (A36 steel, support cables, and fasteners) wherever possible. Depending on the installation location, the cost associated with a support vessel, with the operator, should be accounted for. The planning of the structure and anchoring, and the environmental compliance analysis require an analysis of the reference site, which must be included.

D. OPEX

The maintenance costs, presented in Table I, are based on the hydrokinetic turbine parts failure model for rivers, proposed by Neary et al. [13] in 2014. This cost considers the chance of equipment failure in a hydrokinetic turbine arrangement during a twenty-year operation. The costs presented are appropriate for the current situation and date, 2022.

In addition to these costs, as seen in Figure 1, the cost of the operator involved in maintenance, transportation, necessary consumables, and insurance must be considered. The costs of field operations should be planned around the reference installation location.

It is important to note that operating expenses occur on an annual basis. They are estimates on a future annual operating cost, considering the discount rate, d, equal to 11.75%

$$OPEX = \sum_{n}^{N} \frac{OPEX_n}{(1+d)^n}, \tag{6}$$

based on the annual operating cost, $OPEX_n$, where n refers to the year of operation, and N is the lifetime of the facility.

TABLE I
FAILURE CHANCE OF STANDARD HYDROKINETIC TURBINE COMPONENTS DURING A 20-YEAR LIFETIME. COSTS FOR A 50 KW TURBINE WITH A DIAMETER OF 6.3M ARE ILLUSTRATED FOR REFERENCE. DATA ADAPTED FROM NEARY ET AL. [13].

Component	Failure chance [%]	Reference [US$]
Powertrain		
Generator	0,95%	819,45
Gearbox	1,39%	621,61
Conversor	1,60%	247,91
Transformer	0,10%	36,64
Commutator	0,37%	45,19
Cooling System	2,44%	14,65
Control System	0,59%	59,84
Rotor		
Blades	0,26%	101,31
Shaft	0,05%	239,36
Bearing	0,44%	343,17

III. UnB Microturbine - Generation 2

The first reference model to be evaluated is the Generation 2 turbine, developed by the University of Brasilia, illustrated in Figure 3. This turbine was designed to be handmade, aiming its construction and use by families from the Brazilian countryside. Due to the continental dimension of the Amazon region and the low demographic density, many communities are unlikely to be interconnected to the rural electricity distribution network. The turbine has 1.5 meters of diameter, and it can produce, on average, between 300 W and 2000 W for these families, although it requires a river with regular flow and depth of at least 1 meter due to the turbine size.

Fig. 3. Generation 2 microturbine installed on the Maracá River, AP-Brazil. Installation section with a width of ten meters and depth of four meters. Turbine during the installation process in (a). Turbine submerged and running in (b).

The schematic describing each part of the Generation 2 turbine is illustrated in Figure 4. The turbine has the addition of a diffuser (conical fairing surrounding the runner) and grille. The diffuser enables power generation in rivers with a low-speed flow [15], [16]. The grille protects the turbine from debris prevalent during operation, shifting the focus of maintenance and cleaning from the more complex parts of the equipment, such as the rotor, to the simpler, the grille.

A. Installation Site - Maracá River, AP-Brazil

The reference economic evaluation of the microturbine takes place on the Maracá River in the state of Amapá, Brazil. The installation was carried out in the vicinity of Vila Maracá [17], illustrated in Figure 3. The installation section has a width of ten meters and a depth of four meters. Due to the external attachment of the platform base, a sediment and bathymetry assessment of the site is not required for foundation and anchoring specifications.

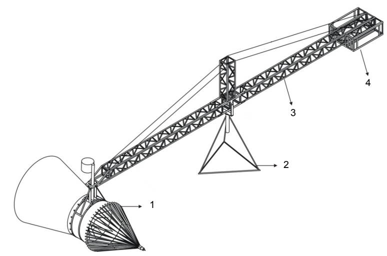

Fig. 4. Schematic of the generation 2 turbine in isometric view. Turbine illustrated in (1), support base in (2), structural arm in (3), and counterweight in (4).

The Maracá river velocity distribution, shown in Figure 5, was developed from local measurements data, where the turbine was installed, and computed with models proposed by Neary et al. [13], [18]. The mean velocity in Figure 5 was 1.39 m/s, and it was used to compute the reference power with the equation 2 [19].

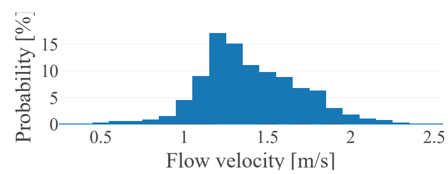

Fig. 5. Estimated velocity distribution of the installation section in the Maracá River.

B. Performance Analysis and AEP Estimation

The power curve of the generation 2 turbine, Figure 6, was produced from the turbine power coefficient, 0.55, and verified with references collected in the field [20]. It is worth remembering that this high power coefficient is due to the presence of the diffuser.

By substituting the velocity distribution obtained from Maracá River, as depicted in Figure 5, into equation 2 and calculating its average, we have determined an average energy production of 665W. This velocity gives an annual capacity factor of 33%, where $Annual\ capacity\ factor = Averaged\ annual\ power\ production/Rated\ power$. As described in Section II-B, this capacity factor leads us to an approximate annual production of 5.8 MWh. The generation 2 turbines were specifically designed to operate in an isolated Amazon area with uncontrolled river flow. In such an environment, there is a higher possibility of encountering floating debris, such as fallen trees and other residuals. The turbines were developed to withstand these potential impacts. Additionally, maintenance of the turbines in this area was challenging, and the available technology at the time limited the assembly process, resulting in handmade turbines. In this way, the estimated equipment lifetime of 10 years [19], where the total expected energy production of 58 MWh. The parameters involved in the performance analysis and energy production are described in Table II.

TABLE II
SUMMARY OF THE OPERATING PARAMETERS OF THE GENERATION 2 MICROTURBINE INSTALLED AT MARACÁ RIVER, AP-BRAZIL.

Specification	per unit
Nominal Power	2 kW
Average Power	665 W
Capacity factor	0,33
Annual production	5,8 MWh
Lifespan	10 years
Total production	58 MWh

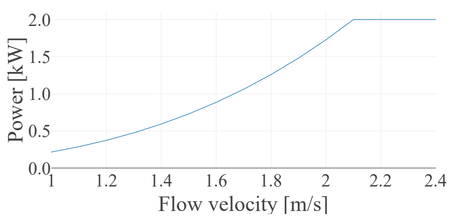

Fig. 6. Power curve from Generation 2 microturbine.

C. CAPEX

As described in Section II-C, manufacturing-related expenses assume the use of off-the-shelf marketable components (generator) and standard materials (A36 steel, support cables, and fasteners) wherever possible. The breakdown of initial costs is illustrated in Figure 7. The values in this section that refer to equipment developed before 2022 are all adjusted for the currency value in 2022. These values are recorded in Table III. No contract with vessels is required for shore operations, given the type of turbine installation. To estimate the environmental compliance assessment cost of Generation 2 turbines, an analysis was conducted on similar sites with turbines in the same rated power range. The analysis was based on previous studies [21], [22]. The total carbon emissions associated with the construction of the turbines were estimated as 13.64 g of equivalent CO2eq per kWh based on the European Union's guidelines for calculating the carbon footprint of electricity [23]. Then the equivalent price was taken into account.

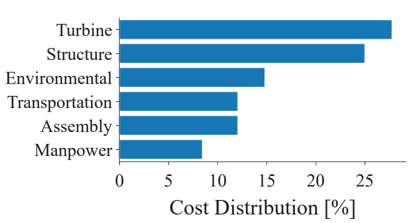

Fig. 7. Generation 2 turbine capital expenditures - CAPEX.

D. OPEX

Following the guidelines of Section II-D, the operating expenses are divided into costs related to maintenance, field operations, operator contract, consumables, and insurance.

TABLE III
GENERATION 2 TURBINE CAPITAL EXPENDITURES - CAPEX [19], [20]. DOLLAR VALUES IN 2022.

Category	Cost [US$]
Turbine	6.300,00
Structure	5.670,00
Environmental Compliance	3.360,00
Transportation	2.725,00
Assembly	2.725,00
Manpower	1.900,00
CAPEX total	22.680,00

Maintenance costs are based on the failure model proposed in Section II-D adapted to the Generation 2 turbine reference situation. These values associated with possible failures are added to the standard maintenance cost: lubricant replacement, belts, and brushes. Due to the simplified intervention type, a monthly local operator salary is assumed to perform the maintenance. No vessel was required for field operations, given the installation on the Maracá river bank. Due to the use of local labor, the cost of transportation is included in the operator's salary. All operating costs are compared in Figure 8 and recorded in Table IV.

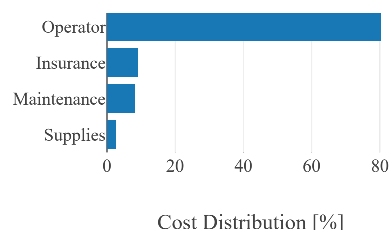

Fig. 8. Distribution of the turbine operation expenses Generation 2.

TABLE IV
GENERATION 2 TURBINE ANNUAL OPERATING EXPENSES - OPEX [19], [20]. DOLLAR VALUES IN 2022.

Category	Annual cost [US$]
Operator	3.113,83
Insurance	350,00
Maintenance	315,12
Supplies	105,00
Annual OPEX	3.883,95

E. Levelized Cost of Electricity - LCOE

The estimated Levelized Cost of Electricity for the Generation 2 turbine is 1.29 $/kWh. This value was calculated following the guidelines specified in Sections II-B, II-C and II-D, considering a discount rate of 11.75% per year in the value of the currency. The impact distribution by category is illustrated in Figure 9 costs, and their specific values are recorded in Table V. It is worth noting the inclusion of the contingency margin and the parts recall and that, due to the social nature of the project, there is no profit margin involved. Due to its small size and capacity, the cost of maintenance and operation is relatively expensive, as this does not scale with the power of the machine.

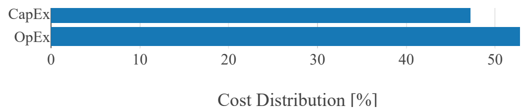

Fig. 9. Levelized Cost of Electricity for the Generation 2 turbine.

TABLE V
LEVELIZED COST OF ELECTRICITY FOR THE GENERATION 2 TURBINE. DOLLAR VALUES IN 2022.

Category	Cost [US$/kWh]
CAPEX	0,61
OPEX	0,68
Total	1,29

IV. HYDRO-K PLATFORM FOR THREE HORIZONTAL AXIS TURBINES

The Hydro-K platform, illustrated in Figure 10, was developed by the University of Brasilia in partnership with the company Hubz [24], in the context of AES-Tietê's R&D portfolio. It was designed to act in the recovery of remaining energy downstream of hydroelectric power plant reservoirs. Such reservoirs have an average efficiency of 80% [25], [26]. Hydrokinetic turbines are a low environmental impact alternative for harnessing the remaining 20% of energy. This platform can generate 30 kW, relying on the power output of three horizontal axis turbines with 2.2 meters of diameter.

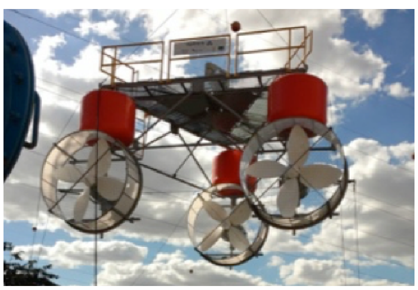

Fig. 10. Hydro-K turbine platform produced by the University of Brasilia with a nominal power of 30 kW.

The upper platform allows the simultaneous use of up to ten people for maintenance and direct monitoring. The turbine also has a guard rail to establish the safety of the local fauna during operation. The sides of the triangular platform have equal dimensions. The turbines are positioned so that the front turbine tracks do not affect the flow speed at the rear turbine [27]. This arrangement is what makes the platform's compact and modular design possible.

A. Planned Installation Site - Rio São Marcos, GO-Brazil

The reference site for economic analysis is the São Marcos River in the state of Goiás, Brazil. The platform was evaluated for a facility downstream of the Serra do Facão Hydroelectric Power Plant. Based on previous site measurements, the analysis was made for a reference cross-section with an average velocity of 1.25 m/s and a flow rate of 95 m^3/s.

The reference site of the Hydro-K platform's energy cost analysis is a hydroelectric power plant (HPP). Because of this, the flow velocity history can be estimated using velocity data collected in the field along with the flow history downstream of the dam. The velocity distribution presented in Figure 11 references the plant's daily defluence data from October 2017 to October 2020 [28]. Unlike a standard river flow distribution, the flow downstream of a power plant is fixed by the flow of that power plant. The Serra do Facão HPP spent most of its operation during these years at the same flow rate, as reflected in the velocity distribution of its flow.

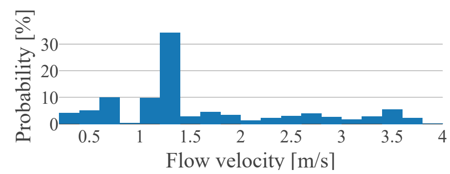

Fig. 11. Velocity distribution in the Serra do Facão UHE installation region. Reference values provided by ONS through the daily operation bulletin, 2017-2020 [28].

B. Performance Analysis and AEP Estimation

The Hydro-K platform power curve, Figure 12, was produced from the power coefficient of each turbine, 0.39, and ascertained with references collected in the field [24].

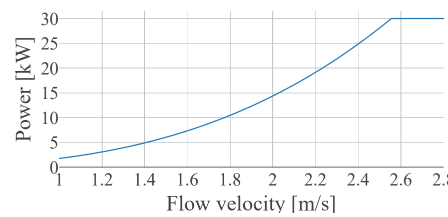

Fig. 12. Hydro-K platform turbine power curve.

Using the velocity distribution collected over the analysis site, Figure 11, and the reference values in the power curve, Figure 12, we have an average power production of approximately 10 kW. This production yields a capacity factor of 0.33 (33%). As described in Section II-B, this capacity factor leads us to an annual production of approximately 84 MWh. The Hydro-K platform was installed in a more controlled river, likely downstream of a dam. The dam's presence ensures that the river flow is regulated, minimizing the risk of collisions with debris. Due to the controlled environment, the Hydro-K platform is expected to have a longer lifespan than the generation 2 turbine, with an estimated doubling of its operational lifetime. Considering the estimated lifetime of the equipment of 20 years [24], the total expected energy production is 1,680MWh.The parameters involved in the performance analysis and energy production are described in Table II.

C. CAPEX

The capital expenditure categories are described in Section II-C and illustrated in Figure 2. The Hydro-K platform is transported in parts to the installation site. Therefore, its assembly and installation occur in the field with the aid of a crane and

TABLE VI
SUMMARY OF THE OPERATING PARAMETERS OF THE HYDRO-K PLATFORM.

Specification	per unit
Nominal Power	30 kW
Average Power	10 W
Capacity factor	0,33
Annual production	84 MWh
Lifespan	20 years
Total production	1680 MWh

vessel, Figure 13. The platform is secured by steel cables pulled on the shore. The cost of the environmental compliance assessment for the Hydro-K platform was estimated based on previous assessments done for the Generation 2 turbine [21].

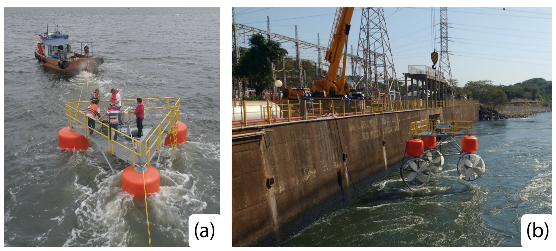

Fig. 13. Hydro-K platform installation. Use of boat in (a) and crane, in (b), for field support.

The breakdown of initial costs is illustrated in Figure 14. The values in this section that refer to equipment developed before 2022 are all adjusted for the currency value in 2022. These values are recorded in Table VII. The Hydro-K platform has an initial cost of US$ 50.745,54.

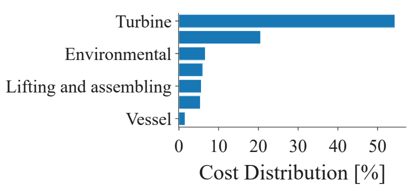

Fig. 14. Distribution of Hydro-K's capital expenditures - CAPEX.

TABLE VII
GENERATION HYDRO-K PLATFORM CAPITAL EXPENDITURES - CAPEX [24]. DOLLAR VALUES IN 2022.

Category	Cost [US$]
Turbines	27.579,00
Structure	10.423,25
Environmental Compliance	3.360,00
Transportation	2.731,05
Assembly	2.850,24
Manpower	3.022,00
Vessel	780,00
CAPEX total	50.745,54

D. OPEX

Maintenance costs are based on the failure model proposed in Section II-D adapted to the Hydro-K Platform reference situation. These values associated with possible failures are added to the standard maintenance cost: lubricant replacement, belts, and brush replacement. The operating cost does not scale at the same level as the power produced by the platform because the price of parts for maintenance is considerably lower than the cost of labor. However, for the maintenance of the Hydro-K platform, it is also necessary to evaluate the cost of the vessel to access the platform. All operating costs are compared in Figure 15 and recorded in Table VIII.

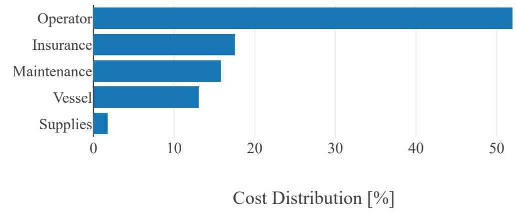

Fig. 15. Distribution of the Hydro-K Platform's operating expenses.

TABLE VIII
HYDRO-K PLATFORM'SANNUAL OPERATING EXPENSES - OPEX. DOLLAR VALUES IN 2022.

Category	Annual cost [US$]
Operator	3.113,83
Insurance	1.050,00
Maintenance	945,36
Vessel	780,00
Supplies	105,00
Annual OPEX	5.994,19

E. LCOE

The estimated LCOE for the Hydro-K Platform is 0.14 US$/kWh. This value was calculated following the guidelines specified in Sections II-B, II-C and II-D, considering a discount rate of 11.75% per year in the value of the currency. The cost of the Hydro-K turbine is significantly cheaper than the Generation 2 turbine. The contributing factors are the flow stability, the larger scale of operating power, the more accessible installation site, and its longer service life. The distribution of impact by category is illustrated in Figure 16 costs, and their specific values are recorded and approximated to 2 decimal places in Table IX. Compared to the Generation 2 turbine, the operating cost has a more significant impact on the LCOE of the Hydro-K platform due to its longer operating time.

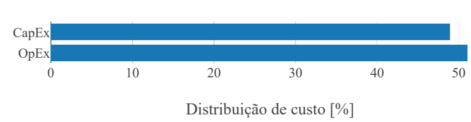

Fig. 16. LCOE distribution for the Hydro-K platform.

V. COST PERSPECTIVE

Figure 17 presents current levelized energy costs from Generation 2 and Hydro-K hydrokinetic turbines in contrast with Smart Hydro's *monofloat* turbine and EnCurrent's

TABLE IX
LCOE FOR HYDRO-K PLATFORM. DOLLAR VALUES IN 2022.

Category	Cost [US$/kWh]
CAPEX	0,07
OPEX	0,07
Total	0,14

modular installation of ten hydrokinetic platforms [13], [29]. The levelized power cost of Smart Hydro's *monofloat* was estimated with available commercial turbine prices, power output from the specifications, and reference operating costs of the Generation 2 turbine, given its similar implementation in isolated communities. Finally, solar PV and wind power are included to establish a benchmark, as both technologies are at an advanced stage of development and implementation.

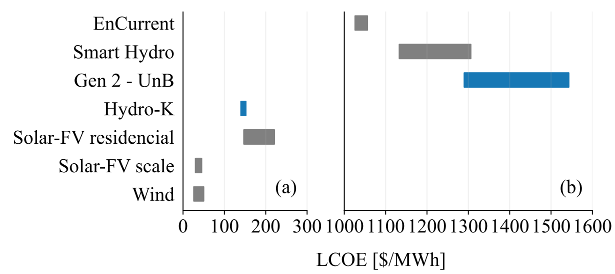

Fig. 17. LCOE comparison between various hydrokinetic energy sources. All hydrokinetic facilities included in (b) can be implemented Off-Grid. The costs shown in (a) assume inclusion in the electric grid [13], [29], [30]

VI. CONCLUSIONS

The Hydro-K platform stands out from other hydrokinetic energy sources due to its installation location and low equipment cost. Its installation downstream of hydroelectric power plants takes advantage of greater stability and flow velocity. These factors enable its simple design: an anchored floating platform, reducing the structure-related cost significantly. The Hydro-K platform is also entirely manufactured in Brazil, further reducing the cost involved. It currently projects competitively with residential photovoltaic solar power at a cost of US$ 140.00/MWh.

In contrast, all three turbines in Figure 17(b) have Off-Grid implementation capability. Both Smart Hydro's *monofloat* and the Generation 2 turbine were developed to use the technology to bring electricity to communities isolated from the grid. Smart Hydro's *monofloat* was marketable in 2014 and featured more efficient equipment, with an approximate Off-Grid cost of 1,306.00 US$/MWh. In contrast, the Generation 2 turbine, designed in 2007, presents a much more simplified manufacturing and maintenance, allowing greater accessibility in Amazon regions of Brazil at an approximate cost of 1,543.00 US$/MWh. The EnCurrent turbine installation presents the lowest Levelized Cost of Electricity, 1,056.00 US$/MWh. However, this installation is designed to be implemented on a large scale, with a nominal power output of 1 MW. This power output requirement reduces the practicality and implementation possibilities of the installation.

Unlike other small hydrokinetic turbine technologies, the Hydro-K platform is in the competitive range of energy production. Currently at the 5º level of TRL (Technology Readiness Level) maturity, with a prototype developed and tested, this technology allows energy generation at the cost of 140.00 US$/MWh. This cost is within the low-cost range, between 100.00 and 500.00 US$/MWh [31]. However, it is worth pointing out again that, unlike other technologies, its cost was calculated with a view to a joint implementation with the national grid. The Generation 2 turbine, designed for a context of energy supply for isolated communities, fits the current observed trajectory of medium energy cost, between 500.00 and 2000.00 US$/MWh.

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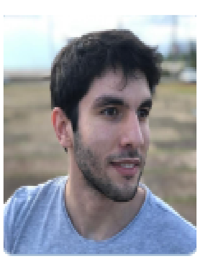

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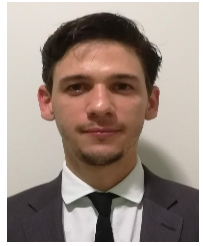

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