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Review Article

Modelling and simulation of tidal energy generation system: a systematic literature review

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Abstract
Tidal energy is regarded as one of the most promising modes of renewable energy generation owing to its environmentally friendliness and predictability. Tidal energy system modelling and assessment also plays a crucial role in leading to the choice of power capacity expansion by demonstrating different strategies in meeting environmental targets and future demands while maintaining and broadening the understanding of tidal energy development. This work is aimed at developing a systematic literature review of the different modelling methods employed in optimizing the output of tidal energy using a marine current turbine system. An analysis is also carried out based on the techniques adopted in modelling and simulation of tidal energy. During the analysis of simulation models, two major objectives were discovered, which are the determination of performance and dynamic loads under varying operating conditions and the development of a speed-dependent turbine operation control system. Hence, it is very necessary and imperative to identify a strategy between the precision of the simulation model and the speed of the loop control. The work is useful to tidal power developers, tidal energy scientist and engineers in evaluating and assessing key techniques and tools necessary for tidal energy generation.

Keywords
Tidal stream energy, Control optimisation, Hydrodynamic modelling, Tidal turbines efficiency, Tidal energy modelling.

1.Introduction
In recent times, a fair amount of global electricity generation comes from fossil fuels. The consequent economic burdens, environmental pollution produced by the consumption of fossil fuels has contributed significantly to environmental degradation which brings about an urgent need to employ other sources of renewable energy that are environmentally friendly [1]. Renewable energy resources are simple technologies with environmental benefits and it is widely abundant all over the world hence stakeholders such as the electric generation industries and the government can harness these renewable energy sources to deliver energy security for countries all over the world and at the same time mitigating greenhouse gas emissions[1−4]. The United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement which recommended that countries in the world adopt technologies and strategies to contain the increase in global temperature to 2°C [5].

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With the Paris Agreement set in motion, the South African government resolved through the minister of environment to engage in technologies that will assist in mitigating the negative impact of Carbon dioxide. This is informed by the fact that South Africa has huge potential for natural resources such as wind, sunlight and tidal. The country has also demonstrated to have the highest speed tides in Africa with significant potential for electricity generation.

Tidal energy generation has shown some exceptional advantages and benefits amongst renewable energy systems (RES). There exists an electricity generation potential from tides that results from tidal generating forces that are generated by the coupled Earth-Moon system. Tidal power has a great advantage over wind power and solar due to the fact that it is the most predictable renewable energy [6]. It is worth noting that advance research on tidal energy technology is still in its developmental stage, hence, the need to optimize these tidal systems and improve the efficiency of the extraction of kinetic energy from free-flowing water is much needed. The basic operating conditions for harnessing tidal turbine energy is based on a free flow velocity of 2 to 3m/s, a depth of 20 and 30m at least for preliminary experimentation with deeper water models (>40 m) [7]. It is very important to mention that a continuous submarine operation needs the tidal system to work reliably with the high availability of tides because various locations of tidal currents can offer a huge amount of energy density which might lead to very high power. This implies that the strategic reduction of site visits is brought to a low, as tidal devices are often mounted in places with powerful tidal currents with high flow speeds [8]. Also, another advantage of tidal generation is that it is linked to tidal networks which present energy transport in close proximity to shore and offshore substations and huge voltage hence, submarine transport will not be necessary. It is therefore proposed that tidal power developers can be utilized to widen the accessibility of their systems by transferring the power electronics from the nacelle (hub, rotor, gearbox, generator, inverters, hydraulics, and bearings) to the shore. This will also limit site visitations since the frequency of power converter failures may be higher depending on the data gotten from the onshore wind turbines [8]. Hence, the tides speeds variations of tides sources are causing problems for the current power grid. It will be of note that the Electric power generation from the tidal may be very high (more than the power demand) or very low (less than the power demand) depending on availability of tides (less than the power demand). Thus, these RES are time-variable, non-dispatchable with limited control, and have a low-capacity credit, which is critical in power system planning. However, variations in power generation or consumption on the grid, caused by generators or loads, or frequent switching on and off, can breakdown utility in the case of grid connected systems. Given the fluctuation of their input power, ocean energy converters, particularly tides converters, may be very likely to create flicker. The amount of flicker generated by ocean energy converters is dependent on a number of factors. Flicker levels are expected to be higher on weak grids than on stronger (higher voltage, more interconnected) grids for a given power variability. Given that flicker is strongly dependent on the local network, three forms of power output variability should be differentiated. The first group of devices is those with a relatively smooth input power that results in a smooth electrical power. This group contains tidal turbines, which uses the tidal stream to generate power in the same way as wind turbines do.

Additionally, the optimal power generation to satisfy the mandatory load demand that must be met, appropriate sizing and design of the hybrid RES with or without storage options, i.e., the hybrid system architecture, choice of proper power electronic converter topology for interconnection with the power choices and their optimal operation, optimized cost of operation and regulation are all aspects of hybrid tidal energy storage systems control.

1.1Concepts, features and characteristics

Tides are regarded as the periodic motion of the body of waters especially that of oceans and seas that results from the inter-allied forces that occurs with the celestial bodies. Tides can also be seen as "*long-period waves*" that passes through a body of water in response to the forces exerted by the sun and the moon. The Moon is the major tide-generating body and as a result of its larger distance while the Sun's impact is only 46% of the Moon's. Tides and ocean currents are practically not the same. Tidal currents are usually compelled by two connected bodies of water balancing their differences in levels which results in a flow of water to a region of low-pressure head from a region of high-pressure head. If the difference in pressures head occur an opposite end of a channel or in a similar restriction, then considerable flow speeds commonly result through comparatively small cross-sectional areas and it is the high-speed flow that enables tidal currents to be a likely candidate for power generation [9].

It is also worthy of note to mention that it is not all tidal currents that happen at the interactions between large bodies of water; there exist or still exists many currents which are functions of the emptying and filing of estuaries and basins, the resonant dimensions of which can in turn influence the flow behaviour.

According to [9], tidal currents can be well-defined as the "*periodic movement of a body of water principally driven, though not necessarily exclusively, by a head difference produced by out-of-phase ocean tides at a different end of a restriction. Other external and, periodically, non-periodic forces are applied to tidal currents and these are largely dependent on the local weather patterns (radiational tides), ocean characteristics (internal tides) and geography*". The amplitudes and the current frequencies of tidal currents can be investigated and presaged by employing mathematical techniques of tidal heights. The procedure of acquiring preliminary data from tidal current is more complex than that of reading tidal heights, but with the origination and advancement in subsea digital electronics, the procurement of substantial quantities of high-quality tidal current velocity data has been quite simple and affordable.

The tidal systems that drive the water bodies are reliable and highly compounded centrifugal and resonance-driven systems and should not be mistaken with other water flows like the Global Conveyor and the Gulf Stream, which rely mainly on thermohaline-induced density variations for their motive force.

Tidal energy systems generation is a new and broad research area with multiple components. Several works in literature have focused on different aspects of tidal energy extraction techniques on the basis of the core method of operation of tidal power plant as well as the algorithms to control and manage the timing of the simulation. This paper however focuses on the review of different modelling and simulation approaches necessary for tidal power generation and also examining further developments and discussions on simulation techniques that includes necessary components and also describing other methods under development. It is important to understand that large-scale adoption of tidal technology will only occur when economic conditions are good, and the industry is operationally competitive.

The gradual increase in the development and design of tidal return projects has sparked the desire to develop simulation modelling tools for the optimization of tidal energy to reduce uncertainties by giving an overview of potential benefits and corresponding impacts [10].

In this work, a systematic literature review is conducted to study the different types of tidal power generation models while examining the simulations performed so as to properly analyse the influences of these various methods on the tidal energy output. In addition, this work will investigate and review various modelling methods by employing different optimization techniques in order to ascertain their output energies. The limitations of the modelling and simulation techniques will also be analysed and grouped. Finally, a possible solution to overcome these challenges will be proposed. This no doubt provides a significant value and vital addition to this research field.

2.Methodology

Systematic literature reviews (SLR) are primarily based on the principle of replicability, proprietary, aggregative, and algorithmic properties which are the basic and core philosophies. This method has been fundamentally applied in the field of medicine but given the positive results it has attained in evidence-based schemes, its application for this purpose has been broadened to encompass other areas like economics, education and supply management. This study is carried out according to the steps proposed in *Figure 1* which is similarly employed in [10, 11]. The figure shows how the analysis will be conducted; step 1-describes the nature of the problem and its limitations, step 2-describes the relevant content in the study, step 3-shows the process of data collection, step 4- organizes and classifies the collection of the data in the simplest form, while step 5 discusses and summarizes the work and finally, step 6-compiles the report.

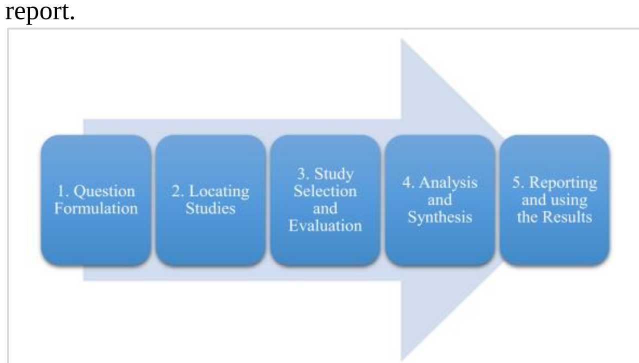

Figure 1 Formative steps for a systematic literature review (SLR)

2.1Question formulation

The current research's objectives are to identify and evaluate all relevant articles that have looked at in modelling and simulation of tidal energy generation system. Understanding the key problems and difficulties associated with choosing each simulation and modelling technique, such as optimization techniques of these tidal systems and improving the efficiency of the extraction of kinetic energy from the tides [12]. The reduction of flicker and harmonic distortion forms of power output with a relatively smooth input power that results in a smooth electrical power [13]. Design and sizing of the RES with or without storage options are other goals of this paper.

In the first step, research questions are formulated which involves the work-study focus. These questions are provided from the assessment of various previous research studies on the same or similar topic. The reports and academic papers analyzed in this article are ready to respond and provide answers to the formulated research questions provided in this work.

- RQ1. What are the different tidal energy modelling systems and their properties?

- RQ2. What is the extraction method technique use for tidal energy generation?
- RQ3. What are the applications use for energy sources of renewable energy tidal? As recent technical advancements suggest that the financial and environmental expenses may be reduced to levels that are competitive and make the tidal energy generation cost effective.

The process of searching comes next. Using keywords and search strings, citation databases and pertinent digital libraries were systematically searched for literature as part of this study. This contain different modelling approaches and tidal energy extraction methods are the keywords that were combined to produce the search string for these studies. Therefore, to adequately determine the literature search, a systematic methodology is used. In order to focus the search, the inclusion and exclusion criteria for this review article serve as the standards for including and excluding research papers from the study. Papers that fit our inclusion criteria and are relevant to any of the search terms are included. In this investigation, papers spanning January 2010 to July 2022 were considered. Additionally, studies that lacked specific data to support the research, lacked clarity, or had solely concentrated on another issue area were removed. Papers that did not specifically address modelling and simulation of a tidal energy generation system were also disqualified. *Table 1* displays the statistics and trend for articles on modelling and Simulation of Tidal Energy Generation System.

Table 1 Statistics of article source

Article source	**Total number of articles**	**Number of conference articles**	**Number of journal articles**
Google Scholar	30	5	6
IEEE Xplore Digital Library	10	2	4
Science Direct	20	1	5
Scopus	30	6	4
Total	90	14	19

A three-phase search strategy including an in-depth literature search and primary scans of all electronic databases including Scopus, Science Direct and Google scholar is utilized. The keywords to remember are those most often used in literature for the description of simulation techniques and the modelling of the tidal energy system. *Table 2* however details the keywords identified in this step.

These keywords were selected in different combinations for the creation of the following channels: the first list comprises of the keywords related to tidal power generation while the second list comprises of those associated with modelling and simulation. The search strings were derived by linking two main words from the two lists with the Boolean "AND". The words used for the search contains both generic search terms in which these generic search terms refer to "uncertainty", "stochastic" and "Energy modelling" which provides extensive coverage of the research results without omitting the vital analysis. More definite search terms were found from past search results which encompassed model words such as "MATLAB" or “computational fluid dynamics” (CFD)".

Table 2 Details of the keywords identified in the step

Keywords identified		
The tidal energy generation system	Modelling	Simulation
Tidal Stream Energy	Hydrodynamic Modelling	Control Optimisation,
Tidal Turbines	3-D Tidal Model	Tidal Energy Modelling
Electric Power Generation	Rotor, Simulation, Tidal Current,	MATLAB–Simulink, Direct Torque Control
Long-distance Drives	Energy Converter Systems	State of the art

Table 3 also displays the distribution of the different papers through the several years it was published. From the table, it is noticed that there are more article papers published than conference papers and the bulk of papers lie between the years 2013 to the year 2018. Therefore, to adequately determine the literature search, a systematic methodology is used. The different sections in *Figure 2* contain different modelling approaches and tidal energy extraction methods. The protocol below indicates how the extraction of data was executed from a huge number of papers using the keywords and a few excluding criteria.

Table 3 Year wise count of papers related to the research area

Years	Articles journals	Conferences journals
2010	2	0
2011	2	0
2012	1	0
2013	15	0
2014	14	0
2015	7	0
2016	12	1
2017	10	1
2018	10	1
2019	5	1
2020	4	1

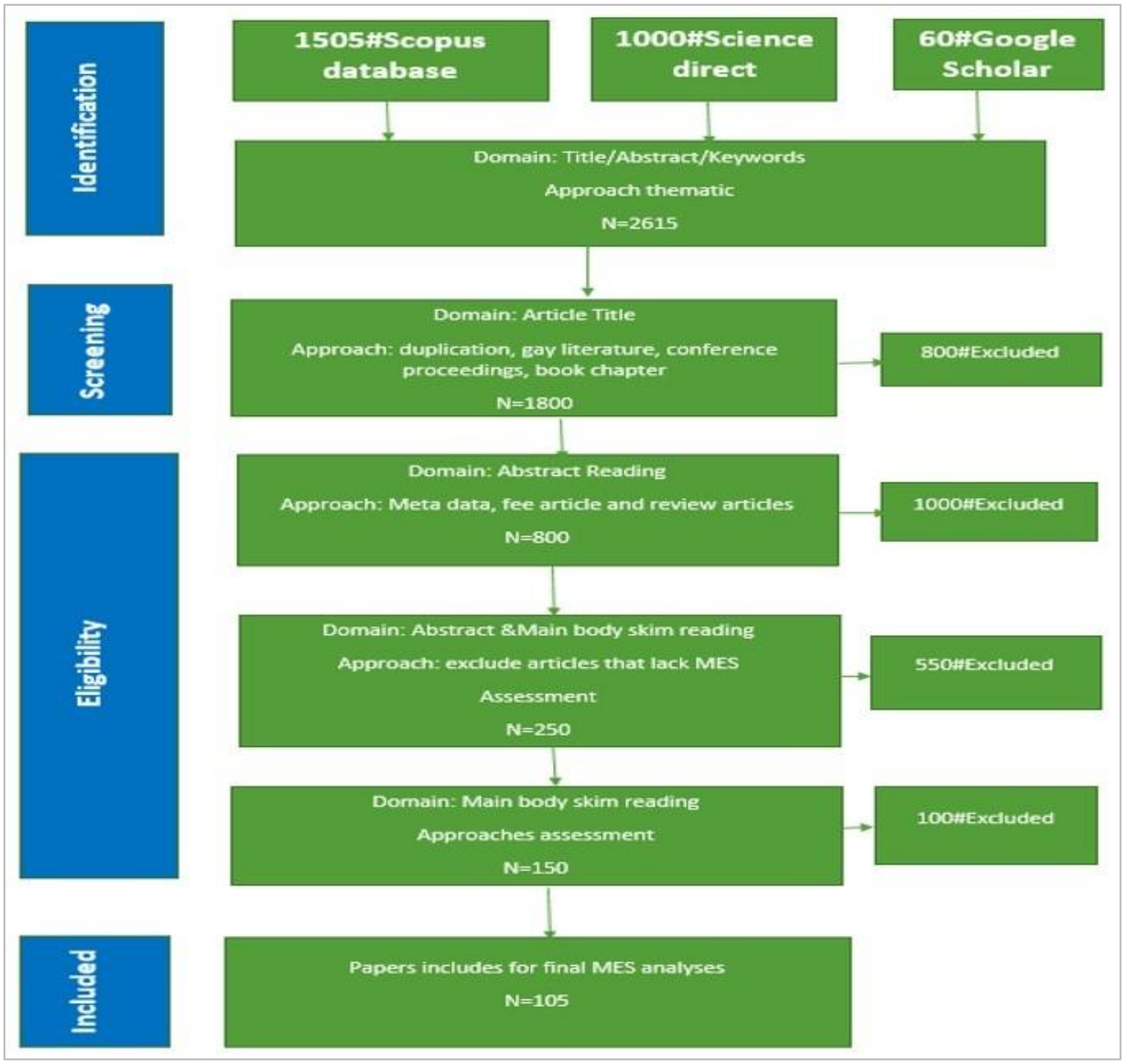

Figure 2 Protocol for systematic literature review (SLR)

3.Results

In this section, we access and analyse the findings and results from the literature review carried out as indicated in the process detailed in *Figure 2.* We start holistically by considering all themes relevant to tidal turbine systems and then begin to narrow down to the subjects which focus essentially on improving the energy output and minimizing the cost so as to have a more cost-effective tidal system.

3.1Grid integration

There are several difficulties encountered when integrating tidal energy into the electrical network. Some of such difficulties are, connecting tidal systems to the network which is observed to be very expensive because of the various components which include the electrical network and an underwater electrical system and the connection of submarine cables to shore that is required. Therefore, it is recommended to have marine power grids nearby as a prerequisite for future developments. Grid integration relies on the transmission and distribution of electricity and must also be viewed in the context of the inclusion of renewable energies in the broad sense [3]. In addition, the variability of power generation from marine power devices could create problems ranging from weak grids to grid congestion and voltage stability issues that are dependent on the development of technological constituents [3, 14]. Often, grid integration relies on the transmission and distribution of electricity and the integration of renewable energies in the broad sense of either grid upgrades or a newly-built capacity [15].

3.2Configuration of arrays

Available literature has shown that several studies have been carried out to comprehend the problems associated with the configuration of the array and the effects of marine energy systems on the hydrodynamic features of the marine environment. The authors in [16] investigated the impacts of the arrangement of a tidal system (capacity and spacing of the turbines) on the water levels and flows in the Shannon estuary in the Republic of Ireland using digital technologies. The results showed that water levels and flows will be disturbed after implementing a huge number of tidal stream turbines leading to a decrease in tidal amplitude and a reduction in tides. The FP7 DT Ocean project (Optimal Design Tools for Ocean Energy Arrays) which forms part of the work on the development of chips, already assessed the capacities of the tools implemented. In their study, they presented a technique on how hydrodynamic interactions can impact on the resource of energy, the energy performance, the cost of the uncertainties and the environment [3].

A couple of studies have also attempted to investigate the effects of network configuration on power output. For example, Wu et al. in [17], analysed the influence of the density and the shape of tidal stream networks (turbines 1000 to 10m in diameter) on hydro-environmental parameters and electricity production in the Severn Estuary and the Bristol Channel in the United Kingdom. The results showed that the configuration of a turbine network do have important effects on the output power and hydro-environmental parameters. The same authors in [17], also modelled the flow of ocean currents for the optimization of the layout of the tidal current turbine (TCT) network.

It was concluded that the efficiency of the turbine increases with the distance between the generators and also, that a diameter that is three times larger than that of the turbine is appropriate. One of the best designs of tidal energy generation is a model where the tidal current obtained from the energy harnessed from tidal resources without the erection of a dam and directly serving the tidal current to produce electricity using energy conversion apparatus/ turbines. This means that the tidal currents can be used interchangeably [18], hence, the associated term: tidal current turbine (also called hydrokinetic turbine [19, 20].

TCT can be used for power generation with differences in altitude between the low and high tides which generates strong currents (similar to wind power) for the generation of tidal energy [20]. TCTs are devices used in capturing tides energy resources from tidal currents via technology that is identical to that of wind turbine [7]. The tidal energy converters and Tidal Stream Generators (TSGs) can be categorized into Horizontal Axis Tidal Turbines (HATT) and Vertical Axis Turbines (VATs) [21], [22]. According to [23], the HATT concept is often exploited by tidal developers given its simplicity in operation and high efficiency (> 35%). On the contrary, VATs possesses a higher torque with a lower peak speed ratio and a lower current speed range which makes them suitable in low current conditions [23]. Jiang et al in [23] and Osman et al in [24] found out that the Horizontal Axis Tidal Current turbine (HATCT) offers great hope for the future among various tidal power devices that has been tested. The choice between HATT and VAT is dependent mainly on on-site specific conditions.

3.3Stream tidal plant

Tidal Stream Energy is the periodic movement of seawater as a consequence of the gravitational pull between the moon and the sun, this however causes the tide (tide is rising and falling of the seawater). Tidal Stream Power Plant Platform (TSPPP) is operated to support turbines, generators and other devices. Several forms of platforms can be grouped, such as floating systems, moored, pile-mounted and seabed-mounted systems that are regulated by gravity. The authors in [24], affirmed the advantages of these TSPPP varieties are as follows: installation and dismantling of moored floating systems are easy, and its maintenance is also simpler; but the pile system is used in deep water (30 to 60m) and their structures are very rigid; and while the seabed system is operated in shallow waters, in which the impacts of waves and wind are minimized [25]. Tidal resources can be exploited to produce electricity at the scale of a couple of kilowatts (kW) by using mini-power plants or using turbines at the scale of tidal farms of larger megawatts (MW).

A tidal farm is an arrangement of interconnected tidal turbines that are working collectively in a similar location on the concept of shared control [26, 27]. For these farms, three separate parameters are to be taken into consideration for the analysis of tidal turbines such as the nature of the tidal turbine itself, the nature of the tidal turbine park as well as the regional scale [28]. The study in [29] has shown that farms comprising of multiple tidal turbines have the capacity to generate multiple megawatts of electrical power with high predictability. The authors in [29−32], indicated in their studies that the economic aspects of tidal energy analysis are necessary because it includes the following parameters: the positioning of the turbines and number of turbines. They also indicated that the number of turbines used can contribute negatively in reducing the efficiency of tidal turbines through different phenomena such as cavitation, and sedimentation. Therefore, the way of solving this situation is the design of tidal turbines which is sufficiently robust and reliable to resist normal operating loads. The technological development of tidal turbines is always done with an emphasis on several diverse factors, such as environmental factors, hydrodynamics, and operations [30]. It was shown that with recent and current technologies, first generation tidal devices require higher peak tidal speeds (SV) of 2.5 m/s and water depths between 25m and 50m. To minimize costs and increase operational flexibility, the operation of a tidal turbine should be uniform for bidirectional flow. Several requirements are necessary for the effective design of this type of turbine [33]. Though, tidal energy projects are still at the level of research and development [1, 34, 35] its installation, implementation and testing has steadily been on a very fast pace.

3.4Optimization and stimulation of tidal arrays

In optimizing and simulation of tidal arrays, a direct assessment of on-site marine energy extraction from tidal resources should be conducted. Often, the 2-D and 3-D modelling approaches are conducted to determine the energy resources of tidal currents by modelling current speeds. Most researchers worked on the evaluation of the hydrodynamic effects during the harnessing of tidal energy. For instance, the variation of the flow field, the variation in the elevation of the water surface or the disturbances of the dynamics of tides were all studied by different researchers. The energy of the tidal current is usually evaluated as a function of the density velocity of seawater, the speed availability factor, the flood/source factor and the maximum tidal speed of spring, peak spring-tide velocity and neap/spring factor.

There are different classes of tidal array optimization. The foremost is the optimizing of operation of the turbines and sluices to increase the energy output from the array, while the second is the optimization of the overall economical design of the array to minimise the cost of energy. This section deals with the development of the digital models over time from different articles which enabled us to select the one that possesses the most replicable results, acceptable, feasible to achieve and the most optimally possible as well as effective.

There is a real need for the simulation models (simulation, optimization, economic equilibrium) in order to allow the conduction of deep and accurate assessments in several forms of energy, economics and engineering models (E4). The design of energy models is fundamentally based on end-users and several different research questions [36]. According to the articles in [37, 38], their analysis have shown that the uncertainty methods available for each type of model are variable. Quite a few analyses have also focused on particular forms of models, for instance integrated assessment models and optimization models. *Table 4* below tabulates the tidal current research areas relating to grid integration, configuration of arrays and tidal stream plants with their authors and year of publication.

Table 4 Tidal current energy resource assessments

Research Area	References	Year of publication
Grid integration	Magana et al. [14]	2014
	Uihlein and Magagna [3]	2016
Configuration of arrays	Fallon et al. [16]	2014
	Wu et al. [17]	2018
	Chen et al. [38]	2018
	Goude and Lundin [19]	2017
	Polis et al. [20]	2017
	Gunawan et al. [21]	2014
	Markus et al [22]	2013
	Priegue et al. [23]	2017
	Sheng et al. [24]	2017
Tidal Steam Plants	Aziz et al. [25]	2015
	Pacheco et al. [30]	2014
	Seo et al. [31]	2016
	Melikoglu [32]	2018
	Chatterjee [33]	2015
	Vazquez and Iglesias [34]	2015
	Yeo et al. [35]	2019

3.5Optimization of the operation of tidal turbines deployment

The authors in [39] analysed tidal current generators which are necessary for the extraction and exploitation of tidal energy. To achieve the extraction of an economically significant amount of marine energy, in this study, Myers and Bahaj in [40] discussed that it is advantageous to deploy several tidal turbines in a turbine network. However, it was also necessary to know how the arrangement of these turbines will be used to ensure the fullest potential of power generation, in which the positioning and individual tuning of the turbines were targeted as a parameter that can play a vital role in the production of energy, therefore it creates a major economic factor.

The formation of this problem as an optimization problem is compelled by a physical model employing an efficient optimization algorithm based on the gradient. The gradient of the power derived concerning the turbine's positioning and their tuning factors is evaluated as a fraction of the time required for a flow solution by resolving the related complementary equations. This leads to a gradient at a cost that is not dependent on the number of turbines. The authors in [40], also conducted an experimental analysis of a deep near-wake (up to seven turbine diameters downstream) of a HATT model in deep water where an acoustic Doppler velocimetry is employed to offer a comprehensive information on the three-dimensional mean and turbulent flow field at five separate depths across the width. This analysis included parameters such as the most completed three-dimensional velocities and well-defined normal stress data and Reynold's shear. The authors used the Reynolds stress anisotropy tensor to determine the degree of anisotropy of the Reynolds stress in the wake of the turbine. The resulting outcome demonstrated the limitations of isotropic turbulence models which is not a good option for modelling near wake dynamics due to the strong anisotropic near wake turbulence hence proposing that isotropic turbulence models is not a suitable model for use to in the dynamics of the near wake. Finally, it was suggested that the modelled optimization models, which did not consider the vortex effects and the modelling of the turbine by absorption discs, may overestimate the rate of decay of the turbulent kinetic energy.

The authors in [41], however estimated the tidal resources of a site located in a macro tidal location with maximum tidal speeds using the 2-DH regional hydrodynamic model. This resource assessment made it possible to construct two different tidal energy extraction scenarios comprising of a 290MW tidal turbine network in two separate locations. Going further, the authors also studied the effects of turbines on hydrodynamics and sediment transport which limits the hydrodynamic disturbance that is located around the system with a speed average reduction locally reaches 0.3m/s (corresponding to 15% of the base speed). The results showed that tidal power extraction tends to decrease the bedload rate and deflect sediment flows after focusing on the variable speed that causes the bed load (exceeding the threshold critical erosion). After performing a

simulation using simple modelling of the transport of suspended sediments, it is so clear that the extraction of tidal energy has a substantial impact on the place of deposition of particles passing through the water.
Author [42] analysed the problem of positioning and individual adjustment of tidal turbines which has much influence on the extraction of power in water streams because of the direct impact it has on economic interest. However, the optimization manual is difficult to use in solving the problem due to parameters such as legal constraints of the site and non-linear correlations of the turbine wakes. Thus, the researchers used the physical model that made it possible to solve the problem using an optimization algorithm based on an effective gradient. It was noted that in each iteration in the optimization, a shallow two-dimensional finite element water model is used in predicting the direction of flow and the performance of the composition of the matrix. The tidal current increases gradually concerning the position of the turbines and their variable elements which is evaluated as a function of time. The optimum slope that is meant to be adjusted to a maximum flux, is determined by some equations which allow determining the fixed values of the power extracted at the positions of the turbine and adjustment parameters.

Authors in [43] performed an analysis that concerned the production of electricity to the maximum point while paying attention to the Betz limit which sets a theoretical upper limit to produce electricity by the turbines expressed in the form of a coefficient maximum power of 16/27. It is shown that the energy produced by wind turbines is lower than the Betz limit. On the other hand, tidal wind turbines in a channel theoretically possesses a power coefficient several times greater than 16/27. However, the extraction of electricity by turbines in large tidal farms also decreases the flow along the channel and stops their maximum power. Despite the limitation caused by the reduced flow, tidal farm turbines can generate enough power to compensate for the energy losses. The Betz Limit can be defined as the highest possible energy that may be derived through an infinitely thin rotor from an amount of water flowing at a definite speed. In turn, the output power of a reduced flow turbine remains higher than the maximum power of a single Betz turbine operating in an unreduced flow. It should be worthy of note that the quantity of turbines plays a very huge role in maintaining the advantage of tidal turbines over wind turbines and the dynamic balance of the channel. This study showed that the development of the tidal turbine park offers tidal turbine parks an economic advantage over wind farms of similar size.

Before the expansion of the technology of tidal turbines, it was recommended to place the turbines in places favourable to the local high-speed navy. According to the analysis by [44], the effectiveness of the tidal turbine and blade forces is driven into a profile at a high shear rate. Recently, this sector has seen significant growth and development as regards unwanted interactions in the marine environment, especially local navigation, higher levels of turbulence and velocity shear formed in water column. It was also seen that a high shear rate is attained as the turbine positioning is lowered in the water column. Accordingly, a speed profile of the Acoustic Doppler Current Profiler (ADCP) measurements served as an input limitation for the CFD analysis. However, in cases where the plate is firmly fixed, the downstream of the turbine will be forced to burp with performance to be minimized over a full rotation. Hence, the amplitude and the growth of the characteristic of the axial load will require careful design considerations and implementation.

Authors in [45] carried out an analysis of the fatigue that could occur on the tidal turbine. For this reason, the simulations were made for large scale conditions using CFD simulations. The simulations used the method of geometry-driven large-scale TCT in comparison with the empirical data from a 1MW machine positioned at the European Marine Energy Centre (EMEC) test site. An average inlet velocity profile with negligible inlet turbulence was also employed. The results showed that the average blade pressures were the same for both types of inlet turbulence. Additionally, in simulating the effects of turbulence on loads using prescribed synthetic turbulence, precursor channel flow simulation was used for the simulation of mean velocity flow profiles, Reynolds constraints and length scales. Reproduction of simulations with low input turbulence was successful in the spectral distribution of blade bending moments under low wave conditions.

In the work in [46], the authors studied the composition and behaviour of tandem propellers of a single horizontal axis counter-rotating tidal turbine. A simulation was carried out using the multiple-objective numerical optimization technique together with the surface response method (SRM) with a genetic algorithm (GA) to acquire suitable blade profiles. During the optimization process, the blade tilt angle distribution is chosen as a variable factor as it plays a very vital duty in influencing the input conditions of the rear blade. The outcome and findings after simulation revealed that the power coefficient greatly improved the performance of the powertrain, and the blades was also improved by optimizing the pitch angle.

Authors in [47] researched the potential effects vertical and horizontal axis turbines have on the navy after deployment. The study used a 2-D hydro-environmental model integrated at a depth that shows that the Depth Integrated Velocity and Solute Transport (DIVAST) has undergone a modification to allow simulation of hydro-environmental impacts of turbines in coastal areas. The results demonstrated that the model is in consonance with the predictions of the 1-D model which was published previously. After carrying out the feasibility study and the accuracy of the model, the arbitrary set of tidal turbines was used in the seven estuaries and the Bristol Channel in the United Kingdom. The results were satisfactory even on the analysis of the effects of the network on the levels of water, tidal currents and levels of sediment and faecal bacteria, and also the tidal energy generated. The properties of the turbine blades are discussed, and the model was defined employing the multiple reference frame (MRF) technique in [48]. Also in the work, the definition and comparison of commercial models based on technology and the challenges of the tidal turbine concept of tidal energy (tides, swell) was also reviewed. Three sites were analysed as to how to carry out the implementation and the feasibility of harnessing energy from tidal turbines considering the substantial elements compared to the 2-D depth-averaged digital tidal power distribution simulation modelling [48−52] which was implemented using Mike 21HD to locate the high flow velocities. After simulation, the authors found out that there is a high-speed current crossing the shore around the coast, the result is that the most suitable location to install the tide park is around the coastal locations. However, the tidal turbine that was used in the experiment had a power coefficient greater than 0.4, whereas in previous publications the values were found to be around 0.35 to 0.45 at their points. *Table 5* shows research carried out in the area of optimizing the operation of the turbines and the maximization of the energy output.

Table 5 Optimizing of the operation of turbines and maximizing the energy yield from an array

Research area	**References**	**Year of publication**
Physical modelling	Ahmadian and Falconer[39]	2012
	Tedds et al. [51]	2014
	Ahmed et al. [45]	2017
The tidal resource’s location	Thiebot et al. [41]	2015
	Funke et al. [42]	2014
	Vennell[43]	2013
	Mason-Jones et al. [44]	2013
	Soleimani et al. [48]	2015
	Zhou et al. [50]	2017
	Li et al. [52]	2017
	Amiri et al. [53]	2019

3.6Optimization of the entire economic design of the array to minimise the cost of energy

A study of the potentials of tidal Stream Energy along the coastal zone using numerical model is carried out in [53]. Previously, the number of tidal turbulences forecast locations is used to solve this type of problem but in this case, this method is not able to solve the problem. Hence, the work in [54] employed a Regional System Model for Ocean Model (ROMS) to identify places with high potential for tidal energy and the resulting outcome were validated against measurements. The wet location topographic features were incorporated into the simulation model with wetting and drying of simulation cells. So, the impact to extract power from estuarine hydrodynamics is simulated using excess deceleration force in the equations of impulse governing in ROMS. This led to two possibilities of extracting power for the simulation at the Canoochee River, Georgia, United States. With that, the first possibility concerns an extraction of roughly 20 percent of the original kinetic energy over the entire cross-section of the river and the second possibility offers a major extraction estimate of about 45 percent. It was noticed that the sum of the eliminated and residual kinetic energies is greater than the original kinetic power in the cross-section, which is influenced by the recovery of the flow pulse after optimization of the current flow energy. It was also observed that the evolution of maximum and minimum water levels was in the range of a centimetre.

In the paper by [55], the authors used a numerical model to simulate extracting tidal energy from water and determine the impacts it has on hydrodynamics and transport stages in a tidal channel and bay system that is connected to a coastal ocean. Marine hydrokinetic modelling (MHK) was integrated into a three-dimensional (3-D) oceanic modelling employing the motion well technique. The authors also compared the models of the well-motion approaches and that of the quadratic of the bottom friction. However, the impacts of the 3-D simulation model on the vertical velocity profile, the maximum extractible power, and the reduction in volume of the flow through the channel were analysed over a succession of numerical experiments. The outcome of the 3-D model showed that the decrease in the volume of the maximum extractable energy flux predicted by the simulation of the 1-D model or the mean of the two-dimensional (2-D) digital model can be overestimated in depth. It was also noted that the remote field impacts of tidal turbines on bay flushing time were also resolved. The results indicated that the extraction of tidal energies had a larger impact on the flushing time than the reduction in the volume of the flow, which leads to a negative impact on the biogeochemical processes in coastal and estuarine waters which is the basis of primary productivity and advanced forms of ocean life. As it was detailed in previous studies that the tidal turbine farms allow an improvement in power and a reduction in costs. So, in the article by [56, 57], the authors systematically explored a large capacity of farm tides in the canals to optimize it using the simulation of 2-D digital network arrangements. The peculiarity of this study is the introduction of the pressure drop during the flow which made a difference compared to the other previous results which considered the velocity as constant. The 2-D adaptive mesh method fills the space between the small-scale and large-scale matrix models. Several turbine configurations and settings were simulated using the turbulent flow in the tidal reversal currents for the exploration of channel-scale optimization and tuning of large farms. The results of the optimization demonstrated that there is an increase in the total energy capture as more rows are added to the tidal turbine network, although the efficiencies of the excess turbines are reduced. Each turbine in a row is set to a fixed position at an optimum position in a small channel capturing 2:5 (0:5) energy of an isolated turbine. It was also shown that in the event of a reduction in power per turbine, one reduces by 1.0 due to the increase in the number of rows and at this time there is an optimal blocking of the energy. However, as the number of tidal turbines increases, the individual small turbines wake up as the pressure drop occur on each row. The speed of the free flow decreases linearly with the capture of the total energy while an increase in the gradient increases with the size of the channel.

The usage of the CFD model for the prediction of the performance of turbomachines, which offered reliable results, is one of the crucial steps to minimize the cost of design. It was noted that the method of actuating disc implemented by Ducoin et al. in [58] compared three methods from previous publications and the results obtained showed that the rotary reference remained constant. It also showed that there is a significant decrease in the computational work when using the d-disk actuation method. However, the expected fluid circulation was relatively negligible as projected. In the works in [54, 59−63], the authors investigated other methods of improving the rotor performance. The open-source blade model program designed in [53] has made a huge improvement in eliminating sharp edges, rough surfaces, and hub assembly issues in blade design. However, numerical modelling (DNS) has been used in [57] to obtain reliable results, as it relates to high computational cost and as well as the resources used [58−60]. The information in *Table 6* shows the research carried out in the area of optimization of the entire economic design of the array so as to minimize the cost of energy.

When the large eddy simulation technique is employed in [47], it was seen to reduce the cost if when in comparison with the Reynolds. The average by Navier-Stokes Turbulence Modelling (RANS) also came at a very minimal and precise cost. The authors further utilized the k- simulation approach for the small relative mesh concerning the Reynolds stress technique and the k-v shear stress transport (SST). On the other hand, the authors in [53, 70−73], made a comparison of five turbulent models using the rotary reference approach. In this model, a performance analysis was made on a rotor in the presence of axial velocity and non-constant waves. This was evaluated by simulating the free surface based on the k-v SST turbulence technique for modelling while bidirectional traffic was calculated using k-v SST simulation modelling [74].

Table 6 Optimizing the entire economic design of the array to minimise the cost of energy

Research areas	References	Year of publication
Numerical modelling	Defne et al. [54]	2011
	Yang et al. [61]	2013
	Divett et al. [56]	2016
	Neill et al. [6]	2018
	Dai et al. [62]	2018
MATLAB/SIMULINK interface.	ElZalabani et al.[63]	2015
	Sousounis et al. [64]	2016
	Ngancha et al. [65]	2017
	Li et al. [52]	2017
	Haverson et al. [66]	2018
Conventional proportional-integral controller - derivative (PID)	Whitby and Ugalde-Loo [67]	2013
	Liu et al. [68]	2015
	Kumar and Shankar [69]	2018
Genetic algorithm modelling	Dai et al. [62]	2018

In the work by [75] and [76], the authors used the turbulence model k-RNG for the improvement of the momentum of the blade elements -CFD Blade element momentum (BEM-CFD). This technique is also employed to analyse the phenomenon of cavitation in the turbine while [51] and [77] used the standard model k for the same purpose.

The work in [78] focused specifically on the dynamic loads of the horizontal turbine axis and the blade's performances in various operating conditions. The element momentum method was used for designing the blades based on the hydrodynamic characteristics of the hydrofoils to the computational fluid dynamic evaluation. However, the authors used the comparison method to differentiate between efficiencies achieved using the analytical method and experimental method with CFD computation. Hence, it allowed the improvement of the highest achievable power coefficient experimentally to about 0.427, i.e. about 1.4% which is higher than using the comparison between efficiencies achieved analytically and experimentally with CFD computation only. The works in [61, 79] evaluated the impacts of extracting tidal energy on hydrodynamics and in a tidal channel motion processed at a coastal ocean. The authors also carried out a simulation comparison of the momentum sink technique and the quadratic bottom friction technique. After the study was completed with a 3-D model, the volume flux diminution at the extractable higher power which has previously been predicted by a 1-D with an analytical technique is seen to be over the limit. Thus, the extractable maximum energy significantly relies on the turbine hub's height in the water column which was found to attain the maximal value when turbine hub height is positioned at an average-water depth.

The work in [52] investigated the water level and the tidal current at the level of the narrow channels. The usage of a semi-implicit three-dimensional model allowed the study of very complicated characteristics of movements of the speed of current tides. The model was programmed with nine tidal components (M2, S2, N2, K2, K1, O1, P1, Q1 and M4) at open boundaries. The effects of energy subtraction were made using the momentum method. The water stream at a high-resolution mesh at the turbine is allotted to arrest the detailed characteristics of the hydrodynamics compared to the operation of the turbine. Finally, the model is applied in a complete system in a water stream experiment and flume simulation results. The results displayed that the new model can correctly be simulated. In the study in [62], the authors employed CFD at a specific sea area. It proposed an initial arrangement scheme of TCTs numbers that were generated from empirical knowledge. The techniques facilitated manual adjustment to mitigate the wake effects and maximize the power output of Tidal Current Farm (TCF). The major drawback of this technique is that it does not effectively recognise other pertinent factors such as benefits relating to the environmental and different operational costs of tidal power.

In the work by [69], the authors examined an optimal operating point since the output power is relative to the operating point. They demonstrated that the further one moves away from the point of maximum energy (MPP) there is a reduction in the energy level. To regulate this operating point, they used the traditional proportional-integral-derivative (PID) controller on the dynamic performance set of the load frequency control (LFC). The study further showed that the reloading process cannot decrease the gradient of the frequency deviation unless control mechanisms that are frequency sensitive such as the character of the control to be damped are considered together with the tidal power plant (TPP) as a viable option for wind power plant (WPP) [80−83]. An analytical development of the TPP's performance in providing quality electrical power to meet consumer needs is much needed. In this regard, authors in [67] analysed the different behaviour of a tidal turbine in pitch and stall regulations (TST). This is a new control approach for monitoring maximum power point (MPP) in a TPP under variable tidal current speed.

The work in [81] applied the same method used by [84] to simulate the conversion system of tidal energy by employing a pitch control turbine and a squirrel cage induction generator combined with a long-range variable speed converter. However, the generator can be optimized based on the variable speed control approaches which allows the work to be operational at a maximum power coefficient. Availability issues associated with tidal generation under the sea can be improved by reducing the number of system components using long tri-phase cables that connect the generator and onshore voltage source converters. It however created a system that converts the achieved power so as to permit a variable speed hydro-kinetic turbine system to produce constant voltage and frequency at variable water speeds. This model incorporated a continuous boost chopper to sustain a constant voltage of the intermediate circuit.
The regulation of the optimized DC current is for the maximum power point (MPPT) of the turbine system while control of the DC link voltage circuit for supplying current to the load is provided by the line-side pulse width modulating (PWM) inverter. According to the works [65, 84] the conversion showed high-quality results for a variable speed hydrographic system.

The work carried out by [52] used MATLAB–Simulink approach to optimize a tidal turbine system by the way of modelling the rotor and the resource. The simulation technique consists of two objectives which are performances and dynamic loads determination in various working circumstances and control systems. During the simulation model, the speed control and pitch are optimized. In this instance, it is important to determine a way around the accuracy of the simulation model and the control-loop computing speed. The blade element momentum (BEM) technique was utilized for the turbine modelling. The simulation model proposed was applied as a sizing and site calculation tool for current turbine installations, it was also used to calculate the extractible power from the Raz de Sein.

This research carried out by the authors in [63] dealt with the advancement of a MATLAB-Simulink technique for a TCT system with the aid of modelling of drive train, generator the rotor and the source. The main purpose of the simulation was to ascertain the operation of tidal current energy system and how it can be integrated into power generation. The harnessing of tidal current power occurs through different categories of water current turbines. In this case, a low-speed turbine suitable for use in the permanent magnet synchronous generator (PMSG) without a gearbox was considered. The turbine rotational motion of the rotor is transferred to the electrical generator using a mechanical transmission system termed a "drive train". The study used MATLAB/SIMULINK interface and the maximum electrical power extraction around the acceptable range of tidal currents to ascertain whether the controller can effectively track the best curve that has any water current speed variation.

In the work by [85], the authors utilised the sound technique to examine the model of the Delta Stream. However, after preliminary trial, a 10MW tidal array was suggested at St David's Head, Wales to examine any likely environmental effects of the array due to energy extraction. An experimental case study of the Pembrokeshire coast was carried out employing a high-resolution depth-averaged hydrodynamic technique Telemac 2-D to evaluate changes from hydrodynamics to morpho dynamics. The resulted outcome showed that the recommended array of 9 tidal energy converters will lead to changes in the eddy propagation resulting to a change in the velocity field up to 24km from the tidal array. Alterations in morph dynamics are predicted via changes to the bed shear stress. Modifications to the mean and maximum bed shear stress over 30 days are discovered to be more localised and range to 12km from the array. These modifications indicated that the proposed tidal array would result to the accumulation of localised sediment and will serve as a hindrance to sediment transport with likely ramifications to the benthic ecology of the area. An optimization method based on two-level programming for TCF measurement coupled with the low cost of production of tidal energy was evaluated [78]. Apart from optimizing features of tidal current velocities and wake effects, this study also investigated and evaluated the commercial costs and environmental gains brought about by the incorporation of TCF using the GA and quadratic programming strategy. The efficiency and flexibility of the proposed method are revealed using measured tidal current data and the IEEE bus test system.

In the work in [64], numerical models were developed to provide all the necessary technical information regarding resource exploitation and their effects including inconsistencies in the simulation model of the results of tidal power plants, program operations and others. In this work, different models were presented for the gradual and systematic introduction of spatial dimensions in resource forecasting applications. The advantages and limitations of each of these models were also discussed regarding the assessment of power generation and the capable hydrodynamic effects of tidal power plant proposals. The results showed that it is necessary to use a hydrodynamic scale stage that will facilitate optimization studies and the robustness of tidal power plant approaches. It also revealed that the production of tidal and fluvial energy in connection with the network can be affected by the oceanic turbulence, thereby causing fluctuation in the output power and the state of the network. This fluctuating power will trigger power problems such as flicker or fluctuating voltages through the operation. It is, therefore, necessary to calculate the flicker emissions and to attenuate the flicker to remedy the power quality problem.

In [57] a battery energy storage system (BESS) interposed between the power converters of the tidal system to minimize flicker under various grid conditions was proposed. It was evident that the BESS contributed towards smoothening out the active power and reduced flicker from the grid. While there is minimal power out of the grid with a reduced impedance angle in the distribution grid, the BESS system produced acceptable and improved results Telemac with interrelated inverters produced in the validation simulation tool of PSCAD / EMTDC. However, the research on optimization, design, analysis, operation, and performance of tidal energy produced new techniques for inspecting numerical optimization and simulation of turbine efficiency. In addition, the MATLAB Simulink model was used due to its potential of predicting flows involving rotation, boundary layers under strong different pressure gradients. Presently, Tidal stream plants are attractive techniques for the large-scale production of electric energy in the marine sector. This is because, knowing the tides and their corresponding available energy resources make it predictable and time-dependent [6]. *Table 7* to *Table 15* displays the key characteristic areas that have been identified in literature relevant to the work. The parameters employed in determining these characteristics are identified in the table and the modelling techniques employed are also documented as well as the authors and the year of publication.

Table 7 Key characteristics area identified I

Parameters	**Modelling technique and tools**	**References**	**Year of publication**
The feasibility study of tidal lagoon power plants in the UK. Surface velocity and flow power.	Integration of the 2-D Verifiable Depth Digital Model with the evaluation of measurements by Doppler acoustic current profilers. The evaluation of the current quantities collected in the space of 5 min, interpolated to another point. The creation of a digital model of the Alas Strait was possible using the Princeton Speed Ocean Model (POM). POM is a 3-D model.	Blunden et al. [80]	2013
		Tedds et al. [51]	2014
		Neill et al. [6]	2018
Marine current velocity	Assessment of the size of current profilers and satellite data. Collection of relevant data at 10 min separated over 20s, then temperature and water level collected.	Goundar and Ahmed[81]	2014
Tidal volume flux, extractable maximum tidal power potential.	The two-dimensional finite element model (TIDE 2-D) was used for simulation with the turbines simulated in certain areas by maximising the drag.	Suthgerland et al. [82]	2007
Kinetic energy flux	Current speed data was collected using DNL (average maximum spring speed). Then, the kinetic energy flow was evaluated using the velocity and the cross-section.	Uihlein and Magagna [3]	2016

Table 8 Key characteristic areas identified II

Parameters	Modelling technique and tools	References	Year of publication
The optimisation of tidal hydrodynamics and developmental analysis of Tidal Stream Energy over the Hulu Island.	The statistical outcomes of the current velocity and tidal elevation were matched with data from field inspections (for water levels and tidal current). In terms of the optimization, the authors used a double-dimensional geometric approach for the simulation of tidal hydrodynamics and developmental analysis of tidal stream.	Gao et al. [86]	2015
Current velocity, flow power density	The Euler - Lagrange Finite Element Semi-Implicit 3-D Model (SELFE) for modelling was used around the coastal seas of the NSC, Taiwan to collect the bottom topographic data from the same region. The method was verified using the ADCP and tidal level measurements.	Chen et al. [87]	2014
Deployment of several tidal turbines, the arrangement of these turbines is used to ensure the maximum possible generation of power and rotational movement of the turbines in a network.	In this analysis, a commonly utilized open-source depth-integrated 2-D hydro-environmental model was employed to simulate the hydro-environmental effects of the turbine in an inshore environment.	Ahmadian et al. [47]	2012

Table 9 Key characteristics areas identified III

Parameters	Modelling technique and tools	References	Year of publication
The performance of the tidal turbine and blade forces, local navigation, higher levels of turbulence and velocity shear in the water column is used to form the maximum power output.	The clarification of the tidal turbine's performance, and the focus was at blade forces that occurred in the course of rotation in a high shear speed profile. The speed profile from ADCP measurements was utilized as an inlet limit for CFD assessment.	Mason-Jones et al. [44]	2013
		Serhadliogu et al. [88]	2013
		Adcock and Draper[89]	2014
		Liu et al. [90]	2016
		Funke et al. [42]	2016
		Petley and Aggidi [91]	2016
		Mendez et al. [59]	2018
The Betz limit sets a theoretical upper limit to produce electricity by the turbines, a coefficient maximum power of 16/27.	The output power of a reduced flow turbine remains higher than the maximum power of a single Betz turbine operating in unreduced flow. The number of turbines played a significant part in maintaining the advantage of tidal turbines over wind turbines and the dynamic balance of the channel.	Vennell [43]	2013

Table 10 Key characteristics areas identified in IV

Parameters	Modelling technique and tools	References	Year of publication
The fatigue that could occur on the tidal turbine	The simulations were made for large scale conditions using CFD simulations. The simulations using geometric-driven full-scale TCTs are matched with the empirical data acquired from a 1MW machine positioned at the EMEC test site. It started with Navier-Stokes (RANS) and Bigeddy (LES) averaged by Reynolds employing an average inlet velocity profile with negligible inlet turbulence.	Finnegan et al. [79]	2021
		Yang et al. [61]	2013
		Bai et al. [92]	2013
		Ahmed et al. [45]	2017
		Amiri et al. [53]	2019
		Divett et al. [56]	2016
The composition and behaviour of tandem propellers of a single horizontal axis counter-rotating tidal turbine.	The simulation was carried out using the multiple-objective mathematical optimization approach together with the surface method. SRM with GA to acquire suitable blade profiles. The results after simulation revealed that the power coefficient considerably improved the performance of the powertrain with the blades was also improved by optimizing the pitch angle.	Huang and Kanemoto [46]	2015

Table 11 Key characteristics areas identified V

Parameters	Modelling technique and tools	References	Year of publication
The potential of tidal Stream Energy along the coastal zone.	The impact to extract power from estuarine hydrodynamics is simulated using excess deceleration force in the equations of impulse governing in ROMS.	Defne et al. [54]	2011
Determination of the impacts on hydrodynamics and transport stages in a tidal channel.	MHK has been integrated into a three-dimensional (3-D) oceanic modelling using the motion well technique. The impacts of the 3-D model simulations on the vertical velocity profile, the maximum extractible power, and the reduction in volume of the flow through the channel were analysed using a sequence of numerical experiments.	Yang and Wang [55]	2013

Table 12 Key characteristics areas identified VI

Parameters	Modelling technique and tools	References	Year of publication
The possibility of extracting tidal energy from small tidal channels Puget sound.	The hydrodynamic modelling measures the energy potential and the effect in association with its displacement movement. After simulation, the results demonstrated the importance of considering the rate of energy extraction in the three energy extraction operations.	Chen et al. [93]	2013
Simulated a group of tidal turbines and the performance of the naval rotor.	Utilised a Coupled Blade Element Model and Computational Fluid Dynamics (BEM-CFD). The BEM-CFD model can simulate many devices in optimizing the performance of a network of 14 turbines. Matched with a regular phase arrangement, the total grid output energy is improved by more than 10%.	Funke and Barton [94, 95]	2016, 2018
The effects, vertical and horizontal axis turbines can have on the navy after deployment.	A 2-D hydro environmental model integrated at depth is employed, which showed that the DIVAST has undergone a modification to allow simulation of hydro-environmental impacts of turbines in coastal areas.	Ahmadian et al. [47]	2012
		Defne et al. [54]	2011

Table 13 Key characteristics areas identified VII

Parameters	Modelling technique and tools	References	Year of publication
The evaluation of the tidal energy resources and the development of efficient devices.	Mike 21HD is used to locate the high flow velocities. After simulation, it was found out that there is a high-speed current crossing the shore around the coast.	Roberts et al. [96]	2016
The compensation of the energy in the OCAES farm power using the tidal energy system.	The authors used the Ocean Compressed Air Energy Storage (OCAES) technique to satisfy the island capacity power demand management. The systems contain the Diesel Generators (DGs) which was used as an alternative supply while the primary energy supply will be produced by the hybrid OCAES system.	Sheng et al. [24]	2017
Comparison of the five turbulent models with the rotary reference technique.	The large eddy simulation technique is utilized to reduce cost, by comparing the Reynolds. Stokes Turbulence Modelling (RANS), the Reynolds stress modelling technique (RSM) and the k- "simulation model for the small relative mesh were also utilized.	Shadloo et al. [97]	2018
		Benard et al. [98]	2019
The performance of elements hydraulic structures.	The 0D simulation model employed has produced the known tidal conditions, the plant operational sequence, and lastly the suitable equations	Angeloudis et al. [99]	2017

Table 14 Key characteristic areas identified VIII

Parameters	Modelling technique and tools	References	Year of publication
The analysis of the potential tidal power resources and the distribution of energy density localised at the middle-flood and middle-ebb of a mean spring tide coupled with the mean energy density.	The authors used a three-dimensional finite element numerical model which included an algorithm for calculating the mean power density and the power density.	Ren et al. [100]	2018
The development of an energy conversion system technique to facilitate a variable speed hydro-kinetic turbine system which is producing a constant voltage and frequency at variable water speeds.	Used a pitch control turbine together with a squirrel cage induction generator, the tidal current energy generation system was also analysed by preparing a full resource-to-grid approach in MATLAB/SIMULINK. A system assessment was carried out concerning the impacts of harmonics in the long sub-sea cable and the optimization of the power of the generator.	Sousounis et al. [8]	2016
		Ngancha et al. [65]	2017

Table 15 Key characteristic areas identified IX

Parameters	Modelling technique and tools	References	Year of publication
To minimize the impact of disturbances occurring during the installation and operation of a group of tidal turbines, the effects on the sea and the hydrodynamics (ocean level and speed of circulation).	The high-resolution model of Ria de Ribadeo (north-western Spain) was employed to determine the capable impacts of operating two potential tidal farms. It was found out that the water level is low, but the speed of circulation is important. Speed is lowered upstream and downstream of the farm and increased beside it. Finally, these optimizations of the flow pattern modify the density of the power available at the level of the tidal turbine, with a decrease of 21% and 12% respectively for the high and minimum energy extraction levels.	Ramos et al. [101]	2013
Generating electricity from tidal turbine farms	A mathematical optimization model of a tidal farm constrained by the concept of water at depth calculated using a highly efficient methodology based on gradients is employed. This method allows the resolution of complex installation constraints, and this could result in maximization of power and/or profit.	Funke et al. [42]	2014
Analysis of the performances of the various components of the network of a farm of 15 tidal turbines. The direction of flow in the wake, the impacts of lateral separations and turbine currents were also examined.	The Momentum Reversal Lift (MRL) turbine was used and positioned in five separate array layouts using as much as 15 devices. The dynamic turbines usage simplifies the addition of assessment of the impacts of flow direction in the wake.	Sutherland et al. [102]	2018

To further examine the advantages and limitations in most of these approaches, *Table 16* illustrates the advantages and disadvantage of various modelling techniques and tools with their references and year of publication.

Table 16 Advantages and limitations of recent tidal modelling simulation techniques

Advantages	Limitations	References	Years
In this study, a hybrid power system that uses a vehicle-to-grid (V2G) and tidal power unit (TPU) is effectively planned as an isolated Micro grid (MG). The primary LFC controller is suggested to be a novel fractional gradient descent (FGD) based on a single-input interval type-2 fuzzy logic controller (SIT2-FLC), where the performance of the LFC is improved by precisely adjusting the footprint of uncertainty (FOU) coefficient of the SIT2-FLC. This method is useful for frequency stabilization by adjusting to the randomness of load disturbances and RESs.	Since Microgrids are powered by renewable energy sources (RESs) with unpredictable properties, the risk of frequency instability has increased as a result of the growing adoption of distributed generation technologies in recent years. In their upcoming research, they can examine how the case study's performance is impacted by the time delay because in order to evaluate the viability and application of the proposed design process from a systemic perspective, a model-in-the-loop (MiL) simulation is performed.	Khooban et al. [103]	2020
A novel technique to maximize the power produced	Several scenarios were taken into consideration	Mohammed et al.	2019

Advantages	Limitations	References	Years
by a hybrid RES made up of a wind turbine, a tidal turbine, a PV module, and batteries is proposed in this work using the particle Swarm Optimization technique (PSO) to reduce the energy cost. The issue is classified as an economic one, the battery charge. Total Net Present Cost (TNPSC) is proposed as the aim function, taking into consideration the high reliability, planning expansion, and optimal system sizing. It enables rapid and precise cost reduction and optimal solution generation. Software called MATLAB was used to create the PSO algorithm program.	during the study, including the stand-alone hybrid renewable system, which consists of (wind turbines, solar panels, tidal turbines) with stored energy, to achieve the lowest (TNPC) and lowest (COE) levels, the stand-alone hybrid renewable system, which consists of two components of renewable energy sources (solar panels and wind turbines, solar panels and tidal turbines and wind turbines), and the stand-alone hybrid renewable system. Thus, it is making the results limited ,in the previous study using Homer many combinations of scenarios it is provided which can offer further results to minimise the cost of energy.	[104]	
A major power grid with electricity using a hybrid system made up of wind and tidal turbines coupled to a microgrid. Stewart Island serves as the case study, two of the island's top objectives, according to locals, are lowering fuel consumption and having a sustainable source of electricity. The HOMER and WRPLOT software programs from the authors are used to simulate several off-grid installations. The optimum design has a larger renewable proportion, lower net present cost, and fewer greenhouse gas emissions when using two wind and four tidal turbines along with a diesel generator as backup.	This study used The HOMER and WRPLOT programs. The authors did not implement any investigations concerning major disturbance in the hybrid wind-tidal energy systems such as, the harmonics distortion, flickers as the frequency adjustment and smooth current and power control which has been developed by the authors. Homer is a commercial software but it does not have better robustness.	Majdi et al. [105]	2021
In this research, a hybrid voltage vector (VV) preselection-based model predictive control (MPC) technique is suggested to suppress the common-mode voltage (CMV), minimize the current total harmonic distortions (THDs), and eliminate ripples of two-level voltage source inverters (2L-VSIs). In order to lessen the CMV spikes brought on by the dead time effects, six synthetic VVs (SVVs) are first defined based on the six nonzero VVs of the 2L-VSIs. A hybrid-VV preselection-based MPC technique is then finally proposed by considering the one step delay effects to entirely remove the CMV spikes after segmenting the three-phase current plane into seven sectors. With an asymmetric hysteresis. The study also includes a control error compensation technique to further increase the suggested method's parameter robustness. The suggested hybrid-VV preselection-based MPC technique may greatly lower the current THDs and ripples in addition to totally restricting the CMV inside udc /6, according to simulation and experimental results.	MPC was also employed to lower the common-mode voltage (CMV) of the 2L-VSIs, as it has the capacity to control several targets simultaneously by creating an appropriate cost function. But in order to balance the many control targets in these methods—which are challenging to develop because of the dearth of theoretical backing weigh-in variables are always needed.	Guo et al. [106]	2019
This study examines current tidal energy trends, ecological impacts, and technological prospects. Although it is necessary for tidal power stations to produce energy in the range of hundreds of thousands of megawatts to gigawatts of power to compete with the production capacity of other conventional and nonconventional sources of energy. Therefore, it is essential to precisely assess the efficiency of the operation of different pieces of power-producing machinery in relation to the amount of power provided to the electrical grid. The difficulty of considering turbulence's effects and their impact on the component's fatigue life has been highlighted by predictability. Therefore, conducting more thorough studies on factors like specific MTBF (mean time between failure) components as well as life expectation, developing the manufacturability of tidal energy converters from first-scale prototype to profitable manufacture, and so on, could be a	To maximize the use of materials, science, and modern manufacturing techniques, an integrated engineering design methodology is essential. The ultimate objective of future exploration is to create technologies that would enable integrated grid networks using offshore transmission lines while lowering installation costs and environmental impacts.	Chowdhury et al. [107]	2021

Advantages	Limitations	References	Years
contributing aspect in reducing the unforeseen conservation requirements. In addition to affecting the expansion of the manufacturing process, this will have an impact on the design of significant modules and sub elements.			
We formulate and resolve the node-state-decision optimization problem using a multi-objective integer linear program, considering the trade-off between energy efficiency and blocking performance, which can determine the specific state of network nodes when a specific traffic profile is given (MOILP). In order to handle the dynamic tidal traffic, we then present an online traffic-aware intelligent differentiated allocation of light paths (TIDAL) method based on stateful grooming and the MOILP. Our illustrated numerical findings demonstrate that the suggested strategy can significantly enhance performance while using less energy.	The tidal traffic phenomenon, which causes patio-temporal disequilibrium in the network traffic load, has been increased by the rising popularity of high-speed mobile communications, cloud computing, and the Internet of Things (IoT).	Zhong et al. [108]	2016
Integrating renewable energy into island energy systems may result in a more diverse energy source and increased system effectiveness, which may result in island residents using less expensive energy. To overcome the intermittent nature of renewable energy sources, this calls for a suitable energy extraction approach along with adequate storage. This study shows how tidal energy can be integrated into an island energy system without costly grid improvements. It demonstrates that increasing the generation duration at the fastest flow velocities while limiting the tidal device's capacity increases the installed system's capacity factor. This tactic increases the business viability and competitiveness.	During the investigation of this study only horizontal axis turbines will be taken into consideration throughout the selection process; other tidal stream technologies won't be considered. I think the study which will take tidal stream in consideration will get better results because the tidal stream arrays have shown much improvement and has started being commercialised. The study does consider the voltage and frequency control which has many consequences on energy generation out. The lack of reducing the current total harmonic distortions (THDs), and eliminate ripples of two-level voltage source inverters (2L-VSIs) can affect the renewable energy generation output.	Almoghayer et al. [109]	2022
DC microgrids are becoming an essential component of a contemporary power system. They also have additional benefits for improving power quality. They can be used to electrify rural areas, such as villages, mountains, and islands. In this study, an island-based DC microgrid with Li-ion battery storage and renewable energy sources including solar, wind, and tidal is used as a case study for islands with tidal energy potential. An ideal energy management system is suggested for resource allocation and use to ensure effective functioning. In order to avoid the overuse of real-time communication bandwidth, this study suggests a two-stage supervisory energy management system for the optimal operation of PV, wind, and tidal microgrids. The first stage improves the operation's efficiency by planning the ideal energy share from each energy source. The usefulness of the suggested energy management strategy in obtaining an optimum operation for an islanded DC microgrid has been experimentally confirmed.	This study is about energy management system of DC microgrids. The simulation does not include the MTT because it does not cover MPPT algorithms. Thus, next investigations should include the MPPT during simulation to get better output results.	Zia et al. [110]	2022
In order to adjust the speed ratios of an infinitely variable transmission (IVT) with respect to variable input speeds brought on by variable tidal speeds, this work proposes a nonlinear closed-loop control in conjunction with an integral time-delay feedback control. The time-delay feedback control's goal is to stabilize the IVT's output speed by reducing speed fluctuations. Validity testing of the time-delay feedback control of the IVT system was done experimentally for tidal current energy applications. Results from experiments with varied tidal speeds	The simulation effective control of the IVT system's speed ratio with a changeable input speed using the tracking error model demonstrates. The output speed and speed ratio of the IVT can be more consistently controlled with time-delay feedback it has demonstrated the control strategy is able to modify and maintain the IVT system's speed ratio at the required output speed after 24 hours simulation, but I think this study could use the real simulation to correct and adjust the error.	Li and Zhu 2022 [111]	2022

Advantages	Limitations	References	Years
indicate that using the suggested control technique, speed ratios of the IVT can achieve outstanding tracking responses for the intended constant output speed and minimize speed variations of IVT output speeds.			

4. Findings and discussions

The modelling and simulation of tidal energy generation is no doubt gaining more attention amongst researchers even though tidal turbines are yet to have an optimal tidal current conversion system (TCCS), which justifies several model designs that have been proposed for tidal energy extraction. While most designs feature a bottom mount with low resistance blades and horizontal axis rotors, the generator side also contains several different techniques used in generator technology. However, the dominant combination of components is a function of the directly driven generators or the synchronous generators containing permanent magnets with gears and squirrel cage induction generators (SCIG). Currently, tidal turbine developers have set the goal of deploying small demonstration networks comprising of about ten tidal turbines with 1MW capacity per turbine. Tidal generation has made a huge progress over time; however, it is still in its developmental stage.

From the illustration in *Figure 3*, it can be observed that many research topics have preferably been focusing on the modelling and simulation of tidal energy system using several model designs for tidal energy extraction. Some of the studies conducted by other researchers were based on running costs and grid connection costs or installation costs and these indicated a lack of effective tools for these types of studies, hence the reason for estimation of results. However, these studies succeeded in establishing a simulation approach of operational costing and device availability to solve various tidal problems. During these analyses, different costs were considered such as the costs of the positions offshore, cable costs, maintenance costs and energy loss costs. This is evident from the improvement of the simulations made for large scale conditions using CFD simulations which utilizes a geometry-driven full-scale tidal current turbine. The MATLAB-Simulink approach for a TCT system via the modelling of the source attracted more research interest and numerous publications are observed in this field. The investigations on marine energy applications and its power output had a substantial publication increase in 2017.

Through this, more publications from various multidisciplinary fields were published and researchers became interested in the research field of modelling and simulation of tidal energy and how it can be implemented in power generation. It is nevertheless expected that the trend will continue to increase, and more innovative research will arise from this field.

Modelling and Simulation of tidal energy generation system is a new way of improving tidal energy output which leads to ensuring that tidal energy technologies are very cost-effective. The numerical models are developed to provide all the necessary technical information regarding resource exploitation and their effects including inconsistencies in the simulation model of the results of tidal power plants, program operations and others. Different models are also presented for the gradual and systematic introduction of spatial dimensions in resource forecasting applications. The advantages and drawbacks of each of these models were also discussed as regards the assessment of power generation and the potential hydrodynamic effects of tidal power plant proposals. The results showed that it is necessary to use a hydrodynamic scale stage that will facilitate optimization studies and the robustness of tidal power plant approaches [57]. It also revealed that the production of tidal and fluvial energy in connection with the network can be affected by the oceanic turbulence, thereby causing fluctuation in the output power and the state of the network. This fluctuating power will trigger power problems for instance flickers or fluctuating voltages while in operation. It is, therefore, necessary to calculate the flicker emissions and to attenuate the flickers to remedy the power quality problem.

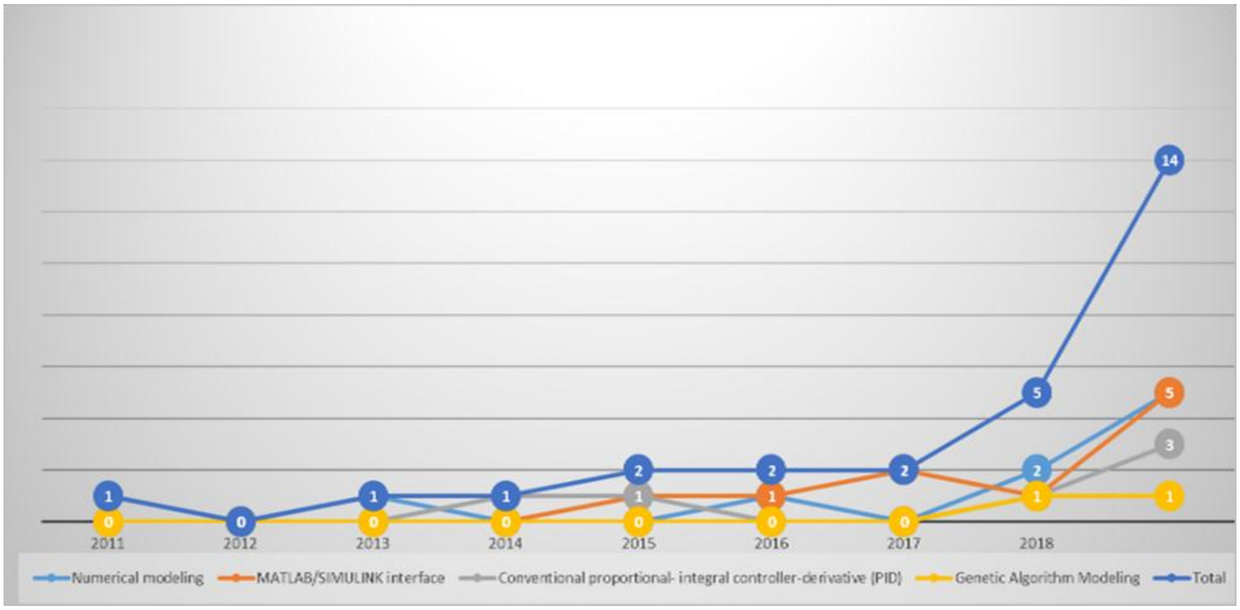

Figure 3 Aggregate number of papers at different years utilised in reviewing the categories of modelling technique tools

Figure 4 illustrates the cumulative number of publications on the topics around the tidal energy simulation and modelling approaches. There is a steady increment in the number of publications around this research area. From the year 2017, there is a high-pitched surge around the research topics as issues relating to minimising the harmonics distortions which results to adequate control of voltage, -current and frequency instability. From the figure, it can also be deduced that over the years from 2006, there has been a very huge increase in the number of publications relating to simulation and modelling of tidal turbine energy. There has also been an increase in the papers submitted to a related conference (International Conference on Offshore Mechanics and Artic Engineering). Also from the Figure, it is noticed that there is an astronomical increase in publications relating to renewable energy, hence, it can be concluded that this area of research is gaining more research visibility as the years roll over.

The results in *Figure 5* also show that there are numerous citations on papers published in marine research areas especially in the year 2019 and this infers that a huge number of developers of tidal turbines currently engaging in researches on the Optimal Tidal Current Conversion System (TCCS) to employ.

According to the keywords search process executed in this work, it has been illustrated that the simulation and modelling of tidal energy system is gradually gaining grounds and in some European countries, tidal power has just started to commercialize its energy. The deployment of orbital marine power in Scotland has recently been connected to the grid making up a multi-megawatt tidal energy panel system, in the same way many techniques have been used to optimize power, such as modelling of mathematical parameters to optimize a constrained tidal farm. The concept of tidal water depth is very easy to assess with the aid of a highly efficient gradient based methodology. Combining these techniques could lead to more research advancement in marine energy and breakthrough in the future of renewable energy which offers a predictable amount of power without any sort of pollution.

A complete list of abbreviations is shown in *Appendix I.*

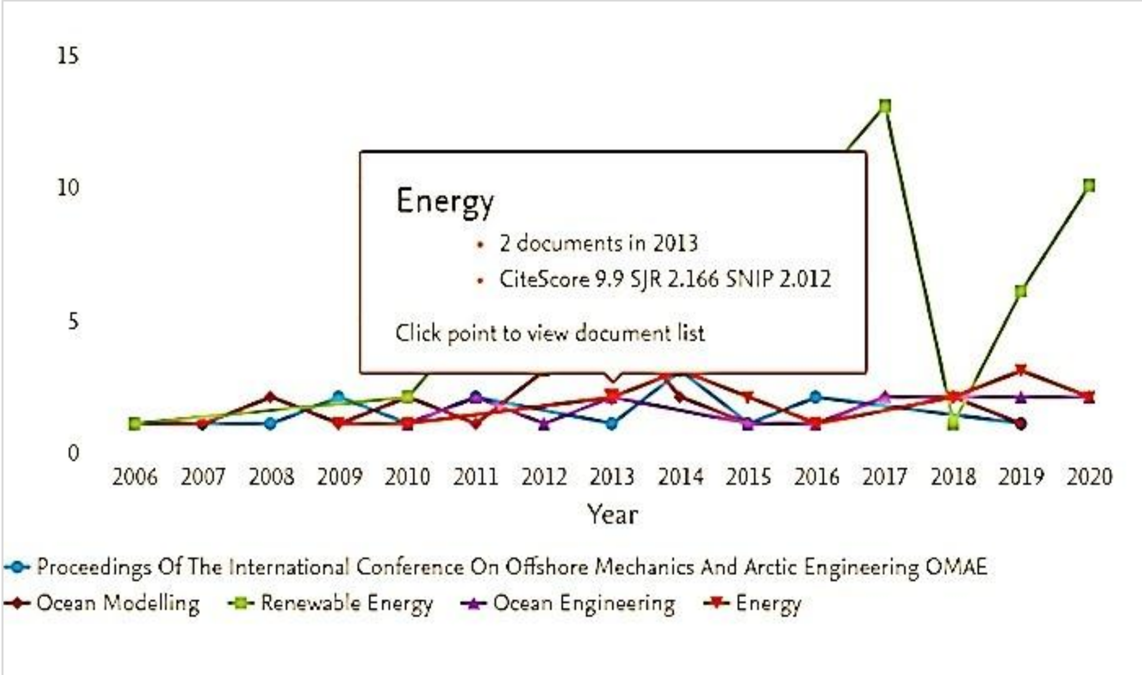

Figure 4 Indicates the cumulative number of publications on the simulation and modelling of tidal turbine energy system

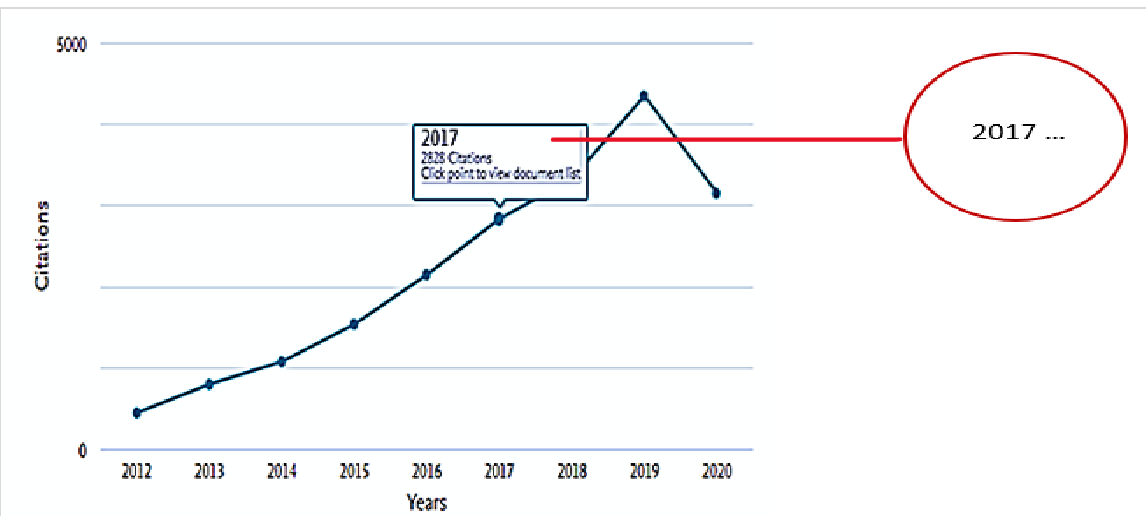

Figure 5 Compare sources and view cite score

5. Conclusion and future research

The key motivation of this paper is to establish an up-to-date outline of techniques, approaches and methods used for the optimisation of tidal stream energy systems. Some studies were done on TCCS with long-distance drives employing low voltage generators. The power generated can only be mounted in rivers or small tidal channels. Most of the work in literature indicated that numerical modelling, experimental simulations, and multiple criteria decision analysis techniques are essential to evaluating a turbine suited to the features of the site and the given flow values. Furthermore, the speed of the tidal current is always subject to sudden changes which are caused by the pulsations on the TCTs. These pulses incur fatigue and strain the final load of the tidal turbine system as well as the operation of the transmission which leads to over-design of the system and costly maintenance.

In future, the importance of research and development in the field of resource assessment and measurement of marine energy coupled with the advancement and validation of appropriate modelling systems must be investigated adequately to proffer technical solutions. However, according to several assessments that estimated the current and future costs of tidal power, researchers found that data are scarce because of much reduced experience at a larger scale. The situation has led to operational costing estimation and system complexities. Some other studies offered simulation models for device availability and operational cost to solve these problems. Other researchers investigated the possibility of integrating tidal energy systems into the electricity grid considering the cost of tidal power arrays and several other components. This will add further load and technical complexities to the electricity line considering that an array of subsea electrical systems and submarine cable connections to the shore are also required. The power quality of tidal energy power converter needs to correspond to the transmission and distribution grid codes. It is required to offer good functionality of some of the parameters in the tidal energy generation such as frequency regulation, active power control, fault ride-through capabilities and voltage regulations and controls.

Based on the various literature that has been reviewed, further research and development is required in the field of tidal power energy assessment, both on the optimization, development as well as the validation of appropriate modelling approaches. However, the harmonization of systems also needs to be improved. Most of the research available in literature recommended that the first large-scale establishment of tidal power technologies must be backed by research analyses on local environmental effects while as for installations, it can be covered by the EIA or other entities as a legal requirement. A complete life cycle assessment (LCA) of marine power grid is lacking and the incorporation of elements such as fluctuating power output, power storage and grid integration would be immensely beneficial. It will also be important if researchers put in much attention on how these technologies will minimize impacts on the marine environment. Currently, several kinds of research are focused on the economic aspects of tidal power and the predictions of future costs of tidal power while significant improvement is still needed on the operational and maintenance costs, coupled with grid integration, energy security and many more.

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Conflicts of interest
The authors have no conflicts of interest to declare.

Author’s contribution statement
Efe Orumwense: Data collection, conceptualization, supervision, writing - review and editing, original draft. **Ladislas Kangaji**: Study conception, design, data collection, writing, analysis and interpretation of results and draft manuscript preparation. **Khaled Abo-Al-Ez**: Conceptualization, investigation, data curation, supervision- original draft.

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Appendix I

S. No.	Abbreviation	Description
1	ADCP	Acoustic Doppler Current Profiler
2	BEM	Blade Element Momentum
3	BESS	Battery Energy Storage System
4	CFD	Computational Fluid Dynamics
5	COE	Total Cost of Energy
6	CMV	Common-Mode Voltage
7	DC	Direct Current
8	DIVAST	Depth Integrated Velocity and Solute Transport
9	DNS	Numerical Modelling
10	EMEC	European Marine Energy Centre
11	FGD	Fractional Gradient Descent

12	FLC	Fuzzy Logic Controller
13	HAT	Horizontal Axis Tidal Turbines
14	HATCT	Horizontal Axis Tidal Current Turbine
15	LCA	Life Cycle Assessment
16	MHM	Marine Hydrokinetic Modelling
17	MHK	Marine Hydrokinetic Showing
18	MPP	Monitoring Maximum Power Point
19	MOILP	Multi-objective Integer Linear Program
20	MPC	Model Predictive Control
21	MRF	Multiple Reference Frame
22	PWM	Line-Side Pulse Width Modulating
23	PID	Integral Derivative
24	PSO	Particle Swarm Optimization Technique
25	RANS	Navier-Stokes Turbulence Modelling
26	RES	Renewable Energy Systems
27	ROMS	Regional System Model for Ocean Model
28	SCIG	Squirrel Cage Induction Generators
29	SLR	Systematic Literature Review
30	SLFC	secondary Load Frequency Control
31	SRM	Surface Response Method
32	SST	Shear Stress Transport
33	SV	Peak Tidal Speeds
34	TCCS	Tidal Current Conversion System
35	TCF	Tidal Current Farms
36	THD	Total Harmonics Distortion
37	TPP	Tidal Power Plant
38	TSPPP	Tidal Stream Power Plant Platform
39	TSG	Tidal Stream Generators
40	UNFCCC	United Nations Framework Convention On Climate Change
41	VV	Voltage Vector
42	V2V	Vehicle to Grid
43	VSI	Voltage Source Inverters
44	WPP	Wind Power Plant