An analysis of the German tidal energy resource

Alexander Korte, Christian Windt, and Nils Goseberg

Abstract—**A transformation of the energy sector towards a low-emission power generation is needed to mitigate global warming and fight the current climate crisis. In recent years, tidal energy technology has matured and shows potential to balance Europe's future power grid. While reviews of the tidal energy resource exist for a number of European countries, the potential of tidal energy along the German North Sea coast is overlooked so far. This review closes this gap and provides a first analysis of the German tidal energy resource. Germany's North Sea coast is characterised by comparatively low current velocities and shallow waters. Using available data from the EasyGSH-DB North Sea Model, Germany's practical tidal energy resource is estimated at 66.6 GWHy^{-1}, under strong restrictions, excluding the most energetic sites in the estuaries of Elbe, Weser, and Ems. Based on the results, future work for a more detailed analysis is suggested.**

Index Terms—**Marine Renewable Energy, Tidal energy, North Sea, German Bight**

I. Introduction

THE share of renewable energy generation in Germany's gross electricity consumption was about $41\,\%$ in 2021 [1]. The primary contributors to this renewable energy share were onshore and offshore wind energy, followed by bioenergy, solar energy, and hydropower. Despite this progress, the majority of energy production still heavily relies on fossil fuels, particularly gas and coal. To address the urgent climate crisis, a paradigm shift in the energy sector towards low-emission energy generation is imperative. The European Union has set ambitious targets to further combat climate change, aiming to achieve climate neutrality by 2050 [2]. Concurrently, the demand for electricity is projected to rise in the coming years. While Germany consumed $565\,\mathrm{TWh}$ of electricity in 2021 [3], this consumption is expected to grow to $658\,\mathrm{TWh}$ by 2030 [4]. To address this challenge, a substantial increase in the proportion of renewable energy within the energy mix is essential. Future electricity supply is anticipated to hinge significantly on solar and wind energy, complemented by other technologies like bioenergy, geothermal energy, hydropower, and energy storage, as indicated, e.g., in [5]. Tidal energy, however, plays no role in Germany's current electricity supply although it has a decisive advantage compared to other forms of renewable energy by being highly predictable [6]. There are specific reasons for neglecting tidal energy in German waters that have not been addressed so far in the pertinent literature; this work hence aims towards closing this knowledge gap by performing a first quantitative assessment of the German tidal energy resource.

A. Tidal energy resource assessment

In 2021, a tidal stream capacity of $39.6\,\mathrm{MW}$ was deployed worldwide [7]. This capacity was steadily building up from the establishment of the first facility for testing and demonstrating tidal stream technology (European Marine Energy Center (EMEC)) in 2003 till today. Fostering a uniform methodology for the assessment of the tidal stream energy resource at a specific location, EMEC published a guideline for such an assessment in 2009 [8], forming the basis of the later IEC TS 62600-201 standard [9]. Following this, several investigations of the tidal stream energy resource in different countries have been carried out in the past years, for example in Norway [10], the United Kingdom [11], Ireland [12], France [13], [14], Spain [15], USA [16], [17], Mexico [18], Chile [19], Iran [20], [21], India [22], China [23], Indonesia [24], Malaysia [25], [26], Australia [27], and Fiji [28]. In previous tidal energy reviews, it is often distinguished between a theoretical, technical, practical, accessible, and viable tidal energy resource [29]. For Ireland, O'Rourke *et al.* [12] estimate the theoretical resource at $230\,\mathrm{TWh\,y^{-1}}$, while the viable resource was finally determined to $0.915\,\mathrm{TWh\,y^{-1}}$. The differences are due varying boundary conditions and limitations in each step of the assessment (e.g. from theoretical to technical resource), such as specific water depth ranges, d, or minimum required current velocities, V. Coles *et al.* [11] only address the practical tidal energy resource for the UK and report that the practical tidal energy resource has been re-estimated at $34\,\mathrm{TWh\,y^{-1}}$ based on the initial Carbon Trust Study [30]. This represents 11 % of UK's current annual power demand and could be achieved by installing tidal current turbines with a total capacity of $11.5\,\mathrm{GW}$ by 2050.

According to EMEC [8], it can further be distinguished between different stages of a tidal energy

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resource assessment (see Table I): During a regional assessment (stage 1), suitable tidal energy sites within a region of interest are screened. On this basis, pre- and full-feasibility studies are carried out in site assessments (stage 2), until the final design is developed in stage 3.

B. Objectives

In Germany, no tidal energy resource assessment of any stage can be found in the literature. The present study aims at performing a first step towards filling this gap. As an initial step, a regional stage 1 assessment is carried out, with the aim of screening suitable sites for energy extraction from the prevalent micro- and mesotidal conditions [31] in the German North Sea. In particular, the specific objectives of this work are:

- To analyse the theoretical, technical and practical tidal energy resource along the German North Sea coast.
- To review and evaluate currently available Tidal Energy Conversion (TEC) devices with regard to their suitability for the German North Sea.
- To identify pertinent future work for a refined assessment.

The remainder of this paper is structured as follows. Materials and methods are detailed in Section II, followed by the resource analysis in Section III and a technology analysis in Section IV. The results of Section III and IV are then jointly discussed (Section V) and conclusions and future work is synthesised in Section VI.

II. Material and Methods

A. Description of study sites

Germany is bordered in the North by both the North and the Baltic Sea. In this study, only the German North Sea is considered, showing tidal ranges between $1\,\mathrm{m}$ to $4\,\mathrm{m}$, with the highest tidal range in the inner Jade bay, close to Wilhelmshaven. The tidal dynamics in the German Bight are predominantly controlled by the M2 tidal constituent, with an amplitude about 10 times higher than that of the S2 constituent [32]. The tidal waves develop in the Atlantic Ocean and propagate from the North-East Atlantic, as well as through the English Channel, into the North Sea, which results in the tidal waves occurring first in western regions before they propagate eastwards in a counter-clockwise rotation. Furthermore, the oscillations of the M2 tide create 3 amphidromic points in the North Sea: the first is located at the eastern tip of Norway, another at 56°N, at the eastern tip of the Dogger Bank, and the third close to the entry of the Southern Bight [33].

Off the southern coastline in Lower Saxony are the East Frisian Islands Borkum, Juist, Norderney, Baltrum, Langeoog, Spiekeroog, and Wangerooge and some smaller Islands such as Minsener Oog and Mellum. Off the western coastline in Schleswig-Holstein are the North Frisian Islands Sylt, Föhr, Amrum, Pellworm, and the Halligen. The rivers Eider, Elbe, Weser, Jade, and Ems drain into the North Sea. The transitions of the Ems, Weser, and Elbe into the North Sea have characteristics of estuaries, and also represent important shipping lanes. The German Bight is characterised by the Wadden Sea, which is largely under nature protection and covers an area of $11\,500\,\mathrm{km}^2$ and a coastline of over $500\,\mathrm{km}$, including parts of the Dutch and Danish coastal waters [34]. A characteristic of the Wadden Sea is a seabed exposure at low tide but again flooded at high tide. All these geographical features of the German coastal waters with the coast-island-Wadden sea interactions make the assessment of tidal energy resources significantly more complex than in places where relatively straight coastlines prevail. Figure 1 A shows a satellite image of the German Bight. The study site is located at 6.367854° / 53.37165° as southwestern boundary and 9.010586° / 55.102917° as northeastern boundary in WGS84. The reference Coordinate System for the data is EPSG 25832: ETRS89 / UTM Zone 32 [35]. All data in this work is visualised and further processed using the Open-Source Geographic information system QGIS v3.24.

B. The EasyGSH-DB North Sea Model

The assessment of the tidal energy resources requires reliable data pertaining the hydrodynamics of the area of interest. A numerical representation of the flow conditions and associated environmental parameters in the German Bight are provided by the EasyGSH-DB North Sea Model [35], [38]. Datasets of the tidal dynamics, salinity, and the sea state in the German Bight for the years 1996 to 2015 were modelled. With a grid resolution of up to $50\,\mathrm{m}$ in the focus area, local and regional effects can be reproduced highly detailed. Considering all relevant tidal constituents, EasyGSH-DB reproduced the tidal dynamics very accurately [8]. Detailed information on the validation of the EasyGSH-DB North Sea Model can be found in [39].

For the presented analysis, the following depth averaged ebb and flood current velocities in a $100\,\mathrm{m}$ grid (mean and maximum values) are extracted from EasyGSH-DB [40]:

- Mean ebb current velocities
- Mean flood current velocities
- Maximum ebb current velocities (95 % percentile)
- Maximum flood current velocities (95 % percentile)

To evaluate the tidal energy resource, the most recent data for the year 2015 will be used in this study; amplitudes of the inter-annual variations and their contribution to tidal flow velocities are deemed to be negligible [41].

By way of example, Figure 1 B shows the water depths within Germany's 12 nautical mile (NM) territorial sea [42]. Figure 1 C shows the mean flood current velocities within the 12 NM territorial sea in the German Bight. In the area exposed at low water, mean current velocities are mostly lower than $0.3\,\mathrm{m\,s^{-1}}$. The highest current velocities are reached in the Elbe estuary near Cuxhaven with $1.0\,\mathrm{m\,s^{-1}}$ to $1.1\,\mathrm{m\,s^{-1}}$. Current velocities above $1.5\,\mathrm{m\,s^{-1}}$ are reached e.g. between the East Frisian islands Baltrum and Langeoog, north and

TABLE I
RESOURCE ASSESSMENT STAGES (ADAPTED FROM [8])

Stage	Category	Aim	Area	Constraints	Permit	Examples
Stage 1	**Regional assessment**	Site screening	Region or country	Limited constraints identified	No	[10]
Stage 2a	**Site assessment**	Pre-feasibility	Whole estuary, channel etc.	Major constraints identified	No	[27]
Stage 2b	**Site assessment**	Full-feasibility	Localised area in a channel, estuary etc.	All constraints identified and assessed	Applied for	[27]
Stage 3	**Site assessment**	Design development	Localised area in a channel, estuary etc.	All constraints assessed	Obtained	[17]

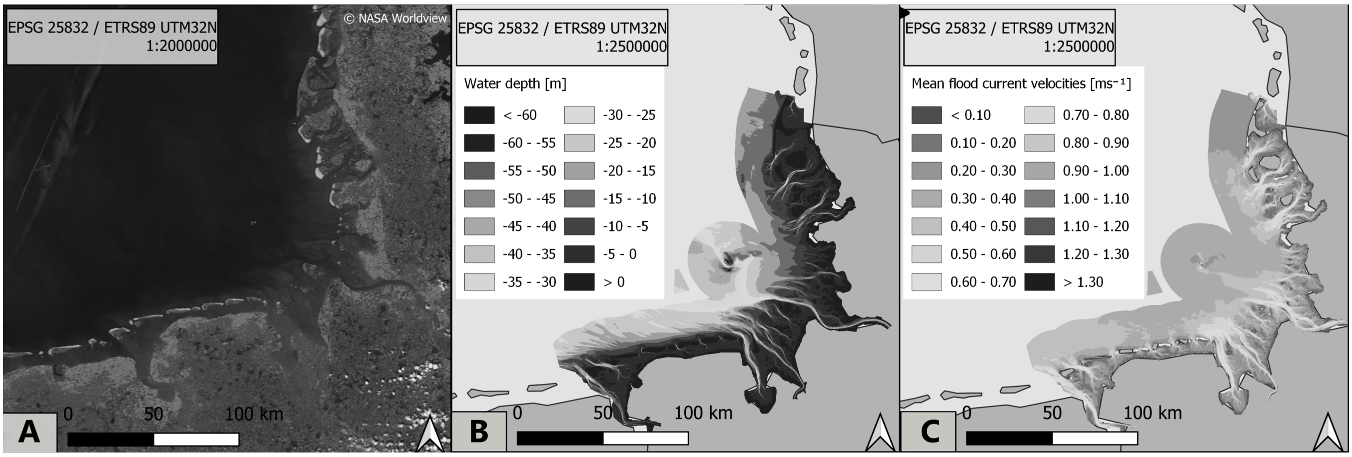

Fig. 1. Overview of the study site, with A) Satellite image of the German Bight from NASA Worldview [36], as well as B) the water depths and C) the mean flood current velocities in Germanys 12 NM territorial sea. Administrative boundaries according to EuroGeographics [37]

south of Sylt, as well as in the estuaries of Ems and Weser. In the Outer Jade, current velocities of $1.75\,\mathrm{m\,s^{-1}}$ are exceeded. The maximum current velocities in the German Bight are reached in the Elbe estuary, where velocities of nearly $2.0\,\mathrm{m\,s^{-1}}$ are reached during ebb current, and even about $2.2\,\mathrm{m\,s^{-1}}$ during flood current.

III. Resource analysis

In this first analysis, only the theoretical, technical, and practical resource is considered in detail. The average power density (APD) in an oceanic cross-section is usually calculated according to Equation (1) [8].

$$APD = \frac{1}{2} \cdot \rho_{SW} \cdot V_{rmc}^3 \qquad (1)$$

In Equation (1), ρ_{SW} is the density of seawater ($\rho_{SW} = 1025\,\mathrm{kg\,m^{-3}}$) and V_{rmc} is the root of the mean cubed current velocity at a specific site following [8]. However, since V_{rmc} is not provided in the hydrodynamic data of the EasyGSH-DB North Sea Model, the assessment in this study is performed using the simple mean current velocities, V_{mean}. Hence, Equation (2) is used to determine the APD.

$$APD = \frac{1}{2} \cdot \rho_{SW} \cdot V_{mean}^3 \qquad (2)$$

A. Theoretical Resource

For the calculation of the theoretical resource, first, the area under consideration is defined. Although EasyGSH-DB provides data for the whole German Bight, the seaward boundary is set to the 12 NM territorial sea (see Figure 1), thereby following [12]. Apart from this, no further boundary conditions are introduced. The theoretical resource can therefore be considered as the amount of kinetic energy in the tidal wave that would be converted into electrical energy without losses. Due to the grid cell size of $100\,\mathrm{m}$ in the EasyGSH-DB North Sea Model, it is assumed that the energy is extracted at intervals of $100\,\mathrm{m}$. Consequently, the theoretical power output, $P_{mean,T}$, follows

$$P_{mean,T} = \frac{1}{2} \cdot \rho_{SW} \cdot \sum_{i=1}^{n} (A_{cross_i} \cdot V_{mean,i}^3)\,. \qquad (3)$$

In Equation (3), $A_{cross,i}$ is the cross-section of the grid cell i ($A_{cross,i} = 100 \cdot h_i$, with h_i = water depth in grid cell i), $V_{mean,i}$ is the ebb and flood averaged mean current velocity in grid cell i, and n is the total number of grid cells.

The theoretical resource is then the theoretical power output over the duration of one year ($8760\,\mathrm{h}$). The accumulated power output is $61.36\,\mathrm{GW}$. The theoretical resource resulting from the accumulated power is $537.51\,\mathrm{TWh\,y^{-1}}$.

B. Technical Resource

The technical resource is the amount of energy that can be extracted from an area under technical constraints. The following constraints are considered in this study:

- **Maximum current velocity:** Sites with maximum current velocities $V_{max} > 1.5\,\mathrm{m\,s^{-1}}$ are considered suitable for tidal current turbine installation, following [12], [43].
- **Rotor Diameter:** A generic Horizontal Axis Turbine (HAT) with a rotor diameter of D = $3\,\mathrm{m}$ is considered for deployment due to the relatively shallow waters in the Wadden Sea.
- **Device spacing:** A device spacing of 10 D in flow-direction and 2.5 D in lateral direction in considered [8].
- **Water depth:** For safe operation of a HAT with D = $3\,\mathrm{m}$, the minimum required water depth is d = $4.5\,\mathrm{m}$ [12].
- **Power coefficient:** A power coefficient of a generic HAT is set to C_p = 0.4, based on [12], [13], [24], [27].

Employing the above stated assumptions, the power output of the maximum available number of turbines in the German Bight is computed following

$$P_{mean} = C_p \cdot \frac{1}{2} \cdot \rho_{SW} \cdot \frac{A_{Site}}{10\,D \cdot 2.5\,D} \cdot A_{rotor} \cdot V_{mean}^3\,, \quad (4)$$

where A_{rotor} is the cross-section of the turbine, A_{Site} is the area size of the considered site, and $10\,D \cdot 2.5\,D$ is the device spacing, which is simplified as the area occupied by one turbine.

Ten sites along the German coast are considered suitable for tidal energy extraction, which are depicted in Figure 2. Table II shows the characteristics of these sites. The technical resource for the whole German Bight is estimated at $2468\,\mathrm{GWh\,y^{-1}}$. The largest potential can be found in the Outer Elbe (Site 7) with a about $176.84\,\mathrm{MW}$ ($1550\,\mathrm{GWh\,y^{-1}}$), followed by the Outer Jade (Site 4) with $52.74\,\mathrm{MW}$ ($462\,\mathrm{GWh\,y^{-1}}$).

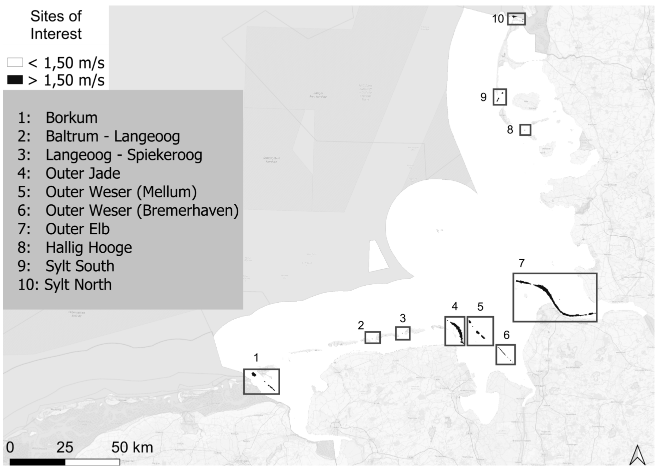

Fig. 2. Sites of interest for technical tidal energy resource in the 12 NM territorial sea

C. Practical Resource

For the assessment of the theoretical and technical resource, no boundary conditions regarding the current use practise of the available marine space in the study site were introduced. For the assessment of the practical resource, this is done by screening the site for shipping lanes, nature reserves, or existing infrastructure like pipelines. GeoSeaPortal [44] serves as the exclusive data base for existing infrastructure and ship traffic in the German Bight.

- **Nature reserves**. Along the German coast, a large part of the coastal areas have been declared nature reserve “Wadden Sea National Park”, and are under nature protection. [11], however, discuss the environmental impact of tidal current turbines, which were found to be an order of magnitude less than the environmental impacts of climate change. For the present stage 1 assessment, it is thus assumed that a deployment of tidal turbines may be permitted in the Wadden Sea National Park.
- **Shipping lanes**. It is assumed that the operation of tidal current turbines does not interfere with the existing ship traffic, as long as a sufficient clearance above the turbine is maintained. However, during the installation and maintenance of turbines, this may be different. Thus, important shipping lanes (Site 1, Site 5 and 6, Site 7), with ship traffic density partly exceeding 150 vessels per day and km^2 [44], are excluded.
- **Pipelines**. A deployment of turbines near pipelines is also theoretically possible, e.g., using a floating support structure [45]. However, the extent to which maintenance work on the pipelines will be affected by a nearby turbine deployment is unknown. The pipeline *Europipe* runs through Site 2 (Borkum), which is, hence, excluded.

The above outlined use purposes may eventually limit or omit the installation or operation of tidal turbines in the identified regions. However, uncertainties exist as to how severe a use purpose may eventually affect a tidal turbine to operate. Thus, in a first approach, it is assumed that strong restrictions apply to the study site, assuming that it is only possible to deploy tidal current turbines at Sites 3, 8, 9, and 10. With this restriction, the assessment of the practical resource results in $66.6\,\mathrm{GWh\,y^{-1}}$. In future work, also other scenarios with a more refined consideration of restrictions shall be performed.

IV. Technology analysis

A. Tidal energy technology

EMEC distinguishes between six main types of tidal current turbines [48]. Descriptions of the operating principles are based on [48], [49].

1) *Horizontal Axis Turbine*. The tidal stream causes the rotation of the rotor around the horizontal axis, similar to the principle of wind turbines.
2) *Vertical Axis Turbine*. The principle of power generation is similar to that of the HAT; however,

TABLE II
CHARACTERISTICS OF INDIVIDUAL SITES OF INTEREST AS DEPICTED IN FIGURE 2.

Site #		1	2	3	4	5	6	7	8	9	10
$\mathbf{n}$	$[-]$	19600	444	311	55866	19822	6800	157333	266	4977	6088
$\mathbf{d_{min}}$	$[\mathbf{m}]$	5.71	5.75	5.46	6.27	8.37	12.98	5.51	9.01	8.03	4.62
$\mathbf{d_{mean}}$	$[\mathbf{m}]$	17.46	14.55	14.03	21.63	17.86	17.25	18.52	16.21	13.73	18.11
$\mathbf{V_{mean}}$	$[\mathbf{m\,s^{-1}}]$	0.83	0.78	0.77	0.87	0.80	0.85	0.92	0.85	0.88	0.89
$\mathbf{P_{mean}}$	$[\mathbf{MW}]$	16.39	0.30	0.21	52.74	17.84	6.11	176.84	0.24	4.94	6.16

n is the number of turbines required, d_{min} is the minimum water depth, d_{mean} is the mean water depth, V_{mean} is the mean current velocity, and P_{mean} is the resulting total power output

in this case, the turbine is mounted on a vertical axis.

3) *Venturi*. The principle of power generation is similar to that of a HAT or VAT. In this design, the turbine is placed in a duct, in which the tidal current velocity increases through the Venturi effect. The turbine can be mounted in axial (horizontal or vertical) or cross-flow direction.
4) *Tidal Kite*. The kite construction, which consists of a hydrokinetic wing with a turbine attached to it, is tethered to the sea bed. As soon as the wing is lifted through the flow, the kite flies eight-shape loops through the water, which increases the current velocity at the turbine.
5) *Oscillating Hydrofoil*. The Hydrofoil is attached to an oscillating arm. The tidal stream flowing on both sides of the hydrofoil causes the motion of the hydrofoil, which in turn can be used for power generation.
6) *Archimedes Screw*. The device consists of a helical surface, which surrounds a cylindrical shaft. The tidal stream flowing through the spiral causes a rotation of the shaft, which is driving a generator.

B. Technology maturity and trends

The Technology Readiness Level (TRL) is a common measure to assess technology maturity. According to a 2019 report by the Joint Research Centre (JRC) [51] there are 30 tidal energy developers with a TRL ≥ 6. Leading manufacturers with a TRL of 8 are Andritz Hydro Hammerfest, SIMEC Atlantis, Nova Innovation, and Orbital Marine Power.

Some practical examples for the different device type including their current TRL are provided below[1].

- **SIMEC Atlantis AR1500 - TRL 8**. One AR1500 turbine by SIMEC Atlantis, rated at 1.5 MW, is installed in the MeyGen Phase 1A in Scotland's Pentland Firth since March 2018. Besides the AR1500, three AH1000 MK1 by Andritz Hydro Hammerfest are deployed in MeyGen Phase 1A, resulting in a 6 MW array. The project aims to show that tidal energy technology is both technically feasible and commercially viable. The four turbines have a rotor diameter of 18 m, operate in water depths of 34 m to 36 m, and the power coefficient was found to be C_p = 0.41. The lifetime energy yield from the four turbines is expected to amount to 450 GWh over a duration of 25 years [53].
- **HydroQuest OceanQuest - TRL 7**. From 2019 to 2021, the 1 MW OceanQuest turbine has been deployed as a demonstration project at the test site of Paimpol-Brehat (Brittany). As a next step, Hydroquest plans to deploy seven next generation turbines with a total capacity of 17.5 MW in the FloWatt project [54]. The new HydroQuest turbine rated at 2.5 MW has a width of 26 m and a height of 21 m, and is designed for water depths of 35 m [54]. No TRL rating is provided by [51], but the technology has potentially already reached TRL 7, due to the tests under real life conditions.
- **Minesto DG100 - TRL 7**. Two units of the DG100 by Minesto, rated at 100 kW each, have been installed in the Vestmannasund project in the Faroe Islands, representing the first tidal kites delivering power to grid in December 2020. The eight-shape loop of a DG100 has a dimension of 50 m width and 17 m height. The tether connecting the kite with the seabed is 35 m long and the devices are operating in a water depth of about 50 m [55].
- **EEL tidal turbine[2] - TRL 6**. After testing several prototypes, a commercial-scale 50 kW EEL tidal turbine has been tested in the Port of Brest, France in May 2022. In the range of products, the smallest EEL tidal turbine has a membrane size of 3×3 m, requires a minimum water depth of 2 m, and is rated at 5 kW; the largest device has a membrane size of 15×22 m, requires a minimum water depth of 15 m, and is rated at 1 MW [56].
- **OpenHydro - TRL 7**. OpenHydro was the first developer deploying a tidal turbine at an EMEC test site in 2006. The first test rig had a generating capacity of 250 kW and was the first tidal turbine generating electricity to UK's national grid. This was followed by larger demonstration projects, e.g. in Canada and France. After the 7th generation of OpenHydro with a rotor diameter of 6 m was installed in 2014, Naval Energies, parent company of OpenHydro, decided to liquidate OpenHydro.
- **Jupiter Hydro 2 MW tidal turbine - TRL 7**. Jupiter Hydro started working on its Archimedes Screw in 2011 and went through several open water tests in 2013 and 2014. Jupiter has a 2 MW Power Purchase Agreement issued by the Nova Scotia Department of Energy and Mines, and aims to deploy the TEC device in the Minas Channel, Bay of Fundy in early 2024. The unit consists of four screws with a

[1]Unless stated otherwise, TRL ratings are based on [51].

[2]Note that the term 'turbine' follows the manufacturer's designation

diameter of 7.26 m which are placed at a 30° angle to the flow [57].

The 2018 Ocean Energy Technology Market Report by JRC [51] stated that a massive expansion of tidal energy technology is expected in the next years. Especially MeyGen Phase 2, where the installation of an additional 80 MW tidal stream capacity is planned, will form a significant step for tidal energy technology. The expected increase in the coming years might also have a significant impact on the cost of tidal energy technologies, which would make tidal energy technology more competitive with other energy technologies.

C. Market overview

Based on the 2018 Ocean Energy Technology Market Report [51], the majority of tidal energy developers (59 %) are situated in Europe, specifically the UK, the Netherlands, and France. Outside of Europe, larger developers are located in the USA and Canada. There are 43 developers with a TRL $>$ 5, 15 developers with a TRL $>$ 7 (of which 13 developers are located in Europe), and only 4 developers with a TRL $>$ 8 (Andritz Hydro Hammerfest, Orbital, SIMEC Atlantis, Nova Innovation) [51]. Table III provides an overview of currently available tidal stream technology, for which relevant data is publicly accessible. It can be seen that there is a wide range within the technology in terms of rated power. Large scale devices (1 MW to 2 MW) are equipped with large rotors ($>$ 10 m) and, therefore, require relatively large water depths. Turbines in the medium scale range (100 kW to 250 kW) have smaller rotor diameters, theoretically resulting in smaller required water depths, and also provide power at lower flow rates. In the small scale range ($<$ 100 kW), turbines are found which can even operate in particularly shallow waters. Since the average water depth at the sites of interest in the German Bight is between 13.7 m to 21.6 m (see Table II), small-scale or medium-scale turbines are considered most suitable for deployment in the German Bight.

D. Levelised Cost of Energy

The LCOE is a common measure for the techno-economic assessment of energy technologies. It compares the costs incurred over the entire life cycle of the project (capital expenses (CapEx), operational expenses (OpEx), decomissioning costs) with the energy yield over the entire life cycle.

In MeyGen Phase 1A, for example, CapEx include turbine development, onshore balance of plant, offshore works, substructures, cabling, project initiation & management, as well as insurance. In total, the CapEx are quantified at £ 51.3 million. OpEx include Lease & insurance, unplanned & planned maintenance, spare parts, onshore inspection & maintenance, cost for operating teams, decommissioning, offshore inspection & maintenance, corporate operations, and equipment purchase. In total, the OpEx are quantified at £ 1.4 million per year [53].

1) Current LCOE of energy technologies: No tidal energy projects have been implemented in Germany so far so that no LCOE data is available for German sites; therefore, data from the UK is referred to. Currently, the LCOE for tidal stream technology is approximately 28.36 € cent / kWh [11]. With that, the current LCOE is not in line with the European Union's targets for reducing the LCOE for tidal energy projects: With respect to ocean energy, the objective of the EU's Strategic Energy Technology Plan (SET-Plan) is to deploy 100 MW of ocean energy capacity (wave and tidal) by 2025 and to reduce the LCOE for tidal energy to 15 € cent / kWh by 2025 [61].

Comparing the current LCOE of tidal stream energy in the UK, for instance, to offshore wind energy in Germany (8–12 € cent / kWh [62]), tidal energy is by no means competing with established renewable energy systems. However, tidal energy technology is not yet as advanced as the other energy technologies, leaving room for significant reduction of the LCOE in the future, as seen, for instance, for onshore wind between 1985 and 1990 [63].

2) LCOE projections: Future LCOE projections are usually based on a technology learning rate, which expresses the percentage by which costs are reduced when the total installed capacity doubles [11]. According to Offshore Renewable Energy Catapult (OREC) [64], the near term cost reduction potential for tidal stream energy depends upon three aspects:

- **Initial accelerated reductions**. These include volume effects (e.g. lower production costs per unit for mass production), as well as economies of scale. In the case of a tidal current turbine, this could be achieved, for example, by increasing the rotor diameter [11].
- **Learning by doing & Innovation**. Over time, processes are better understood and procedures are optimised as a result, which has been observed at EMEC tidal test sites. This includes, for example, developing a strategy for O&M measures to maximise turbine uptime or optimising processes in the supply chain. Also, innovation, e.g. improved structures and moorings, can reduce the costs [64].
- **Cost of Capital**. Funding for tidal energy projects in the UK is currently provided through grant support and private finance. However, due to increasing technology maturity and the resulting lower financial risks, part of the project could be financed through commercial loans, as in the case of offshore wind energy [64].

LCOE projections for tidal stream energy are provided by [64] and [11], amongst others. The LCOE projections are based on different technology learning rates ranging from 9 % to 26 %. With that, and an expected cumulative capacity of 160 MW in the UK by 2031, [11] projects a LCOE of 21.5 € cent / kWh, 17.7 € cent / kWh, and 11.3 € cent / kWh for technology learning rates of 9 %, 17 % and 25 %, respectively.

TABLE III
CHARACTERISTICS OF SELECTED TIDAL STREAM DEVICES, SORTED FROM LARGE-SCALE TO SMALL-SCALE DEVICES.

Developer	**Device name**	**Required depth [m]**	**Rotor diameter [m]**	**Operational speed [m s^{-1}] (cut-in / rated / cut-out)**	**Rated power [kW]**	**Ref.**
			HAT			
Orbital	O2	> 23.2	2 × 10	1.0 / 2.5 / 4.5	2000	[65]
SIMEC Atlantis	AR1500	> 30	18	- / 3 / 5	1500	[66]
Andritz	HS1000	35 - 100	21	1 / - / -	1000	[67]
Sabella	D10	55 op.	10	- / 4 / -	1000	[68]
Tocardo	T-2	-	4.7 - 9.9	0.4 - 0.9 / 2.0 - 4.5 / 2.6 - 6.8	103 - 248	[69]
Nova Innovation	M100-D	-	8.5	0.5 / 2.0 / 6.0	100	[70]
Tocardo	T-1	> 4	3.1 - 6.3	0.4 - 0.9 / 2.0 - 4.5 / 2.6 - 6.8	42 - 98	[69]
			Other			
Guinard Energies	P66	1.5	-	1.2 / 3 / -	3.5	[71]
Guinard Energies	P154	3	-	1.2 / 3 / -	20	[72]
Minesto	DG100	50 op.	-	1.2 - 2.5	100	[55]
EEL Energy	EEL Tidal Turbine	1 - 15	-	0.7 / - / -	5 - 1000	[56]

- not available; op. operational in projects, but no information on required minimum depth provided

V. DISCUSSION

A. Germany's tidal energy resource

The tidal energy resource in the German Bight was determined using data from the EasyGSH-DB North Sea model. While the technical tidal energy resource in Germany is estimated at $2468\,\mathrm{GWh\,y^{-1}}$, the practical resource can fall down to $66.6\,\mathrm{GWh\,y^{-1}}$, when severe restriction are being assumed. With respect to the total power consumption of $595\,\mathrm{TWh}$ in Germany in 2018, tidal stream energy could only make a minor contribution and given the projected increase in total power consumption to $658\,\mathrm{TWh}$ in 2030, the share of tidal energy would become even less. Nevertheless, with the deployment of tidal current turbines in the German North Sea, power could be generated for more than 21200 households annually (assuming a household power consumption of $3100\,\mathrm{kWh\,y^{-1}}$ [73]).

In the present stage 1 assessment, some important aspects regarding turbine deployment could not be considered. Also, the EasyGSH-DB North Sea Model was not primarily developed to conduct a tidal energy resource assessment. Simplifications were made which result in uncertainties. For instance, due to unavailability, V_{mean} was used for the calculation of the APD, instead of V_{rmc}. Furthermore, averaged current velocities are being used; thereby, disregarding velocity distributions. Table II also reveals a relatively high number of installed turbines, which may be unfeasible for installation, operation, and maintenance. Other uncertainties, such as the impact of the turbines on the flow conditions at site, may also come into play during the assessment and shall be discussed in future work.

B. Tidal energy technology

The assessment of technologies indicates that tidal energy is still at an early stage compared to other energy technologies. Nevertheless, it has made significant progress in recent years, demonstrated by the plans for MeyGen Phase 2. Anticipated growth in capacity over the forthcoming years is poised to drive down the LCOE further. With a $1\,\mathrm{GW}$ installed capacity, the LCOE for tidal energy in the UK is estimated to range between $9.5\,€\,\mathrm{cent}\,/\,\mathrm{kWh}$ to $16.5\,€\,\mathrm{cent}\,/\,\mathrm{kWh}$. The projection of LCOE data from the UK to Germany is uncertain. In the UK, numerous turbine trials have been conducted and valuable insights have been acquired, in contrast to Germany, where tidal current turbines remain untapped. Nevertheless, it can be assumed that through learning by doing & innovation in other projects, cost reduction will be achieved, independent of project location. This process can also benefit from economies of scale [76], particularly considering the expected global increase in tidal turbine deployments. However, given the expected preliminary testing phase rather than immediate large-scale deployment in the German Bight, the initial LCOE in Germany will likely be higher than that of the UK. Nonetheless, diversification of energy technologies remains crucial for ensuring a stable power supply. In this context, tidal stream energy emerges as a dependable option due to its predictable tidal patterns.

VI. CONCLUSIONS AND FUTURE WORK

Based on the presented work, the following conclusions can be drawn:

- In international comparison, the potential for harnessing tidal energy in Germany is found to be rather low. The practical tidal energy resource may drop as low as $66.6\,\mathrm{GWh\,y^{-1}}$, compared to $2468\,\mathrm{GWh\,y^{-1}}$ technical resource and $537.51\,\mathrm{TWh\,y^{-1}}$ theoretical resource.
- Tidal energy technology has matured in recent years and a significant expansion can be expected globally. In particular, there are several small-scale and medium-scale devices under development, which could be suitable for deployment in the German North Sea.

On the basis of the results from this resource analysis, the following pertinent future work can be identified:

- Perform a stakeholder analysis to answer questions as to whether or not stakeholders are currently considering Germany as a site for tidal

energy, what conditions (soil, water depth, current speed) are required for the deployment of their technology, and how the potential barriers and future trends for tidal energy look like. This will give insights to researchers and policy makers
- Re-iterate the resource analysis, including more details on uncertainties, laying out different scenarios (weak to strong restrictions) for the practical resource analysis, and exploiting the input from the stakeholder analysis.

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