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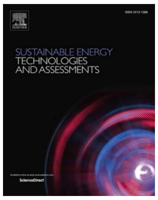

Strategic development of environmental impact assessment decision support tool for offshore energy enables decreased costs, increased utilization, and quality

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ABSTRACT

In the transition to a sustainable energy system, there is an urgent need for expansion of offshore renewable energy installations. To ensure sustainable development also with respect to the marine environment, a variety of decision support tools (DSTs) are currently under development, aiming at potentially increased quality and efficiency for environmental risk assessment (EIA) of planned offshore energy installations. However, the savings potential of a DSTs is to a large extent governed by the timing of the DST development, which in turn is directly dependent on the investment rate over time. A set of development scenarios were evaluated, simulating different degrees of strategic implementation and successful utilization of the DST for offshore energy. Using the situation in Sweden as a case study, we demonstrate that a planned investment can lead to considerably lower total costs for the EIA at a national level, at the same time allowing for improved quality of the EIA in line with the ambitions in both marine spatial planning and existing goals within marine environmental management.

Introduction

Offshore energy is an integral part of the Blue Economy, identified as key in the transition to sustainable energy production [1–3] and forecasted to continue to multiply in the near future [4–6]. In terms of offshore wind energy, within the European Union (EU), the plan is to go from 20 GW in 2020, to reach a capacity of ca 300 GW before 2050 [7]. This will require multi-billion € investments [8,9], of which permit-related expenses in terms of environmental impact assessment will be substantial. Project planning and implementation of offshore energy installation projects are complex and involve multiple time-consuming permit application processes, where Environmental Impact Assessment (EIA) is a significant contributor in terms of time and cost [10]. EIA, here defined as the assessment of environmental pressures (P) on an ecosystem (E), can be labour-intensive and long-drawn [11,12]. For example in Sweden, the extensive permitting processes have led to a high degree of'failed projects', and the expansion of the offshore wind industry is claimed to be unpredictable [13]. In 2009 the Swedish Parliament passed an action plan with the intention of 10 TWh yearly offshore wind capacity by 2020 [14]. In reality, from 2009 to 2020, roughly a total of 0.3 TWh per year capacity came from new offshore wind installations [15], i.e. less than 1 % of the planned energy capacity was built, despite that 32 TWh of yearly capacity had been rigorously planned through EIA processes [15] [16, section 4] and 4.5 TWh had been fully permitted but delayed and subsequently referred to as not being cost-effective to continue with at current state [17]. Protracted EIA processes are likely one explanation of the failure to reach the target [16, section 4]. The time a typical Swedish offshore wind farm project spends in the EIA process, has been estimated to be on average, 7.4 years and up to 14 years in some cases [17–22]. The remaining project lead times are, on average, 4.4 years before the projects become operational, i.e., the time for the EIA process corresponds to, on average more than 60 % of the total project lead time. Yet, EIA is essential to minimize the risk of deterioration of environmental status [23–27], and there is an urgent need to improve and speed up the EIA process, without compromising quality and reliability of the assessment [28]. This need has played a pivotal role in motivating development and use of Decision Support Tools (DSTs) for Marine Spatial Planning (MSP) including regional Cumulative Impact Assessment (CIA) [29,30], hereafter referred to as DST in this paper.

Current DST implementations are often based on individual case studies and focused on single species or habitats, resulting in large uncertainties regarding cumulative impacts [31]. Many DSTs have high

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Nomenclature

$c_{computcomponent}(t)$	Development cost of computational component [€]
$c_{DSTdevelopment}$	Total development cost of DST [€]
c_{EIA}	EIA costs [€]
$c^{ij}_{PE\mu}$	EIA cost per pressure-ecosystem impact pair [€]
c_{MWh}	Cost per year and MWh of offshore wind energy [€/MWh]
$d^{ij}_{PE\mu}$	Cost distribution of PEμs
E_i	Ecosystem i's presence
$f_{application}$	Fraction of offshore project costs being EIA process
$f_{failurerate}$	Permit failure rate per MWh
$f_{offshore}$	Fraction of EIA process being offshore versus onshore
I_{rate}	DST investment rate [€/year]
$N_{PE\mu}$	Number of computational components, PEμs
P_j	Pressure j presence
r	DST efficiency
r_k	DST development component k's efficiency
s	DST savings [€]
$s_{tool}(t)$	DST savings potential [€]
$t_{available}$	Available time window [years]
$t_{DSTdevelopment}$	Time to develop all of the DST's computational components [years]
$t^{EIA}_{lead-time}$	Project lead-time EIA process
t_{left}	Time left after a computational component is developed [years]
$t^{other}_{lead-time}$	Project lead-time other aspects, e.g. build time
t_{total}	Scenario time window [years]
U	Total utilization of DST
$U_{computcomponent}(t)$	Utilization of computational component of environmental impact pair
μ_{ij}	vulnerability combining a pressure j and an ecosystem i
W	Offshore wind in yearly MWh capacity [MWh]

Abbreviations

CIA	Cumulative Impact Assessment
DST	Decision Support Tool
E	Ecosystem, (or part of ecosystem e.g. key species selected for the ecological significance, public value or due to regulatory requirements)
EIA	Environmental Impact Assessment
GW	Unit of power in gigawatts (10ˆ9 W)
MSP	Marine Spatial Planning
MWh	Unit of energy in megawatt hours (10ˆ6 Wh)
P	Pressure (e.g. oil spill, shipping noise)
PEμ	Impact pair of ecosystems and pressures
SEA	Swedish Energy Agency
SwAM	Swedish Agency for Marine and Water Management
S1P	Scenario 1 Planned
S2P	Scenario 2 Planned
S3P	Scenario 3 Planned
S1U	Scenario 1 Unstructured
S2U	Scenario 2 Unstructured
S3U	Scenario 3 Unstructured
TWh	Unit of energy in terawatt hours (10ˆ12 Wh)

Subscripts and Superscripts

tot	Total

Greek symbols

μ	Ecosystem vulnerability to a Pressure (impact weight)

ambitions for future improved functionalities and are predicted to allow automated accelerated and enhanced analysis, particularly capabilities to assess long-term and cumulative impacts on the marine environment [29]. However, developing this kind of advanced DST is an extensive endeavor, both in terms of development time and costs, and to make full use of the DST, environmental monitoring data of high spatiotemporal resolution is required and associated with further costs [32]. Networks of subsea observatories has been proposed as one solution to increase the marine environmental data availability, a prerequisite for improved DST functionality [31]. A well-functioning DST in turn, has the potential to increase the quality and efficiency of the EIA and offshore energy planning processes in general and, subsequently, a substantial cost-saving potential. This potential should therefore be compared with the costs directly related to marine environmental monitoring data collection and mapping aspects, essential to development and validation of a DST. A good example of the costs for extensive marine environmental monitoring is the Norwegian program MAREANO, which has been continuously progressing since 2005. Until 2021 the program has achieved governmental funding corresponding to 127 M€ for mapping and monitoring subsea sediments and biotopes [33].

Considering the expected rapid growth of offshore energy to meet renewable energy demands and still ensure sustainable use of the marine environment, it will become increasingly vital to effectively balance challenges in reaching renewable energy goals and protecting and restoring the environment when allocating resources [10,27]. To assess the economic incentives of advanced DST development, it is therefore important to identify the break-even between the cost savings of EIA and the cost of further development of a DST. Lange et al. [34] made an analogous analysis of the planning of maritime logistics concepts for offshore wind farms, enabling simulations of various logistical specifications of maritime supply chains in offshore wind energy, however, the EIA perspective was lacking. On the other hand, the available scientific literature on offshore energy EIA is extensive (e.g. [3,10,31]), yet the analysis of the economic incentives on the strategic development and optimization, i.e. how and when different functional parts of an advanced DST is prioritized, is lacking.

Such analysis can inform decision-makers on how to take advantage and maximize savings in utilizing an advanced DST. However, there is a time constraint, or window of opportunity, to allow for maximized use of the advanced DST and subsequent contribution to reaching set sustainability goals, such as carbon neutral by 2050. In addition, as the EU and Sweden are planning to build much offshore renewable energy in the near term, a rapid development of the DST is required to utilize the savings potential. To conclude, rapid development of the DST is required to fully utilize the savings potential. This situation is a global problem applicable to all countries aiming at sustainable offshore energy as part of their way to meet national goals and international sustainability and energy needs.

Therefor, this study explores the potential strategic importance of the timing of investment and the resulting usefulness and utilization in developing an advanced DST, for use in offshore project planning to reduce costs and lead times. The development progress of the DST over time will affect the possible increased efficiency of permit application processes, and it is, therefore, essential to optimize the development process of the DST.

This study connects to broader research themes of the improvement and facilitated development of offshore EIA DSTs in terms of protection assessment and management of the environment and efficiency improvements of secondary effects, e.g., permit costs for offshore sustainable energy development. One step towards improved DST effectiveness is understanding, and analysis of costs and benefits and analysis of how and what needs should be addressed.

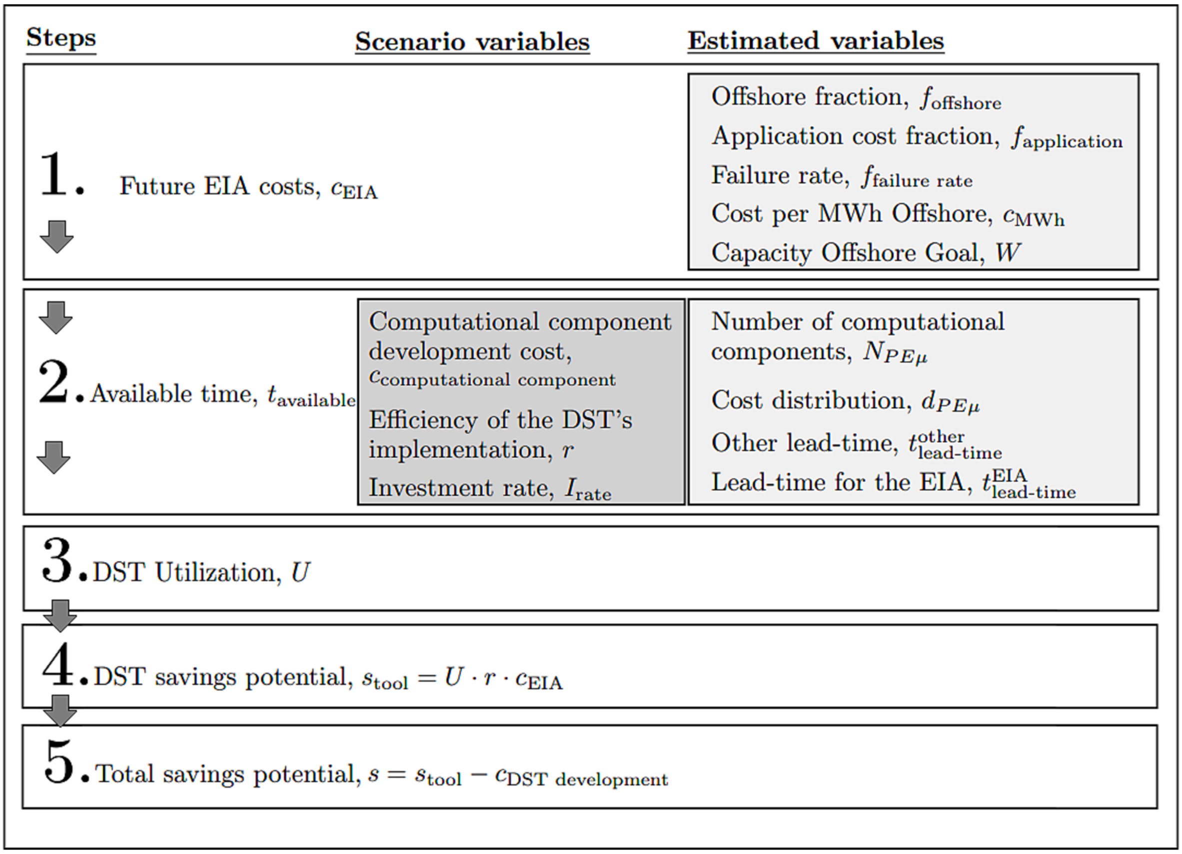

Fig. 1. Flowchart of the five steps involved in the model, describing method step of EIA costs to estimation of total savings potential of the DST development. Estimated variables are in the light gray boxes and the scenario variables in the dark gray box.

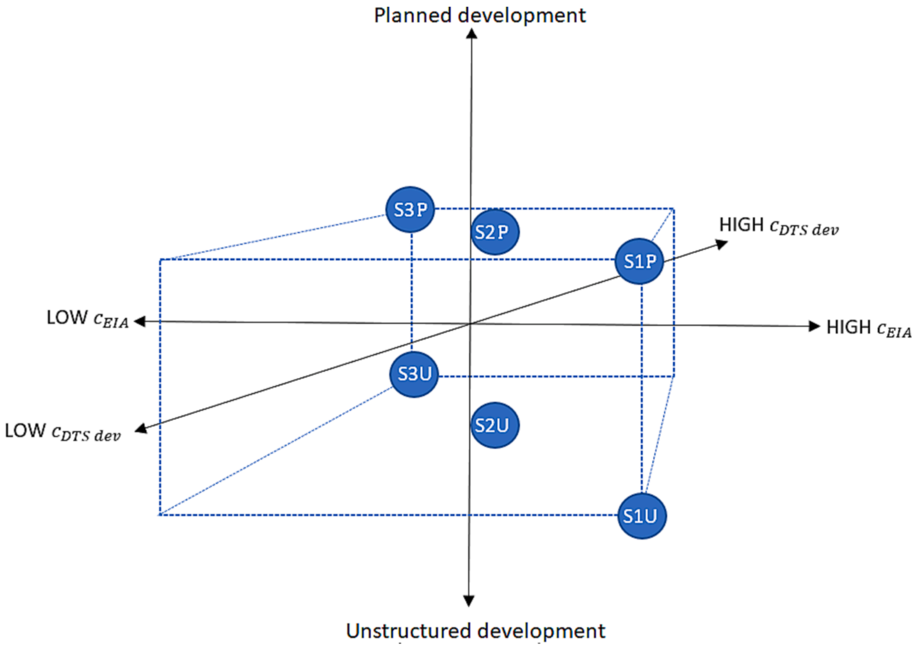

Fig. 2. Scenario 1 Planned (S1P) is considered the most advantageous scenario, while Scenario 3 Unstructured (S3U) is the most unfavorable and shall result in the most versus the least value of development of a DST. Each scenario's parameters are set into a simple linear model to analyze the savings potential over time. Planned development represents the planned ordering of the defined tool components for development, while unstructured is the average statistical outcome. This'optimization' is to straightforwardly consider for what or whom the DST is developed.

To evaluate the resource efficiency of different DST-development and investment scenarios, detailed data on both offshore energy installation related EIAs and DST development and usefulness are is needed. In addition to the EIA data available from the Swedish permit applications until 2020, the Swedish Agency for Marine and Water Management (SwAM) has started to develop the DSTs Symphony [35] and Mosaic [36]. Like in many other DSTs [29,32], expert elicitation has been used to develop Symphony and Mosaic and their main idea is the identification of E and P, and from pairwise combinations with their impact weight, μ, generate their relative individual $PE\mu s$ and cumulative impacts $\sum PE\mu$ [37] to be used in the MSP. Currently these DSTs are not detailed enough for use in EIA of individual offshore energy project applications, but as Stamoulis et al. [32] suggest, the technological development within marine environmental management should enable more extensive use of in situ data leading to improved DSTs. However, the existing Swedish marine DSTs were used in the latest national MSP work by SwAM and the Swedish Energy Agency (SEA), identifying an ambition to allow for offshore wind installations of 23–30 TWh by 2045 [38]. Hence there is an immediate incentive to advance the functionality and effectiveness of the Swedish marine DSTs. In addition, Symphony and Mosaic provide easy access to publicly available data, strengthening the use of Sweden as a suitable case study. To conclude, there is a major discrepancy between the desired and forecasted capacity versus recent development of offshore wind energy installation in Sweden [15]. The EIA-part of the permit application process, however, is identified as a general bottleneck [39,40]. Beyond the scope of this study, there are also non-EIA-related possible reasons for delays, e.g., the Swedish Armed Forces have objected to many offshore installations [41,42]. Therefore, the focus of this study is to use hypothetical future scenarios of DST development, where the potential for increased investment and optimization of DST development are highlighted, to assess the savings potential for the future cost of EIA.

Materials and methods

To estimate savings potential for EIA, a methodological approach in five steps were used (Fig. 1). In the first step (1), the future EIA costs are estimated for offshore wind energy production. In the second step (2), the available time is estimated, using scenario variables and estimated variables. Thereafter follows calculations of DST utilization (U), DST savings potential (s_{tool}), and total savings potential (s), in the steps 3, 4 and 5 respectively.

Scenarios for EIA costs and DST development

To evaluate s in step 5, six future scenarios were developed (Fig. 2). Scenarios were based on assumptions for the calculation of EIA costs (c_{EIA}) in step 1, and cost of DST development (c_{DST}) development in step 5.

The most advantageous scenario (S1P) was defined as the high cost of EIA and low cost of development of a DST in combination with an planned DST development. At the other end, a more unfavorable scenario (S3U) was defined by a low-cost EIA and high cost of DST development in combination with unstructured DST development. Midrange alternatives for planned versus unstructured DST development defined scenarios for the mid estimate for EIA costs and a mid-value for EIA development costs (S2P versus S2U).

Considerations and assumptions assessing the future offshore energy development

Modeling hypothetical future scenarios to calculate the EIA cost savings potential requires many assumptions for the modeling, variables, and parameters, both with respect to the offshore industry development and with respect to EIA and DST development and performance. Sweden was chosen as a case study to delimit data collection and analysis. Information from relevant national energy and marine spatial planning strategies, together with publicly available digitized historic offshore energy permit applications formed the basis to determine how, and at what cost, EIA for offshore energy installations in Sweden have been carried out. This background was used to estimate and motivate choice of variables, parameters, and methods, further described in [16, section 4].

Practical limitations, such as EIA costs, are assumed to be spent linear over the time window, and therefore potential savings of EIA costs are calculated as a function of the state of DST over time. The simplifying assumption of the future progress of offshore wind energy development for Swedish waters will follow the linear expenditure (constant rate) derived from the total TWh in offshore energy applications during the period 2009–2020. If these assumptions are over relatively small time windows linear, the future expenditure may evolve more dynamically, but for the conclusions in this study, simpler assumptions of behavior from year to year, or decade to decade, are close enough. In addition, these assumptions simplify the analysis for the reader, and currently there is no other, more appropriate assumption of time dependency to apply. Therefore, s (step 5) was defined through subtraction of a future EIA or permit cost from the DST savings potential (s_{tool})(Fig. 1).

Utilization for planned versus unstructured DST development

The total utilization U represents the hypothetical utilization of a fully developed DST. It is calculated through the incremental development of individual, so-called’computational components’ that make up the DST. The computational components are the solutions to the problems the DST solves for its users performing an EIA. The computational problems are the environmental impact that must be assessed for each pair of P and E.

For the analysis, two distinct development paths are defined, where the first defines an *unstructured development* (Fig. 2), which can be regarded as a complete lack of prior knowledge about which component is the most cost-efficient to develop. Hence, the unstructured development is represented by the average statistical outcome of random development of the DST, which is assumed to be an expected method/behavior. The second development path is called *planned development* (Fig. 2), i.e., it is assumed that the most cost-efficient computational component for the DST will be developed first, and then the rest in descending order with respect to cost-efficiency.

Future EIA costs

The future expenditure for EIA by the offshore energy industry in their permit application processes was defined as the future EIA cost in step 1 (Fig. 1). The future EIA cost estimate was based on e.g., projects in Sweden, the national offshore development goals, historical built data, and failure rate. Ideally, the EIA permit cost estimation could be based on bookkeeping from historical projects, but such data were not publicly available. Hence, the cost estimate was based on available data originating from publicly available project applications. The model assumes a minimum constant installation rate, i.e. c_{EIA} was assumed to be incurred linearly over the time interval ($t_{\mathrm{available}}$). The linear Eq. (1) can estimate offshore EIA application costs for a given time frame, but requires several assumptions and parameter estimations, outlined in [16, section 4].

$$c_{EIA} = \frac{1}{1 - f_{\mathrm{failure\ rate}}} c_{\mathrm{MWh}} W f_{\mathrm{application}} f_{\mathrm{offshore}} \tag{1}$$

In Eq. (1), the estimated cost per year and MWh of offshore wind energy W was assumed to correlate with national energy goals and planning; hence input was sourced from three places; the working document for the Swedish Marine Spatial Plans, where 23 TWh yearly capacity planned with lowest total utilization of the space; the higher value was set to 89 TWh is the maximal realizable available by SEA

Table 1
Parameters are chosen based on national goals, direct estimates, or calculated from a combination of sources. The lowest median or average and the highest possible value are presented per parameter. In order to limit unnecessary complexity for the cost of the c_{EIA}, which is calculated of the other parameters as defined in Eq. (1), three values (lowest, median and highest combination of above parameters) were chosen for the further analysis of the respective scenario.

Parameter	Low	Median/Average	High
Cost per MWh Offshore c_{MWh} (€/MWh)	240	510	670
Capacity Offshore goal W (TWh)	10	24	89
Application cost fraction $f_{\mathrm{application}}$	0.015	0.03	0.11
Offshore fraction f_{offshore}	0.44	0.66	0.89
Time window t_{total} (Years)	19	24	29
Failure rate $f_{\text{failure rate}}$	0	0.85	0.99
EIA cost $c_{\mathrm{EIA}}(t_{\mathrm{total}})$ (M€)	15.7	1,580	555,600

report [43] when projects with permits are excluded; the lower bound was set to 10 TWh, being the Swedish Parliament's 2020 goal [14].

The fraction of project costs related to the application process ($f_{\mathrm{application}}$), e.g. environmental surveys, consent, compliance etc, was described by three estimates 1.5 % [44], 3 % [45] and 11 % [46], based on studies of project costs for offshore wind. Further, the fraction of the application process contributed to projects offshore-part (f_{offshore}) assumed a linear relationship between page count and value of EIA and was estimated of what amount of the EIA reports concern onshore versus offshore [16, section 4, subsection Fraction of offshore project costs being EIA process].

The cost per year and MWh in capacity c_{MWh} was established from the low, average, and high value of surveyed Swedish applications, containing cost estimates [16, section 4, subsection Cost per year and MWh of offshore wind energy for sourced data]. The model assumes that the EIA assessment quality improvement from the DST was the main contributing factor to permit failure rate $f_{\text{failure rate}}$, less uncertainty in the process should lead to acceptable projects (non failed applications) and is indirectly included in any cost reductions. For the determined failure rate per MWh, $f_{\text{failure rate}}$, the analysis differentiates between 1) failure rate due to projects not completing the application step and 2) projects getting a permit but not being completed. The second aspect is referred to as the failure of projects due to lead-time where, i.e., outdated technologies make the project nonviable. These two high and medium values, and the idealized case with no failure rate as the low value, were used in the advantageous, midrange, and unfavorable scenarios, respectively (Table 1). Together with assumed cost of development $c_{\text{DST development}}$ ranging from values 50, 100 and 500 M€. The cost to develop the DST is represented by $c_{\text{DST development}}(t) = \sum c_{\text{comput - component}}(t)$ and is the sum of equal cost to develop the computational components.

Available time window

In the step 2 (Fig. 1) $t_{\mathrm{available}}$ is calculated based on t_{total}, which was set to the 2040 goal [47], the 2045 goal [48], and the 2050 goal [49]. The definition of $t_{\mathrm{available}}$ is the available time to complete projects, while after $t_{\mathrm{available}}$, projects will not complete in time to contribute to achieving set energy goals at the end of the scenario time window, t_{total}. Hence there is a cutoff point where future energy developments have to be initialized. The numerical calculation of $t_{\mathrm{available}}$ from t_{total} is described by Eq. (2).

$$t_{\mathrm{available}} = t_{\mathrm{total}} - t^{\mathrm{other}}_{\mathrm{lead-time}} - t^{\mathrm{EIA}}_{\mathrm{lead-time}}\frac{1}{f} \tag{2}$$

Where the EIA lead-time fraction of reduction (f) is defined by (Eq. (3)).

$$f = \frac{c_{\mathrm{EIA}}}{c_{\mathrm{EIA}} - \sum_{x=1}^{N} c_{\mathrm{EIA}}\, rH\left(t - t_{\text{DST development}}\frac{x}{N}\right)} \tag{3}$$

The total lead-time for a offshore energy project is taken from the average of previous Swedish offshore energy projects $t^{\mathrm{other}}_{\mathrm{lead-time}} + t^{\mathrm{EIA}}_{\mathrm{lead-time}} = 11.8$ years. Similarly, the lead-time for the EIA/consent process average is $t^{\mathrm{EIA}}_{\mathrm{lead-time}} = 7.4$ years. Further information can be found in [16,

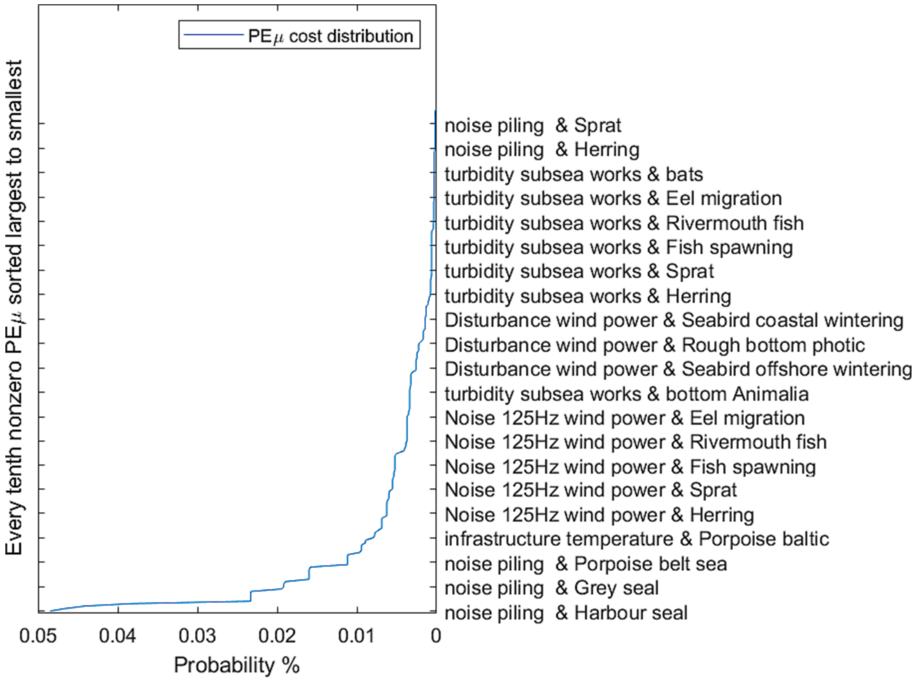

Fig. 3. The estimated cost distribution of each non-zero impact pair *PEμ* is on the x-axis, where every 10th pair is displayed and sorted by probability. Ecosystems and Pressures start with capital letters as if defined by *Symphony*, while lowercase is introduced definitions by this study. Each pair is represented by the presents of the pair in reviewed EIA reports found in the [16, section 4, subsection Analyzed Project Applications for Word Count Analysis]. This data is then assumed to correlate with EIA costs per pair, resulting in a Pressure-Ecosystem distribution for the study.

section 4, subsection Estimated Project lead-time EIA process and Project lead time other aspects]. In the analysis, a lead-time reduction was assumed to scale linearly with cost savings, thereby prolonging how long offshore energy buildup may continue to reach future energy goals. Hence, if the permit lead-time can be significantly decreased, it may significantly impact cost savings.

Cost distribution $d_{PE\mu}$ of P and E pairs

The offshore wind energy industry projects' EIA focus may vary from project to project. Hence, their permit costs will also vary. Development of DST in the analysis assumed EIA computational components to be divided into different environmental impact problems *$PE\mu$s*. The DST implemented computational component was assumed to improve future EIA costs from implemented time and forward into the future. The estimated total utilization over time $U_{utilization}$ as DST are being developed considered compositions of workload with various outcomes. Each computational component was assumed to be of equal development cost ($c_{comput\ component}$). Hence, the savings enabled by using a developed DST computational components was described by the efficiency of the implemented components, (r), affecting the EIA costs but at the component level. Each DST's implemented computational component's r was assumed to represent improvements in time and cost for the developed DST. In practice, r concerns DST usability and reusability by the final users. Furthermore, the efficiency improvements represent the DST predictability of environmental outcome projects or MSP strategies. Hence, DST savings $s_{\mathrm{tool}}(t)$ are defined as the sum of developed computational components j developed for a DST that improve the DST efficiency r_k of the existing estimated base c_{EIA}. Each project consent process pertains to considering environmental impact aspects, i.e., the ecosystem's E_i vulnerability μ_{ij} to each pressure P_j. This study divides the DST's EIA costs and development costs by their impact components, each assigned to a corresponding impact. A cost reduction by the DST over time was defined as the expenses expected to be spent on the applications/ EIA process $s_{\mathrm{tool}}(t)$, subdivided into environmental impact component costs. Each environmental impact component $P_iE_j\mu_{ij}$ was represented by an impact component cost $c_{PE\mu}$.

Estimation of EIA cost per EIA component $PE\mu$ was conducted by word analysis of the EIA process per ecosystem's E_i vulnerability μ_{ij} to a pressure P_j to represent the cost distribution $d\,{}^{ij}_{PE\mu}$. Through word analysis of Swedish EIA offshore energy applications, the distribution $d^{ij}_{PE\mu}$ was estimated (Fig. 3). The cost per impact $c_{PE\mu}$ was defined as a function of the total EIA costs c_{EIA} as in Eq. (4). Where the total costs is $c_{\mathrm{EIA}} = \sum c^{ij}_{PE\mu}$. Further insight into data and analysis can be found in [16, section 4, subsection EIA Cost Distribution for Computational Components].

$$c^{ij}_{PE\mu} = d^{ij}_{PE\mu} c_{\mathrm{EIA}} \tag{4}$$

DST utilization

Following the definition of available time in step 2 a function for the DST utilization over time is defined as the step 3 (Fig. 1). Modeled savings estimation of the DST should be viewed as the reduced permit cost and its total utilization U over time. An early-developed computational component will be utilized for a longer time. To determine the utilization of the DST U, the development of each computational component results in utilization by Eq. (5).

$$U^{i}_{computational\ \ component}(t) = \begin{cases} \quad 0 & : t < t^{i}_{left} \\ \dfrac{c_{PE\mu}}{c_{EIA}} \dfrac{t^{i}_{left}}{t_{available}} \dfrac{t - t^{i}_{left}}{t_{available} - t^{i}_{left}} & : Otherwise \end{cases} \tag{5}$$

and t is time, t^{i}_{left} left is time left after computational component i is developed, $c_{PE\mu}$ is total EIA cost for that $PE\mu$, r is the efficiency of the DST's implemented computational components and $t_{\mathrm{available}}$ is the available time window. The available time $t_{\mathrm{available}}$ depends on the DST efficiency to lower permit lead times, and hence, if this factor is important, it may significantly impact the time window the DST effectively can be utilized. The time after a computational component of the DST was completed constitutes the usable time, i.e., the time the component can be used. In this study, the implementation order of the cost distribution was used to differentiate between the planned implementation versus the unstructured implementation (expected outcome of random implementation).

Table 2

Assumed parameter ranges used for the scenarios, r are efficiencies of implemented computational components, c_{DST} development are the total costs to develop the DST, I_{rate} are estimated investment rates and $N_{\mathrm{PE\mu}}$ are the number of computational components of non-zero impact pairs. A smaller set of parameters are used to limit the scope of the analysis but at the same time enough visualize interesting behavior. Each parameter chose is further motivated in Olsson et al. 2023 [16].

Parameter	Ranges
r	[0.1 0.5 0.9]
$c_{\mathrm{DST\ development}}(t)$ (€)	[50•10^{6} 100•10^{6} 500•10^{6}]
I_{rate} (Years)	[1•10^{6}.. 9•10^{6}]
$N_{PE\mu}$	231

It was assumed that time and cost-effectiveness in computational component development scale linear with the investment rate I_{rate}. As the cost distribution $d^{ij}_{PE\mu}$ is the only variable in the model, it results in the most cost-effective implementation order to be sequential.

To consider savings for an uncorrelated implementation order of $d^{ij}_{PE\mu}$, i.e. costs are not considered, but will be represented by an expected cost $c_{PE\mu} = E(d^{ij}_{PE\mu} c_{\mathrm{EIA}}) = \frac{c_{EIA}}{N_{PE\mu}}$.

Utilization is defined by Eq. (6).

$$U(t) = \min\left(1, \sum_{x=1}^{N_{PE\mu}} H\left(t - t_{DST\ \ development}\frac{x}{N_{PE\mu}}\right)\cdot\left(t - t_{DST\ \ development}\frac{x}{N_{PE\mu}}\right)\cdot\begin{cases} \dfrac{d^{x}_{EIA}}{t_{available}} & for\ optimized\ development \\ \dfrac{1}{N_{PE\mu}} & for\ unoptimized\ development \end{cases}\right. \tag{6}$$

The time to develop the DST $t_{\mathrm{DST\ development}}$ with a constant investment rate I_{rate} can be written as $t_{\mathrm{DST\ development}} = \frac{nc_{computationalcomponent}N_{PE\mu}}{I_{rate}}$. Which further leads to cost of development of DST (Eq. (7)).

$$c_{DST\ \ development}(t) = \begin{cases} \dfrac{nc_{computational\ \ component}N_{PE\mu}}{t_{DST\ \ development}}t & : t < t_{DST\ \ development} \\ nc_{computational\ \ component}N_{PE\mu} & : Otherwise \end{cases} \tag{7}$$

Investment rate I_{rate} was assumed to be constant and span from 1′000′000 € per year to 9′000′000, 3 times the investment rate of current SwAM overall IT development budget I_{SwAM} at 3′000′000 € per year. The model parameters utilized in this study are presented in Table 2.

DST savings potential

The DST savings potential is defined as the mitigated EIA costs by using a DST as the step 4 (Fig. 1). The function for the DST savings (8) was derived from Eq. (5)

$$s_{\mathrm{tool}} = U \bullet r \bullet c_{\mathrm{EIA}} \tag{8}$$

The efficiency of the DST r is defined as a constant factor of the mitigated cost; three different model parameters for the DST efficiency r will be used, assuming that 10 %, 50 %, and 90 %, respectively, of the subsequent EIA cost, will be mitigated.

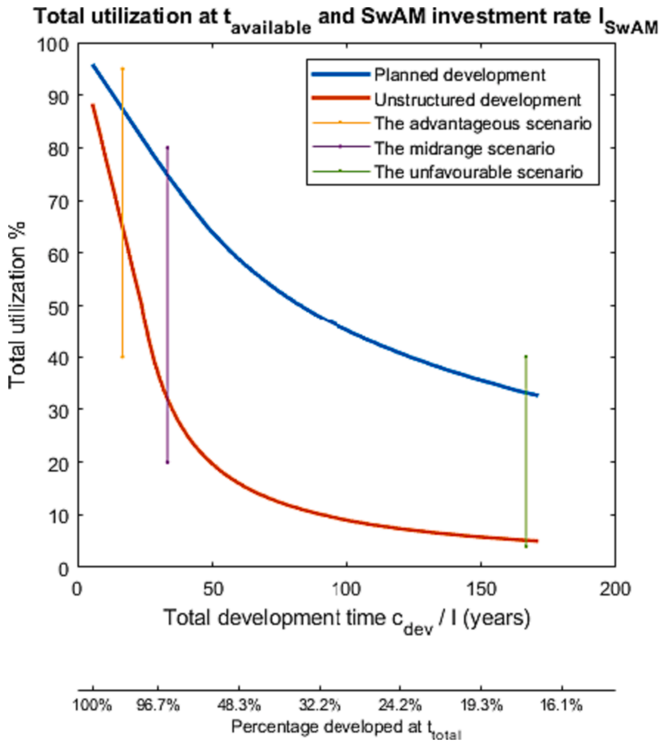

Fig. 4. Impact on Total utilization at what speed of DST implementation under the available time window ($t_{available}$) where utilization is scaled to mitigated cost, i.e., when an impact contributes 10% of the overall permit costs. A computational component (solution to this impact) is developed halfway through, the multiple of fraction time left and cost fraction leads to a DST utilization of 5%, then cumulative add savings from other developed computational components to get the total utilization. The planned curve is where the most cost-efficient computational components are developed first, and the statistical average(random) development is unstructured. Each scenario is represented at the defined investment rate I_{SwAM}, which is the assumed/estimated investment rate of DSTs by the Swedish SwAM agency. The blue and red line is the resulting upper. It lowers the bound of the total utilization model where the parameters for the three vertical lines' advantageous, midrange, and unfavorable scenarios intersect with the type of development for this paper's model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

DST savings

The DST savings s in the last step 5 (Fig. 1) is defined as the alternative future EIA process costs s_{tool} over time by Eq. (9):

$$s(t) = s_{tool}(t) - c_{development}(t) \tag{9}$$

The total utilization U and hence total savings potential, s, is dependent on how fast the DST is developed. A higher investment rate, I_{rate}, leads in general to higher savings potential, if total utilization U times cost of EIA c_{EIA} is larger than cost of development $c_{DST\ development}$ at the end of available time window $t_{available}$. Potential savings were estimated for six scenarios (Fig. 2) at different DST efficiencies.

Break-even

The break-even is defined as when savings over time, mitigated by the DST minus the development cost $c_{DST\ development}$, becomes positive. Over time it follows that a DST's computational components will start to mitigate EIA costs for the impact pairs $PE\mu$. Additionally, the unstructured and planned development order of computational components differ, it is expected to lead to different outcomes for the savings and the break-even point.

Results and discussion

A wide analysis has been conducted, the mid-range scenario results in 40 % percentage points better utilization of a developed DST in this case study. The specific relation to the development DSTs give insight and guidance. In a more general sense, there is lessons to be learned for many similar type of development projects.

Total utilization

The future total savings potential of DST development is defined in six scenarios, of which three have an planned and three an unstructured development. The core differentiation determining savings potential between planned versus unstructured development is the degree of utilization of the DST over the time window of interest, i.e., total time window. Each scenario results in a considerable difference in the total utilization. The midrange scenarios (S2P, S2U) result in a 42.8 % percentage points maximal difference between the planned versus unstructured development (Fig. 4). The unfavorable scenarios (S3P, S3U) result in the maximal relative difference at 547 %, but the planned and unstructured development have low utilization, with the planned at 33.2 % and 5.1 %, respectively. These results indicate that planned development is vital to consider realizable utilization and not only the savings potential. In other words, it will be relevant to consider how the DST is to be developed, which likely will impact its performance.

However, several of the considered assumptions directly impact the behavior of the model outcome. The most critical aspects regard the limited industry and academic foresight in the cost, performance, options, and composition of development of a DST's computational components. Firstly, the assumption that the cost of development $c_{DST\ development}$ for each of the computational components was evenly distributed is a simplification. In reality, the computational components have indeed radically different design requirements. Additionally, there will be a workload associated with completion done by engineers and programmers, which will not scale linearly with the number of developers on a specific component. These together will impact both potential development costs, and the planned development could be more parallel in nature for a realistic scenario.

Secondly, more realistically, the estimations and validation of cost are uncommon, as is the case for the computational component's efficiency, where the future of these cost estimations should be considered highly uncertain.

Thirdly, both the planned and unstructured cases only develop the components found relevant to offshore wind energy, implying that 14 % of non-zero value components are excluded. Naturally, most interactions are irrelevant, but some additional aspects are likely to be developed in the unstructured case, which would not contribute to any savings potential.

Lastly, essential functionality components, such as the platform and user interface, will be required to deploy other components. Likely there is an increase in dependencies between ecosystems and pressures if higher functionality and DST efficiency are to be reached, which need to be considered. These challenges typically would result in early developments being more straightforward but limited to efficiency but at a reduced cost; on the other hand, higher complexity scales with the number of growing dependencies and hence higher development costs would generally result in more costly high efficient solutions.

Given the limited data available, the assumptions made in this work were necessary, however, we argue that it is sufficient for our broad and general analysis, e.g., the significance of a high investment rate. Hence, the results indicate essential aspects to consider to enable cost-efficient development and implementation of a DST. Additionally, aspects have been identified that need to be further explored to develop future DSTs efficiently.

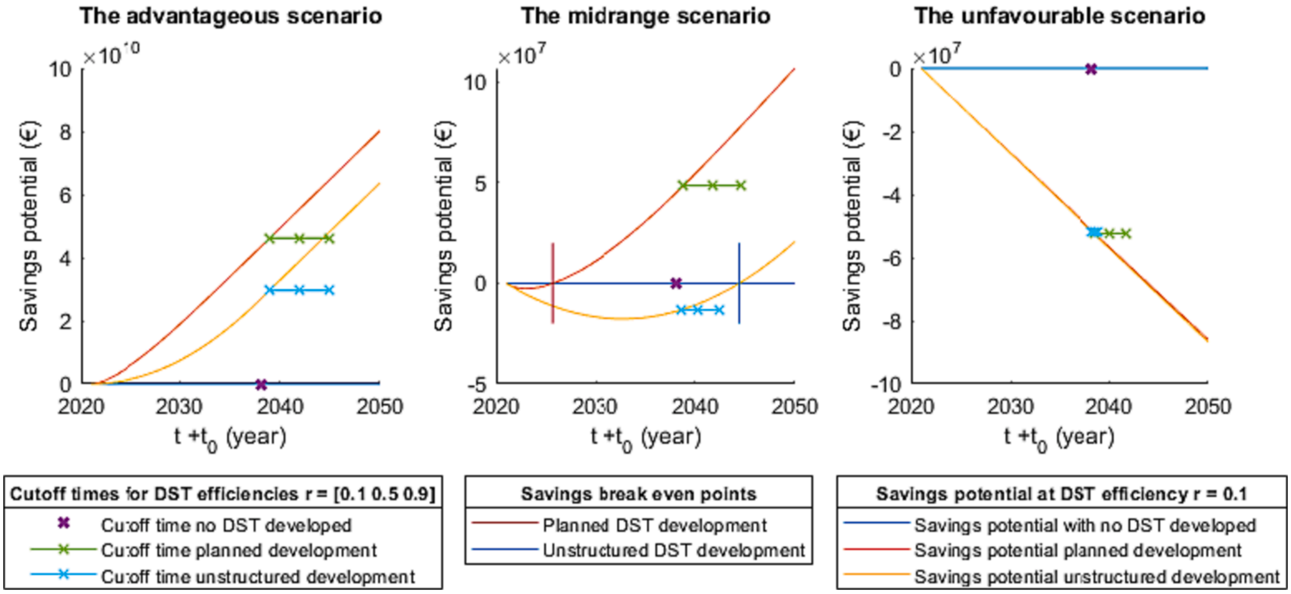

Fig. 5. Results of savings potential over time for the advantageous (S1P, S1U), the midrange (S2P, S2U), and the unfavorable scenarios (S3P, S3U) for future offshore energy savings potential respectively at I_{SwAM} investment rate and efficiency of the DST at 10%. The available time is modified based on the finishing project before the cut-off time calculated using Eq. (2), and the development of the DST modifies this value based on its assumed efficiency and completion. The different extended available times $t_{tavailable}$ are presented for each DST efficiency for planned and unstructured development. The midrange scenario exhibits break-even for the DST savings and development costs for planned and unstructured DST development. The three scenarios present the three primary different savings outcomes of development, advantageous, break-even, and unfavorable.

Savings over time & available time window

If the goal is to develop a DST that can transform maritime management, it would likely be a costly endeavor. However, considering the large number of offshore energy projects that are being planned in the near future, there may be a substantial savings potential in terms of reduced permit costs for future projects if there is a readily available analysis by a DST capable of offering the industry efficient and harmonized EIAs.

In each scenario is either the savings potential or development costs the dominant variable. In the midrange scenario, the planned development reaches a positive savings potential of 106,9 M€, ca 0.7 % of the EIA costs, and 20.8 M€ for the unstructured scenario at DST efficiency at 10 % (Fig. 5). This scenario is based on the cost of a recently developed IT platform in Sweden with expenses above 100 M€ and the Norwegian program MAREANO for sediment and biodata collection, at around 127 M€. While the midrange development cost is set to 100 M€, the other scenarios use half and five times this development cost to span a wide range of outcomes. These different development cost estimates resulted in three primary patterns, where the midrange case cost and savings potential are of similar size, while for the other two, these diverge drastically.

The primary factor contributing to savings, apart from utilization, is the estimated cost of EIA, c_{EIA}. The advantageous scenario's savings potential reached 79.9 and 63.7B€, 14.4 % and 11.5 %, respectively, of EIA costs, while there was only a tiny difference between the planned and unstructured development (for tool efficiency at 10 %). There was a negative, approximately −85.6 M€ or 545 % of EIA costs for both planned and unstructured development in the unfavorable scenario.

The definition of future EIA costs results in a wide span of possible outcomes for the available estimators. It was hard to argue that one combination of estimators is more reliable or probable than another at this point in the study. Therefore three scenarios for a low, mid, and high value have and should have the most impact on the results (Fig. 5). Further research should focus on narrowing down and defining probable outcomes. It would lead to reduced uncertainty choices made during development to take maximum advantage of the savings potential.

Lead-time

The lead-time of the development of offshore wind energy has been described as a significant obstacle, with project installation and permit processes taking more than a decade in some cases, inferring indirect costs and project failure rate [17,18]. A robust and capable DST is argued to be the central solution that consistently could lower lead-time without compromising environmental protection. The available time window is extended for the planned midrange scenario (S2P) by 0.68, 3.58, and 6.48 years for respective DST efficiency, *r* (Fig. 5). The shorter lead-time could result in a long time to complete projects to meet set energy goals. In the analysis, lead-time for an impact $PE\mu$ is assumed linear to the cost reduction for the impact, implying that if the cost for EIA is reduced by 50 %, the lead-time for the EIA will also be reduced correspondingly. The available time to reach the energy goals is thus increased by the reduction in time to complete the project, i.e., an improvement in the available time increases the effective window of the DST. Lead-time reduction for each DST efficiency is nearly the same as for the advantageous scenario as each tool has similar utilization(Fig. 5). Hence, it results in the midrange scenario getting the most significant difference between planned and unstructured development. For the unfavorable scenario, the reduction would be minimal due to the assumption that only a tiny percentage of the tool is fully developed. The lead-time of permits affects the cost in terms of delayed projects. It is usually due to preset technical specifications set many years earlier in the permit applications that differ too much from the current state-of-the-art wind energy technology. For example, a project can turn inefficient if too small a tower size and height specifications limit what can be built later [17]. This effect will induce more failed projects by new applications that need to be revised and sent in again following the same procedures, inducing additional EIA/permit costs. As mentioned, EIA's cost and its lead time are likely correlated and constitute a significant factor in possible cost reductions. Further, it would also impact how the DST should be developed to maximize savings concerning energy goals set in the near future.

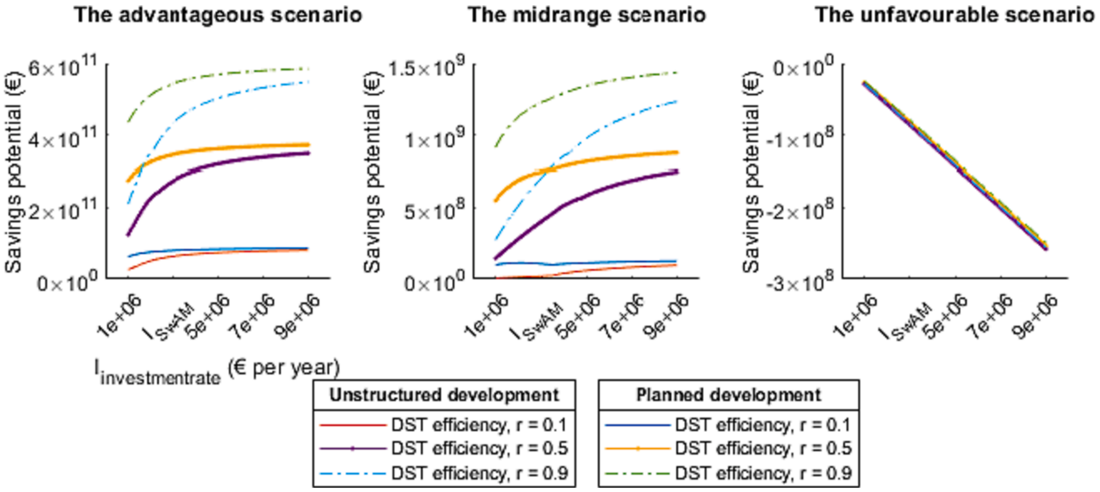

Fig. 6. The savings potential estimated from the model at the end of the scenario time window $t_0 + t_{total}$, with varying investment rates I_{rate}. The subplots are for the advantageous, midrange, and unfavorable scenarios with different DST efficiencies and optimization levels. In the first two subplots, there is a weakening improvement over time due to a lessening change in of utilization of the DST development components. For the third subplot, the unfavorable scenario is that the potential is smaller than the DST development costs over time, resulting in a near-linear negative savings potential.

Analysis of efficiency of the DST's implemented computational components r and investment rate irate

In addition to building an efficient DST is the question of funding, especially for large and costly projects. Concurrently with this case study, a publicly funded Swedish DST is being developed. The coordination of current and coming development efforts, and its funding, will ultimately dictate if a DST can be built and if the DST will be ready in time to be utilized (Fig. 4), to hopefully be indirectly break even or produce some savings potential (Fig. 6).

A reference investment rate was used to assess development, this being the SwAMs budget for IT development. The assessment in this paper is that this budget is used for many other projects apart from Symphony. It is unclear if their budget includes, e.g., engineering costs, but it is nevertheless likely a gross overestimation of expenditures in the near term and the past couple of years. How the three scenario's savings potential changes using a different investment rate depends on whether potential savings $r \cdot c_{EIA} \cdot U$ or $c_{DST\ development}$ is dominant. The fast rise in savings potential for the advantageous and midrange scenarios at the low range of investment rate, and the steep loss for the unfavorable scenario, indicate how important analysis of the development of DSTs for marine EIA may become. The largest uncertainties for a successful financial DST development are DST efficiency r and potential EIA costs. Further investigation into these factors should be necessary for future investment decisions.

Conclusions

This study presents a comprehensive analysis resulting in cost, benefit and development aspects for future EIA DST development. Using historical data as starting point, several potential future scenarios have been presented. First, the relationship between the cost of developing and operating a DST was compared with savings potential when having an advanced DST developed, to facilitate EIA in offshore energy installation projects. Secondly, identification of a relationship within a limited time window to build DSTs, resulted in realistic settings with respect to impacts savings potential for the offshore wind economic sector. Thirdly, exemplified through a simple model, multiple scenarios were used to evaluate the usefulness of the DST when there is a limited time frame. The main conclusion is that there are potentially substantial savings, improving resource efficiency and high quality EIA if the DST development is planned strategically. The main midrange scenario results in potential cost savings of 1,580 M€, and the mid cost and mid tool efficiency for the planned and unstructured scenarios are estimated to be 820 M€ and 590 M€ respectively.

The results of this study can help guiding future decision-making regarding environmental data collection and analysis, and offshore EIA DST development. Further, an extra dimension is added to the motivation for the DST development by addressing its economic impact on future energy development and not only the environmental protection perspective. The main uncertainty of the study is the estimates used in the simplified forecast of future development of the energy sector. Further, using Sweden as a case study may not be directly applicable to other countries, and the outcome should not be interpreted as an absolute result, but rather as an indication of possible future development. Future research in this area should focus on expanding the case study to an international level, considering EIA DST developed in cooperation. Further, DTS tool research and policy makers should utilize this paper beyond the accuracy of its environmental accuracy to assess or consider the proposed models or tools in terms of its life cycle, cost of development, reliability, efficiency.

CRediT authorship contribution statement

Andreas Olsson: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft. **Ida-Maja Hassellöv:** Supervision, Writing – review & editing, Visualization. **Oskar Frånberg:** Supervision, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2023.103493.

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