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BRIEF COMMUNICATION

Offshore deployments of wave energy converters by Uppsala University, Sweden

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Abstract

Ocean can provide an inexhaustible amount of energy. Many marine energy converters have been developed but most of them have not surpassed the experimental phase due to the high costs in installation, operation, and maintenance. Since 2002 Uppsala University has developed and deployed several units of wave energy converters of various designs. The Uppsala University wave energy converter concept consists of a linear generator directly connected to a point absorber buoy that is mounted on a concrete gravity foundation. Uppsala University deployments have been carried out using different deployment vessels and methods. Three main methods were utilized for these deployments that are discussed in terms of cost, manpower, and time efficiency. Depending on the desired outcome—multiple- or single-device deployment, low budget, etc.—one of the proposed methods can be used for the optimal outcome.

Keywords Offshore operations · Specialized offshore deployments · Uppsala University · Wave energy converters · WEC deployment methods

1 Introduction

With the perpetual use of fossil fuels and the consecutive climate change, research is turning to electricity derived from non-pollutant, endless resources. These renewable resources of energy include hydropower, modern biomass, geothermal, solar, wind, tidal, and wave [1, 2]. Regarding wave energy, although many types of wave energy converters (WECs) have been developed and tested worldwide [3–9] only a small percentage of those has gone beyond the experimental phase, indicatively the Pelamis, the Wave Dragon, the PowerBuoy, and the Oyster [10–13]. This is due to a high cost of a generators' deployment, operation, maintenance, and decommissioning [9, 10, 13].

In this paper, the focus is on the methods used to deploy the Uppsala University (UU) WECs offshore in the past years and each UU deployment is given as an example of the deployment method implementation. This way, an optimal offshore deployment methodology can be developed to make future installations as efficient as possible in terms of safety, costs, and time. UU has been developing the WEC since 2002. From 2006 when the first full-scale WEC (L1) was installed, to present, thirteen more WECs and two marine substations have been deployed and tested at the Lysekil research site (LRS) and one generator at Åland, Finland [14, 15]. All the deployment expenses mentioned in this paper are extended in a time span of 10 years and initially given in SEK, and therefore have been converted to their net present value (NPV) of January 2019,[1] and consecutively converted to USD in prices of January 2019,[2,3]

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[1] https://markets.businessinsider.com/.

[2] https://www.exchange-rates.org.

[3] https://www.inflationtool.com.

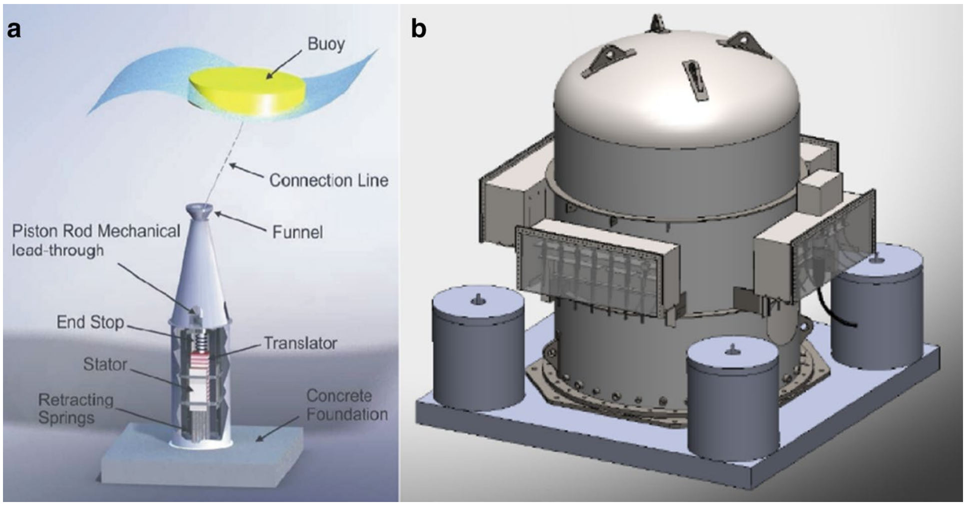

Fig. 1 **a** The Uppsala University wave energy converter [14]; **b** the Uppsala University marine substation [19]

1.1 The UU WEC and substation concept and deployment locations

The UU WECs (Fig. 1a) are of a point absorber type with a direct-driven linear generator power takeoff [16]. The buoy, which is directly connected with the linear generator, is moving with the wave motion. The kinetic energy of the buoy motion is transformed into electricity by the generator. The WECs are stabilized on the seabed with concrete gravity foundations; they are robust and designed to work at a sea depth of 20–100 m. The dimensions of the devices vary in height and weight, depending on its design and year of build, from 7 m to approximately 11 m high (without the funnel), the generator weights approximately 8–13 tons and the translator, 1.2–9.8 tons [14, 17]. The foundations are of cylindrical or quadrate shape and their weight is within 35 and 50 tons [18].

Since one device delivers a limited amount of power, the WECs are connected to a marine substation underwater (Fig. 1b). The substation minimizes the overall cost, reduces the sea cable expenses, provides controllability and good electrical damping of the generators, and maximizes the electrical efficiency. Moreover, it rectifies every generators' current to DC and subsequently to AC for grid connection [19–21].

The UU deployments have mostly been performed at the LRS within the ongoing "Lysekil project" which began in 2002 [22]. The LRS (Fig. 2) is located at the west coast of Sweden and its seabed consists of sandy sediment. The site's convenient location being 2 km from shore, combined with the comparably shallow waters of 25 m, contributes to a simplified deployment method and lowered costs. One of the UU deployments took place in Åland, Finland (Fig. 2), 700 m southwest from the shore in Hammarudda. The location's depth is between 20 and 30 m with a homogenous, sandy sea bottom [15].

2 Methods and results

This paper presents three methodologies of offshore WEC deployments carried out by UU, based on (a) information obtained in personal communication with Robert Leanderson, Rafael Waters, Jan Sundeberg, Andrej Savin, Erland Strömstedt, and Mats Leijon, (b) published studies [16, 21–23], and (c) personal experience gained by the authors' active participation in some of the deployments analyzed. This offshore deployment study is conducted from a perspective of time, cost, and safety.

A general WEC offshore deployment methodology for this generator type consists of the following steps [16, 23]:

Fig. 2 Lysekil and Åland

1. Preparation: assembly of the generator, factory acceptance test (FAT), leakage tests, induction (voltage) test, connection to deployment equipment (slings, shackles, chain, pressurization, protection, lines, etc.).
2. Transfer of the WEC to the port and the deployment spot.
3. Deployment: pressurizing, lifting the WEC, and placing it on the seabed.
4. Final processing: divers/remotely operated vehicles (ROVs) make cable connection and untie slings and shackles.

In all installation cases, the pressurizing was done manually by feeding the WEC with nitrogen gas of 0.1 bar for every meter of submersion. Besides L1 deployment, Marine Works (MW) divers' crew was employed. To load the WEC on the tugboat and to submerge it in the sea, four lifting slings were connected from the WECs foundation to the crane. As the WEC is lowered, a crew member holds and keeps track of the pressurizing hose so it does not get tangled with the WEC or crane, bents or falls. Once the WEC is at the sea bottom, the divers disconnect the shackles and slings which are pulled up on the vessel, by crane.

The UU deployments examples below serve as case studies of practical implementation of the presented deployment methods. They can also be used to illustrate how the planned price can deviate from an initial budget based on particular conditions and unpredicted events. Moreover, they point out the different outcomes from different deployments, under a variety of circumstances.

2.1 Hydraulic jacks method

This method (Fig. 3a) includes a tugboat transporting a barge to the installation spot, and the barge with a special structure of steel beams and wire jacks welded on its aft.

The first full-scale WEC, L1, its buoy, and 100 m of power cable were deployed at the beginning of March 2006, using the following vessels and equipment: (a) Belos tugboat (Buksér og Berging), (b) Kanalia barge (Sandinge Bogsering & Sjötransport), (c) wire jacks, and (d) a special structure consisting of four metallic beams, welded on the barge by the company Tunga Lyft. The structure at the aft of the barge was utilized to transport and deploy L1, thus, no cranes were employed. Four pairs of hydraulic wire jacks were expanded from the structure and out of the barge, holding the WEC's foundation from its four corners. The WEC was submersed by releasing the wires hydraulically. During transportation the WEC was hanging behind the barge semi-submerged, with the foundation under water, which made it lighter. After the WEC was standing on the seabed, the divers disconnected the pressurizing hose and lifting wires and released the buoy.

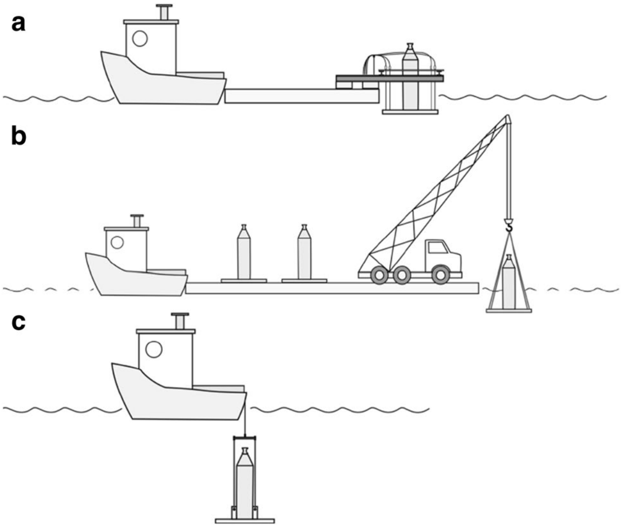

Fig. 3 Schematics of the three deployment methods: **a** Hydraulic jacks method, **b** Barge–crane deployment method, **c** Tugboat deployment method [36]

For further information on L1 design, experiments, and deployment, the reader is referred to [20, 22, 24, 25].

2.2 Barge–crane deployment method

This method, illustrated in Fig. 3b, uses a tugboat to pull a large barge with a crane mounted on it. The generators are transported to the site with the barge, and loaded on the barge and lowered to the sea bottom with the crane. The crane is usually mobile, of high capacity, and placed on the barge.

This method was first introduced in February 2009, at the installation of generators L2 and L3 [26, 27]. A medium-sized barge was used with a fixed crane of approximately 100 tons capacity, common lifting equipment, GPS, and a depth measuring device. Two tug boats were used during the deployment, to keep the barge in position. The prominent problem during this deployment was keeping the barge position and stability. When positioning the vessel for deploying L2, the middle-sized tug boat was utilized as a fourth point. For small boats, the use of four anchors on each corner of the vessel, at a certain distance and for bigger boats, a dynamic positioning (DP) system, could solve this problem. Lifting and deploying L2 WEC with chains instead of slings could damage the generator, at least the capsule, therefore, lifting L3 with slings was preferred. The criterion of choosing this barge was to keep the operation economical.

In December 2009, L9 generator [28, 29] was deployed. For this operation, Boa Barge 41 from Röda bolaget was rented, since the barge arranged from Sweden was not delivered on time, Boa Siw tugboat, and a Kynningsrud mobile crane. The problem caused delay which was the difficulty to position the barge in a stable way, due to the manual ropes to the anchors that had a pre-chosen length and could not be dropped exactly in position. Winches and a wire drum were utilized to adjust the rope length after positioning. Three positioning points were used, including the tugboat pulling the barge from one side.

In November 2010, the WECs L4, L5, L7, and L8 were deployed. Experiences from deploying L9 helped improve this deployment by using a more efficient anchoring system. The deployment was carried out by a Svitzer barge from Norway, Lindo, Svitzer Boss tug boat, and a Havator crane secured on the barge, of about 300 tons capacity. An advantage during this deployment was the excellent positioning of the barge, which was safe and firm: a wire coming from the barge went out to the anchors allowing them to set on the exact spot and lock them.

In January 2012, the WESA (Wave Energy for a Sustainable Archipelago) project [15, 30–33] took place in Åland, Finland. This deployment was a challenging task, due to the harsh weather and the icy and slippery conditions during the operation that could jeopardize safety. A customized L2 WEC, with its buoy, and a wave measurement buoy were deployed within an 8-h day. The deployment was completed using: Varma tugboat, a mobile crane mounted on the barge of about 300 tons lifting capacity, a barge from Åbo, a small boat used for cable installation from "Subsea Åland." A vessel hired from Baltic Line transported the WEC from Sweden to Åland.

The positioning method was planned as follows: with GPS assistance, the barge was maneuvered into the right deployment position with a ± 1 m accuracy. The fixed barge position was secured with propulsion systems and anchors, so that the barge could not shift more than ± 0.5 m at most, in any direction in the horizontal plane. However, an anchoring problem occurred when the barge and the tugboat drifted away from the deployment spot and took 1–2 h to return in the position. This was due to the seabed being too soft and the anchoring points being only two and lighter than needed.

In March 2013, L12B was deployed within a 10-h day using Svitzer Boss tugboat to drag Svitzer Ark barge with high-capacity "Nordic crane" mounted on it. In [14, 34, 35], more technical details on the WEC design can be found. In July 2013, L6, L9 (for the second time), L12A, and the substation were deployed, with a tugboat, Svitzer Ark barge, and a high-capacity mobile crane mounted on the barge. All devices were loaded on the barge with a high-capacity crane of the Lysekil's harbor.

2.3 Tugboat deployment method

The most recent deployment method, illustrated in Fig. 3c, transports the generator to the site submerged behind a tugboat, which also positions and deploys the generator.

Fig. 4 Simultaneous installation of L12D with its buoy [36]

In March 2015, the first attempt was made to deploy L10, using Svitzer Thor tugboat. No cranes were needed, except the harbor crane for moving the generator within the dock and to hang it from the tugboat. This deployment attempt failed, and even damaged the WEC, because the wrong type of wire was used to tug the generator. As commonly used for tugging, the steel wire used was not rotation free, which caused it to rotate and get tangled with lifting slings, lines, and pressure equipment as the WEC was lowered down to the sea floor at site. As a consequence, the pressurization hose ripped and the generator was filled with sea water. The operation was aborted, the WEC was emptied from water, and the deployment was rescheduled for August 2015.

In August 2015, a new attempt was made, deploying both L10 and L12C. Svitzer Thor tugboat was used and in its crew one person was added. The difference was the use of non-rotating wire and better equipment to protect and guide the pressure hose, as a correction from the previous time. Due to insufficient fastening of the pressurization hose, drag forces from the flowing water during transportation and positioning caused a bending moment and vibrations on the pressure connection on the generator, which resulted in its breaking. Again, the deployment was aborted. A few weeks later, a third deployment attempt was made, using the same method, with improved fastening of lines and pressure equipment. This time L12C was successfully deployed, in roughly half a day.

In June 2017, this deployment method was further developed to reduce the need for diving work and the weather window restrictions, installing L12D together with its buoy, and making the procedure safer (Fig. 4). The same vessels and equipment were used as previously, with the following optimizations: the number of lines was decreased, the generator's lifting points were relocated to its top part, and the previously rotation-free wire was substituted with a synthetic fiber line. The WEC was tugged fully submerged by the tugboat's rope, while the buoy was floating, firmly placed at the back of the tugboat. To make sure that the buoy would

Table 1 The three Uppsala university deployment methods: advantages, disadvantages, accomplishments, cost, time

Method	Advantages	Disadvantages	Accomplishments	Cost	Time (h/WEC)
Hydraulic jacks	Safe	Not recommended for multiple deployments	Deployed one WEC w/ buoy	399,592 USD	12
Barge–crane	A safe/fairly safe procedure, depending on the weather	Recommended for multiple deployments	Deployed ten WECs	Varying from 143,776 to 322,922USD	8
Tugboat	Safe	Not recommended for multiple deployments	Deployed one WEC w/ buoy	32,566 USD/day	Varying from 5 to 6

not move, it was additionally held tightly by a rope from the diver's boat during the submersion.

Some costly lessons were learned regarding the tugging procedure. Besides using a rotation-free tug wire, it is important to keep control over all the lines and hoses going between WEC and tug boat, since they risk being swept into the tug boat propeller. Apart from these issues, the new installation way is efficient, and cheap. This method can only be used to deploy one generator at a time, but two such deployments can be completed in a day.

Each deployment method is summarized in Table 1. The costs presented are based on practical implementation of each deployment method and include the uncertainty due to weather, delays, and vessels coming from a long distance.

3 Discussion

3.1 General issues

The deployment cost depended on the method chosen and weather. Due to weather additional costs might rise. For example, the delays caused by restrictive weather, for offshore operations, can result in extra rental costs for idle vessels and even cancelation and rescheduling of the entire operation.

The advantage of the hydraulic jacks method was the ability to deploy a WEC with its buoy simultaneously. The wire jacks were safer than a crane, which in high waves could tip over and fall into the water. The structure fitting on the barge was prepared before the operation and the structure itself, reduced the vessel's maneuverability. Moreover, the specialized structure with the wire jacks takes time and expenses to be made and welded on the barge and only one WEC can be carried and deployed per vessel trip. The deployment took 12 h, partially because lowering the WEC to the seabed was done at a slow pace. Installing the WEC simultaneously with its buoy, saved one extra day of divers' work, thus 11,274USD of costs. A four divers' crew from the company Dyk & Sjötjänst i Uddevalla AB was hired. The rest of the crew were four people from the tugboat and about three more from UU and the barge. This operation is the most expensive deployment operation of UU so far.

The barge–crane deployment method, is convenient for multiple deployments: the spacious deck of a large barge combined with high-capacity crane makes it possible to deploy up to five generators per day. A simultaneous deployment of a WEC and its buoy is possible with this method as it was discussed in [23]. The disadvantages are the high costs and the limited vessel maneuverability that cause time loss. For example, L2 and L3 WECs were deployed in two 8-h days, which is considered fairly efficient timewise. A medium-sized barge was used with a crew of five people and ten basic workers; four divers and three people from UU also participated in the operation. This was a comparably cheap deployment, with a cost around 67,953 USD for both days. The delay cost for each day was 13,590 USD. Nevertheless, the crew number was over the optimal.

Another example is the L9 deployment that costs 147,853 USD, due to delays and the barge coming from Norway. It took a 12-h day to complete, and the crew comprised of five barge employees and four divers. The high-capacity crane, made the procedure functional and quick.

Deploying L4, L5, L7, and L8 took a 12-h day, aligning with the planners' expectations. The cost was 151,615 USD, although the initial expenses calculation was three times less. This was because the first barge rented from Sweden was not delivered, instead, Lindo barge from Norway was ordered and delivered as a last minute solution.

The workforce of the WESA project comprised of a crew of two divers from a Finnish company, two people from UU and SIAB, one from Åbo University as an observer and tugboat crew of four. The barge arriving from Åbo, besides being very big and showing little maneuverability, came later than required, causing time loss.

The installation of L12B was typical, however not fully optimized operation, accomplished within a 10-h day and cost about 143,776 USD.

The deployment of L6, L9, L12A, and the substation, was completed in two 10-h days with a cost of 322,922 USD. Although it seems rather costly, the expense raise was due to the weather delays adding the daily idle vessel cost.

The third method, employing a tugboat and a divers' crew, is the most economical and time efficient. It provides excellent vessel positioning, fast transportation to the site and deployment. Tugboats operate under rougher weather and wave conditions than barges, extending the operational weather windows and resulting in less time losses. The simultaneous deployment of the generator with its buoy will further facilitate this installation procedure. In addition, if organized properly, this could be a diverless deployment [16]. Alternatively, the divers can focus on bringing the buoy so it gets connected on the same day, instead of a day after. The underwater connection of the electrical cables can be done by ROVs. On the downside, this method is better for deploying single or pairs of generators. For instance, in the L10 deployment, the crew consisted of four people tugboat crew, four UU employees, and four divers. The tugboat cost 13,268 USD for 24 h including its crew, plus 8443 USD to bring the vessel from Denmark and get it back. The divers' crew cost about 9649 USD and the harbor crane costs 1206 USD per WEC. The sum of a tugboat deployment cost is 32,566 USD per WEC. This price compared to the cost of using a barge with a crane and a tugboat (starting at 143,776 USD) is considered low, saving more than 111,210 USD per deployment.

The suggested number of crew members for each deployment method is shown in Table 2.

3.2 Cost and time efficiency comparison of the methods

Comparing the three methods in strictly cost terms, the first method is the least advantageous, deploying one generator for 399,592 USD. In Fig. 5, the best case scenarios for the second and third methods are presented. Cost and time of deployment process are investigated with respect to number of WECs. We assume that no delays occurred at any point of the process. To calculate the tugboat method cost, we summed up the following: (a) the tugboat cost: 21,979 USD/day, (b) the divers' cost: 9649 USD, and (c) the harbor's crane cost: 1206 USD/WEC. To calculate the barge–crane method cost, we considered: (a) the barge, tugboat, crews, and mobile crane costs: 96,819 USD/day, (b) one day of barge use for preparation: 16,136 USD, and (c) divers' crew: 12,917 USD/day.

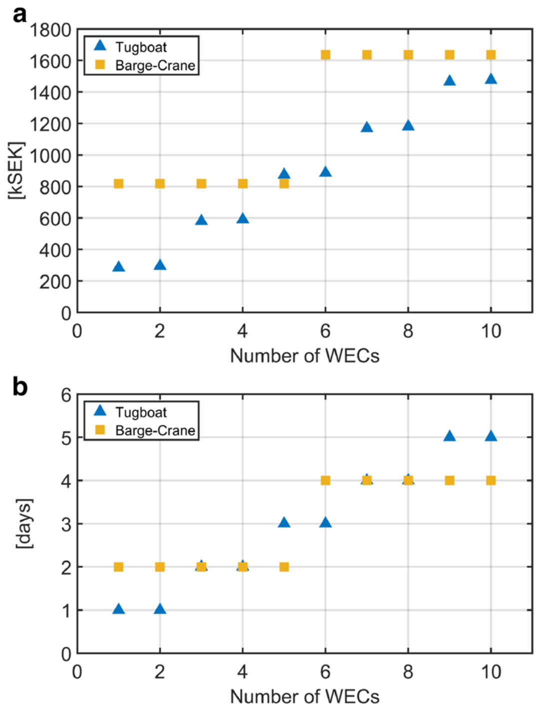

Fig. 5 The deployment costs for the tugboat method and the crane–barge method for one to ten WECs (**a**). The deployment time for both methods for one to ten WECs (**b**)

It is shown in Fig. 5a that even in mass deployments the tugboat method is the most cost-efficient. If ten WECs are to be deployed with the tugboat method, it will require five days of operating the tugboat that cost 168,864 USD, including the divers' crew. With the barge–crane method, one full day of preparations will be necessary to set up the barge prior to each deployment day, and two days to deploy the same amount of WECs. This will cost 290,459 USD. The sudden "jump" at the barge–crane deployment cost as shown in Fig. 5a, is because of doubling the deployment days that doubles the expenses.

The time-efficiency comparison between these two methods is presented in Fig. 5b. Time is simple to calculate. The tugboat is hired to operate for 24 h, with switching crews and very short preparation time is required. With this method, two WECs can be deployed in one 24-h day. To deploy ten

Table 2 The optimal number of crew members for each deployment method

Method	Optimal crew number employing divers	Optimal crew number using ROV/ROVs
Hydraulic jacks	12 (4 divers, 4 people from the tugboat, and 3 from the barge, 1 UU employee)	8 (4 people from the tugboat and 3 from the barge, 1 UU employee)
Barge–crane	13 (4 divers, 4 people from the tugboat, 3 from the barge, 1 crane driver, and 1 UU employee)	9 (4 people from the tugboat, 3 from the barge, 1 crane driver, and 1 UU employee)
Tugboat	9 (4 divers, 4 people from the tugboat, and 1 UU employee)	5 (4 people from the tugboat and 1 UU employee)

WECs, 5 days are necessary. The barge–crane method differs: to deploy with this method, one day of hiring the barge for preparations is needed. However, with this method five generators can be deployed the same day, so it takes 2 days to deploy ten generators, which adds up to 4 days in total including preparation days. Although the barge method is more efficient for multiple deployments, both methods use the same time to deploy three to four and seven to eight WECs (Fig. 5b).

4 Conclusions

A deployment log should be created, to help avoid repeating mistakes and provide guidance for future offshore operations. Moreover, a cost and time estimation according to the operation type, vessels, crew, and equipment used should be made in a table form, covering as many cases as possible.

The cost can vary a lot in some cases depending on the vessel transportation and rent costs, the divers, and the amount of generators being deployed. For example, a vessel coming from a large distance will double the expenses, making the whole operation uneconomical. The divers' costs (crew and divers' boat) are high and so, a diverless deployment may lower the operational cost. The simultaneous deployment of WECs with their buoys is beneficial economically, and time efficient.

The tugboat method requires substantially less coordination work than the other two deployment methods, since only the boat manager has to be contacted beforehand, reducing the planning time. This method also requires the least number of crew members. Therefore, the tugboat method seems to be more efficient in terms of cost and time, especially since it can facilitate a simultaneous WEC–buoy deployment. Comparing time and cost efficiency, the tugboat method seems to provide value for money, being the least expensive while deploying in a similar amount of time as the barge–crane method.

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