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Economic viability assessment of European flat oyster restoration on offshore windfarm infrastructure

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Abstract – European oysters (*Ostrea edulis*) once covered large areas of the North Sea, but have disappeared due to a combination of overexploitation and the destruction of benthic habitats including hard settlement substrate. Offshore wind parks offer an opportunity for oyster restoration as fishing is banned inside these parks and scour protection provides hard settlement substrate. However, ecological restoration of marine systems is capital-intensive. The success of restoration projects is mainly determined by the choice of methods and techniques and consequently costs. Costs and cost-effectiveness information are therefore key in decision making processes concerning the selection of restoration efforts and techniques. So far, economic viability of marine ecosystem restoration have mainly focused on near-shore shallow habitats. The aim of this study was to provide insight into the most cost-effective deployment options to create a European flat oyster reef in an offshore wind farm in the North Sea. Within the current policy and legislation framework, several deployment scenarios were identified based on best practices, expert knowledge, and preliminary results of several pilots. The 9 scenarios included 'adults placed loose on the seafloor', 'adults glued on granite', 'spat settled on shells', 'spat settled on granite' and a combined 'adult and spat' scenario. Cost-effectiveness of the different scenarios was determined by modelling the expected reef biomass post-deployment both with and without the option to add additional settlement substrate post-deployment. The main conclusions from this exercise were that: 1. based on investment value, the scenarios 'adult loose on the seafloor', 'adults in cages' and 'spat on shells' had the highest revenues per Euro invested; 2. adding substrate in the years post-deployment increased cost-effectiveness in the model for all scenarios, and 3. the time post-deployment to reach a self-sustaining adult oyster population was, with 8–10 yr, shortest for the scenarios 'spat settled on shells' and the combined scenario of 'adults placed loose on the seafloor' and 'spat settled on shells'.

Keywords: Modelling / *Ostrea edulis* / adult and spat outplacement / North Sea

1 Introduction

A transition of the energy system from fossil fuels towards more sustainable alternatives is needed to mitigate the effects of anthropogenic climate change (Creutzig et al., 2014). Wind energy is an upcoming important source of sustainable energy. In Europe, the total wind energy capacity was 236 GW in 2022, with a total of 25 GW coming from offshore installations (WindEurope, 2022). For the coming years, 7.1 GW additional offshore capacity is planned, and offshore wind energy is expected to become of major importance in the future. In the Clean Energy section of the European Commission's Green Deal one of the key actions is "to develop the full potential of offshore wind energy of the member states" (Directive 2018/2001/EC). For example, in the southern North Sea only, there were 62 wind farms by the end of 2020, and their number is still increasing (Ter Hofstede et al., 2023). The large-scale formation of offshore wind farms offers an opportunity for the recovery of European flat oyster (*Ostrea edulis*) aggregations. This species once occupied large areas of the North Sea (Olsen, 1883), but populations declined as a result of overfishing and the destruction of benthic habitats including hard substrate

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necessary for settlement of oyster larvae (Friedrich et al., 2016). The construction of offshore wind farms is accompanied by the deployment of rock material on the seafloor, called scour protection, to stabilize the seabed around the base of wind turbines. These hard structures provide opportunities for the development of hard substrate communities including native oysters in an otherwise mostly soft bottom habitat. Due to the ban on bottom-trawl fishing inside most wind farms (European MSP Platform, 2021), there is no seabed disturbance during the operational lifetime of a wind farm, which is also considered key to the recovery of oyster reefs.

Ecological restoration is capital-intensive, with the restoration of marine systems (De Groot et al., 2013) being far more expensive compared to the restoration of terrestrial systems (Bayraktarov et al., 2016). In general, the success of restoration projects is mainly determined by the choice of methods and techniques (Kimball et al., 2015; Bayraktarov et al., 2016), and consequently the costs. Information about costs and cost-effectiveness is therefore key in decision making processes concerning the selection of restoration efforts and techniques. So far, marine ecosystem restoration cost assessments have mainly focused on coastal habitats including mangroves, salt marshes, seagrass, and oyster and coral reefs (Lewis, 2001; Gutrich and Hitzhusen, 2004; Bayraktarov et al., 2016).

The aim of this study was to provide insight in the most cost-effective options to place European flat oysters on or near wind turbine scour protections in the North Sea to kick start a reef. First an overview of the requirements from current policy and legislation, related to European flat oyster and substrate deployment in the North Sea was made. Within this framework, several deployment scenarios were identified based on current best practices, expert knowledge and preliminary results of pilots. For all resulting scenarios, associated costs were estimated. Restoration effectiveness, defined here as the expected oyster population 15 yr post deployment for each scenario was estimated using a population growth model and compared to the minimum population size which is considered needed for a self-sustaining population (20,000 individuals, Kamermans et al., 2020). Cost-effectiveness was evaluated as revenue (in number of oysters) per Euro invested and compared between scenarios.

2 Box 1. Biology of Ostrea edulis

The native range of *Ostrea edulis*, the European flat oyster, is along the north Atlantic coast of Norway down to Morocco, and in the Mediterranean and Black sea (Fofonoff et al., 2018; FAO, 2022). The oysters can grow to a maximum shell length of 11 cm and have an average lifespan of 5–10 yr. Individuals take part in the reproduction cycle from the age of 3 yr (MarLIN, 2017). Flat oysters are a protandrous alternating hermaphrodite, meaning that they first reproduce as male and then alternating as female or male. Males release their sperm in spring; females take in the sperm by means of filtration and eggs are then fertilized in the mantle cavity. After 7–10 days the larvae are released into the water column. A female can produce up to 3 million larvae (Helm and Bourne, 2004), with fecundity increasing with size (Cole, 1941). Flat oyster larvae stay in the water column for 6–14 days (Colsoul et al., 2021), which is relatively short compared to other bivalves. Consequently, their migration distance is fairly short, also because of self-recruitment (Rodriguez-Perez A et al., 2020). Once ready to settle, the larvae migrate towards the sea floor, where they preferably settle on living conspecifics, shells of conspecifics, mussel shells or other calcified surfaces (Cole and Knight-Jones, 1939; Mandirola, 2017; Rodriguez-Perez et al., 2019; Colsoul et al., 2020). Once oysters are settled, they are called spat.

3 Policy and legislation framework

3.1 Reference area

The wind farm location Borssele V was chosen as a case study area. The wind farm is located more than 22 km from the Dutch coast, at the southern border of the Netherlands Exclusive Economic Zone (EEZ) and 0.5 km from the Belgium EEZ (RVO, 2017), (Fig. 1). The water depth ranges from −20 m to −40 m. The Borssele site is characterized by the local occurrence of high sand waves, but on shear stress well below the threshold for oyster residence (Kamermans et al., 2018). Sediment consists of coarse to fine sand, average suspended particulate matter (SPM) concentrations are 10 mg l-1 and 10-year average chlorophyll-a concentrations vary between 1.2 µg l-1 in winter and 4.4 µg in spring. Water temperature varies between 4–20 °C (Smaal et al., 2017; Kamermans et al., 2018). A modeling exercise showed that larval retention in the area is high (Kamermans et al., 2018). It was concluded that the area is suitable for oyster deployment (Smaal et al., 2017; Kamermans et al., 2018).

3.2 Requirements

All potential scenarios in the cost-effectiveness analyses for reef initiation in the wind farm Borssele V through deployment of live oysters had to comply with current Dutch legislation and preferably with suggestions from the Native Oyster Restoration Alliance (Pogoda et al., 2017). An overview of the requirements, current legislation and advice for deployment of European flat oysters in the North Sea is given in Table 1.

A parasitic pathogen that is known to cause high mortality rates in populations of European flat oysters is *Bonamia ostrea*. *Bonamia* is present in the Dutch Delta area and in oyster farming areas in France, Ireland, the United Kingdom and Spain. Some bays are disease-free, like Tralee Bay in Ireland and natural European flat oyster populations in some fjords and bays in Norway and Sweden (Sas et al., 2020). Since it is unknown whether *Bonamia* is present in the North Sea, it is recommended to use only *Bonamia*-free oysters for deployment (Pogoda et al., 2017). *Bonamia*-free supply of spat from hatcheries, is currently very limited and insufficient to be considered for large scale deployment. At present none of the Dutch hatcheries have the required certification to produce flat oyster spat for deployment in the North Sea. This means that oysters have to be obtained from alternative sources, such as wild beds and hatcheries in disease fee areas (Kamermans et al., 2020).

For the deployment of oysters originating from outside the Dutch North Sea, an import permit is required. A pre-requisite for this permit is a treatment of the oysters according to the Alien

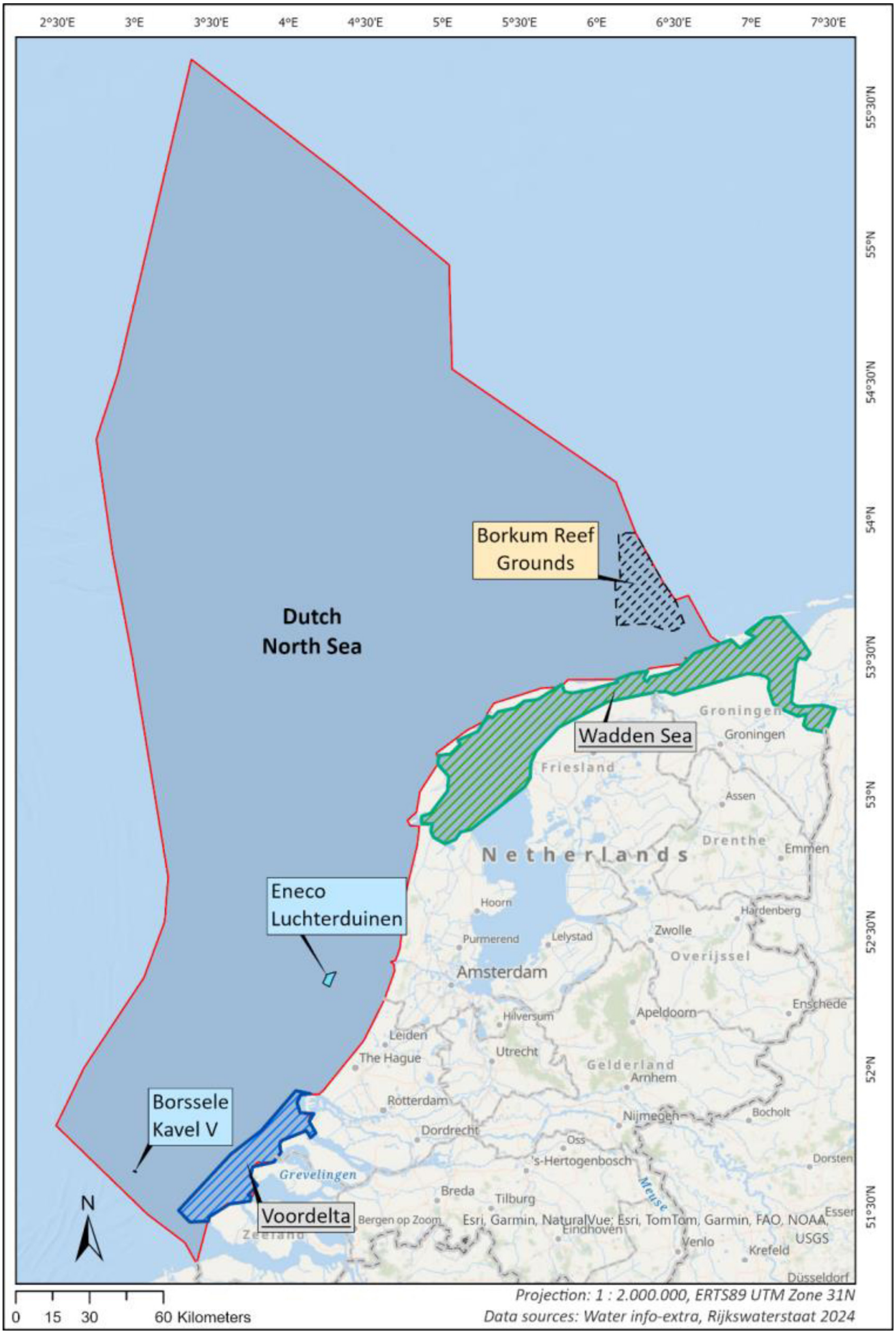

Fig. 1. Map of the Netherlands showing all pilot locations where native oysters have been deployed.

Table 1. Requirements for deployment of European flat oysters in the Dutch North Sea for restoration purposes.

Requirements	Source
Advice Native Oyster Restoration Alliance	
Deployment with disease free oysters	https://noraeurope.eu/wp-content/uploads/2018/Berlin-Oyster-Recommendation-Part-1.pdf
Alien Invasive Species	
Treatment required when deploying oysters harvested from other areas than the Dutch North Sea	Kamermans et al., 2020
Animal Health Conditions (implementation decision (EU) 2015/1554 laying down provisions for the implementation of Directive 2006/88/EG	
Hatchery produced native oysters for deployment in *Bonamia* free areas need certification. The certification requirements include the production under a strict protocol as well as the confirmation of *Bonamia* free oysters for 3 yr in a row.	Kamermans et al., 2020
Permits and regulations	
Nature Conservation Act permit	Sas et al., 2018
Water Act permit	Sas et al., 2018
EU Directives for import of live animals	Sas et al., 2018
North Sea policy	
Removal of non-natural infrastructure at the end of deployment period	Ministry of Infrastructure and Water Management, 2015

Invasive Species (AIS) protocol. Treatments within this protocol include submerging the oysters in fresh water and exposing them to a solution of sodium hypochlorite ensuring the removal of oyster associated species and thereby avoiding their introduction at deployment sites (Kamermans et al., 2020).

In the prevailing national water program 2022–2027 (Ministry of Infrastructure and Water Management, 2022), the building of wind farms at sea is considered to be an opportunity for nature reinforcement. While both the absence of fishing activities as well as the provision of habitat for hard substrate species by the scour protection around the base of each wind turbine foundation is favorable, current policies regarding infrastructure in the Dutch North Sea are strict. After the end of a deployment period −usually 30 yr for wind turbines-, all materials that are not natural or native to the area have to be removed (Duimel et al., 2019; Ministry of Infrastructure and Water Management, 2022). This duty also includes the material deployed to kick start (oyster) reefs in the North Sea. The mandatory removal adds to the total costs of this type of reef structure as well as increased risks on effectiveness as the removal might damage a newly formed reef. When using material native to the area (e.g. empty bivalve shells), or reef material that dissolves after a certain period of time (e.g. steel structures), removal is not needed (Didderen et al., 2018).

4 Oyster deployment scenarios

In the Dutch part of the North Sea, native oysters are considered ecologically extinct (Lotze et al., 2006; Beck et al., 2011), therefore supplying substrate always has to be accompanied with the deployment of actual oysters to initiate reef development. Either larvae, juvenile ("spat") or adult oysters can be deployed for restoration efforts (Lallias et al., 2010). In the current study only the latter two options were considered. A selection of the nine different scenarios was made, based on proof of concept in oyster restoration projects in mainly in the North Sea area, recent pilots, and expert knowledge of oyster farmers (see Tab. 2).

4.1 Adult deployment scenarios

Three scenarios were considered for adult deployment. Adults in this study were defined as European flat oysters from different size classes, but over 3 yr of age.

(1) Placing **adult oysters loose on the seafloor** is the most basic method, requiring the least amount of effort and is considered a baseline scenario. Risks include drift or mortality due to sand burial. Elsewhere, survival for this option ranged from 26% at the Voordelta (Fig. 1) restoration sites (Didderen et al., 2019) to a survival of 79–94% at the Borkum Reef grounds pilot (Fig. 1) (Didderen et al., 2020). Numbers from Borkum Reef however were calculated from retrieved oysters and did not include losses from the original deployment population. The larvae produced by the deployed adult oysters in this scenario are assumed to settle on the conventional scour protection (granite).

(2) Placing **adult oysters in cages** or racks on top of or next to conventional scour protection will theoretically increase chances of survival compared to the baseline scenario since no drift can occur. At other sites, survival ranged from 40% to 73%, depending on basket size at the restoration site of Borkum Reef grounds (Didderen et al., 2020) and from 40% to 80% at the Voordelta restoration pilots and was dependent on oyster size and origin (Didderen et al., 2018). Differences in survival between the aforementioned pilots were also suspected to be related to oyster condition and handling before deployment. At the pilot restoration location Luchterduinen (Fig. 1) a survival of only 15% was recorded for oysters in cages, caused by unexpected burial of some of the cages. In

Table 2. Overview of potential deployment scenarios for European flat oysters in the Dutch North Sea.

Nr	Scenario	Reasoning
1	Adult oysters loose on seafloor next to conventional scour protection	Baseline scenario – minimum costs
2	Adult oysters in cages	To prevent dislodgement and burial (if placed on top of scour protection), needs removal
3	Adult oysters on concrete structures	Structures as nature enhancing reef building material, needs removal
4	Adult oysters on steel structures	Structures as nature enhancing reef building material and structures degrade over time
5	Oyster spat on shell	Resources available, proven settlement success on shells
6	Oyster spat on granite	Current scour protection material, needs removal
7	Oyster spat on concrete structures	Structures as nature enhancing reef building material, needs removal
8	Oyster spat on sandstone	Widely available resource, needs removal
9	Combination of attached adult oysters on concrete structures and oyster spat on shell	To spread risk, diversify age structure and potentially enhance success, concrete (with adults) needs removal

cages that were not buried, 80% of the adult oysters survived (Stichting De Rijke Noordzee, 2019). Burial of cages was also observed in cages outplaced at several pilot locations in the Dutch Wadden Sea (Fig. 1). There, overall survival was 13%, while in the cages that were not buried survival varied between 27–75% (Jacobs et al., unpublished). A downside of deployment of oysters in cages is that cages will have to be removed after a certain amount of time, unless they are made of steel that corrodes over time (see paragraph 'requirements'). Another downside might be suffocation due to the risk of severe fouling on the cages. Settlement of larvae in this scenario was assumed to occur on the conventional scour protection (granite).

Attaching (glued) **adult oysters** to (3) **concrete** or (4) **steel reef structures**. Reef structures, e.g. made of concrete and steel material, encourage biodiversity (Van Duren et al., 2016) and provide settlement substrate for larvae. In the Borkum Reef grounds, the majority of glued adults on 3D reef sandstone structures seemed to have detached (Didderen et al., 2020), though in Borssele V (Fig. 1), up to 62% of the oysters attached to a concrete structure were still thriving 9 months after deployment (Schutter et al., 2021). Experiments with steel indicate quick dislodgement of oysters from the structures, as the adhesive's bond badly with steel, likely due to the corrosion of the material (Van Belzen et al., 2021). Under current policy, concrete structures have to be removed, while steel reef structures are considered degraded after a deployment period of 30 yr and do not have to be removed. Settlement of larvae was assumed to be on concrete or steel respectively.

4.2 Oyster spat deployment

Another option is placing oyster spat (juvenile oysters) on the seafloor. Since oyster spat is less expensive per individual, the same budget accounts for large number of oysters that can be deployed. On the downside, reproduction after deployment and consequently natural recruitment is delayed.

Oyster spat settled on mussel shells, or (5) 'oyster **spat on shell'** is the best available source for this method since the practice is commonly used by shellfish farmers. Bivalve shells, including mussel and oyster shells, are considered the preferred settlement material for *Ostrea edulis* larvae (Colsoul et al., 2020; Hemrai et al., 2022). However, shell material is getting scarce and therefore expensive to use in large quantities (Hemrai et al., 2022). Other substrates that have been tested for suitability are (6) **granite**, the material used as conventional scour protection, and ECOncrete, a concrete mixture that includes natural additives (Ter Hofstede et al., 2024) which is referred to in this study as (7) **concrete**. (8) **Sandstone** is moderately suitable as substrate for spat (Colsoul et al., 2020; Ter Hofstede et al., 2024), but is readily available in sufficient amounts.

Combinations of the above-mentioned methods are expected to enhance success of oyster reef restoration, therefore the scenario (9) of **combining adults on concrete with spat on shell deployment** is also considered.

5 Research design and model estimation method

Information on costs and effectiveness (population size) was retrieved from (peer reviewed) publications, websites, quotations (in 2020), and communication with oyster farmers and other experts.

5.1 Cost model

Information on costs associated with the different deployment scenarios was collected and divided between costs for material, labor, transport shipping, and oysters (Tab. 3). Appendix 1 provides details on all cost-estimates.

For the scenarios involving deployment of adults, costs were generally considered per individual (e.g. acquiring costs) or per surface area (structures). This was different for scenarios

Table 3. The five cost categories and sub-categories distinguished. Prices are in Euros. Also given is the input used in the model.

Cost category	Sub-category	Specification	Estimated cost	Input in model
Oysters	Acquiring	Adults	€ 0.85/ oyster	12,000 oysters
Material	Substrate	Cages	€ 200/ m^2	400 m^2
		Concrete-structure	€ 117/ m^2	400 m^2
		Steel-structure	€ 5/ m^2	400 m^2
		Mussel shells	€ 40/ m^3	5 m3
		Concrete	€ 117/ m^3	5 m3
		Sandstone	€ 178/ m^3	5 m3
		Granite	€ 136/ m^3	5 m3
	Anchoring		€ 150/ m^2 or m^3	400 m^2 or 5 m^3
	Glue		€ 0.30/ oyster	12,000 oysters
Labor	Deployment		€ 150/ h	275-1,825 h
	Removal		€ 150/ h	40 h
Transport	Material	Concrete	€ 1,375/ container	1 container
		Spat	€ 3,875/ container	1 container
Shipping	Deployment		€ 23,500/ d	1 d
	Removal		€ 35,250/ d	1.5 d

involving deployment of oyster spat for which costs were generally provided per volume.

To estimate the costs, a model was developed (MS Excel, Appendix 1) with a variable input of desired volume of substrate/structures (m^3) for oyster spat deployment, desired oyster density and surface area (m^2) for adult oyster deployment and hourly rate. For this study, input in the model for scenarios regarding adult oyster deployment was set to 400m^2, with a fixed density of 30 animals per m^2, which amounted to 12,000 individual oysters. The estimated weight of these oysters totaled 1,000kg. To be able to compare costs between scenarios, input in the model for the scenarios involving oyster spat was set to 5m^3, which is the equivalent of 1,000kg of oyster spat on shell (scenario 5).

Costs for adult oysters included the costs for purchasing oysters outside the Netherlands, and transport costs were included in the price per oyster. Cost to acquire oyster spat were not provided per oyster but defined as costs for renting spatting ponds. As such, these costs were included in 'material' costs (Tab. 3). Material costs also included costs for structures, substrates, anchoring and glue. For labor costs a differentiation was made between deployment costs which included travelling time back and forth to the deployment site, but also the gluing of oysters to substrate, placing oysters in structures, and the treatment of oysters according to the alien species protocol (AIS). For some scenarios (Tab. 2) removal of structures is mandatory after the deployment period. Money for this removal needs to be guaranteed before deployment takes place and was therefore also included in the estimation of costs.

The labor cost for removal only included travelling time. Transportation costs included the cooled transport from the breeder to the Netherlands for scenarios regarding deployment of oyster spat. For scenarios regarding deployment of adult oysters, transportation costs were included in the oyster price, and no transport costs were calculated except for the scenario 'adult oysters on concrete'. Here the specific type of concrete (ECOncrete) was not available locally (as is assumed for all other materials) and had to be obtained elsewhere. Transportation costs for both oyster spat and adults was per container. Shipping costs was based on the costs of hiring a ship multiplied by the number of days. Removal time was expected to be longer than time needed for deployment due to the time needed for relocation of structures.

Costs for monitoring were not considered, as they were assumed to be similar for all scenarios. Overhead costs, usually a fixed percentage of total budget were also not considered. In this study, a fixed hourly rate for labor of €150 was used, but this rate can be adjusted in the model if desired. An overview of how the cost model is build up can be found in Figure 2.

Since (the lack of suitable) substrate is considered to be an important factor limiting oyster larval settlement the model also allowed for the option to calculate the costs for adding additional settling substrate for five consecutive years. The settlement substrate is 50 m^3 empty mussel shells per years, the corresponding costs include costs for shell material, labor and ship time and are equal for all scenarios. Costs for maintenance were not included in the calculations. Details for all costs can be found in Appendix 1.

5.2 Restoration effectiveness and cost-effectiveness

The restoration effectiveness of each oyster deployment scenario was expressed as the resulting oyster population post-deployment. To estimate this population size, a population model (MS Excel, Appendix 1, Fig. 3) was used. Development was calculated 5, 15 and 30 yr post-deployment. In the results, only the population size after 15 yr is shown. Table 4 gives an overview of values used as input in the model. The cost-effectiveness was expressed as the number of oysters 5, 15 and 30 yr post-deployment per Euro invested.

Growth of European flat oysters were considered to follow a normal growth pattern, thus assuming that environmental conditions were not limiting, and a reproductive state of the initial population was reached at the age of four (after the third year).

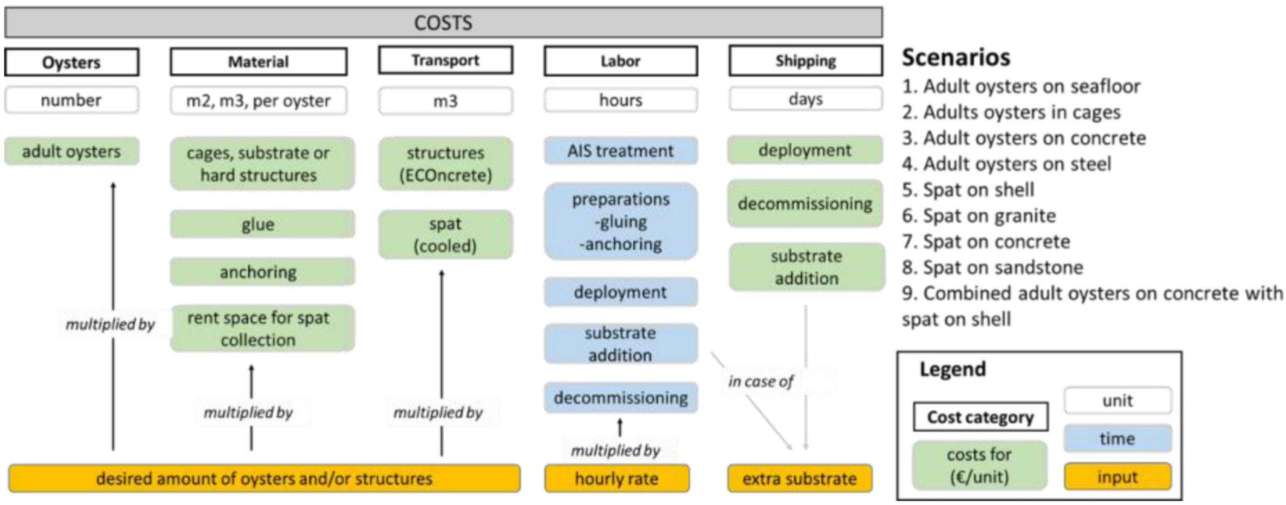

Fig. 2. Cost model categories for European flat oyster restoration in Dutch wind farms, split up for all assessed components, either expressed per unit m^2, m^3, per labor hours or ship time in days. AIS=alien species protocol.

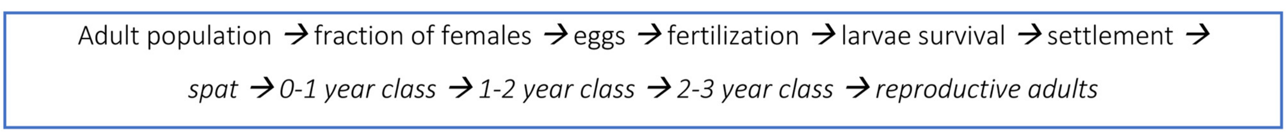

Fig. 3. Steps in the population model over time to simulate the dynamics of the complete life cycle for reproducing adult oysters and spat including survival for all steps. The adult scenarios start with the number of females in the adult (reproductive) population, the number of spat produced from this population depends on the number of offspring produced and survival of both larvae and spat. The spat scenarios start with the number of spat settled on the settlement material which will result in a reproductive population in year 4 see Table 4 for parameter estimates.

For scenarios regarding the deployment of adult oysters, the initial input was 12.000 adult oysters (see cost model). Mortality of adult oysters after deployment is mainly due to dislodgement or burial, and differed for each scenario (Appendix 1). Yearly survival of the reproductive adult oyster population was under the assumption that *Bonamia* was not present in the deployment area.

For scenarios involving the deployment of oyster spat, settlement success on the different substrates was based on the most realistic scenario of retrieving spat from Tralee Bay, Ireland (personal communication, Tralee Bay oyster farmers). Since no oyster larvae counts were available, data of settlement numbers of oysters for each substrate relative to the baseline settlement of oyster spat on shell was estimated. Recruitment for the deployment scenarios 'adult oysters on seafloor' and 'adult oysters in cages' was assumed to be on standard scour protection material: granite. Survival of oyster spat after treatment with the Alien Invasive Species protocol and transport from collection area was based on oyster spat with a size class of ± 8mm.

In the model there is the option to add additional settlement material (50 m^3 shell material) in the first period (up to five years) post deployment to increase the chances of recruitment. Therefore, settlement success in the case of 'additional substrate added' settlement success was a factor 0,05. Under the option 'no additional substrate' it was assumed that fouling of potential settlement substrate would hamper settlement of new larvae, settlement success for each year was therefore decreased with a 'fouling factor' of 0.15 (Tab. 4). The addition of settlement substrate only has significant effects on the population size when adult oysters are present in the population. Therefore, years four to eight in the oyster spat deployment scenarios were taken as the time for substrate addition, when the oysters were mature and expected to reproduce.

5.3 Sensitivity analysis

Since most of the parameter values in the cost and −population model were based on current pricing, assumptions from literature or personal communication, a sensitivity analysis was carried out to project the consequences of changes in a parameter value and to identify those parameters that had the large effects on the outcome. The sensitivity analysis was performed on two scenarios that were most commonly applied in restoration pilots: 'deployment of adult oysters on concrete structures' and 'deployment of oyster spat on shell' with no subsequent substrate addition. For cost categories (e.g. material, oysters) the estimated minimum and maximum prices were used (Appendix 1). If no minimum or maximum prices were known, a decrease and increase in cost of 40% was used in the calculations. For ship time (in number of

Table 4. Parameter estimates used in the population model as well as start values for scenarios.

Model parameter	Value	Unit	Remarks and source
Number of reproductive adults	12,000	N	Model input for adult scenarios: nr of adults outplaced (400 m^2 with 30 animals/m^2)
Adult survival after AIS treatment	0.9	Fraction	Personal comment, A van den Brink, WMR
Adult survival after deployment	0.26–0.70	Fraction	Didderen et al., 2018, 2019, 2020; Stichting De Rijke Noordzee, 2019
Females in population	0.2	Fraction	Utting and Spencer, 1991; Helm and Bourne, 2004; Joyce et al., 2013; Kamermans et al., 2020.
Eggs per female	$1\ 10^6$	N	Utting and Spencer, 1991; Helm and Bourne, 2004; Joyce et al., 2013; Kamermans et al., 2020.
Fertilization success	0.5	Fraction	Utting and Spencer, 1991; Helm and Bourne, 2004; Joyce et al., 2013; Kamermans et al., 2020.
Larvae survival	0.01	Fraction	Utting and Spencer, 1991; Helm and Bourne, 2004; Joyce et al., 2013; Kamermans et al., 2020.
Settlement success	0.004–0.06	Fraction	Ter Hofstede et al., 2024. Depends on settlement substrate, with lowest success on steel and highest on granite. If additional settlement material is added than survival is 0.05 (cf. survival on empty mussel shells).
Fouling effect	0.15	–	Tonk et al., 2020
Number of spat settled on substrate	200–600	N/m^2	Ter Hofstede et al., 2024.
Conversion	35–260	m2/m^3	Ter Hofstede et al., 2024.
Initial number of spat	$6.6\ 10^4$–$2.6\ 10^5$	N	Ter Hofstede et al., 2024. Is the product of volume of substrate deployed (5m^3), the number of oyster spat settled (N/m^2) and for each substrate a conversion (m^2/m^3).
Spat survival AIS treatment	0.69	Fraction	unpublished data, Ter Hofstede et al. in prep.
Spat survival transport	0.85	Fraction	unpublished data, Ter Hofstede et al. in prep.
Spat survival deployment	0.40	Fraction	unpublished data, Ter Hofstede et al. in prep.
Spat survival after deployment year class 0-1	0.15	Fraction	Kamermans et al., 2020; Tonk et al., 2020 Both for outplaced oyster spat as well as recruited spat.
Spat survival after deployment year class 1-2 & 2-3	0.9	Fraction	Gangnery et al., 2004; Kamermans et al., 2020
Time to reproduce	3	years	
Yearly survival of reproductive adults	0.9	Fraction	Gangnery et al., 2004; Lynch et al., 2014

days) the current estimated of respectively 1 day for deployment and 1.5 days for decommissioning was taken as the minimum time needed. As a maximum a doubling of these time was used in the calculations. This resulted in a hypothetical change in cost price or time spent for each 'cost category'. These new minimum and maximum costs were then used to calculated the total cost of the deployment, while other cost categories remained unchanged. The percentage change in the total deployment costs was then calculated according to equation (1):

$$1 - \frac{Total\ cost\ with\ changed\ cost\ category}{Total\ costs} \quad (1)$$

With regard to the parameters in the population model, the same deployment scenarios and fixed input were used as for the cost model. For the sensitivity analysis for each model parameters the minimum and maximum values found in literature was used (see Appendix 1 for details). Note that for the 'fouling' effect, the original fraction was increased under the more negative manipulation and decreased to obtain a more positive scenario (Tab. 4). Results were expressed as fraction of change in population size after 15 yr using the default values. In case of increasing parameters values related to survival, manipulation was carried out until the maximum survival could be obtained (e.g. not beyond 100% survival). The change was calculated according to equation (2):

$$\frac{Total\ population\ with\ manipulated\ parameter\ value}{Total\ population\ with\ default\ parameter\ value}. \quad (2)$$

6 Results

6.1 Costs

The scenario where adult oysters are placed on the sea floor (scenario 1) is, under the assumptions used in this study and within the time span of 15 yr, the cheapest scenario, costing around € 100,000. The cost for the 'spat on shell' scenario lies

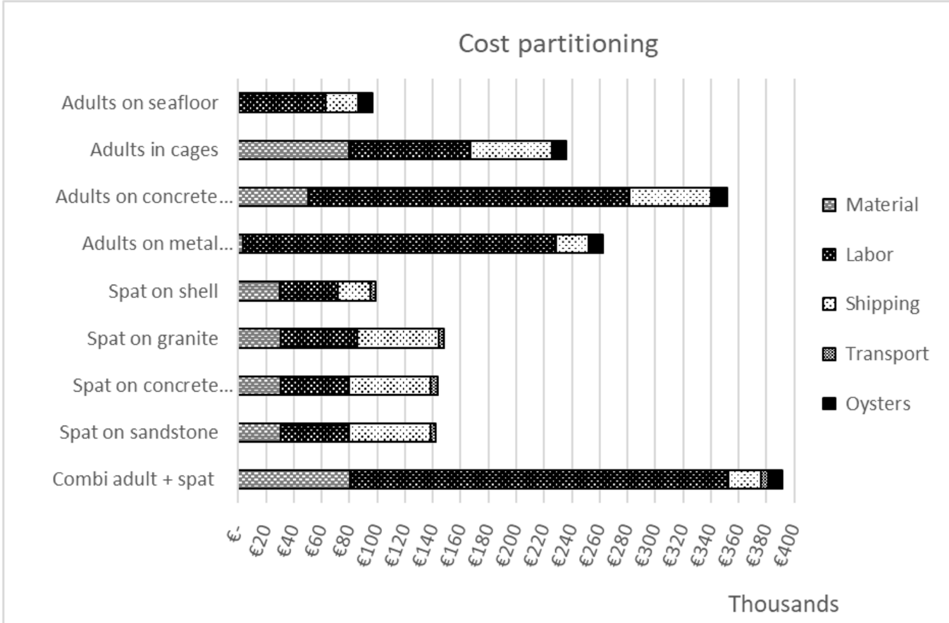

Fig. 4. Total costs and cost partitioning for different deployment scenarios for European flat oyster restoration in Dutch Wind farms. Assumption for the calculations were the deployment of 1,000 kg of adult oysters and 1,000 kg of oyster spat on shell corresponding to $5m^3$ of substrate. Addition of substrate in the years post deployment is not included, but roughly amounts to € 72,000, – for five years, regardless of scenario.

in the same range. The other adult deployment scenarios are much more expensive adding up to well over € 300,000, in the case of the scenario 'deployment of adults on concrete'. The deployment scenarios 'spat on concrete' and 'spat on sandstone' are slightly more expensive compared to the scenario 'spat on shell', while 'spat on granite is the most expensive scenario involving spat deployment, mainly due to higher labor costs (Fig. 4).

The combined scenario of deployment of 'adults on concrete' and 'spat on shell' is evidently the most expensive option. Regardless of the scenario, the largest contributor to European flat oyster restoration costs is labor, followed by costs for ship time and material (Fig. 4). Costs for source material and transport are of less importance.

Overall, cost of labor is high for deployment scenarios 'adult oysters on seafloor', 'adult oysters in cages' and all scenarios involving oyster spat deployment due to the treatment according to the AIS protocol recommended for source material coming from other areas. In these scenarios applying the treatment accounts for more than 50% of the labor costs (Appendix 1). For the scenarios deployment of 'adult oysters on structures' (either steel or concrete), labor costs are dominated by the fact that oysters need to be counted, and glued to structures manually. For all but the deployment scenarios 'adult oysters on seafloor', 'adult oysters on metal structures' and 'oyster spat on shell', structures have to be removed by law at the end of the deployment period therefore one and a half extra days of ship time is included to account for removal costs.

6.2 Effectiveness (population development)

The initial population size and the subsequent development of the oyster population was dependent on the deployment scenario but to a much larger extent to the management decision whether or not to add substrate during the first years post-deployment (Fig. 5). With or without the addition of substrate, the scenario with the highest population 15 yr after deployment was the combined deployment of adult oysters and oyster spat. However, the decision of adding substrate in the first couple of years post-deployment showed a large effect on population increase in later years, up to a 10 times larger population in the 15th yr compared to population development without extra substrate added. In case of oyster spat deployment, a larger number of oysters was deployed, but as no reproduction was assumed to take place in the first 3 yr, there was a delay in population development. Population development 30 yr post-deployment can be found in Appendix 3.

For all deployment scenarios the number of oysters per invested Euro was calculated after 15 yr, contrasting the differences for both the option to add additional substrate for a period of five years or not to add additional substrate (Fig. 6). The investment value for 30 yr post-deployment can be found in Appendix 3.

When no additional substrate was added after deployment, the scenarios with the highest revenues (in number of oysters) per Euro invested were the scenarios 'deployment of adult oysters on the sea floor' followed by 'deployment of adult oysters in cages' and 'deployment of oysters spat on shell'. For the scenarios involving adult oysters, the high revenues were attributed to high settlement success of oyster larvae on the conventional scour protection material (granite). The investment value of the deployment scenario 'oyster spat on shell' was comparable to the deployment scenario 'adult oysters in cages', the high investment value was mainly due to the large initial number of spat per m^3. Although the patterns in investment value of adding substrate were similar to what was

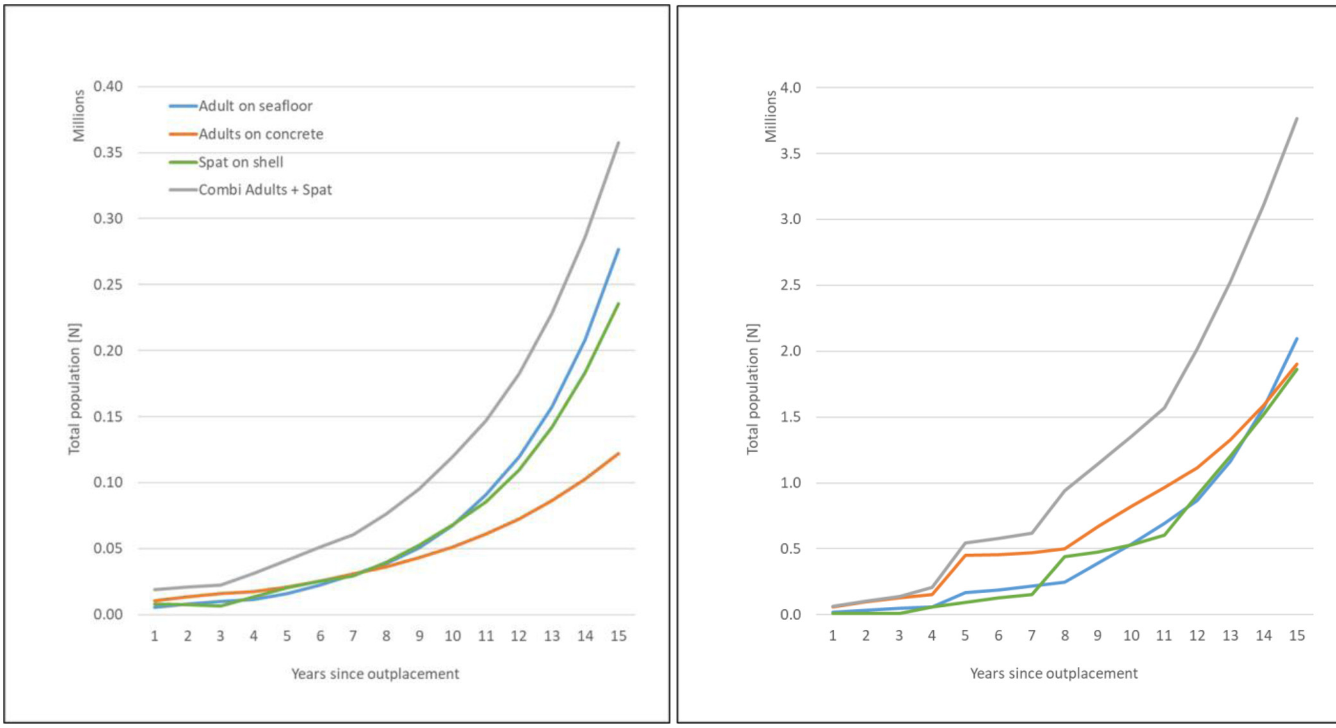

Fig. 5. An example of population development depending on the deployment method without additional substrate during the five years after deployment (top) and with additional substrate deployment (bottom). Note the different scales on the *y*-axis.

seen when no substrate was added, it is clear that the addition of substrate largely increased investment value, from 2.5 to almost 11 times, depending on the scenario (Fig. 6).

6.3 Sensitivity analysis

6.3.1 Cost model

Even though the magnitude differs between the two compared oyster deployment scenarios (Tab. 5), total deployment costs can be largely affected by change in material costs, cost for acquiring adult oysters and cost for shipping. When the time needed for deployment increased from 1 to 2 days, which is not unrealistic. Changes in the time spent on preparation for adult deployment on structures (in this model calculated per oyster): a 40% change in time spent per oyster (in this case 12,000 oysters) can reduce total costs by 21%. For the deployment scenario ‘oyster spat on shell’ changes in material cost also had a large influence in total costs. Changes in the price of oysters (scenario involving adult oysters) was of least importance on the total costs. For both scenarios changes in transportation costs had only a minimal effect on total deployment costs.

6.3.2 Population model (effectiveness)

High sensitivity was found for all parameters in the population model (Tab. 6), the largest influence on the total oyster population after 15 yr in the scenario of deployment of adult oysters on concrete was due to manipulations in adult survival. Also, large effects were calculated with changes in the number of females in the population, the number of eggs produced per female and settlement success of larvae. Note that an increase in survival had a larger effect than a decrease in with the same percentage. When increasing the negative effect of fouling on larval settlement the effect on total population size was bigger than when this factor was decreased (Tab. 6). For the deployment scenario ‘oyster spat on shell’, an increase in survival in the year after deployment had the largest effect on the population of oysters. Survival of adults was also a large factor as it was for the deployment of ‘oyster spat’ scenario, but to a lower extent as this factor only became relevant 4 yr after deployment.

In all the deployment scenarios using adult oysters, the required minimum self-sustaining population size of 20,000 adult oysters is reached after 8–10 yr in the scenario without substrate addition, except for the deployment scenario ‘adult oysters on steel’ where the numbers did not reach 20,000 even after 30 yr. For the oyster spat deployment scenarios it takes between 10 and 22 yr to reach 20,000 adult oysters, except for the combined adult and spat scenario where it takes only 8 yr.

7 Discussion

7.1 Model constrains

7.1.1 Costs

Cost in the cost-effectiveness model were based on estimated with the best available information at the time of writing. Prices however change in time and between regions. But for the main aim of this study, to make a comparison between deployment scenarios for oysters they can be considered as accurate enough.

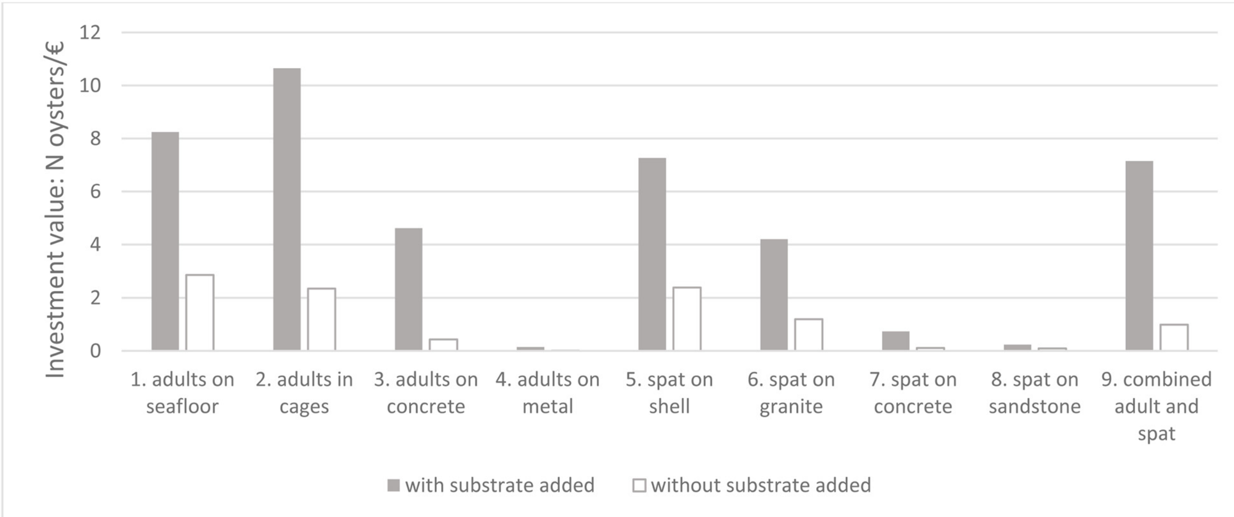

Fig. 6. Investment value in terms of number of oysters per invested Euro of a European flat oyster bed in a wind farm 15 yr post deployment with and without additional deployment of 50m^3 settlement substrate for five consecutive years after deployment of oysters.

Table 5. Percentage change in total deployment costs using the estimated minimum and maximum cost price per category, for the scenarios 'outplacement of adult oysters on concrete structures' and 'outplacement of spat on shell'. Bold numbers indicate large increases or decreases in total deployment costs.

Adults on concrete							
Category	Type	Min price	Max price	Unit	Nr of units	% change in costs min price	% change in costs max price
Material	Concrete structure	€ 70.2	€ 348.2	€/m^2	400 m^2	−5.2	**25.9**
	Glue	€ 0.15	€ 0.35	€/oyster	12,000 oysters	−0.5	0.2
Labor	AIS protocol	€ 90	€ 210	€/hour	300 h	−5.0	5.0
	Preparations & outplacement	€ 90	€ 210	€/hour	1,280 h	**−21.5**	**21.5**
Shipping	Outplacement	€ 23,500		€/days	2.5 d	0.0	16.4
Transport	Concrete structure	€ 1,375	€ 1,925	€/days	1 d	0.0	0.2
Oysters	Acquiring	€ 0.52	€ 3.83	€/oyster	12,000 oysters	−1.1	10.0

Spat on shell							
Category	Type	Min price	Max price	Unit	Nr of units	% change in costs min price	% change in costs max price
Material	Settled spat	€ 20,000	€ 45,000	€/unit	1	**−9.7**	**14.6**
Labor	AIS protocol	€ 90	€ 120	€/hour	150 h	**−8.8**	0.2
	Preparations & outplacement	€ 90	€ 210	€/hour	153 h	**−8.9**	5.0
Shipping	Outplacement	€ 23,500		€/days	1 d	0	**22.9**
Transport	Settled spat	€ 2,325	€ 5,425	€/days	1 d	−1.5	1.5

Potential costs outside the model limitations, like monitoring costs or the rent of a large flow-through basin (for storing oysters prior to deployment in case of unfavorable conditions offshore) were not considered but were assumed to be equal for all scenarios. This will not influence the comparison between scenarios but will of course add to the total deployment costs.

Changes in hourly rate in the future can have significant effects on total deployment costs. In most cases costs were estimated at the higher end of the range, and the total costs are expected to go down especially when differentiation will be made in hourly rates for different staff. The time needed for preparation and AIS treatment was difficult to estimate. Some experience with treatment of adult oysters for the Borkum Reef

Table 6. Population size of oysters after 15 yr when using the minimum and maximum population model parameter as well as the fraction of change for two oyster deployment scenarios: 'adult oysters on concrete' and 'oyster spat on shell'. See also Table 4 for further explanation and values.

Adults on concrete				
	Population size in y15		Change in population	
Change in	Min	Max	Min	Max
Eggs produced per female per year	122,060	2,313,477	1.0	19.0
Fouling effect substrate on survival	49,821	720,750	0.4	5.9
Survival year 1	122,060	2,313,477	1.0	19.0
Survival adults	16,176	284,387	0.1	2.3
Female/male ratio	84,096	1,354,660	0.7	11.1

Spat on shell				
	Population size in y15		Change in population	
Change in	Min	Max	Min	Max
Eggs produced per female per year	235,414	3,432,778	1.0	14.6
Fouling effect substrate on survival	99,945	1,211,271	0.4	5.1
Survival year 1	235,414	10,298,333	1.0	43.7
Survival adults	42,932	473,902	0.2	2.0
Female/male ratio	165,361	2,134,860	0.7	9.1
Nr of spat settled	117,707	1,177,068	0.5	5.0

grounds was available (Didderen et al., 2019), but not for oyster spat on substrate, where it was necessary to estimate time per volume. In the end, the hours spent for preparation and AIS treatment will also be dependent on the final design of desired structures. In addition, in the current study the wind farm Borssele V was used as a reference site, in the current study, for other wind farms at different locations shipping cost might be different.

And finally, ship time was estimated as real time needed to go back and forth to an offshore location, but down time due to bad weather condition, when ship rent still needs to be paid was not considered either and therefore costs for ship time might be severely underestimated. Higher costs for shipping will be more pronounced for the scenarios that have a dismantling obligation.

Manually gluing large numbers of oysters to structures significantly increased labor costs compared to scenarios where oyster spat is used that already settled, while dislodgement can be significant (Didderen et al., 2020), so this option has high costs without potentially not having the expected benefit.

7.1.2 Effectiveness

Currently, information regarding efficiency of deployment methods in terms of survival and optimal recruitment is lacking. The population model is largely based on assumptions and estimates of parameters from literature. Data on the number of oyster spat settled for each settlement substrate was retrieved from Tralee Bay. Results from a pilot (Ter Hofstede et al., 2024) comparing settlement success in the natural environment (Tralee Bay, Ireland) with that in a spatting pond (New Quay, Ireland), showed that, depending on substrate type, the number of settled larvae was significantly higher in the spatting ponds. Higher initial settlement for example for ‘spat on shell’ was 5 times higher, resulting in a 5 times larger population size after 15 yr as was seen in the sensitivity analysis (Tab. 6). The initial number of spat settled is thus very variable not only between location but also between years (Kamermans et al., 2004) and is difficult to know beforehand. However once spat is obtained, settlement numbers can be estimated with much less error and easily adjusted in the model.

The sensitivity analysis indicated that the model was very sensitive to changes in number of larvae produced per female, survival rates and the male-female ratio (Tab. 6). Settlement success was not included in the sensitivity analyses. It is an unknown factor, in this study it was assumed to be 5% (Kamermans et al., 2020). High retention of larvae near the location of release is considered an important factor influencing recruitment and should therefore be taken into account when selecting a site (Appendix 2). For the Borssele V site, larval retention is estimated to be high, and the baseline settlement parameter in this model (5%) seems therefore reasonable to predict recruitment here.

In the current study the fraction of oysters reproducing as females was set to 0.2, which is on the low end of fractions reported. In most species a sex ratio of 1:1 is assumed (Fisher, 1930), but for protandrous species like the European oysters a male biased ratio is expected (Allsop and West, 2004). Ratios reported for natural populations vary widely from a male-female ratio of 1:1 to 7:1 (Cole 1942; Millar 1964; Boudry et al., 2002; Kamphausen et al., 2011; Joyce et al., 2013). In very skewed populations the fecundity is limited (Joyce et al., 2013; Eagling et al., 2018), while a ratio converting to 1:1 will highly increase fecundity. It is largely unknown which factors influence the sex ratio of oyster, but higher water temperatures seem to increase the proportion of males in a population (Eagling et al., 2018).

The number of larvae a female can produce is dependent on size and condition of the female. Hatchery manuals estimate 1 to 3 million larvae per European flat oyster female under good brood stock conditioning (Utting and Spencer, 1991; Helm and Bourne, 2004). Although food quantity (as chlorophyll-a concentration) at offshore locations in the North Sea is within the range considered suitable for growth and reproduction of flat oysters (Appendix 2) the lower end of this range was taken and considered as the best available information at the moment. For survival parameters, better estimates can be given based on results from European flat oyster pilots at other locations in the past year, and confidence in these numbers will increase as more results from monitoring efforts become available and min-max range of parameter values can be lowered.

While some sensitive parameters might give an overestimation (settlement), there are also sensitive parameters that were estimated on the lower side of the available range of data (female-male ratio, larvae per female) and some parameters that gained increased confidence based on recent European flat oyster pilot results (e.g. survival), potentially evening out the impacts on the outcome. Still, the model should be used to compare cost-effectiveness results and to gain indicative information of what potentially can be expected with the proposed scenarios rather than use it as a predictive population model. Large ranges of parameter values and the lack of location specific information make this model unfit to predict population size over such a large number of years.

Adding substrate 5 yr post-deployment is expected to increase recruitment at a relatively low cost. However, to maximize the settlement chances for oysters it is important to place the substrate at the time of expected larval settlement to prevent biofouling of other animals. This small temporal window of opportunity makes that this scenario has a high risk of not enhancing settlement as predicted by the model (Tab. 4).

A final note on the population model. In the current study mortality caused by *Bonamia* is not considered as it is assumed that in offshore areas in the North Sea *Bonamia* is absent. Current policy is, for deployment of oysters in the Dutch North Sea is to use oysters that originate either from hatcheries that produce (certified) *Bonamia*-free oysters or from disease-free areas. However, these oysters have never been previously exposed to the parasite, and if *Bonamia* would reach offshore areas, morality is expected to be very high, up to 100% (Culloty et al., 2004). The use of Bonamia tolerant oysters is suggested as this might increase survival (Kamermans et al., 2023), which could be an incentive for using (Bonamia tolerant) spat reared in a hatchery for initiating oyster reef restoration. Efforts are currently made to develop Bonamia tolerant oysters by deriving offspring from Bonamia-free broodstock selected from a Bonamia infected area (Kamermans et al., 2023).

7.2 Deployment scenarios

Deployment of adult oysters or the combined deployment of adult oysters on concrete with oyster spat on shell all resulted according to our model to a population of at least 20,000 reproducing oysters within 10 yr post deployment. At deployment the initial numbers of adult oysters were 12,000. Ter Hofstede et al. (2023) concluded based on calculation that deployment of an initial broodstock of 1000 adult oysters would result in 35.000 mature oysters in 10 yr. The higher fecundity used by Ter Hofstede et al. (2023) to the estimate population size after 10 yr explains the higher population size, despite the lower parameter values used for survival until becoming an adult.

According to the assumptions made in the population model, the amount of oyster spat should be at least 30 times higher than the number of adult oysters to be able to have a similar population development. For the deployment scenario of ‘oyster spat on shell’ using spat from Tralee Bay (default value in the population model), the modelled population never exceeded the population size reached in the deployment scenario ‘adult oysters on the seafloor’, but when starting with oyster spat on shell from a spatting pond as was used in the sensitivity analysis, population size exceeded the deployment scenario ‘adult oysters on the seafloor’ by 4 times after 15 yr (Tab. 6). Showing again the importance of the initial number of settled spat for the population estimate.

There are only a few (pilot) projects aiming at starting (or enhancing) an oyster reef. One of the strategies applied in these projects was the placement of either a large number of spat (100,000) or adult oysters (80,000) on the seafloor in combination with one or multiple additions of settlement substrate (RESTORE project, see Appendix 2). Based on the analysis in the current study, this strategy was one of the most cost-effective ones. Another deployment method in the pilot projects was the placement of relatively low numbers of adult oysters in cages, racks or on oyster tables with additional settlement substrate (Borssele III & IV, see Appendix 2), which turned out to be not so cost-effective. In a recent project (Gemini wind farm, see Appendix 2) 5,400 adult oysters, > 100,000 spat and shell material were deployed, combining two of the most cost-effective scenarios. Deployment of shell material could enhance the cost effectiveness by the addition of a few years of fresh settlement substrate.

Model predictions show a self-sustaining population for most deployment scenarios after 8–10 yr. With uncertainty about mortality rates for both adults and spat, it seems wise to increase the number of oysters deployed as much as possible, aiming to reach a critical population mass as soon as possible. Also sowing thick layers of oysters in case of loose adults might help (Colden et al., 2017; McArdle et al., 2022). However, at present adult oysters are acquired by means of harvest from natural banks, impacting these wild populations. This argues against the unbridled use of large numbers of (loose) oysters especially when the percentage of loss is expected to be great or unknown. The deployment of larger numbers, under approval of ethics and availability, might also have economic benefits since although the "return-on-investment "of oyster restoration varies, generally the returns increases with project size (Bersoza Hernández et al., 2018).

The results presented in this paper showed that the development of a self-sustainable reef is possible within 10 yr time for most of the deployment scenarios investigated. The most effective scenario’s in terms of population size reached after 10 yr had an estimated deployment cost between 262 k€ and 601 k€ (including the cost for additional substrate supplement for 5 yr post deployment). These costs are roughly 0.01% of the total estimated costs to install the foreseen wind parks in the North Sea (De Ingenieur, 2018).

The model used in this study was based on assumptions and results from a few pilots only. Ongoing research will hopefully give information on preferred substrates for larval settlement, on recruitment and survival rates that can be used to improve the model.

8 Conclusions and recommendations

Based on the investment value the scenarios of deploying 'adult oysters on the seafloor' 'adult oysters in cages' and 'oyster spat on shell' had the highest revenues per Euro invested. Adding substrate in the years post-deployment increased cost-effectiveness in the model for all scenarios due to a potential increase in recruitment, for a relatively low cost investment.

The deployment scenario 'oyster spat on shell' and the combined scenario of deploying 'adult oysters on concrete' and 'oyster spat on shell' were the preferred scenarios in terms of fastest population development. If there are no budget restraints, it is recommended to deploy as much adult oysters as availability allows since the larger the initial population, the higher the integrity, which will likely increase success rate. The estimated time to success for these oyster restoration scenarios is long and depends highly on population parameters like survival and recruitment. To validate the model outcome and to improve parameter estimates, longtime monitoring of the restoration site is essential.

Monitoring should focus on collecting data regarding presence of oyster larvae, settlement time and success as well as survival of spat and adults to improve the model outcomes. In addition data providing insight on the condition of oysters as well as the male: female ratio would be valuable.

In this study a cost model and a population model were used to systematically compare costs and resulting population size between 8 different oyster deployment scenarios in offshore areas. Such a systematic approach, adjusted to newest insight, current costs and local conditions might help in future projects to decide on the most cost-effective deployment option.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

Supplementary material

Appendix 1. Excel 'Costs, benefits and sensitivity analysis'.

Appendix 2. Overview offshore oyster restoration or enhancement projects incl. site characteristics.

Appendix 3. Population development & cost-effectiveness 30 yr after deployment.

The Supplementary Material is available at https://www.alr-journal.org/10.1051/alr/2025010/olm.

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