Plan and Cost Estimate for a Demonstrator

- a floating wind turbine unit equipped with pumps for oxygenation of the deepwater, and associated patents and immaterial rights

BOX WIN

Technical report no.8

Holger Eriksson &
Thomas Kullander

C104
Rapport
Gothenburg 2013

Department of Earth Sciences
University of Gothenburg

Naturvetenskapliga fakulteten

GÖTEBORGS UNIVERSITET

UNIVERSITY OF GOTHENBURG
Department of Earth Sciences
Geovetarcentrum/Earth Science Centre

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Mailing address
Geovetarcentrum
S 405 30 Göteborg

Address
Geovetarcentrum
Guldhedsgatan 5A

Telephone
031-786 19 56

Telefax
031-786 19 86

Geovetarcentrum
Göteborg University
S-405 30 Göteborg
SWEDEN

Abstract

This report serves to estimate the cost of design, construction, installation, operation and maintenance of a Demonstrator, which is a floating wind turbine and pumping unit located in the Bornholm basin of the Baltic proper. It also serves to provide an estimated schedule for the design, construction and installation of the Demonstrator until final handover of the vessel to the operator. Secondly, this report compares the estimated costs of a number of differently configured pumping units advanced from the original conceptual design for large scale restitution of the Baltic proper.

The cost of a Demonstrator being designed, constructed, installed and ready to operate on location in the Bornholm basin of Danish waters is estimated to 354 MSEK, including all provisions assumed as described by the conceptual design but excluding taxes and fees. This estimate includes 146 MSEK for the turn-key installation and connection cost of 20 km submarine cable offshore and 10 km land cable onshore.

The cost of operating, maintaining and conducting research of the Demonstrator is estimated to 10 MSEK per year. The design life time is 20 years for the Demonstrator. Removal and demolition is estimated to 15 MSEK without any residual value.

The time from contract award (project start) to contract delivery (ready to operate) is estimated to 27 months. The first 12 months duration of the project is engineering, followed by another estimated 12 months for construction of the steel substructure, commissioning and testing. Procurement is conducted in parallel. The next 3 months is scheduled for installation, commissioning and start up assuming a suitable weather-window.

During operation of the Demonstrator, efficiency and performance are to be tested for a minimum period of three years, extendable to five years.

Post-operation requires demobilization, disassembly and scrapping; this time is estimated to 3 months of duration.

A complete oxygenation system for the Baltic proper requires pumping of 10,000 $m^3 s^{-1}$. If the floating pumps are arranged in clusters, powered by wind turbines of different size or by diesel, the total annual cost for six alternative configurations varies between 695 and 1244 MSEK. For a limited system for the Bornholm Basin, based on 10 Demonstrator units with a total pumping capacity of 1000 $m^3 s^{-1}$, the total annual cost is estimated to 104 MSEK.

Sammanfattning

Syftet med denna rapport är att ge en kostnadsuppskattning och beräknad tidsplan för uppförandet av en Demonstrator i Bornholmsbassängen i södra Östersjön. Demonstratorn är en pumpanläggning i ett flytande vindkraftverk med ändamål att syresätta djupvattnet med syrerikt vatten intaget ovanför språngskiktet på cirka 40 m djup. Rapporten ger även en uppskattad tid från start av projektering till färdig anläggning på plats. Som en bistudie har ett flertal olika konfigurationer av vidareutvecklade pumpenheter jämförts med varandra i en tänkt vindkraftspark för storskalig restaurering av hela egentliga Östersjön i syfte att uppskatta vilka effekter dessa varianter skulle få för kostnaden utslagen på 20 år.

Kostnader för projektering, projektledning, tillverkning och installation av en driftfärdig Demonstrator utplacerad i Bornholmsbassängen på danskt territorialvatten uppskattas till 354 MSEK, inklusive alla konstruktionsförutsättningar angivna i konceptstudien men exklusive skatter och avgifter. Uppskattningen innefattar 146 MSEK i installationskostnader av 20 km sjökabel och 10 km landkabel, inklusive alla anslutningar ombord Demonstratorn och i land.

Kostnader för drift, underhåll och forskning under Demonstartorns antagna ekonomiska livslängd på 20 år uppskattas till 10 MSEK per år. Nedmontering, bortforslande och upphuggning av Demonstratorn uppskattas kosta 15 MSEK utan restvärde.

Den totala projekttiden från kontraktteckande (projektstart) till leverans är beräknad till 27 månader. De första 12 månaderna beräknas omfatta projektering, därefter följer 12 månaders tillverkning och provning; varvid inköp och viss tillverkning förutsätts starta innan hela projekteringsarbetet är färdigt. De påföljande 3 månaderna är planerade för installation, slutprovning och överlämnande av Demonstratorn liksom dess förankringssystem under förutsättning av ett tillräckligt långt och bra väderfönster.

Under drift kommer Demonstratorns funktion och effektivitet att mätas i tre till fem år. Efter fullgjord uppgift kommer Demonstratorn att monteras ner och forslas bort för upphuggning. Denna demontering och skrotning beräknas ta 3 månader att genomföra.

I det tänkta fallet att ett flertal vidareutvecklade pumpenheter i framtiden skulle ingå som en enhet i en större flytande pumpfarm för hela egentliga Östersjön och därigenom behöva modifieras, eller konceptet för kraftförsörjning behöva ändras, har sex olika konfigurationer studerats. De totala kostnaderna för att pumpa 10 000 $m^3 s^{-1}$ i 20 år uppskattas då variera från 695 till 1 244 MSEK/år. Kostnaden för ett system för Bornholmsbassängen, vilket bygger på 10 Demonstratorenheter som tillsammans skall pumpa 1000 $m^3 s^{-1}$, kan uppskattas till 104 MSEK/år.

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Preface

In 2008, Formas and Naturvårdsverket (Swedish EPA) announced available funding for research on the possibility to use deepwater oxidation as a mean to combat eutrophication in the Baltic Sea. Two projects, BOX, "Baltic deepwater OXygenation" and PROPPEN were funded at the end of December 2008. These projects have shown that phosphorus leakage from anoxic bottoms in small coastal basins may be stopped by oxygenation. BOX has shown that this also is true for the Baltic proper. The BOX-WIN project "winddriven oxygenation by pumping and generation of electrical power" builds on BOX.

Results from the BOX-WIN project will be presented in a series of reports from the Department of Earth Sciences at the University of Gothenburg. A wide range of subjects are covered by BOX-WIN. Technological, environmental, economical and legal facts and circumstances must be considered to develop and locate a full-scale Demonstrator composed of a self-supporting, floating wind turbine unit with a generator producing electric power for deepwater oxygenation by pumping and for delivery to the grid. The Demonstrator will be developed for the Bornholm Basin, which at times has anoxic water in its deepest parts. The Demonstrator developed by BOX-WIN will hopefully be built to conduct tests in the Bornholm Basin. This would be an important step towards installation of a regional system of full-scale floating wind turbine units with pumps in the Bornholm Basin. An updated list of BOX-WIN reports is included at the end of the report.

The present report "BOX-WIN Technical report no. 8 – "Plan and Cost Estimate for a Demonstrator – a floating wind turbine unit equipped with pumps for oxygenation of the deepwater, and associated patents and immaterial rights" is written by Holger Eriksson & Thomas Kullander. The work is funded by the Swedish Agency for Marine and Water Management and by the Baltic Sea Action Plan under the Nordic Investment Bank.

Gothenburg 5 June 2013

Anders Stigebrandt

1. Introduction

This report serves the purpose to present cost and schedule estimates that are realistic and thus confident enough to recommend for the configuration of a Demonstrator.

The Demonstrator is a full-scale floating pumping device for restitution of the deepwater oxygen concentration by pumping down so called "winter water", see Ödalen and Stigebrandt (2013)[1], which is rich in oxygen and lower in density, from an inlet above the halocline to an outlet above the sea floor. The power, which is required for running the pumps, is delivered by a wind turbine, which is integrated with and atop of the Demonstrator. See drawings in Figures 1 and 2 for general views of the Demonstrator design, which is conceptual at this stage. Displacement is approximately 5500 tonnes; of which 2000 tonnes are steel weight; 3000 tonnes are ballast and 500 tonnes are the weight of the 3 MW wind turbine.

The Demonstrator design is the result of a feasibility study conducted in the BOX-WIN project. The concept is based on the proven design of the floating wind turbine unit (FWTU) named Hywind, which has been moored in the Norwegian Sea west of Stavanger Norway at about 500 m of water depth and operated continuously since 2009. The Hywind FWTU is referred to as Hywind I. Its design has been modified by BOX-WIN to accommodate a water pumping device for deepwater ventilation on an assigned location at about 100 m of water depth in the Bornholm Basin of the Baltic proper. Further, some evolving FWTU technologies of the Hywind II concept have been assessed by keen assistance of Statoil AS, the owner of the Hywind concepts. The risks, which are associated with the modifications of Hywind I and location in the Bornholm Basin, have been assessed as presented in BOX-WIN Technical Report no. 5.[2]

Swedish project management and execution on Swedish ground by use of Swedish suppliers are imperative to the estimated cost and schedules. However respected, this is not possible to achieve in its full extent as presented in BOX-WIN Technical Report no. 7.[3]

An additional purpose of this report is to provide cost estimates of a number of differently configured pumping units developed from the original conceptual design for large scale restitution of the Baltic proper, should these be arranged in a future cluster of floating pump farms; variations of which are described as six different configurations in section 8.3.

Cost and schedule estimates of the Demonstrator are to be detailed in the basic design phase. More specific data will then be available for more precise calculation so the accuracy of the estimates presented in this report can be narrowed.

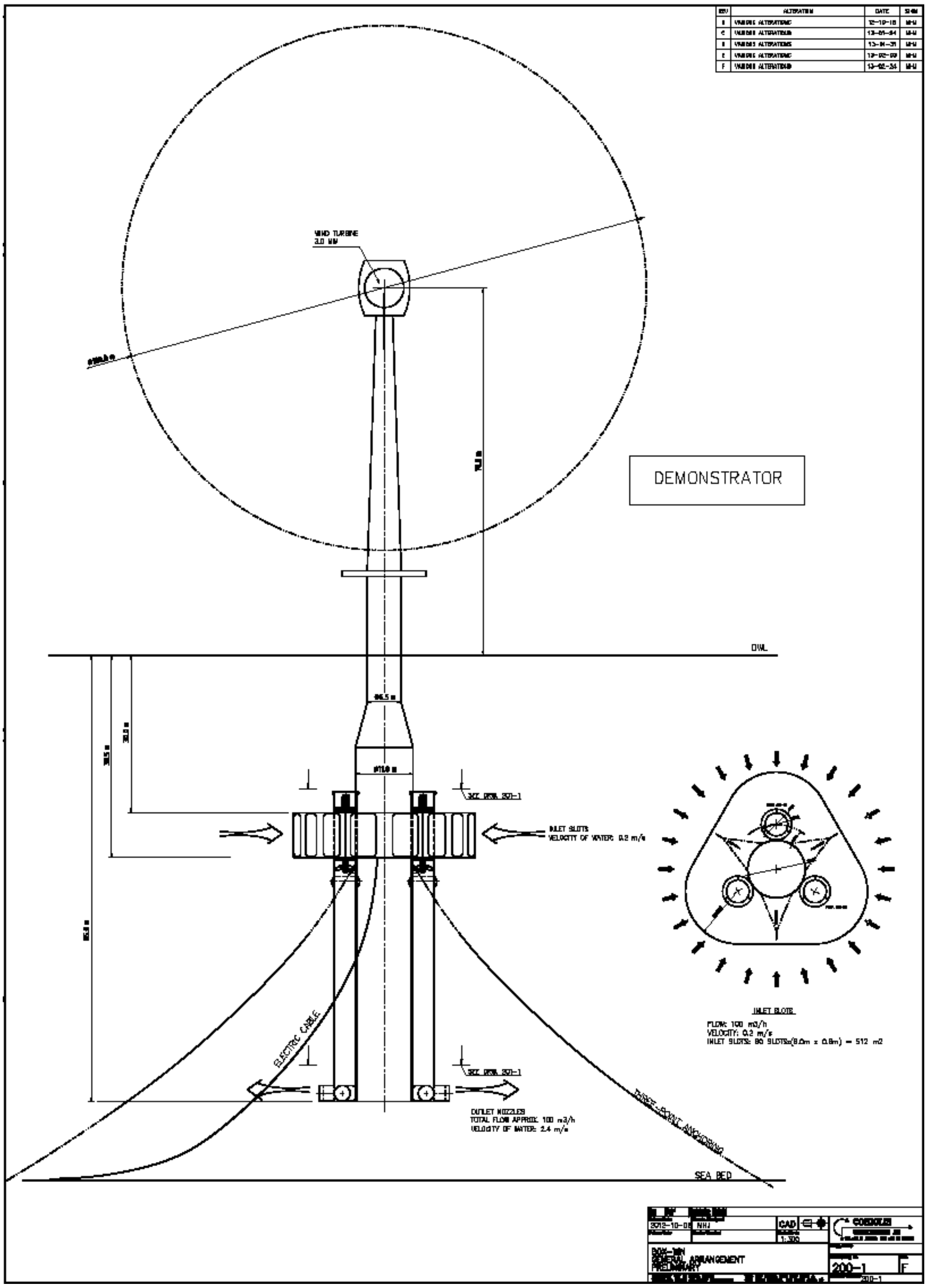

Figure 1. Conceptual design drawing, vertical cross section view of the Demonstrator and horizontal cross section view of the pump configuration (small image on lower right side of the image).

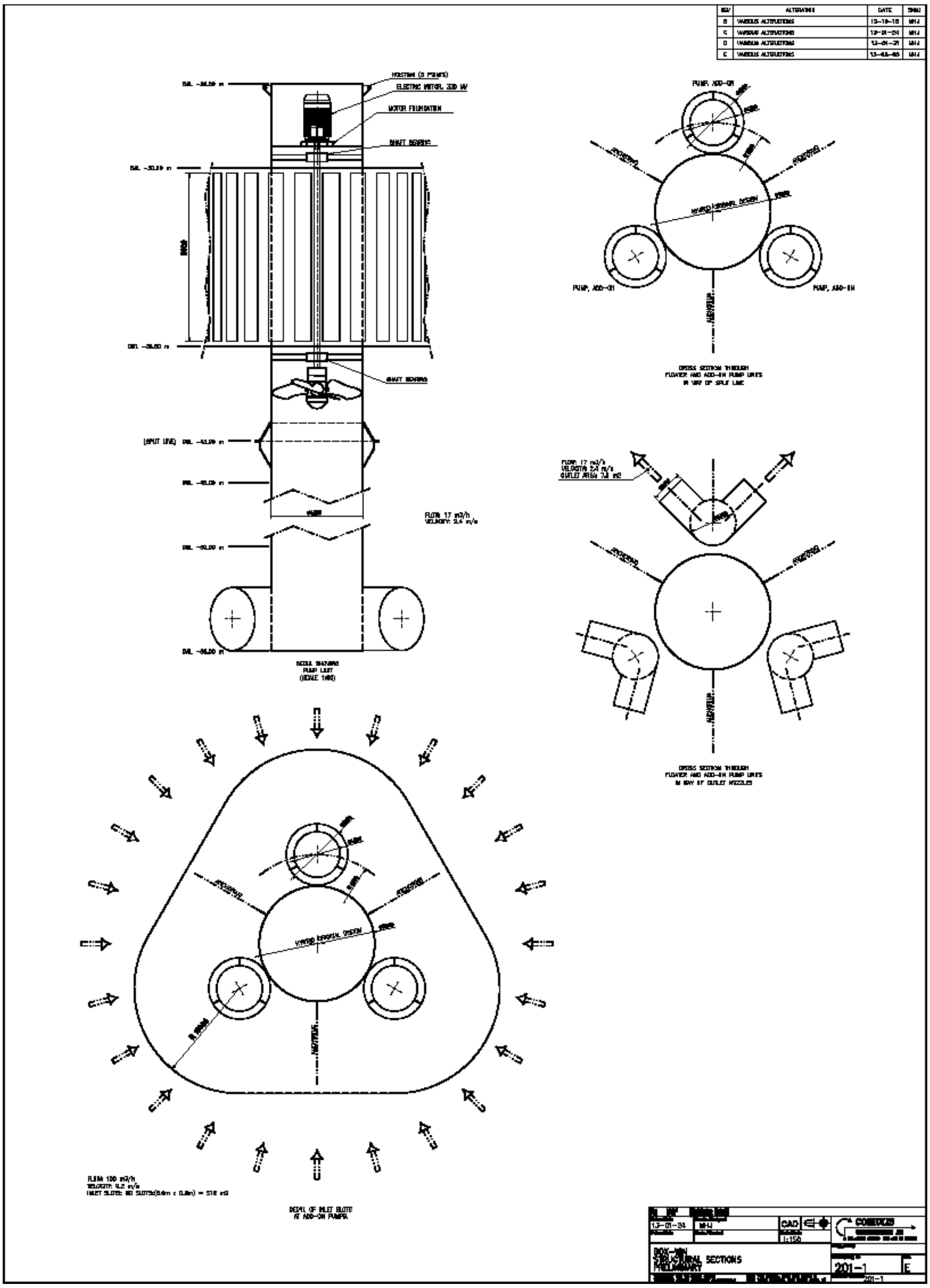

Figure 2. Conceptual design drawing, horizontal cross section views of the Demonstrator and its pump configuration, and vertical cross section view of a pump unit (top left image).

2. Basis for Cost Estimate

Cost estimates are primarily based on data provided by Statoil A/S from their Hywind I floating wind turbine unit. In addition, cost and schedule estimates are generally based on the assumption of the Demonstrator being designed and constructed in Northern Europe; in particular, cost estimates are derived from Swedish shipyards based on conceptual drawings of the Demonstrator and corresponding weights. Estimates are presented in aggregated sums without further detailing, since these figures are confidential, and based on information available to the authors at the time of report.[4,5]

Costs of the substructure depend primarily of the weight of the unit and are secondly detailed on materials, labour, purchased services and components. Weight is directly related to the cost of bulk materials, e.g. steel and welding consumables, as these are purchased by steel yards in units of mass. Labour costs for engineering and construction are also related to the weight. The weight and centre of gravity of the Demonstrator also have major influence on the equipment and means for transports, lifting and movements at the construction yard as well as on the hydrostatical and hydrodynamic properties of the vessel during installation and in operation.

Established practices by large oil companies for estimates of early design phase studies of offshore units in the North Sea are included for information in Table 1.

Table 1 indicates the level of expected accuracy of weight, technical information and cost. It also indicates the expected level of confidence and the amounts of additional costs ("extras") which are statistically attributable to an early design. For the Demonstrator conceptual design, which is mainly based on the proven Hywind I design, Table 1 will generally be conservative; however, the estimates of accuracy of weight and level of contingency are still applicable.

Table 1. Estimates of accuracy and contingency used in early design phase.

Weight estimate accuracy	Accuracy of technical information	Cost estimate accuracy	Level of Confidence	Level of Contingency
± 25%	± 40%	± 40%	80%	25%

The total estimate is subdivided into cost items and separated in capital and operational expenditures, Capex and Opex, as follows:

- Engineering - Capex
- Client Preliminaries - Capex
- Construction - Capex
- Marine Operations - Capex
- Cable - Capex
- Operation, Maintenance and Monitoring - Opex

All costs are in SEK as per Q2 2013 without taxes, VAT or other duties included. Financial costs and other effects of financial aspects are not included.

Cost items are described in section 3 and Capex and Opex estimates are presented in Tables 2, 3, 4 and 5. A contingency of 25 % has been added to Capex to account for changes to the design and other changes that may emerge in upcoming phases of the Demonstrator project.

3. Capex Cost Estimate

Capital expenditures (Capex) are expenses for creating future benefits, i.e. to deliver the Demonstrator in the state of being ready to operate on the location.

3.1 Engineering

The engineering cost item includes all phases of engineering, e.g. basic design, detail design and work shop drawings; and includes all engineers under the Project Engineering Manager or corresponding Discipline Lead Engineers.

This estimate is normalized to manhours/tonnes of steel and is based on experience from marine and offshore projects in Sweden. The substructure cost is estimated to 15 man-hours/tonne. The cost of SEK 850/manhour is currently used.

Engineering cost is estimated to 2000 tonnes × 15 × 850 SEK = **26 MSEK**

3.2 Client Preliminaries

The cost item of client preliminaries account for all contractor management costs, e.g. project management, project approvals, cost control, planning, contract control, procurement, quality, interface management, etc.

This estimate is based on experience to be approximately 60 % of the engineering cost, or 10 - 15% of the total Capex.

Client preliminaries cost is estimated to 0.60 × 26 MSEK = **15 MSEK**

3.3 Construction

This cost item is split into the substructure, which is fabricated at the ship yard; the pumping units, which are manufactured by the pump supplier; and the wind turbine unit, which is manufactured in the supplier's work shop.

3.3.1 Substructure

The substructure is the bottom part of the Demonstrator which is supporting the wind turbine tower, i.e. its topmost part is located below the tower on level at about 15 m above the waterline in operation. See Figures 1 and 2 to view the conceptual design of the Demonstrator.

The steel weight of the substructure includes all primary and secondary steel of the central cylindrical structure, the three pumping pipes, the separation roof with water inlets, and the water outlet nozzles. The steel weight has been estimated by method of summing up each volume factor per discipline, which is based on experience from previous offshore and marine projects, giving for each discipline:

Estimated discipline weight × discipline direct man-hour norm × man-hour unit rate

The sum totals 30 SEK/kg, hence 30,000 SEK/tonne of steel weight, including all management, administration, facilities, buildings, equipment, etc. This estimate applies particularly for construction in Sweden. Additional work is estimated to have the same cost per tonne including all costs for management and facilities.

Substructure cost is estimated to 2000 tonnes × 30,000 SEK/tonne = **60 MSEK**

3.3.2 Pumping Units

The estimate for three retractable pumping units including electric motors, shafts, bearings, power and control system is 3 pumping units × 3 MSEK = **9 MSEK.**

3.3.3 Wind Turbine Unit

The wind turbine unit consists of all functions required to generate energy, i.e. including but not limited to blades, nacelle and tower. The cost estimate is based on information and figures provided for the Hywind I and Hywind II projects. The cost for a complete 3 MW offshore wind turbine unit including tower, nacelle, blades, etc. is estimated to **39 MSEK,** as delivered to the construction site for assembling onto the substructure.

3.4 Marine Operations

The cost for marine operations includes all marine activities such as load-out, transport from the construction site in Sweden to the mating site in the Bornholm Basin; assembly of the wind turbine unit including tower, nacelle and turbine blades; installation of the substructure, commissioning, ballasting, start-up, lay-out of mooring equipment and mooring operations.

Based on figures related to the Hywind I and the Hywind II project the cost for the marine operations required for the floating of the Demonstrator is estimated to **33 MSEK.**

3.5 Capex - excluding Cable

Estimated costs for the Project Management, Engineering, Substructure, Installation and Marine operations that were calculated in sections 3.1 – 3.5 are presented and summed in Table 2.

Table 2. Estimated Capex – excluding Cable for the Demonstrator.

Cost Item	**Cost Estimate (MSEK)**
Engineering	26
Client Preliminaries	15
Construction, Substructure	60
Construction, Pumping Units	9
Construction, Wind Turbine Unit	39
Marine Operations	33
Sum	182
Contingency: + 25%	45
Total Capex - excluding Cable	227

3.6 Cable

The Demonstrator is located in the Bornholm Basin at about 20 km of distance from a suitable landing point onshore, with another 10 km of distance to the connection point to the national electrical grid. This connection is needed both for transferring surplus electrical energy to shore and for supplying the Demonstrator with electricity when there is not enough wind. The low voltage cable is manufactured by the supplier and installed by trenching down into the sea-bed offshore and in the ground on land. The cost estimate of the cable connection to the grid is based on figures for the Hywind projects (classified information) and the details of the estimate presented in Table 3.

Table 3. Estimated Capex of cable (only), including installation and infrastructure.

Cost Item	Cost Estimate (MSEK)
Offshore infrastructure	36
Onshore infrastructure	26
Marine operations	40
Transport and logistics	3
Project management	10
Insurance	2
Sum	117
Contingency: + 25%	29
Total Capex of Cable (only)	146

3.7 Total Capex

The total Capex is the sum of section 3.5 and 3.6. These figures are presented in Table 4.

Table 4. Estimated Total Capex – including Cable for the Demonstrator.

Cost Item	Cost Estimate (MSEK)
Capex – excluding Cable	227
Cable	146
Total Capex	373

4. Opex Cost Estimate

Operational expenditures (Opex) are expenses incurred in the course of ordinary business, i.e. to operate and maintain the Demonstrator on location.

Based on information from Svensk Vindenergi, the cost for operation and maintenance of an offshore wind turbine is approximately 0.2 SEK per kWh/year, i.e. 0.7 MSEK per MW/year as based on 3500 hours of operation on average each year. For the 3 MW Demonstrator wind turbine unit, this cost is estimated to **2 MSEK/year**.[6,7,8]

Operation and maintenance of the deepwater pumps are estimated to require a cost per kWh and year equivalent to that of the wind turbine unit. The pumping unit consists of three separate pumps, together rated 1 MW. Operation and maintenance cost for the pumping unit is hence estimated to **1 MSEK/year**.

During operation of the Demonstrator, a research and monitoring program will be required to verify the effect of the oxygenation of the deepwater, also including biological effects such as impact on cod reproduction and impact on the sea bed. This program will be operated by scientists from universities and engineers of the monitoring companies. The manpower costs related to this program are estimated to **7 MSEK/year**. [9,10,11,12]

In total, costs for operation, maintenance, research and monitoring are estimated to **10 MSEK/year**, see Table 5.

Table 5. Estimated Total Opex per year for the Demonstrator

Opex Cost Item	Cost Estimate (MSEK/year)
Operation of Wind Turbine Unit	2
Operation of Pump Units	1
Research and Monitoring	7
Total Opex	10

5. Cost Estimate of Immaterial Rights

5.1 Statoil A/S

Statoil A/S has developed the Hywind concepts and is the principal owner of that design, i.e. has the legal rights to copy the Hywind design including all drawings, calculations, operational data and internal research reports that are applicable to the design.

Statoil has patented several of their solutions to some of the technical challenges or problems encountered previously with this type of floating wind turbine unit:

US2011316277	Blade pitch control
GB2476790	Hydraulic transmission system
KR20110059613	Towing a Demonstrator with mounted wind turbine unit

The Demonstrator conceptual design is based on the Hywind design and will infringe on the patents owned by Statoil A/S.

It is assumed that Statoil will be engaged in the basic design phase of the Demonstrator project and will incur a license fee for each Demonstrator being constructed based on the Hywind design. The license fee is assumed to cover both the patent infringement and copy rights of Statoil A/S and amount to about 0.5 % of Capex excluding cable, i.e. approximately 1 MSEK. For the different configurations presented in section 8, this license fee is included in the construction cost if applicable.

The EU trade mark “Hywind” no. 1146811 is registered by Hywind A/S, which is a company owned by Wind Power A/S, which in turn is company owned by Statoil A/S.

5.2 Sea of Inventions

Sea of Inventions is a database that provides free information on patented technology designed to reduce environmental problems affecting the Baltic Sea.

The patent database contains a variety of technologies categorized according to the environmental problem or technical field they are intended to address; environmental problems related to eutrophication, hazardous substances and biodiversity; and technical fields within agriculture, fishing, household, industry & infrastructure and shipping.

The Demonstrator is mainly aimed at resolving problems emanating from eutrophication by aeration of the sea water, which categories are split into aeration in bays, aeration in lakes, aeration in the ocean, aeration with removal of algae, wave or tide powered, chemical or electrically powered, and sun or wind powered.

The database for eutrophication contains 43 patents, none of which describes the method used by the Demonstrator to oxygenize the deepwater by means of pumping down water.

5.3 Utility models

Utility models (sv. *bruksmönsterskydd*) can be registered in most EU countries, including Denmark, but not in Sweden. By utility models, inventions which are of less economic importance than those protected by patents, can be protected quicker and cheaper since neither the prior art nor novelty of the invention is reviewed.

Several utility models on pumps are presented by the Danish Patent and Trademark Office (Patent- og Varemærkestyrelsen), none of which are applicable to the method used by the Demonstrator to oxygenate the deepwater by means of pumping down water.

5.4 Technical areas to be further developed

Several technical solutions need to be developed as evident from previous BOX-WIN Technical Reports. This particularly includes the risk mitigation actions presented in Technical Report no. 5.[2]

6. Project Schedule Estimate

The basis for the project schedule estimate is that the substructure is constructed at the coast in the southernmost part of Sweden and that the wind turbine unit is imported as indicated in the BOX-WIN Technical Report no. 7.[3] Input to this schedule is data received from Swedish shipyards, such as Oresund Heavy Industry, and from Statoil A/S as related to the Hywind I and Hywind II. Input from suppliers of main equipment and marine operators has also been used to set the overall schedule.

The duration for engineering, procurement, pre-commissioning and construction has been estimated to 24 months. After that, the marine operations including load-out from quay, wet towing to site, hook-up, final commissioning, start-up and hand over to owner are estimated to last for 3 months. The overall project schedule totals 27 months: from contract award and formal start of basic design, to delivery of the FWTU ready to operate. This is visualized in Table 6 below.

It is further assumed that all remaining conceptual design work has been finalized prior to the EPCI contract award, and that the concept has been selected and is well defined. It is also assumed that all the preparation works have been performed and all required approvals have been obtained.

There are, however, several risks, other than technical, which are normally associated with a project schedule and some of these are specifically applicable to the Demonstrator project. These are further discussed in subsections 6.1 – 6.4.

Table 6. Estimated project schedule and duration in months.

Estimated project schedule and duration in months																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Project Management																											
Engineering																											
Procurement																											
Construction of Substructure																											
Construction of Wind Turbine																											
Marine Operations																											
Cable																											

6.1 Procurement Risks

Delay of procurement, delivery and testing of the deep water pumping units may have critical impact on the overall schedule. Particularly, the connection of the pump houses to the seats in the pumping pipes and separation roof must be checked and adjusted on the construction site, since that function is crucial for retracting the pumps. It cannot wait until the Demonstrator arrives on site, because the seats are then located about 30 – 40 m below the waterline and not possible to adjust.

Due to long delivery times of some specific equipment, the so called long lead items, it is necessary to start procurement activities already in the basic design phase in order to obtain vendor information, to execute detail engineering and to produce the work shop drawings in time. Long lead items are the deep water pumps, high voltage equipment, submarine cable manufacturing and installation, wind turbine nacelle and blades. A detailed procurement plan with schedules is to be developed early in the basic design phase.

6.2 Interface Risks

In principle, the Demonstrator is assembled as two separate entities; primarily, the substructure comprising the steel structure, pumping units, mooring equipment and other marine systems, which is constructed at a shipyard or large construction site and built in accordance to marine rules and regulations; secondly, the wind turbine unit comprising the wind tower, nacelle, blades and a control unit. There will be dual construction locations; one primary site for the substructure (in Sweden); and one secondary site for the wind turbine (outside Sweden). For this reason, and since these entities must interface with each other during installation onboard the Demonstrator, the project must be organized to assure that this interface is professionally managed and that the project schedule does not become jeopardized.

6.3 Marine Operation Risks

The number of vessels suitable for transportation, heavy lift operations and offshore installation of the Demonstrator is limited on the international market; many of them are engaged in lucrative offshore oil and gas projects worldwide or in the extensive development of offshore wind power projects in the North Sea.[3] The combination of the unavailability of these vessels and the narrow weather windows for the Bornholm Basin may be critical with a severe impact on the overall project schedule.[2]

One of the characteristic challenges of the project is the mating of the floating substructure with the wind turbine tower on location in the Bornholm basin. The tower is prefabricated in three or four tubular sections which are lifted by a heavy lift vessel or barge and bolted together, first with the substructure, then with each other and finally with the nacelle atop. Jack-up vessels are conveniently used for this operation of wind towers offshore, which are grouted to foundations fixed in the sea-bed at about 30 – 40 m of water depth, but cannot be used for the Demonstrator because of large water depth (>50 m). Both the substructure and the heavy lift vessel or barge are then to be fixed by each other, so both moves together as one body in the waves. Lifting and assembling operations are complex and need to be synchronized and performed in a suitable weather window without too large waves or much wind. For this reason, it is important to engage suppliers who are experienced.

6.4 Risk Mitigation Actions

In order to mitigate these risks to the project schedule, BOX-WIN recommends to start the detailed design phase earlier than what is normal for a marine new-building project, immediately after the requests for approval have been submitted to the authorities instead of waiting for their response. The main contractors and suppliers of long lead items should be signed in to the Demonstrator project early, based on a "Letter of intent" with cancellation fees to be paid by the project, if the project is stopped, or significantly delayed, by the authorities.

7. Results

The Capex cost for the 3.0 MW Demonstrator FWTU ready for operation in the Bornholm basin is estimated to 227 MSEK. Cost for the manufacturing and installation of the cable connection to the electrical grid on Bornholm is estimated to 146 MSEK. Total Capex cost is estimated to 373 MSEK. These estimates are based on proven FWTU technologies where technical and project schedule risks have been mitigated, Swedish project management and engineering, construction of the substructure in Sweden, and experienced suppliers with qualified personnel for executing the transportation and installation work.

The Opex cost for operation and maintenance of the Demonstrator, together with research and monitoring programs, is estimated to 10 MSEK/year

The duration of the project schedule is estimated to 27 months, from contract award and formal start of the engineering work until the Demonstrator is complete and ready to operate.

8. Discussion of Costs

8.1 Restitution objectives

The large-scale significant environmental objective for restitution of 70,000 km^2 of the Baltic proper is met by a total assembly of several pumping devices by pumping down 10,000 $m^3 s^{-1}$ in annual average of so called “winter water” from above the halocline at about 30 – 40 m depth to the deepwater through an outlet about 10 m above the sea floor.[13]

The Demonstrator is capable to pump 100 $m^3 s^{-1}$ by 1 MW installed pump effect. That implies 100 Demonstrator units are required to supply in total 100 MW of average pump effect a year. By 8760 hours in a year, this totals 876 GWh of pumping energy required each year. Table 7 compiles this overview.

Table 7. Restitution of the Baltic proper objectives, estimated figures per year.

Item	Formula	Total
Pumping capacity of one Demonstrator Unit		100 $m^3\ s^{-1}$
Number of Demonstrator Units required to pump 10,000 $m^3\ s^{-1}$	10,000 $m^3\ s^{-1}$/ 100 $m^3\ s^{-1}$	100 units
Installed pumping effect of one Demonstrator Unit		1 MW
Total continuous pumping effect required	100 units × 1 MW	100 MW
Total pumping energy required each year	1 MW × 100 units × 8760 h	876 GWh

8.2 Basis for discussion

Assuming at least 20 years of restitution period is required for the Baltic proper. The cost for one Demonstrator is estimated to 373 MSEK (total Capex) plus 10 MSEK a year (Opex). The cost for 100 Demonstrators operating in 20 years then becomes unreasonably large amounting to (100 × 373 + 20 × 10) = 37,500 MSEK, or 1880 MSEK each year.

This cost would easily be considerably reduced by the scale of restitution which is discussed below.

The total pumping energy required, i.e. 876 GWh, could be provided by different configurations of pumps and floating units and the parameters of which could be combined with each other to obtain minimum cost:

- by change of pump size, number of pumps and installed pumping effect per floating unit,
- by change of wind turbine size and number of FWTU's versus floating units,
- by change of cable distribution system and connection points ashore or by exclusion of cable connection,
- by change of power source type.

BOX-WIN has not elaborated on all of the above parameters but options for the number of FWTU's and floating units, the cable system and connection points, and an alternative power source have been evaluated to find if these are potentially significant to cost reduction.

8.2.1 Cable connection to shore

The connection of a standalone Demonstrator to the land-based power supply grid is very expensive as the submarine cable, installation on or in the sea bed, jointing the land cable and connection to the transformer station will all together form a substantial part of the total cost of the project. As described in section 3.6 this cost is estimated to 146 / 373 or approximately 40 % of the total Capex cost for the Demonstrator. However, connection to the grid also provides the advantage of continuous pumping at 8760 hours a year; compared to an estimated 3500 hours/year, thus approximately 40 % of the annual total, which is the normal operational time for wind turbines offshore.

8.2.2 Cost for energy, electric and diesel

In the feasibility study, the costs for energy, or the price to buy and sell energy, are assumed equal for all configurations. The price for both purchased and sold electrical energy is estimated to 1000 SEK/MWh and for diesel to 10,000 SEK/m^3, which is equivalent to the cost for electric energy (1000 SEK/MWh). These prices are considered to be gross prices including taxes and fees and are mainly based on historical development, presupposing that the realization of the Demonstrator and later a large scale pumping system will be performed some years into the future. The price levels may be somewhat conservative, i.e. on the high side, and updated cost estimations have to be performed both during the basic design phase and in later stages of the project.

8.2.3 Cluster arrangement

Several floating pumps can be arranged in a cluster of two or more slave pumps supplied by energy from a master FWTU, all connected via inter-array cables from the FWTU.

A number of such clusters would all together serve to restore the Baltic proper, whereof the conceptual Demonstrator design is used or elaborated as the FTWU. The optimum configuration of clusters has not been further elaborated on by BOX-WIN.

Since the operating time during a year may vary between the different configurations, i.e. grid connected or not, the required total number of floating units will also vary to achieve the Baltic proper objectives of 876 GWh a year.

8.2.4 Another power source

For comparison of costs, a non-renewable energy source in the form of diesel power is studied. The maximum number of production hours per year for diesel generators is set to 8760 hours.

8.2.5 Production costs

For configurations where no wind turbine unit is installed on the floating unit, the cost of production, anchoring and installation are significantly reduced; particularly the heavy duty and high lifting crane vessels are not needed and no rock ballast is required.

From large-scale development with hundreds of pump units, it is assumed that a number of effects from large-scale production and manufacturing in the Baltic countries will reduce the cost per m^3 of pumped oxygen-rich water.

Manufacturing in the Eastern Europe or in Asia has not been included in the discussion, nor has any country-specific subsidies been accounted for. Large-scale production in the Baltic Sea region should be the subject of an extended study and a more detailed cost-benefit analysis.

8.3 Identified and compared configurations

For large-scale restitution, BOX-WIN has elaborated on the electrical connection to the land based grid, where configuration I – III has electric connection to the network onshore while configuration IV – VI has no cables ashore, i.e. standalone configurations. All floating units in all configurations each have a pumping capacity of 100 $m^3 s^{-1}$. Maximum operational time for the pumps is set to 100% of the year. Reduction due to maintenance is neglected at this stage.

8.3.1 Configuration I

In this original Demonstrator configuration evaluated by the BOX-WIN project, units are equipped with 3 MW wind turbines and three water pumps with a total effect of 1 MW. The units can deliver (sell) and receive (buy) electricity from land. The cable to shore allows for sale of surplus energy and purchase of energy as required for pumping with full capacity at all times.

It is assumed that 3500 hours (40%) of the year are produced by the wind turbine operating at 3 MW, of which 1 MW is required for pumping of water and 2 MW cabled to shore and sold. During the remaining part of the year (60%) 1 MW is purchased from ashore. Estimated annual figures for configuration I are shown in Table 8.

Table 8. Configuration I, estimated figures per year.

Item	Formula	Total
Generated energy/unit	3 MW × 40% × 8760 h	10.5 GWh
Sold energy/unit	2 MW × 40% × 8760 h	7.0 GWh
Purchased energy/unit	1 MW × 60% × 8760 h	5.2 GWh
Net cost for energy (neg. value is profit) at a price of 1 MSEK/GWh	5,2 – 7,0 = -1,8	-1.8 MSEK
Annual maximum pumping hours per unit		8760 h
Number of Units to pump 10,000 $m^3 s^{-1}$		100 units
Annual total cost for all units	(see Table 14 *iii)*	695 MSEK

8.3.2 Configuration II

In this configuration alternative, units are equipped with 1 MW wind turbines and 1 MW water pumps and can only receive (buy) electricity from land. The cable to shore allows for purchase of energy as required for the pumps to operate with full power. It is assumed the 1 MW wind turbine operates fully during 40% of the year, during which time all energy (1 MW) is required for pumping of water. During the remaining part of the year (60%), 1 MW of electrical energy is purchased from shore. Estimated annual figures for configuration II are shown in Table 9.

Table 9. Configuration II, estimated figures per year.

Item	Formula	Total
Generated energy	1 MW × 40% × 8760h	3.5 GWh
Purchased energy	1 MW × 60% × 8760 h	6.3 GWh
Net cost for energy (price 1 MSEK/GWh)	6.3 × 1	6.3 MSEK.
Annual maximum pumping hours per unit		8,760 h
Number of Units to pump 10,000 $m^3 s^{-1}$		100 units
Total annual cost for all units	(see Table 14 *iii)*	1065 MSEK

8.3.3 Configuration III

In this third configuration alternative, no wind turbines are installed and all the power is purchased from the onshore grid. Equipped with 1 MW water pumps, these pumps can fully operate 100% of all hours of the year. Estimated annual figures for configuration III are shown in Table 10.

Table 10. Configuration III, estimated figures per year

Item	Formula	Total
Purchased energy	1 MW × 60% × 8760 h	8.7 GWh
Net cost for energy (price 1 MSEK/GWh)	8.7 × 1	8.7 MSEK
Annual maximum pumping hours per unit		8760 h
Number of Units to pump 10,000 $m^3 s^{-1}$		100 units
Total annual cost for all units	(see Table 14 *iii)*	1239 MSEK

8.3.4 Configuration IV

This configuration suggestion comprises solitary clusters, consisting of a master unit equipped with a 3 MW wind turbine and a 1 MW water pump, connected via an inter-array submarine cable to two slave units, which are each equipped with 1 MW water pumps but have no own wind turbine units.

The generated energy (3 MW) from the wind turbine on the master unit supplies energy to the pumps on the master unit (1 MW) plus two other standalone floating slave units, equipped with equivalent pumps (2 × 1 MW). The pump operates only when the wind turbine generates electricity.

Since the slave units are not equipped with wind turbines, the substructure whose function is to stabilize the wind turbine can be reduced. This means that the steel structure mainly consists of the three pump units and a smaller pipe up above the sea surface. The estimated weight for this reduced construction is the same as for mere pump units to the Demonstrator, i.e. approximately 500 tonnes. Estimated annual figures for configuration IV are shown in Table 11.

Table 11. Configuration IV, estimated figures per year

Item	Formula	Total
Generated energy per cluster	3 MW × 40% × 8760 h	10.5 GWh
Used energy per cluster	1 MW × 3 × 40% × 8760 h	10.5 GWh
Operating factor(total running hours for the pumps/available hours)	3 × 40% × 8760 h / 8760	120%
Annual maximum pumping hours per master unit		8760 h
Number of Solitary Cluster to pump 10,000 $m^3 s^{-1}$		83 clusters
Number of Master Units		83 units
Number of Slave Units	2 × 83 units	166 units
Total annual cost for all units	(see Table 14 *iii)*	1199 MSEK

8.3.5 Configuration V

In this alternative, the configuration consists of totally solitary units, powered by a wind turbine of 1 MW equipped with 1 MW water pumps.

The absence of a cable to land limits the pumping to the time when the wind turbine provides energy. It is assumed the wind turbine produces 1 MW during 40% of the year. All the produced energy is required for pumping of water. During the remaining part of the year (60%) winds are not sufficiently strong and no pumping is performed. Estimated annual figures for configuration V are shown in Table 12.

Table 12. Configuration V, estimated figures per year

Item	Formula	Total
Generated energy	1 MW × 40% × 8760 h	3.5 GWh
Used energy	1 MW × 1 × 40% × 8760 h	3.5 GWh
Operating factor (total running hours for the pumps/available hours)	1 × 40% × 8760 h / 8760	40%
Annual maximum pumping hours per unit		3500 h
Number of Solitary Units to pump 10,000 $m^3 s^{-1}$		250 units
Total annual cost for all units	(see Table 14 *iii)*	1151 MSEK

8.3.6 Configuration VI

This final configuration suggestion also consists of totally solitary units, but in this case without wind turbine, and instead powered by a diesel power plant of 1 MW equipped with 1 MW water pumps. Diesel on-board provides the ability to pump water 100% of all hours of the year. Estimated annual figures for configuration VI are shown in Table 13.

Table 13. Configuration VI, estimated figures per year

Item	Formula	Total
Generated energy	1 MW × 100% × 8760 h	8.7 GWh
Used energy	1 MW x 100% x 8760 h	8.7 GWh
Operating factor (total running hours for the pumps/available hours)	8760 / 8760	100%
Number of Solitary Units to pump 10,000 $m^3 s^{-1}$		100 units
Total annual cost for all units	(see Table 14 *iii)*	1244 MSEK

8.4 Identified cost reduction factors

For a full scale development of a pumping system in the Baltic proper, with 100 or more floating units located within the territorial boundaries or exclusive economic zones (EEZ) of both Sweden as well as other countries around the Baltic Sea, the following cost reduction possibilities have been identified. The comparison between six different configurations of the floater and modes of operation of the power generation equipment and the deep water pumps is shown in Table 14. The estimated cost of a system for the Bornholm basin based on 1000 $m^3 s^{-1}$ pumping capacity is described in section 8.5.

8.4.1 Project Management, Engineering, Client

Project management, engineering and client related costs for the first five units are estimated to be the same as for the Demonstrator; then a cost reduction due to mass production and economies of scale is assumed to be 10% of the related cost for the Demonstrator.

8.4.2 Construction cost due to reduced steel weight and lower labour cost

It is assumed that the potential weight reduction from optimization of the steel substructure from the Demonstrator to the subsequent units is on par with that from the Hywind I (approximately 1500 tonnes) to the Hywind II (about 1100 tonnes), i.e. a weight reduction potential of 30%.

As described in Section 2, construction costs of large marine and offshore steel units or vessels are based on weight. The weight of a mass-produced unit, as compared to a one-off unit, is estimated to be 30% less and, consequently, the construction cost will be reduced to 70%

It is further assumed that 30% of the total amount of steel substructures will be constructed in Sweden and Finland and with equal cost level. The remaining 70% will be constructed in the Baltic countries, Russia, or Poland with a cost level of 60% compared to Sweden. Based on 100 units, this provides an average cost for the construction of approximately 70% of the cost in Sweden. In total, this will this reduce the cost for construction of the substructure with 50%.

8.4.3 Components and equipment

Costs of components and equipment are assumed to decrease as a result of negotiations during large-scale manufacturing. The discussion is based on expected cost of hours worked and a price on purchased services and components per unit to be reduced compared to the one off Demonstrator down to 70% of the original price.

8.4.4 Installation cost

The large scale development of a pumping system in the Baltic proper is estimated to be structured in groups, or farms, of 20 plus units. This results in lower start-up costs, higher utilization of equipment and vessels, as well as an optimized mooring system. The cost of installation and anchor equipment is assumed to decrease to 50% per unit compared to the Demonstrator.

8.4.5 Submarine cable, installation and grid connection

In the alternatives with cable connection to shore it is assumed that only one main cable including onshore and offshore cable will feed a group of 20 floating units. The related cost for cable and installation per floating unit is assumed to be 5% for each of the units compared to the cost for cable to the Demonstrator (i.e. 146 MSEK).

8.4.6 Inter-array cable, installation and connection

In those alternatives where the units are internally connected, it is assumed that the inter-array cables connect units of a group of 20. The estimated cost for array cable is 2 MSEK/km and the distance between each unit in a group is estimated to 5 km. Hence, the cost for array cable amounts to 10 MSEK per floating unit.

8.4.7 Research and monitoring

The cost for research and monitoring of environmental effects in average per mass-produced unit is assumed to be 10% of the costs estimated for these programs for the Demonstrator.

8.4.8 Operation and maintenance of the wind turbine

The cost for the operation and maintenance of the wind turbine itself is assumed to be 0.7 MSEK/MW. The cost for a 3 MW turbine is thus 2 MSEK/year and for a 1 MW turbine 0.7 MSEK/year.

8.4.9 Operation and maintenance of the under water pumps

Cost for operation and maintenance of the mass-produced pumps are assumed to be reduced to 50% compared to the Demonstrator.

8.4.10 Operation and maintenance of the diesel generators

The cost for the operation and maintenance of the diesel generator set is assumed to be in line with the related cost for wind turbines of 1 MW equal to 0.7 MSEK/year.

Table 14. Principle comparison of i) Capex data, ii) Opex data iii) and total annual costs between six different configurations of the floater and modes of operation of the power generation equipment and the deep water pumps.

i)

Capex data	**RF**[a)]	**I**	**II**	**III**	**IV**			**V**	**VI**
					Master	**Slave units**			
Max. generated energy (MW)		3	1	0	3	0	0	1	1
Max. purchased energy (MW)		1	1	1					1
Max. sold energy ((-)MW)		-2							
Pumped volume per unit ($m^3 s^{-1}$)		100	100	100	100	100	100	100	100
Part of year with own energy production		0.4	0.4	1	0.4	0.4	0.4	0.4	1
Part of year pumps are running		1	1	1	0.4	0.4	0.4	0.4	1
Part of year energy is purchased		0.6	0.6	1	0	0	0	0	1
Water volume (m^3) pumped by sub units					40	40	40		
Annual average pumped volume per unit or cluster ($m^3 s^{-1}$)		100	100	100	120			40	100
No. of units to pump 10,000 $m^3 s^{-1}$ in BP[b)]		100	100	100	83	83	83	250	100
Engineering & Client	0.1	4	4	4	4	2	2	4	4
Pump equipment	0.7	6	6	6	6	6	6	6	6
Substructure 1500 tonnes	0.5	30			30				
Substructure 1000 tonnes	0.5		20					20	
Substructure 500 tonnes	0.5			11		11	11		11
Wind turbine unit (3 MW)	0.7	27			27				
Wind turbine unit (1 MW)	0.7		11					11	
Diesel (1 MW)	0.7								3
Marine operations (3 MW WTU)[c)]	0.5	17			17				
Marine operations (1 MW WTU)[c)]	0.35		5					5	
Marine operations (no WTU)[c)]	0.35			4		4	4		4
Cable to land per 20 units (MSEK)	1	6	6	6					
Array cable per unit in 20 unit clusters	1	10	10	10		10	10		
Insurance (MSEK)	1	2	2	2	2	2	2	2	2
Capex per unit (MSEK)		100	62	41	84	33	33	46	28
Capex for sub units in BP[b)] (MSEK)					7008	2733	2733		
Total Capex for BP[b)] (MSEK)	-	9995	6190	4065	12,475			11,513	2760

ii)

Opex data	RF[a]	I	II	III	IV Master	IV Slave units		V	VI
O & M[d], 3 MW WTU[c] (MSEK)	0.7	210			175				
O & M[d], 1 MW WTU[c] (MSEK)	0.7		70					175	
O & M[d], 1 MW Diesel (MSEK)	0.7								70
O & M[d], 1 MW Pumps (MSEK)	0.5	100	100	100	83	83	83	250	100
R & D[e] per unit (MSEK)	0.1	60	60	60	50	50	50	150	60
Cost for electric energy (MSEK)	8.76	526	526	876					
Income for sold elect. energy (MSEK)	8.76	-701							
Cost for diesel fuel (MSEK)	8.76								876
Opex for sub units in BP[b] (MSEK)					308	133	133		
Total Opex for BP[b] (MSEK)		195	756	1036	575			575	1106

iii)

Annual costs (MSEK/year)	No. of years	I	II	III	IV	V	VI
Depreciation	20	500	310	203	624	576	138
Total Opex in BP[b]		195	756	1036	575	575	1106
Total annual cost		695	1065	1239	1199	1151	1244

a) RF – Reduction Factor
b) BP – Baltic Proper
c) WTU – Wind Turbine Unit
d) O & M – Operation and Maintenance
e) R & D – Research and Development

8.5 Estimation of costs for development of the Bornholm Basin

A pumping system for the Bornholm Basin is assumed to require 10 units based on the Demonstrator design, i.e. configuration I (see section 8.3.1), with totally 1000 $m^3 s^{-1}$ of pumping capacity. The factors for cost reduction per floating unit will increase compared to figures estimated for mass production of 100 or more units. Project management, engineering and client related costs for the first two units are estimated to be the same as for the Demonstrator; for the remaining units it is assumed to be 25% of the related cost. Cost for construction, labour and marine operations is assumed to be 70% of the Demonstrator. The cost for research and monitoring program per unit is assumed to be 30% of the cost for one

Demonstrator, compared to 10% in mass production. Marine operations are assumed to be reduced to 70 %. It is further assumed that the 10 units will be connected by array-cables at an average internal separation distance of 10 km, thus giving approximately 100 km of total length of inter-array cables; as for the Demonstrator, only one feeder cable will be connected to shore. Cost estimates are to be detailed during the basic design phase based on final locations, distances, connection point on shore and market situation.

Table 15. Estimation of costs for development of the Bornholm Basin by 10 Demonstrator units.

Development of the Bornholm Basin by 10 Demonstrator units, electrically connected to shore and internally by array cables	
Capex (MSEK)	1584
Opex and depreciation (MSEK)	104
Electric energy cabled to Bornholm (GWh/year)	18

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