A preliminary techno-economic comparison between a grid-connected and non-grid connected offshore floating wind farm

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***Abstract*— Non-grid connected (NGC) floating offshore wind (OW) turbines can signify a solution for harvesting wind energy far offshore, addressing some key issues including the deep waters and lack of grid connection, while also exploiting the higher capacity factors. Towards this direction, on-board energy storage in the form of hydrogen production is one of the most promising solutions, often cited in literature. This study aims to perform a preliminary techno-economic analysis to assess the trade-offs, in terms of cost, between a far offshore grid-connected (GC) floating wind farm and a NGC wind farm integrated with an electrolyser for the production of hydrogen. To this end, a lifecycle techno-economic model coupled with an O&M model developed for offshore wind installations are employed. The model is applied to a hypothetical wind farm located 200km from the shore. For the GC system, O&M costs along with the costs of acquisition of the electric system (offshore cable and offshore substation) appeared to be the main contributors to the Levelised Cost of Electricity (LCOE). As far as the NGC system is concerned, it was concluded that a higher annual capacity factor (>60%) could potentially achieve viability of the investment.**

Keywords—non-grid connected offshore wind farm, hydrogen storage system, techno-economic analysis

I. INTRODUCTION

According to the Offshore Valuation Study published in May 2010, Scotland has 206 GW of offshore wind (OW), wave and tidal resources - almost 40% of the total UK resource [1]. NGC floating OW can address some key issues of Scottish OW, including the deep waters and the lack of grid connection. Furthermore, NGC wind can be used to take advantage of the far OW energy potential (characterised by high winds and limited seasonal variations), which would be prohibitively expensive to connect to the grid. UK is one of the windiest countries in Europe and it has been argued that the scale of wind power development exceeds the ability of the grid to integrate the intermittent wind energy capacity.

To further increase the technical potential, offshore wind farms which can be deployed far offshore must be considered. At such long distances, economic aspects of grid-connected wind turbines need to be further investigated, as connection to the grid becomes a complicated process. On board storage of electricity in a series of forms (compressed air energy storage, batteries, hydrogen, etc.) can address this issue by transferring the energy from the source of production to the consumer. Energy storage solutions, such as hydrogen, can help manage the issue of intermittency, as the stored energy can be fed back into the grid when demand rises or used for other purposes, as well as offer the potential to channel renewable electricity to sectors which are difficult to decarbonize, such as industrial and transport applications [2].

Innovative solutions, presenting market potential, have been explored by industry and academia, at a conceptual level, to exploit the untapped wind energy potential, far offshore. Related activities that can be possibly performed for NGC wind farms include, for example, the production of hydrogen through water electrolysis, the production of ammonia and for the production of aquaculture (fish, shellfish, sea weeds, etc.). Concepts for multi-purpose platforms in deep waters have been investigated in the past by research projects, such as the TROPOS project [3], which aims to develop a modular multi-use platform, coupling several activities, amongst which aquaculture production and renewable energy conversion, as well as the H2Ocean project [4] developing a wind-wave power open-sea platform equipped for hydrogen generation.

In this paper, we perform a preliminary techno-economic analysis to compare the feasibility of grid-connected in comparison to non-grid connected wind farms. Hydrogen production as a means of energy storage for far NGC offshore wind farms was chosen for further analysis of its techno-economic potential.

The rest of the paper is organized as follows: in the next section, a short overview of energy storage options is performed also mapping the hydrogen market potential; the techno-economic model developed is outlined in section 3. Next, section 4 presents the case study and the results from the application of the technoeconomic model. In section 5, key conclusions of this work are drawn.

II. Energy storage options for offshore wind energy

A major challenge for offshore wind farms installed far offshore is the transportation of the electric energy to end users, as the connection to the grid is not economic on such long distances from shore [5]. There are numerous energy storage options available which are based on different physical principles (e.g. chemical, mechanical) with different conversion efficiencies, energy densities, and location conditions. Common applications include pumped-hydro storage, compressed air storage, batteries (Li-ion, metal-air batteries), production and storage of fuel (e.g. hydrogen) for fuel cell electric vehicles, among others [6]. A general overview of different storage technologies coupled with wind energy farms is provided in [7,8], describing the operating principles and specifications (capital cost, discharge time, power density, storage duration, lifetime and impact on the environment) of storage technologies.

Specific energy of storage technology options is a key parameter when considering wind energy storage, as it affects the amount of energy that can be stored in the available onboard space. Li-ion batteries and hydrogen based energy storage systems are among the options with the highest specific energies, namely 120–200 Wh/kg [9] and 400–1000 Wh/kg [10], respectively.

In this study, a hydrogen storage was considered as a suitable option for storing wind energy of far offshore floating wind turbines. Hydrogen can address the decarbonization challenge of certain sectors that may be difficult to decarbonize by means of electrification; for example, in industry for the production of ammonia, the transport sector in fuel cell electric vehicles and power generation through injecting certain amount of hydrogen into existing natural gas grids. Hydrogen from renewable energies could facilitate the integration of high levels of intermittent renewable energy into the energy system. The produced hydrogen can be stored in a compressed form and transferred either for direct use as a fuel (e.g. fuel cells) or further processing. It can, therefore, offer a flexible load and can provide an extra source to cover the demand for hydrogen.

Over 60 million tons of hydrogen are produced every year globally [11]. The hydrogen generation market is rapidly growing over the last decades and is expected to reach $199.1 billion USD in 2022. Hydrogen has received a great deal of attention across the mobility, industry (large and light) and electricity production sectors.

As far as the mobility sector is concerned, hydrogen can be used in fuel cell cars, vessels, buses, trucks and as fuel for aircrafts. However, the competition with electric vehicles and the lack of hydrogen distribution infrastructure, which is a greater problem for fuel cell than it is for electric vehicles, have restricted their wide deployment. Industrial applications include the production of ammonia, the crude oil processing in refineries and the methanol production in the chemical industry. Finally, another niche hydrogen market lies in the production of electricity, through medium scale stationary fuel cell systems (200-1000kW) and CHP (Combined Heat and Power) or CCHP (Combined Cooling, Heat and Power) plants for district's scale power generation.

Hydrogen generation from wind energy can be realised by the electrolysis of desalinated water. To this end, an appropriate seawater desalination system needs to be installed, which will feed the electrolysers with pure, distilled water. The electrolyser uses direct current (DC) electricity to initiate the non-spontaneous chemical reaction for the dissociation of water into hydrogen and oxygen. A recent study assumes that the current energy consumption of the electrolyser system amounts to 58 kWh/kg [5], which is in agreement with [12], while the current electrolyser cost amounts to 1000 EUR/kW. The main wind-hydrogen technology components include [4] the wind plant, the desalination unit, the electrolyser and the compressed hydrogen storage unit. There are three types of electrolyser technologies used or under development today: Alkaline (ALK) electrolysers, Proton exchange membrane (PEM) electrolysers and Solid oxide electrolysers [2].

One of the issues that need to be further investigated regarding the potential for offshore production of hydrogen is the storage and transportation. Since the pipelines for far OW energy installations are not a feasible option, moving tanks of liquefied (LH2) or compressed gas hydrogen (CGH2) need to be employed. Transportation of hydrogen can be realised by means of OW converters and tube tankers [5]. OW converters can sail to the port terminal to unload the hydrogen when their on-board storage tanks are full. Considering that the speed of the wind energy converters can be as high as 20 knots [13], it will take the converter approximately 8.1 hours to cover 300 km to reach the terminal. Tube trailers can potentially be applied for wind energy converters installed farther from shore, which would require offshore collection infrastructure and carriers to transport hydrogen to the port. However, it should be noted that the capacity of CGH2 tankers is less than a third of the capacity of a LH2.

III. Lifecycle techno-economic model

This section summarizes the main features of the techno-economic model developed, distinguishing the components included in the grid connected (GC) system and the ones in the non-grid connected (NGC) system. In the case of GC systems, main difference is the existence of the electric system (inter-array, export cables and offshore substation) for the integration and transmission of the produced electricity to the grid. In the case of the NGC systems, the infrastructure that performs the hydrolysis system along with the marine transportation of hydrogen need to be accounted.

The general technoeconomic model follows a lifecycle approach covering the main stages during the life of the asset, namely the Development & Consenting, the Production & Acquisition, the Installation & Commission, the Decommissioning and the Operation & Maintenance.

A. *Grid connected system*

The GC floating wind farm consists of the wind farm turbines and the balance of the plant (BoP). The electric system of the wind farm enabling the integration and transmission of electric energy consists of: two offshore substations, Mean Voltage (MV) submarine cables used as array cables, High Voltage (HV) export cables, which carry the stepped-up voltage from the offshore substation to the grid connection point. More details on the assumptions on lifecycle costs of the offshore wind farm can be found in [14].

Costs and specifications of the spar floating structure (floating substructure and mooring system) were adopted from [15]. O&M costs were estimated through an in-house tool which is described and applied in [16]. The calculation of the installation costs of the floating wind turbines was based on the methodology developed by [17], while the decommissioning process is assumed to follow a reverse installation process estimating the cost of bringing the components ashore. However, this process was assumed to be performed simpler and faster than the installation. As such, for simplicity, these costs were estimated as a percentage of the installation costs [15], as shown in Table 1.

B. *Non-grid connected system*

As mentioned above, the offshore wind park of the NGC system bears the same characteristics as the GC system, apart from the fact that the electricity produced by the turbines is not injected to the grid; rather, it is used for electrifying the production process of hydrogen. Hence, no integration and transmission infrastructure is required and therefore these components were omitted from the calculation. The storage device analysed in this study is coupled with the wind turbines. The system consists of an electrolyser for the production of hydrogen from the electrical energy produced by the wind farm, a compressor and a storage device (Figure 1). The electrolyser is used to decompose water to hydrogen and oxygen, which is subsequently compressed using a compressor to allow for efficient storage in the offshore terminal. The desalination of sea water is assumed to be realised through a desalination system; however, since according to [18], capital cost and energy consumption of this system accounts for less than 1% of the electrolyser cost, this cost was neglected. Hydrogen can also be liquified through a liquefication process before its storage. The compression/liquefaction processes have also electricity requirements, which are assumed to be covered by the power produced by the wind turbine; hence, these components also need to be installed on board (an alternative would be the use of fuel cells to convert to produce electricity from hydrogen, but low efficiency would render the process non-economic [5]).

Transportation of the compressed hydrogen to the shore can be realized via carriers using hydrogen as fuel. This process has also been used for the transportation of offshore natural gas, by boiling-off natural gas to power ships used as carriers. Amount of natural gas consumed is approximately 0.1-0.25% of the cargo according to [19]. In this study, a rate of 0.2% was assumed for a cargo of 153 tons. The compressed hydrogen is then stored in the onshore terminal which is further delivered to end-users via trucks. Key characteristics of the NGC system are included in Table 2.

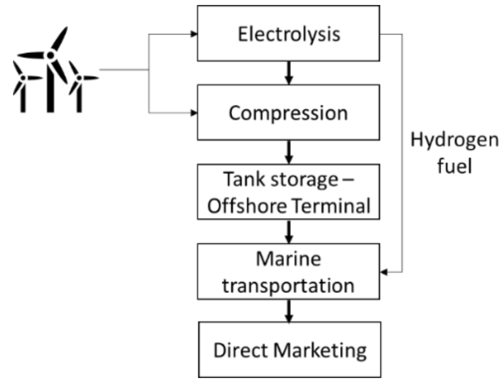

Figure 1 Components of NGC system

IV. Results - Case study application

The 360 MW wind farm is located 200km from the shore in the North Sea and is comprised of 100 floating wind turbines with a spar platform as substructure. Water depth in the installation site was assumed 200m.

A. *Grid connected system*

Table 1 summarizes the cost components of the techno-economic analysis of the GC wind farm. Total produced energy was calculated 983,450 MWh/year, the capacity factor 40.5%, the time-based availability 77% and the LCOE 103 £/MWh. The breakdown of the LCOE (see Figure 2) indicates that production and acquisition costs have the highest share (43.2%), followed by the O&M costs (37%). During the latter stage, the share of cost of offshore substations (19.5%) and the cost of export cables (15%) are the main contributors of this stage, while the breakdown of the O&M costs indicates that downtime due to weather unsuitability has the highest value (Figure 3). NPV was estimated £-181.3 million at a real discount rate 6.15% and strike price 100 £/MWh (from year 6-20) and electricity market value 45 £/MWh (from year 21-29).

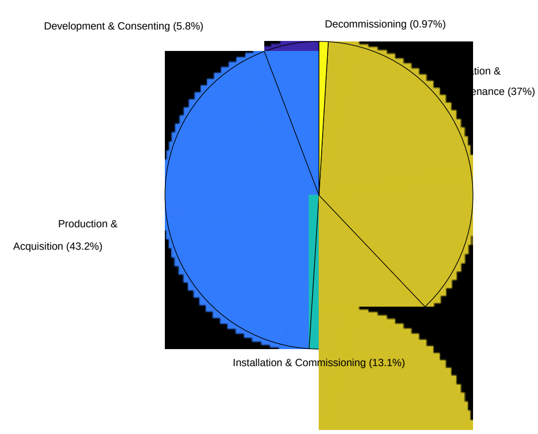

Figure 2 Breakdown of LCOE of the GC system

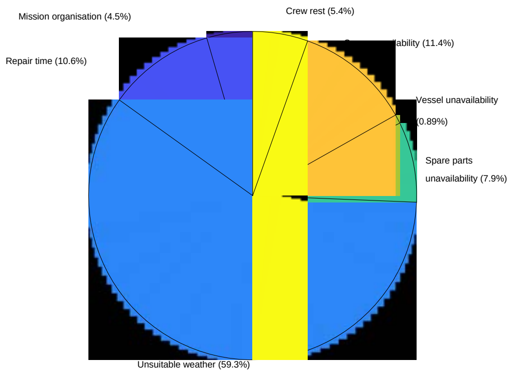

Figure 3 Breakdown of O&M downtime of the GC system

B. Non-grid connected system

The main input parameters of the NGC wind farm case study coupled with a hydrogen production unit are summarized in Table 2 and the resulting lifecycle costs are listed in Table 3. Data were adopted from [5,20,21]. The produced hydrogen is compressed and stored in tube trailers whose capacity was estimated 340 kg of hydrogen per trailer at 540 bars while the ratio of stored hydrogen mass to trailer mass is 0.03 [5,22]. Tube trailers are loaded to marine carriers (maximum capacity was assumed 153 tons per cargo, according to [5], which is equivalent to 13 tube trailers) and transferred to the onshore terminal for direct marketing. Offloading, compression, offshore storage, etc. may lead to losses of hydrogen, which cumulative can reach the percentage of 11%. Taking into account the energy density of hydrogen (33 kWh/kg), along with the losses and conversion efficiencies of the processes, annual production of hydrogen was estimated 14,850 tons/year. The total investment cost of the hydrogen production infrastructure amounted to £191.4 million, while annual operation and maintenance costs from the hydrogen production (£6.2 million/year) were further added to the total costs of the wind farm (excluding costs associated with the electric system, as mentioned above). Price of hydrogen was assumed 5£/kg and the lifetime of the asset comprises 30 years in total (5 years of construction and licensing processes, 25 years of operation and 1 year for the decommissioning).

Under the above conditions and assumptions, the NPV of the investment was negative (£ -232 million) at a real discount rate 6.15% indicating that the investment would not be viable under the current conditions. Nevertheless, following a preliminary sensitivity analysis (shown in Figure 6), it was concluded that a positive NPV would be possible for an average annual capacity factor equal to or higher than 60% (instead of the calculated 40.5%) (NPV=£73.9 million at an assumed real discount rate 6.15%). Higher (than the estimated) capacity factors can be realised considering the fact that Equinor's Hywind Scotland pilot park has achieved an annual capacity factor of 56% [5,23]. The effect of change of the discount rate and investment cost of electrolyser is also illustrated in Figure 6. The capacity factor appears to have the greatest influence on the NPV of the investment, namely an increase of NPV by 132% was estimated when increasing the capacity factor to 60.7%, followed by the discount rate (-41%) and the installation cost of electrolyser (-18%).

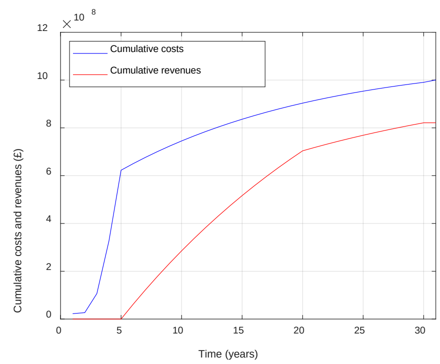

Figure 4 Cumulative cost revenues profile of the GC system

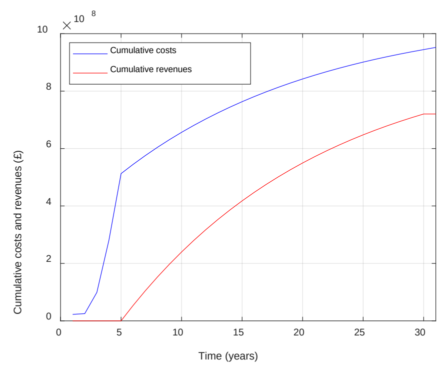

Figure 5 Cumulative costs and revenues of the NGC system

Table 1 Lifecycle costs of GC offshore wind farm

Lifecycle Phase	Cost components	Value	Units
Development and Consenting	Development, legal, environmental studies	20,6559.5	£/MW
Production and Acquisition	Turbine & Tower	1,495,000	£/MW
	Substructure	748,000	£/MW
	Grid connection		
	Inter array cables	281,000	£/km
	Export cables	443,000	£/km
	Offshore substation (x2)	320,833.3	£/MW
	Mooring system		
	Steel wire	66	£/m
	Chain	250	£/m
Installation and Commission	Wind turbine	154,830	£/MW
	Floating structure	42,940	£/MW
	Electrical infrastructure		
	array cables	410.2	£/km
	export cables	2,153.6	£/km
	Substation	1,194.6	£/MW
	Cost of start up	600,000	£
	Mooring lines and anchors	41,065	£/turbine
Decommissioning	Complete wind turbine and substructure (70% of installation cost)		
	Electrical infrastructure		
	Subsea cables	10% of installation	
	Offshore substation (x2)	90% of installation	
	Mooring lines and anchors	90% of installation	
Total capital cost		814,292	k£
Total O&M of wind turbines		37,343	k£/year
LCOE		103	£/MWh

Table 2 Key characteristics and results of hydrogen production system

	Electrolyser	Compressor	Storage-trailer	CGH2 Marine carrier
Storage capacity (kg/unit)	-	-	720	153,000
Conversion efficiency	66%	85%	100%	-
Total investment cost (£/unit)	881,100	720,900	20,425.5	489,500
Total maintenance cost (£/year)	56,070	7,209	204.3	-
Number of units	100	64	563	3
Annual production of energy/hydrogen	644,394.0 kWh/year	547,734.9 MWh/year	14,772.2 tons/year	-

Table 3 Lifecycle costs of NGC system

Lifecycle Phase	Cost components	Value	Units
Development and Consenting	Development, legal, environmental studies	20,6559.5	£/MW
Production and Acquisition	Total offshore wind energy installation	As in Table 1, excluding grid connection	
	Electrolysers (incl. installation)	88,110	k£
	Compressors (incl. installation)	46,137.6	k£
	Trailers (incl. installation)	11,500	k£
	Carriers (incl. installation)	1,468.5	k£
	Other (incl. installation)	44,165	k£
Installation and Commission	Total offshore wind energy installation	As in Table 1, excluding grid connection	
Decommissioning	Total offshore wind energy installation	As in Table 1, excluding grid connection	
Operation & Maintenance	Electrolysers	5,607	k£/year
	Compressors	461.4	£/year
	Trailers	115.02	k£/year
Total capital cost		666,231.3	k£
Total O&M of wind turbines		43,526.3	k£/year

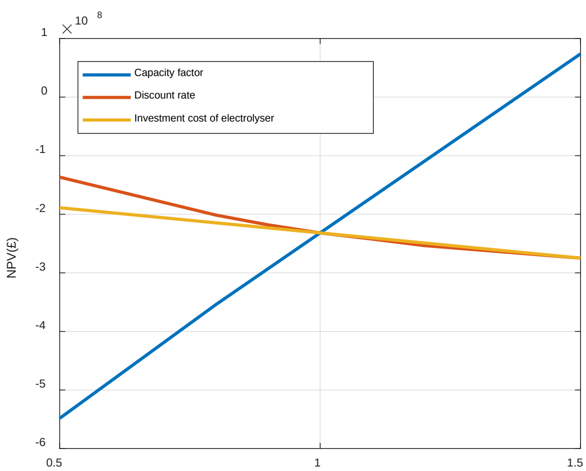

Figure 6 Sensitivity analysis of key parameters of NGC system

V. Conclusions

There is currently an increasing research interest in hydrogen production from renewable energy sources and its potential to be an energy storage option. Electrolysers are usually used to split water into hydrogen and oxygen using electricity. Electrolysers coupled with wind energy power turbines can become a carrier for renewable electricity and enable the integration of intermittent renewables in the energy system, offering a flexible load. Hydrogen has multiple applications in the industry and transport sector as well as for gas grid injection.

Far offshore wind farms, not being economical to be grid connected, can potentially use this technology for on-board production of hydrogen, taking advantage of the high wind potentials and low conflicting uses of the sea space is these areas.

This paper aims to investigate this potential and compare the economic feasibility between a far offshore grid connected and a non-grid connected system which is integrated with hydrogen production infrastructure, by performing a techno-economic analysis. The analysis combines a high-fidelity lifecycle techno-economic model along with an O&M model developed for offshore wind installations. To this end, a hypothetical case study of a wind farm located 200km from shore was investigated. It was shown than, for the conditions considered, neither system is expected to be profitable. For the GC system, the higher contributors of the LCOE were the resulting O&M costs along with the costs of acquisition of the electric system. As far as the NGC system is concerned, the comparatively higher capacity factor was not enough to compensate for the extra costs induced by the hydrogen production infrastructure. However, it was concluded that the investment could become viable under higher capacity factors (>60%).

Acknowledgements

This work was supported by grant EP/S000747/1 for University of Strathclyde, SUPERGEN ORE HUB 2018, UK Engineering and Physical Sciences Research Council (EPSRC).

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