international journal of hydrogen energy xxx (2018) 1–24

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters

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ARTICLE INFO

Article history:
Received 21 December 2017
Received in revised form
19 February 2018
Accepted 22 February 2018
Available online xxx

Keywords:
Offshore wind energy
Sailing wind turbines
Energy ship
Hydrogen
Techno-economic analysis

ABSTRACT

Innovative solutions need to be developed for harvesting wind energy far offshore. They necessarily involve on-board energy storage because grid-connection would be prohibitively expensive. Hydrogen is one of the most promising solutions. However, it is well-known that it is challenging to store and transport hydrogen which may have a critical impact on the delivered hydrogen cost.

In this paper, it is shown that there are vast areas far offshore where wind power is both characterized by high winds and limited seasonal variations. Capturing a fraction of this energy could provide enough energy to cover the forecast global energy demand for 2050. Thus, scenarios are proposed for the exploitation of this resource by fleets of hydrogen-producing wind energy converters sailing autonomously. The scenarios include transportation and distribution of the produced hydrogen.

The delivered hydrogen cost is estimated for the various scenarios in the short term and in the longer term. Cost estimates are derived using technical and economic data available in the literature and assumptions for the cost of electricity available on-board the wind energy converters. In the shorter term, delivered cost estimates are in the range 7.1–9.4 €/kg depending on the scenario and the delivery distance. They are based on the assumption of on-board electricity cost at 0.08€/kWh. In the longer term, assuming an on-board electricity cost at 0.04€.kWh, the cost estimates could reduce to 3.5 to 5.7 €/kg which would make the hydrogen competitive on several hydrogen markets without any support mechanism. For the hydrogen to be competitive on all hydrogen markets including the ones with the highest GHG emissions, a carbon tax of approximately 200 €/kg would be required.

Introduction

By the end of 2016, the total installed capacity of offshore wind energy in Europe was 12.6 GW, corresponding to approx. 3600 grid-connected turbines [1]. All of them were bottom-fixed wind turbines. According to the European Energy Agency [2], the constrained technical potential for bottom-fixed offshore wind energy (water depth less than 50 m) is 3500 TWh per year by 2030. It corresponds to 16% of the forecasted 2030 energy

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https://doi.org/10.1016/j.ijhydene.2018.02.144
0360-3199/

demand in the European Union (21,000 TWh/y) in the reference scenario in [3]. Moving farther offshore is thus necessary to increase the offshore wind technical potential.

Floating wind turbines have been developed (e.g. [4,5]). They address the challenge of deeper water. The world's first floating wind farm is expected to start producing by the end of 2017 [6]. The offshore wind technical potential available nearshore (<90 km) and in intermediate water depth (<200 m) is in order of 180,000 TWh/y according to [7], which is less than the forecasted energy demand in 2050 in the reference scenario of [8] (240,000 TWh/y). To further increase the technical potential, wind energy conversion technologies which can be deployed far offshore (hundreds to thousands of km from shore) must be developed. There, it is no longer feasible from an economic perspective to use grid-connected wind turbines because grid-connection increases linearly with increasing distance to shore [9]. Other means to transfer the energy from the source of production to the consumer must be considered. It involves energy storage for which many options (compressed air energy storage, batteries, hydrogen, etc.) are available [10].

A remarkable benefit of on-board energy storage for far offshore wind energy converters is that the constraint for the supporting platform to be stationary is removed. In other words, the system can be mobile. Being mobile has two advantages. Firstly, it removes the need for moorings & anchors which has a significant impact on capital expenditures (CAPEX). According to [5], moorings and anchors (including installation) account for approximately 20% of CAPEX of typical floating offshore wind projects. Secondly, the system being mobile, it may sail to the resource which may lead to greater capacity factors. Note that capacity factor for offshore wind turbines is already rather high, being in average approximately 40% according to [5]. Still, for harvesting the far offshore wind energy resource, it appears that mobile wind energy conversion systems may represent a cost competitive alternative to floating offshore wind turbines.

To our knowledge, there has been only a small number of technology proposals for harvesting wind energy far in the ocean with mobile systems [11–18]. These systems implement quite diverse technologies, see Fig. 1. However, they can broadly be classified in two categories: sailing wind turbines and energy ships. Sailing wind turbines make use of conventional wind turbines [14]. They can be vertical-axis wind turbines [18]. In these concepts, wind energy is directly converted into electricity. In energy ships, wind energy is primarily used to propel the ship. Electricity generation is obtained through a water turbine attached to the hull of ship. For wind propulsion, it has been proposed to implement conventional sails [11,13,16], kites [15,18], rigid wing sails [16] or Flettner rotors [17]. Regarding the hull shape, catamarans are used in most proposals. One exception is the proposal of [14] which uses a very large proa-shaped hull. Obviously, other hull shapes are available such as monohulls, trimarans etc.

A common feature of all the aforementioned technology proposals is the use of hydrogen for the storage of the harvested energy. Note that in [15], it is proposed to further convert the produced hydrogen into methanol or to use it to convert carbon dioxide into storable forms of liquid for Carbon Capture and Storage (CCS). The concept of using renewable energy sources or renewable feedstock for hydrogen production or other high value chemicals is widely spread nowadays. Renewable hydrogen production can be achieved from biomass [19,20], from solar energy through photolytic processes [21,22], or from renewable electricity through water electrolysis (e.g. [23]). Pilot plants for hydrogen production from renewable electricity have been reviewed in [24]. Techno-economic studies are available for hydrogen production from wind farms, e.g. [25,26].

To our knowledge, only a few references discuss the techno-economic potential of one or the other of concepts of energy ships or sailing wind turbines. Promising cost estimates for LH2 (Liquid hydrogen) have been obtained in [27] for two particular designs of an energy ship implementing a large kite sailing at high altitude. However, some of their economic and technical data is questionable (for example: 50US$/kW for the electrolyser). In [15], it is shown that fleets of such energy ships deployed in the Southern oceans and the North of the Pacific Ocean could provide 47 TW of average power output which corresponds to 170% of the forecasted global energy demand for 2050. Thus, this study indicates that there is a huge potential of renewable energy available in the winds over the oceans. Recently, in [28,29] a techno-economic study of optimal ocean wind energy converters was published using a multi-pole systems analysis. In [28] the minimal levelized cost of hydrogen was determined to be 13.9 €/kg, whereas in [29] it was claimed that the operation of small sailboats could produce a profit at a hydrogen price of 10 €/kg.

Thus, it appears that no comprehensive study of the far offshore wind energy potential is available in the literature. Also, all technology proposals suggest converting wind energy to hydrogen but they don't discuss the other options nor the hydrogen market requirements. Finally, it is well-known that hydrogen is a challenging fuel to store and transport which may have a significant impact on the cost of hydrogen when delivered to the end-user. Therefore, the aim of this paper is to address these knowledge gaps.

The far offshore wind energy resource

The global wind energy resource is estimated to 15, 000, 000 TWh/y [30]. This estimate takes into account wind energy from the lower to the upper atmosphere. According to [7], the onshore wind energy resource in the lower atmosphere is 1,100,000 TWh/y. It is the wind energy resource that can be harvested using conventional wind turbines. Note that there are attempts to develop new technologies for harvesting the wind energy resource at higher altitudes. An example is the energy kite developed by the Makani company [31].

Regarding offshore, the nearshore (<90 km) wind energy technical potential in the lower atmosphere and in intermediate water depth (<200 m) is 180,000 TWh/y according to [7]. Curiously, it seems that there has been no assessment of the global offshore wind energy potential in the lower atmosphere (including the far offshore). Since the oceans cover 2/3 of the planet surface, a rough estimate of this potential is twice the onshore potential. It leads to 2,200,000 TWh/y. It corresponds to 12 times the near shore wind energy resource and more importantly 9 times the 2050 forecasted energy demand

Please cite this article in press as: Babarit A, et al., Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.02.144