Viability of hydrogen production from a dedicated offshore wind farm-underground storage in the Irish Sea in 2030

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Abstract. This paper presents a concept of hydrogen production (H2P) from a dedicated offshore wind farm (OWF) and stored underground. A new model is introduced to assess the viability of a fixed-bottom OWF in a potential offshore wind pipeline in the Irish Sea, where all costs are projected in 2030. It explains the need to develop market opportunities for the vast offshore wind potential in Ireland, to ascertain both decarbonisation and energy security in multiple sectors, where dedicated H2P-OWFs are potential drivers. It reviews hydrogen storage methods and shows artificial underground salt caverns suitable to store hydrogen at large scales and long-terms. The OWF consists of 16×6.33MW turbines and proton exchange membrane electrolyzers. The net present values and discounted payback periods (DPBs) are calculated at offloading periods of 2, 7, 15, 30 and 60 days, and in good agreement, where the DPBs are 7.8, 8.6, 10.0, 12.1 and 20.3 years, respectively. Both economic indicators show that the H2P-OWF is profitable with the hydrogen price at €5/kg but marginal at €3/kg. Offloading at shorter periods of 2-15 days is more profitable. A seven-day offloading period requiring 120 ton storage capacity and compatible to the future tankers is recommended.

1. Energy security and climate change issues in Ireland

Energy consumption in Ireland in 2017 in heat sector is 32.45% and in transport sector is 34.6% which is as large as in electricity sector (33%) [1]. Whereas, it can be seen that renewable energy, especially wind contributes significantly to electricity sector but very marginally in transport and heat sectors. Oil still fuels most of transport sector (95%) and significantly the heat sector (43%). In the shares of total energy supply in figure 1, oil accounts for 48% whereas only 4.4% was from wind.

During the period 2014-2017, 19% emissions were from energy industries and 20% from transport activities [2]. These emissions even increased 4% in energy sector and 6% in transport [2]. These will challenge the proposal of 30% greenhouse gas emissions reduction in the recent Climate Action Plan [3]. Ireland target for 2030 is to increase electricity reliance on renewables from 30% to 70% by adding 12GW of renewable energy [3]. The dominant shares of fossil fuels in transport and heat sectors are the opportunity for renewable fuels in those sectors to meet the Climate Action Plan targets.
Ireland’s sea area is around ten times the size of its landmass, at circa 100,000 km², and the country has one of the best offshore renewable energy resources in the world. This offers significant potential for offshore wind, wave and tidal energy. Ireland’s Offshore Renewable Energy Development Plan (OREDP) [4] indicates that the total amount of offshore wind farm (OWF) development is 34.8 GW – 39 GW without likely significant adverse effects on the environment. Such an excellent offshore wind potential in Ireland can provide significant support to meet the set targets of the Climate Action Plan.

In order to develop big market opportunities for offshore wind energy, alternative approaches to the other sectors and grid requirement should be considered [5]. Dedicated OWFs for hydrogen production are the good options those can overcome power load and grid constraints, and produce hydrogen without usage of fossil fuel and emissions of greenhouse gas [6]. However, such systems have not been widely studied; the available literature has mainly focused on electrical aspects and development of the systems. Performance and energy analysis of a standalone hybrid wind-hydrogen power system that consists of wind turbines, batteries for the short time energy storage, electrolyzer, fuel cell and hydrogen tank for long time energy storage were studied [7]. An off grid standalone 3 kW power consumer in Arctic targeted on the development of an autonomous Wind-Hydrogen Powered Plant was recently developed [8]. A concept of hydrogen production from a dedicated OWF in a potential offshore wind pipeline in the Irish Sea including storage methods and viability assessment is therefore presented in this paper.

2. Hydrogen energy storage
Hydrogen produced from offshore wind energy will be at large scales and requiring long-term storage with low-cost infrastructure for commercial purposes. The methods currently used or being developed to store hydrogen include: (i) Physical storage as compressed gas, (ii) Physical storage as cryogenic liquid hydrogen, and (iii) Materials-based storage or solid-state storage [9]. The first two methods are the most mature and widely used whereas the last range of methods is still largely under research and development, highly dependent on the development of advanced materials [9]. The commercial usage of the methods (iii) is unlikely to happen in a near future [10].

The cryogenic liquid process (ii) is advantageous in density of the liquid and storage efficiency, and best suited for long distance transportation using specifically designed trucks/ships [10] [11]. Cryo-compressed storages take the best of both methods (i) and (ii), in which, hydrogen is cooled and compressed before storing in a high-pressure storage tank to minimise the evaporation losses. Such storage tanks are designed to store both liquefied and gaseous hydrogen, thus improving its flexibility [12], potential to be widely used but challenging in the availability and cost [10].

In method (i), hydrogen is stored in compressed forms at pressures varying from 20 to 100 MPa in cylindrical vessels or underground storages. The cylindrical vessels are simple and having high fill/refill...
cycles that make hydrogen more versatile for fuel cells, but the volumetric density does not increase proportionally with increase in pressure [9]. Underground storage provides long-term or seasonal storage of hydrogen and higher safety levels in comparison with above-ground storage methods [10], and consists of two options: artificial salt caverns and natural formations like saline aquifers or depleted oil fields. The salt caverns offer natural seal and prevents loss of hydrogen either through evaporation or through microbial consumption, and are chemically stable and offer substantial protection against leakage as well [12] as salt is inert and it would not react with hydrogen [10]. The technical knowledge is already gained as about 170 caverns are being used in Germany for storing natural gas, three in Texas, US, and three in the UK [10]. In depleted natural gas reservoirs or natural aquifer formations, hydrogen reaction with micro-organisms and minerals needs to be studied [10]. Artificial salt caverns are therefore considered in this study for long-term underground storage of hydrogen.

3. Hydrogen production from a dedicated offshore wind farm

As the wind farm is off-grid and dedicated to hydrogen production, the electricity for all other services including water purification and hydrogen compression must be sourced from the wind farm. Figure 2 presents a concept where hydrogen is produced from a dedicated OWF, stored long-term in underground artificial salt caverns in the form of compressed gas, and periodically offloaded and transported by tankers. The design of OWF layouts can be found from [13]. The design storage capacity should be in accordance to technology advancement. The produced hydrogen will be pumped into underground storage that will then be periodically offload by tankers. An integrated and analytical model enabling calculation of wind power, electrolysis plant size, and hydrogen production amount and assessment of the project cash flow [14] is used in in this paper to assess the viability.

\[
W_{H_2,\text{prac}}(t) = \begin{cases} 
0 & \text{If } P_{farm}(t) \leq P_{farm,\text{low}} \\
\frac{P_{farm}(t)}{E_{elec} + E_{pcl}} & \text{If } P_{farm}(t) < P_{H_2,\text{plant}} \left(1 + \frac{E_{pcl}}{E_{elec}} \eta_{\text{conv}}\right) \\
\frac{P_{H_2,\text{plant}}}{E_{elec}} \eta_{\text{conv}} & \text{If } P_{farm}(t) \geq P_{H_2,\text{plant}} \left(1 + \frac{E_{pcl}}{E_{elec}} \eta_{\text{conv}}\right) 
\end{cases} \quad \text{[kg/hr]} \quad (1)
\]

Figure 2. A dedicated OWF – hydrogen production with periodically-offloaded underground storage.
\[ \text{DPB} = \ln \left( \frac{R_{aa}}{R_{aa} - iC_0} \right) \ln(1 + i) \]  

\[ \text{NPV} = \left( \frac{I_i - C_{l,0&M}}{(1 + i)^1} \right) + \left( \frac{I_2 - C_{l,0&M}}{(1 + i)^2} \right) + \ldots + \left( \frac{I_N - C_{l,0&M}}{(1 + i)^N} \right) - C_0 \]  

In the viability model [14], the amount of hydrogen practically produced per hour \( W_{H2,prac}(t) \), discounted payback period (DPB), and net present value (NPV) are respectively calculated by Eqs. (1), (2) and (3). In which, \( P_{farm}(t) \) is the time-varying power output of the entire OWF, \( P_{farm,low} \) is the lower limit of the real-time power output of the OWF when the electrolyser need to be turned off for efficiency. The terms \( P_{H2,plant} \) and \( \eta_{conv} \) are the rated capacity and conversion efficiency of the hydrogen electrolysis plant, respectively. The parameters \( E_{elec} \) and \( E_{pct} \) are the electricity amounts consumed for electrolysis a unit weight of hydrogen and for water purification and compression of hydrogen at the production pressure to the storage pressure, and other losses. \( R_{aa} \) is the average annual revenue calculated from \( W_{H2,prac}(t) \), \( i \) is the discount rate and \( C_0 \) is the total cost of initial capital (CAPEX) of the OWF and electrolysis plant. \( N \) is lifetime of the OWF, \( I_t \) is the total income in the whole year \( t \), and \( C_{l,0&M} \) is the total operation and maintenance expenditure (OPEX) at year \( t \).

4. Viability of a dedicated offshore wind farm- hydrogen production in the Irish Sea in 2030

A hypothetical site in a potential offshore wind pipeline in the Irish Sea is selected in the neighborhood of offshore wind sites having consent authorised (Arklow Bank Phase 2, Codling) or consent application submitted (Codling Extension, Dublin Array). The site is 12 km offshore and the site conditions are assumed to be similar to those of the operating Arklow Bank Phase 1 wind farm, where the water depth is between 5-25m and the annual wind speed is 8.13 m/s. The wind speed data [15] was collected from SEAI’s Wind Atlas [16] where the website provides wind speed information for the year 2006, the most typical wind year and used in this study. The monthly-average wind speed is shown in figure 3.

![Figure 3. Average wind speed for each month at 100m above the mean sea level.](image)

The rated power, cut-in, rated and cut-out wind speeds, and hub height of the chosen wind turbines are 6.33MW, 3.5m/s, 11.5m/s, 30m/s and 100 m, respectively. The wind farm is assumed to consist of 16 turbines making up the total rated capacity of 101.28 MW. The CAPEX and OPEX of the wind farms, electrolysis plants and hydrogen storage in most of viability assessments in the literature were taken at different time events where the present costs were sometimes used to study future systems leading to impractical assessments. Therefore, all cost figures projected in 2030 are used in this study, where the
CAPEX of fixed-bottom offshore windfarms in the Irish Sea is 1.2€M/MW. The OPEX per year and decommission expenditure (DECEX) are assumed to be 3% CAPEX and 5% CAPEX, respectively [14].

The proton exchange membrane (PEM) electrolyser technology is chosen because of their durability and flexibility and better suitability for intermittent power sources [17]. The suggested specifications of electrolyser and storage in 2030 used in this case study are listed in table 1 [14]. Hydrogen is sold at €5/kg. The cost of underground storage infrastructure is €5/kWh or €166.67/kg [14] and assumed to vary linearly with the storage capacity. Table 2 lists the suggested costs of electrolyses in 2030.

The NPV flows calculated by using Eqs. (1) and (3) with offloading periods of 2, 7, 15, 30 and 60 days are in figure 4. In this figure, the respective DPBs: 7.8, 8.6, 10.0, 12.1 and 20.3 years are in good agreement with those calculated by using Eq. (2), which validates Eq. (3). The NPV flows and DPBs demonstrate that the dedicated OWF for hydrogen production and underground storage in the Irish Sea are profitable in 2030 with the hydrogen price of €5/kg. When hydrogen is offloaded as the most often as every two days and sold at €3/kg, the DPB is 18.7 years and the positive NPV flow is marginal.

Due to the large capital costs of the underground storage infrastructure, offloading at shorter periods (2, 7 or 15 days) is more profitable with significant positive NPV flows compared to that at longer periods (30 and 60 days). At two-days offloading period, the CAPEX is lowest (€140.5M), the DPB is shortest (7.8 years) and the OWF owners have 17.2 years to earn benefit reaching €179.4M at year 25. At 3.5 and 7.5 times-longer offload periods (7 and 15 days), the respective DPBs are 10% and 15% longer and the CAPEX are €154.6M and €177.1M, respectively. A baseline case of seven day-offload period requiring 120 ton storage capacity that is compatible to the future tankers is recommended.

Table 1. PEM electrolyser and storage specifications, predicted in 2030.

| Specification                          | Unit     | Value  |
|----------------------------------------|----------|--------|
| Hydrogen density at 0°C and 1 atm       |          | 11.12347 |
| Energy consumption for electrolysis, $E_{elec}$ | kWh/kg   | 50     |
| Energy for water purification, hydrogen compression and losses, $E_{pcl}$ | kWh/kg   | 3      |
| Conversion efficiency, $\eta_{conv}$    | %        | 93     |
| Plant size, $P_{H2\_plant}$            | MW       | 90     |
| Stack lifetime, $T_{stack}$             | year     | 12.5   |
| Limit input power to turn off electrolysis plant $P_{farm\_low,\%P_{H2\_plant}}$ | %        | 5      |

Table 2. Costs of electrolyser and storage, predicted in 2030.

| Cost                                      | Per Unit (€M/MW) | Per whole plant (€M) |
|-------------------------------------------|------------------|----------------------|
| CAPEX (initial plant)                     | 0.6 €M/MW        | €54.0M (90MW plant)  |
| CAPEX (stack replacement, at year $T_{stack}$) | 0.15 €M/MW      | €13.5M               |
| OPEX per year (2% CAPEX)                  | 0.012 €M/MW      | €27M for 25 years    |
Figure 4. NPV of the OWF – hydrogen production with storage offload periods 2 - 60 days.

5. Conclusions
In this paper, the need to develop big market opportunities in multiple sectors for offshore wind energy has been explained where dedicated offshore wind farms (OWFs) for hydrogen production are shown to be the good options. Hydrogen storage methods have been reviewed and artificial underground salt caverns are found suitable to store hydrogen at large scales and long-terms. A concept of hydrogen production from a dedicated OWF and its viability assessment model have been applied to a fixed-bottom OWF in a potential offshore wind pipeline in the Irish Sea. In the assessment, the monthly-averaged wind speed at 100m is used where the annual wind speed is 8.13 m/s, the OWF consists of 16×6.33MW turbines and PEM electrolyser technology is chosen. All cost figures have been projected in 2030, in which the OWF CAPEX is 1.2€M/MW and its annual OPEX and DECEX are 3% and 5% of the CAPEX, respectively. The energy consumption for the electrolysis is 50 kWh/kg and the conversion efficiency is 93%. The cost of underground infrastructure for hydrogen storage is €166.67/kg. The CAPEX for the initial electrolysis plant and for stack replacement, and the annual OPEX are 0.6 €M/MW, 0.15 €M/MW and 2% of initial CAPEX, respectively. The NPVs and DPBs at offloading periods of 2, 7, 15, 30 and 60 days have been calculated and in good agreement where the DPBs are 7.8, 8.6, 10.0, 12.1 and 20.3 years, respectively. Hydrogen production is profitable at the price of €5/kg but marginal at €3/kg. Due to the large capital costs of the underground storage, offloading at shorter periods (2 -15 days) is more economical. A seven-day offload period requiring 120 ton storage capacity and compatible to the future tankers is recommended.

Acknowledgments
The author has been funded by Science Foundation Ireland (SFI) Research Centre: MaREI - Centre for Marine and Renewable Energy (12/RC/2302). Thanks to Vaishnav Pushpoth for handling the wind data.

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