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Techno-economic assessment of hydrogen production from seawater

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HIGHLIGHTS

- Overview of hydrogen production technologies.
- Assessment of cost of desalination processes in relation to the total hydrogen production costs.
- Investigation of applicability of offshore hydrogen production from seawater.
- To assess the green hydrogen production potential offshore.

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ABSTRACT

Population growth and the expansion of industries have increased energy demand and the use of fossil fuels as an energy source, resulting in release of greenhouse gases (GHG) and increased air pollution. Countries are therefore looking for alternatives to fossil fuels for energy generation. Using hydrogen as an energy carrier is one of the most promising alternatives to replace fossil fuels in electricity generation. It is therefore essential to know how hydrogen is produced. Hydrogen can be produced by splitting the water molecules in an electrolyser, using the abondand water resources, which are covering around $^2/_3$ of the Earth's surface. Electrolysers, however, require high-quality water, with conductivity in the range of 0.1–1 μS/cm. In January 2018, there were 184 offshore oil and gas rigs in the North Sea which may be excellent sites for hydrogen production from seawater. The hydrogen production process reported in this paper is based on a proton exchange membrane (PEM) electrolyser with an input flow rate of 300 L/h. A financially optimal system for producing demineralized water from seawater, with conductivity in the range of 0.1–1 μS/cm as the input for electrolyser, by WAVE (Water Application Value Engine) design software was studied. The costs of producing hydrogen using the optimised system was calculated to be US$3.51/kg H_2. The best option for low-cost power generation, using renewable resources such as photovoltaic (PV) devices, wind turbines, as well as electricity from the grid was assessed, considering the location of the case considered. All calculations were based on assumption of existing cable from the grid to the offshore, meaning that the cost of cables and distribution infrastructure were not considered. Models were created using HOMER Pro (Hybrid Optimisation of Multiple Energy Resources) software to optimise the microgrids and the distributed energy resources, under the assumption of a nominal discount rate, inflation rate, project lifetime, and CO_2 tax in Norway. Eight different scenarios were examined using HOMER Pro, and the main findings being as follows:

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The cost of producing water with quality required by the electrolyser is low, compared with the cost of electricity for operation of the electrolyser, and therefore has little effect on the total cost of hydrogen production (less than 1%).

The optimal solution was shown to be electricity from the grid, which has the lowest levelised cost of energy (LCOE) of the options considered. The hydrogen production cost using electricity from the grid was about US$ 5/kg H_2.

Grid based electricity resulted in the lowest hydrogen production cost, even when costs for CO_2 emissions in Norway, that will start to apply in 2025 was considered, being approximately US$7.7/kg H_2.

From economical point of view, wind energy was found to be a more economical than solar.

Introduction

Population growth and industrial expansion have resulted in ever increasing energy consumption. Combustion of fossil fuels to generate energy releases greenhouse gases and adds to air pollution. CO_2 concentration in the atmosphere is increasing continuously, and its lifetime in the atmosphere is over 1000 years [1]. These are the main reasons for why scientists and governments are concentrating their efforts on lowering the CO_2 levels in the atmosphere. One possible solution, for avoiding increased CO_2 concentration in the atmosphere and thereby reduced global warming effect, is replacing fossil fuels with alternative energy resources.

Hydrogen, with one of the highest specific energies (142 MJ/kg), can be an excellent alternative to fossil fuels [2,3] Hydrogen can be produced from water electrolysis, using electricity from renewable energy sources that result in lowest CO_2 foot print worldwide [4]. Water is an abandoned resource, covers approximately 71% of the Earth's surface, but the main portion of it is saline water, found in oceans and seas [5]. Current electrolyser technologies cannot utilize seawater directly as feed stock. It needs purified water with low conductivity [6]. On the other hand, potable water is of high value in many parts of the globe, like the Middle East and Africa, causing conflict of interest. Therefore, water desalination has a vital role to play in producing hydrogen from seawater using electrolysers, while enabling access to potable water.

The North Sea is considered as the most important location for renewable energy generation in Europe, which makes it an excellent source for both energy and water for electrolyser-based hydrogen production. The overall objective of this study was to assess the technical and economic feasibility of offshore hydrogen production using seawater. For this purpose, a North Sea platform, i.e. the Q13a Platform, which is the first offshore green hydrogen project [7], was chosen as the location of interest for this study. An optimal economic system, based on the existing processes and equipments, was designed for this platform, to produce water with low conductivity for use as electrolyser feedstock. The optimum cost of hydrogen production, based on economic factors and renewable energy resources, was also analysed. Finally, the cost of hydrogen production from seawater was calculated and is reported in this paper.

The five main objectives of this research work were as follows:

- Designing an optimal seawater treatment system to provide feed water to an electrolyser for hydrogen production.
- Conducting economic optimisation of the hydrogen production from seawater using renewable energy.
- Determining the cost of hydrogen production using a small scale electrolyser.
- Comparing the costs of producing purified water with the total cost of hydrogen production.
- Assessing the effect of future CO_2 emission taxes on the cost of hydrogen production from seawater.

In this study the commercial software package HOMER Pro was used for the optimisation of microgrids and distributed energy resources. Given the fact that cost data for the components of the system used in this study were not available in open litterature, the data presented in a paper, "Technical and economic analysis of one-stop charging stations for battery and fuel cell EV with renewable energy sources" [8] was used as a reference for all cost calculations.

The interest- and inflation rates used in this study was taken from a thesis titled "Cost optimisation of distributed power generation in southern Norway, with focus on renewable hybrid system configurations" [9] representing the economic conditions in Norway, for the design cases analysed.

Literature review

Hydrogen is the lightest, simplest and most abundant element in the world and exists in water and in organic compounds. The specific energy of hydrogen is more than three times of gasoline, 142 MJ/L [2], and the exhaust gas from hydrogen combustion consists mainly of clean water. Hydrogen is also a competitive energy storage option for long-term energy storage.

There are a number of reasons for why hydrogen should be studied further as a future energy carrier, among those are

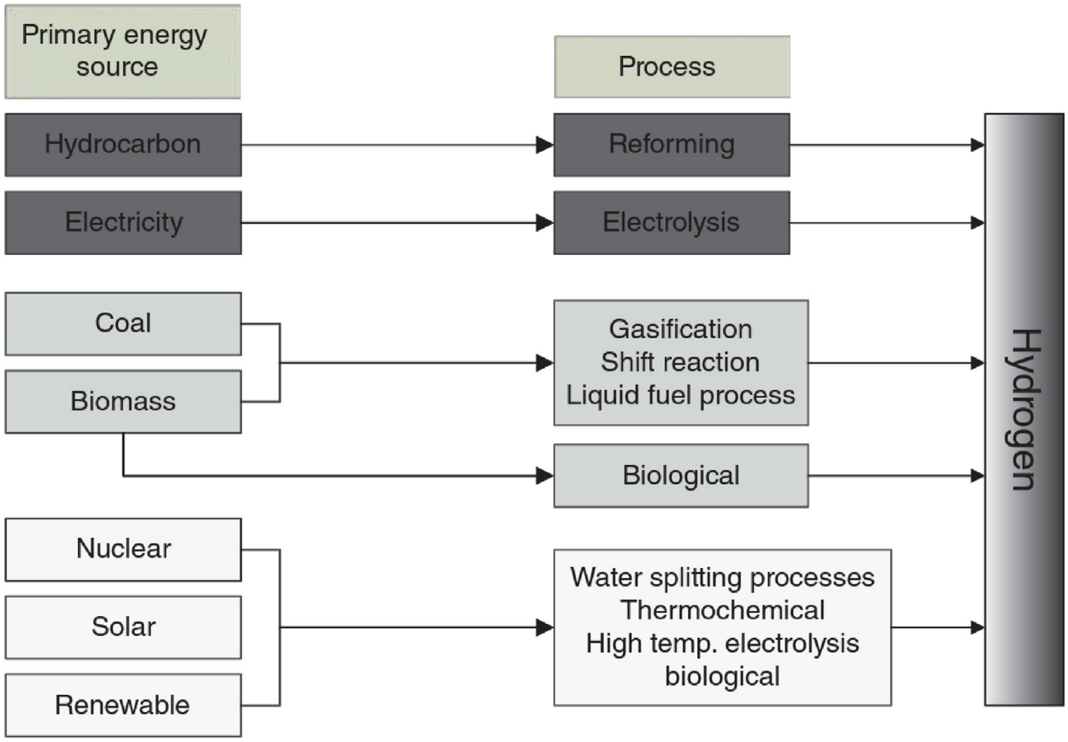

Fig. 1 – Standard methods for hydrogen production [11] (p.12).

reduced dependency on fossil fuels, reduced green house gas emissions and enabling future zero-emission power using renewable resources [10].

Various primary energy sources can be used for production of hydrogen, ranging from fossil fuels, to nuclear-, geothermal-, solar-, wind- and tidal energy. Fig. 1 shows the standard methods and energy sources for hydrogen production.

Fig. 2 shows some applications using hydrogen.

Hydrogen can be produced from water using various technologies, such as electrolysis, sonoelectrolysis, sonolysis, radiolysis, thermolysis, thermochemical cycling, and photochemical processes. In electrolysis, water is split into oxygen and hydrogen using electricity.

The cost and efficiency of hydrogen production depends on the energy source and the production method. The cost of hydrogen production, storage and transport is higher than other alternatives [12]. For instance, the cost of shipping liquid hydrogen is 5–7 times higher than LNG [13]. Table 1 lists different methods of hydrogen production and their cost and efficiency levels.

It should be noted that the scale of hydrogen production varies for different methods. Steam reforming of natural gas is the most commercial and large-scale production method today. Fig. 3 shows global hydrogen production, demand and sources [19]. As Fig. 3 shows, the largest hydrogen production sources are natural gas, oil, coal and water electrolysis respectively. Water electrolysis is the smallest (4%) contributor to hydrogen production worldwide.

Each hydrogen production method has its advantages and disadvantages, as shown in Table 2 [20]. Table 2, however, shows that water electrolysis is the cleanest method for green hydrogen production [21].

The cheapest and most abandoned feed stock for hydrogen production is water. A major challenge for water based hydrogen production is the water purity level required for electrolysis. Therefore, seawater treatment or desalination process must be conducted prior to hydrogen production via electrolysis.

Electrolysis

Seawater electrolysis is used as hydrogen production method in this study. Therefore this technology is discussed furthermore in the following section.

Water electrolysers split water into oxygen (anode) and hydrogen (cathode), using electricity, and have the lowest greenhouse gas emissions when green electricity (renewable sources) is used. Purity of the produced hydrogen is high, and therefore there is no need for post-processing after production. Table 3 lists the costs of renewable electricity sources for electrolysis with zero CO_2 emission.

As Table 3 shows, power generation efficiency and thereby cost of hydrogen production differs for different energy sources. However, the geographic location is the most crucial factor for renewable power generation. Hydrogen as energy carrier is an interesting alternative to fossil fuels, but the cost of production and storage is still high [12].

Classification of water electrolysis technologies

Electrolysers can be classified based on the type of the electrolyte used and anion transferred [28,29]. There are four main types of electrolysers, as shown in Fig. 4.

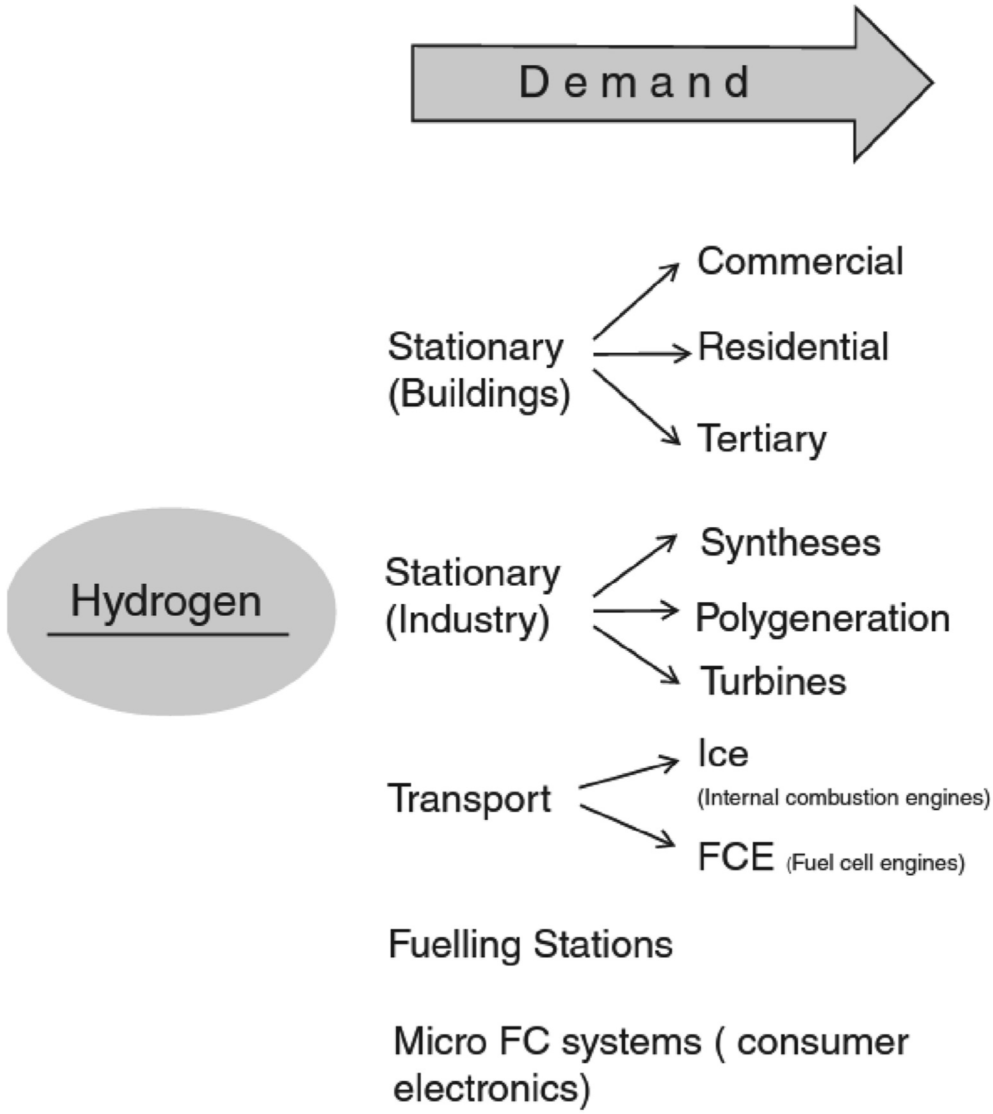

Fig. 2 – Potential hydrogen applications [11](p.12).

I. Proton exchange membrane water electrolyser (PEMWE)
II. Alkaline water electrolyser (AWE)
III. Anion exchange membrane water electrolyser (AEMWE)
IV. Solid oxide electrolyser cell (SOEC)

Table 4 shows a summary and comparison of these electrolyser types.

Table 1 – Hydrogen production and cost.

Method	Hydrogen cost (US$/kg)	Efficiency (%)	Reference
Natural gas reforming	<2	70–80	[14]
Gasification of coal	4	50–60	[15]
Solar thermochemical hydrogen (STCH)	6	35	[16]
Electrolysis	10	60	[17]
Biomass gasification	3.33	69	[18]

WAVE (Water Application Value Engine)

WAVE is a new software package, which is an alternative to the more traditional DuPont Water Solution's ROSA software for membrane-based designs. The WAVE software was used in this study to simulate and design a desalination system for seawater due to its higher accuracy. By modelling water treatment systems (ultrafiltration, reverse osmosis, and ion exchange), designers can simulate the processes to find the most efficient system. The software makes the design process simple and reduces the time required to develop a water treatment system [35].

Key features of WAVE

- The user is able to combine and use ion exchange, ultrafiltration, and reverse osmosis processes.
- The user can specify the input or the output flow rate of the system.

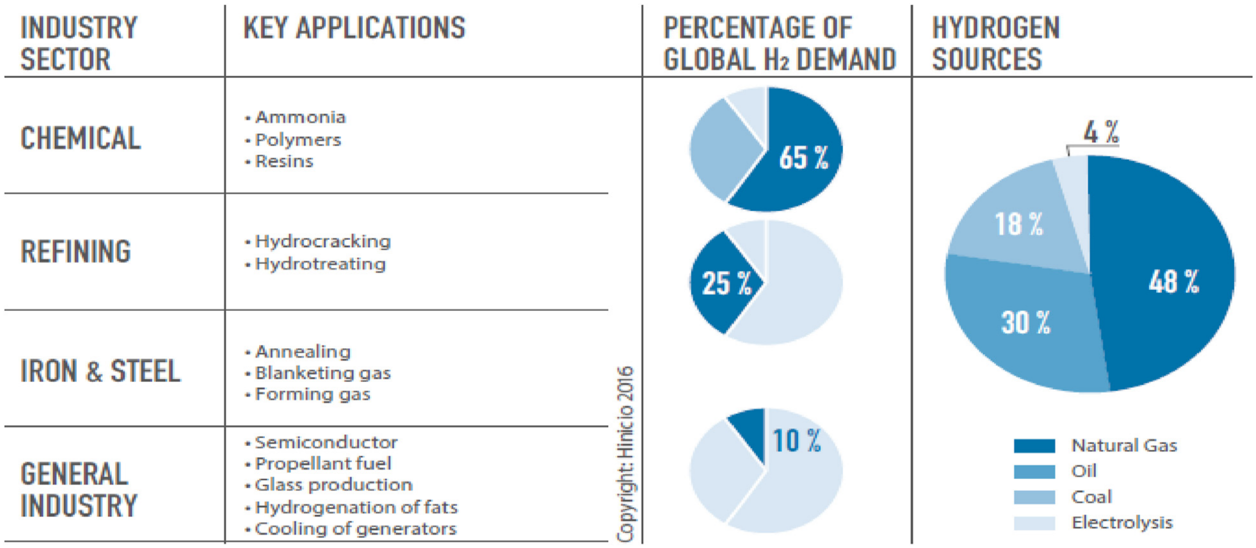

Fig. 3 — Global hydrogen demand and production from various sources [19] p.14.

Table 2 — Comparison of different resources for hydrogen production [20] p3.

Source	Advantages	Disadvantages
Natural gas	Low production cost; accessible infrastructure	Environmental impacts during extraction of natural gas; production of greenhouse gases
Oil	Low production cost; accessible infrastructure	Environmental impacts during extraction of oil; production of greenhouse gases
Coal	Low production cost; accessible infrastructure	Environmental impacts during extraction of coal; production of greenhouse gases
Electrolysis	produced with low greenhouse gas and zero emissions when using renewable energy sources [22]	Low efficiency, high cost of production, limited infrastructure, production of greenhouse gases when powered with fossil fuels

Table 3 — Costs of renewable electricity sources for electrolysis.

Source	Hydrogen cost (US$/kg)	Efficiency (%)	Reference
Solar	30	17	[23]
Wind	4.4	50–60	[24]
Hydro	6	35	[25]
Geothermal	1.1	38.37	[26]
Nuclear	3.24	25.5	[27]

- Water with different components can be analysed.
- The chemical properties of water and its behaviour in the system with respect to temperature and system life can be analysed.
- Embedded parameters that accurately represent the output of an actual membrane from DuPont can be modelled.
- Water with different properties from different parts of the world can be modelled [36].

Numerous simulation studies have used ROSA and WAVE for optimisation and designing of the reverse osmosis process.

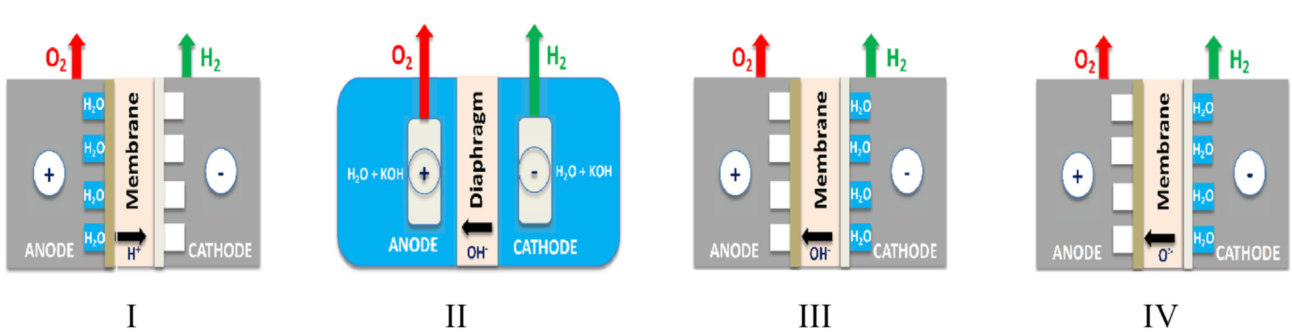

Fig. 4 — Four types of electrolysers [29].

Table 4 – Comparison of different electrolysers.

Name	Reaction	Ion Transfer	Capacity range (Nm^3/h)	Pressure range (bar)	Temperature (°C)	Advantages	Disadvantages	References
PEM Water Electrolyser (PEMWE)	Anode: $H_2O\ (liq) \rightarrow \frac{1}{2}O_2(g) + 2H^+ + 2e^-$ Cathode: $2H^+ + 2e^- \rightarrow H_2(g)$ Net Reaction: $H_2O(liq) \rightarrow H_2(g) + \frac{1}{2}O_2(g)$	H^+	<100	1–30	50–80	-More compact- High energy- efficiency up to 80%- -Compatible with intermitent renewable energy systems (fast response)	- Not performing well at high temperature - Cost issue (Use of PGMs, high initial CAPEX)	[30]
Alkaline Water Electrolyser (AWE)	Anode: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$ Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ Net Reaction: $2H_2O \rightarrow 2H_2 + O_2$	OH^-	<800	1–30	<60-80	- 70% efficiency - Cheap - Mature technology - Long term lifetime	- Leakage at high temperatures and pressure - corrosion - Performance to be improved,Dynamic operation capability	[29,31]
Anion Exchange M embrane Water Electrolyser (AEMWE)	Anode: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$ Cathode: $H_2O + 2e^- \rightarrow H_2 + 2OH^-$ Net Reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$	OH^-	<1	1–30	40–90	- Promising technology for low temperature electrolysers - Low-cost selective anodes (operate using low-cost electrocatalysts) - High performance - Dynamic operation potentials	- Not mature yet - - Poor durability- Improved lifetime required, - Novel supporting electrolyte required	[29,32]
Solid Oxide Electrolyser Cell (SOEC)	Anode: $O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$ Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$ Net Reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$	O^{2-}	<300	8–50	700–900	Different electrodes- 99.99% efficiency- Highest hydrogen production- Thermal energy integration	- Main disadvantage is the lack of flexibility (allows small change of operating temp. per time unit) and expensive due to high operating temperatures - - Fast d egradation at cell. - Poor intermittent operations	[33,34]

In one study, ROSA was compared with mathematical and experimental modelling for the RO process. The model analysed mass and energy balance. The system was designed for 50 m^3/day, and the RO membrane in this study was from the BW30 series from DOW. In addition, the salt rejection was between 94.58 and 97.45%. It demonstrate that the simulation results are over 96% consistent with ROSA and over 80% consistent with laboratory results [37].

Fig. 5 shows the number of recent articles on water treatment systems in which ROSA and/or WAVE was used for the design.

Another study examined softening and desalination of brackish water with TDS between 1570 and 2910 mg/L using ROSA. The membrane type for this study was BW30-2540 (one of the membranes used in our study), and the feed water flow was 0.3 m^3/h with 13% recovery. The salt rejection was 98.64 with 39.41 mg/L TDS [39].

A study on small scales (2.5 and 4 in) desalination and purification system using the DuPont software found the experimental and mathematical modelling consistent. Table 5 shows the results of some studies on simulation and designing the water treatment system using the DuPont software.

Furthermore, WAVE can be used for energy and cost analyses. Based on the results shown in Table 5, and the experience of the authors with WAVE for designing water treatment systems in different industries, WAVE was considered applicable for design and simulation of the water treatment systems presented in this article.

Homer software

The model used for analyses and optimisation of the best energy supply system in the present study was developed in the commercial software HOMER Pro (here in after referred to as HOMER). The HOMER (Hybrid Optimisation Model for Multiple Energy Resources) software, is a program that allows users to model and optimise small grid designs in all sectors and to compare different power generation technologies. HOMER also has direct access to meteorological data, such as air temperature, wind speed, and solar radiation, which made it suitable choice for the current study. The software can handle three different core processes: simulation of the energy system, optimisation of the system with respect to cost, and analysis of the sensitivity of the variables defined by the user.

1. Simulation

The software can simulate all combinations of the equipments selected by the user. The number of alternative simulations may reach billions, depending on the problem definition.

2. Optimisation

The program checks all possible options, considering both economic and thermodynamic aspects, to find the optimum solution based on selected optimisation variables.

3. Sensitivity Analysis

The impact of changes in parameters' value can be investigated over a user defied range followed by an optimisation process [46].

HOMER has been used for techno-economic assessment in numerous studies [47–50]. The software has been used extensively by scientists in the field of hydrogen production, storage and use. Using load data over 8760 h, Babaei et al. [51] developed reliable, cost-effective, and clean hybrid micro-grids. In this study, the cost of hydrogen production in three different island by Homer were analyzed. The results showed that hydrogen costs in Saint Pierre Island were lower than those reported by Pelee Island and Wolfe Island, and were achieved respectively, by \$7.5/kg H_2 and \$15.8/kgH_2. Same software was used by Javier de la et al. [52], to investigate the

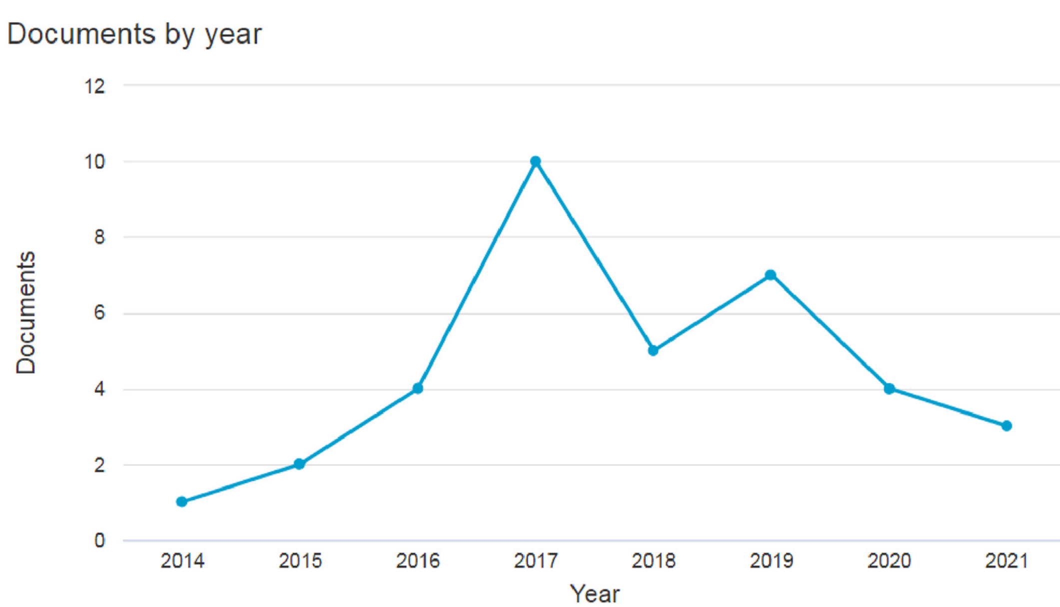

Fig. 5 – The number of articles on water treatment processes by using ROSA and WAVE [38].

Table 5 – Results of studies on the design of water treatment systems using the DuPont software.

Type of membrane	Feed TDS/salinity/SDI/conductivity	Flow rate	Recovery	Salt rejection (%)	Permeate TDS	Reference
SW-2540	Salinity: 40,000 mg/L	0.625 m^3/h	20	99	435	[40]
NF270 NF90 BW30	Salinity: 2222–5394 mg/L	7.9 L/min	13–18%	50–90+	79–200 mg/L	[41]
BW SW	TDS: 35,600 mg/L	10 m^3/day	40%	99	<500 mg/L	[42]
Tw30-2540	TDS: 3.852 g/dm^3	0.001–0.01	4–15	99.05	77–1112 g/dm^3	[43]
XLE440 2 sages	Conductivity = between 1333.8 and 2515 μS/cm	Stage 1: 506 and Stage 2: 208 m^3/h	Stage 1:58.7 Stage 2: 54.1	90%	Stage 1:101 and Stage 2: 258 mg/L	[44]
SW30XLE-440i	TDS: 37952.90 mg/L	100 m^3/day	35%	99	133 mg/L	[45]

possibility of storing hydrogen and using hydrogen for producing electricity. Their results indicate that using hydrogen can reduce CO_2 emissions with up to 27% compared to electricity production by diesel. In addition, this study shows that hydrogen can be used for energy storage throughout the year.

Other studies on hydrogen production from seawater

Other studies have been performed on producing hydrogen from seawater in the large scale [7,53,54]. However, all of these have relied on cost data for desalination from literature, or have neglected the desalination processes completely. The current study is aiming at bridging this gap, by providing a through analysis of the seawater treatment (desalination) system, targeting a specific conductivity range suitable for electrolyser. Table 6 summarises some of the published results from other studies on the production of hydrogen from seawater in the large scale.

Methodology

The methodology used in this paper uses two computer software packages:

-WAVE was used to conduct water treatment system modelling, simulation and analyses. All water treatment process components being from the DuPont Water Solutions portfolio of water treatment technologies [36].

-HOMER was employed to conduct hybrid renewable energy system modelling. This software was used to simulate and model the profitability of a microgrid system for different scenarios [58].

This section first presents a short description of the procedure used and information required to design the desalination process using WAVE. The amount of energy and the cost of producing water with conductivities in the range of 0.1–1 μS/cm, which is the range required for the water input to the electrolyser, are calculated. This section also addresses the use of HOMER Pro to calculate the optimal hybrid plant for supplying energy.

Desalination process

System design

Seawater must be brought to the Ultra Filtration (UF) system, then pumped to the reverse osmosis membrane (RO), and finally passed through the ion exchange (IX) process. Based upon existing components for seawater treatment systems in WAVE and DUPONT with the required input for electrolyser, there are different possibilities for all of these system components, and we can introduce different cases for these options. Based upon system input and our need for treated water, there are therefore three options for the UF module (SPF-2660, SFP-2860, SFP-2880), two options for the RO system (SW30-2540, SW30-4040) and two options for mixed-bed IX (AMBERPACK, Internal regeneration) [36]. We can also use two RO passes, which represent further design options. This means that, in total, we have 24 options (12 options for single RO and 12 options for double RO). Fig. 6 shows all 24 options

Table 6 – Other studies on hydrogen production from seawater.

Source	Hydrogen cost	Estimated year	Cost of desalination	Reference
PV cells and battery	$2.5/kg	2030	Neglected	[55]
Grid with 25% load factor	€2.46/kg	2030	Neglected	[56]
Grid with 70% load factor	€3.3/kg	2030	Neglected	
Grid with 100% load factor	€5.5/kg	2030	Neglected	
Offshore wind and battery	$4.9/kg	2021	$0.01/kg H_2	[57]
Offshore wind farms and battery	€6.88/kg	2020	Neglected	[58]
Offshore wind farm connected to the grid coupled offshore with a battery and an electrolyser	€7.067/kg	2020	Neglected	
Offshore wind farm connected to the grid coupled onshore with a battery and an electrolyser	€7.394/kg	2020	Neglected	

for our design. The output water for all processes is approximately 300 L/h.

So, WAVE was used to analyse each element and the complete UF, RO, and IX systems for all 24 cases. All calculations, methods and definitions were added to Appendix number 4. Three essential factors were extracted from the results, as shown in Table 5.

- Total specific water cost: the total price for producing 1 m^3 of permeate for the electrolyser.
- Total chemical and utility cost: the total cost of chemical washing materials for the membranes and the cost of wastewater disposal.
- Total energy: the total energy used by the complete system per day.

Table 7 shows that cases 3 and 15 had the lowest measure of input water and chemical and utility cost. These two cases also had almost the lowest operating cost and cost of producing permeate flow. Both have the same facilities, which

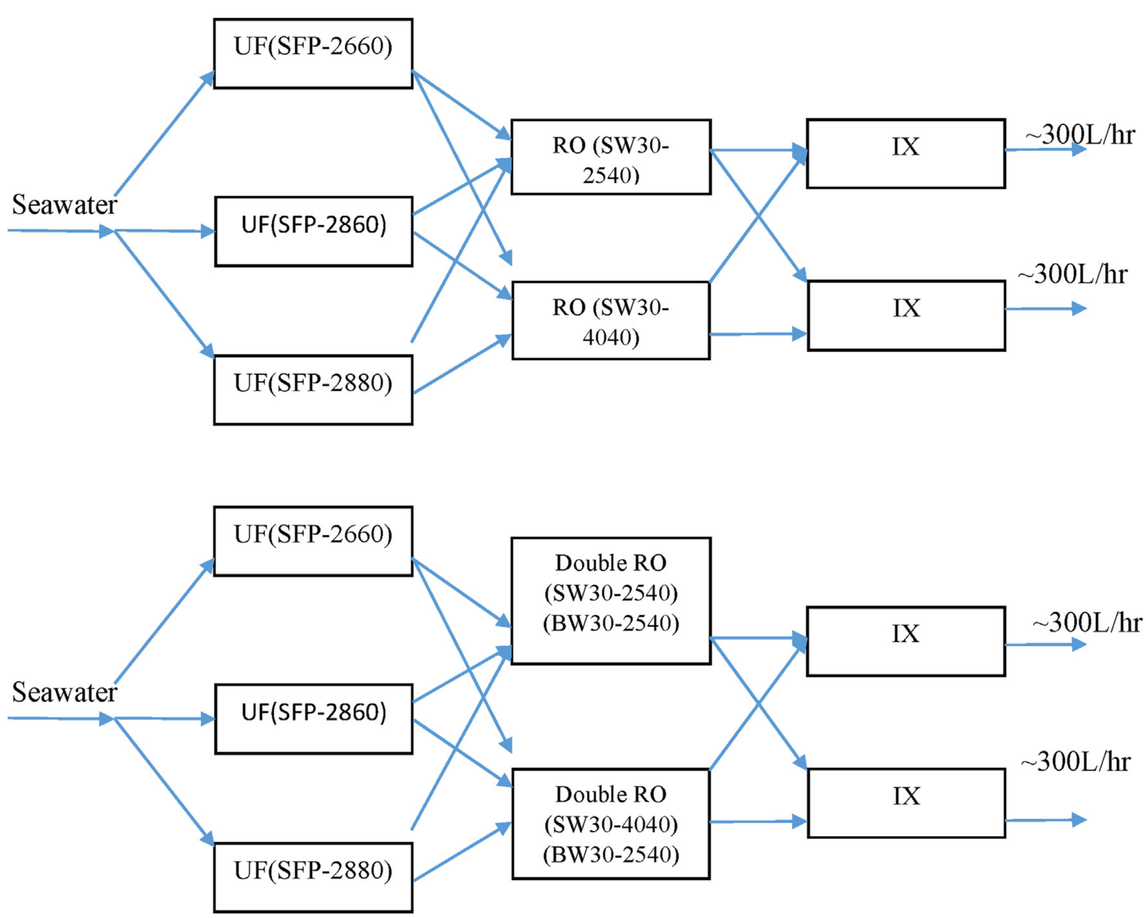

Fig. 6 – Options for our system design.

Table 7 – Final results for each case.

Case	Total specific water cost ($/m^3)	Total chemical and utility cost ($/d)	Total energy (kWh/d)	Total energy (kWh/hr)
1(RO)	1.261	10.25	90.01	3.750
2(RO)	5.849	15.11	108.77	4.532
3(RO)	1.072	8.84	89.06	3.710
4(RO)	1.696	13.82	105.66	4.402
5(RO)	1.377	12.16	92.06	3.835
6(RO)	1.362	12.21	101.45	4.227
7(RO)	1.131	7.39	90.22	3.759
8(RO)	1.874	16.307	140.57	5.857
9(RO)	1.361	12.43	101.66	4.235
10(RO)	2.078	18.32	124.2	5.175
11(RO)	1.083	11.74	109.09	4.545
12(RO)	1.703	16.01	113.29	4.720
13(Double RO)	1.14	9.57	69.3	2.887
14(Double RO)	1.552	13.26	81.55	3.3979
15(Double RO)	1.094	9.22	65.12	2.713
16(Double RO)	1.819	15.35	81.95	3.414
17(Double RO)	1.277	11.49	65.98	2.749
18(Double RO)	1.858	16.58	80.22	3.342
19(Double RO)	1.289	11.69	68.28	2.845
20(Double RO)	1.758	15.82	81.13	3.380
21(Double RO)	1.122	10.86	64.53	2.688
22(Double RO)	1.612	15.2	77.76	3.240
23(Double RO)	1.172	11.26	67.15	2.797
24(Double RO)	1.697	15.91	81.7	3.404

confirms that the design is optimum. A summary of details for each case is presented in Appendices 1 to 3. Table 8 illustrates the optimum (low operating expense) desalination systems.

Discussion

In this study, we used an electrolyser to produce hydrogen from seawater, which requires water with conductivity of between 0.1 and 1 μS/cm. The seawater used as the electrolyser feed had to be purified to achieve conductivity in required range. As previously mentioned, the aim of this part of the study was to develop a desalination process with the lowest possible operating cost to produce permeate flow as electrolyser feed. We used WAVE to determine the lowest operating expense costs for the RO process and the double RO process (one pass and two passes, respectively).

We can determine the total energy required to produce hydrogen, by adding the measure of total energy from the optimal case for the water treatment system to the measure of energy for the electrolyser. HOMER Pro was used to analyse the source of energy and its cost, to determine the optimum hybrid plant for supplying energy.

Optimising microgrids and distributed energy resources using HOMER

HOMER was used to analyse and optimise a system for the required energy supply in this study. The procedure for optimising microgrids and distributed energy resources using HOMER involved the following steps:

1 Define the study location, to obtain appropriate data on renewable resources.
2 Define all components of the hybrid power plant (cost of components was taken from Bansal [8]).
3 Determine financial parameters, such as interest rate, inflation, and carbon emission cost.
4 Define different use scenarios, to determine the best hybrid power plant design for an entire system for the production of hydrogen from seawater.
5 Define financial scenarios, based on the lowest cost of electricity (COE).

Table 8 – Optimised cases.

Case	UF	RO	IX
3	UF(SFP-2660)	RO (SW30-4040)	IX (AMBEROACK)
15	UF(SFP-2660)	RO (SW30-4040) and BW30-2540	IX (AMBEROACK)

Renewable resources

HOMER is connected to the NASA Surface meteorology and Solar Energy (SSE) data set, from which local data were obtained. The study site is platform Q13a which is the first offshore platform site that producing hydrogen from seawater in **52°11′28.032"N** and longitude **4°8′10.259"E**. The SSE data set contains surface meteorology and solar energy data, monthly air temperature averages and average monthly wind speeds for at least the last 10 years.

Solar radiation. Fig. 7 shows the monthly average solar global horizontal irradiance (GHI) data. It includes the clearness index and daily radiation over a 22-year period. The clearness index demonstrates the atmosphere's clearness and the fraction of solar radiation that reaches the Earth's surface. This number is between 0 and 1, typical values being between 0.25 and 0.75. As the figure shows, the range of clearness index values in this study is between 0.304 and 0.52, with the daily radiation values being between 5.55 and 0.54 kWh/m^3/day.

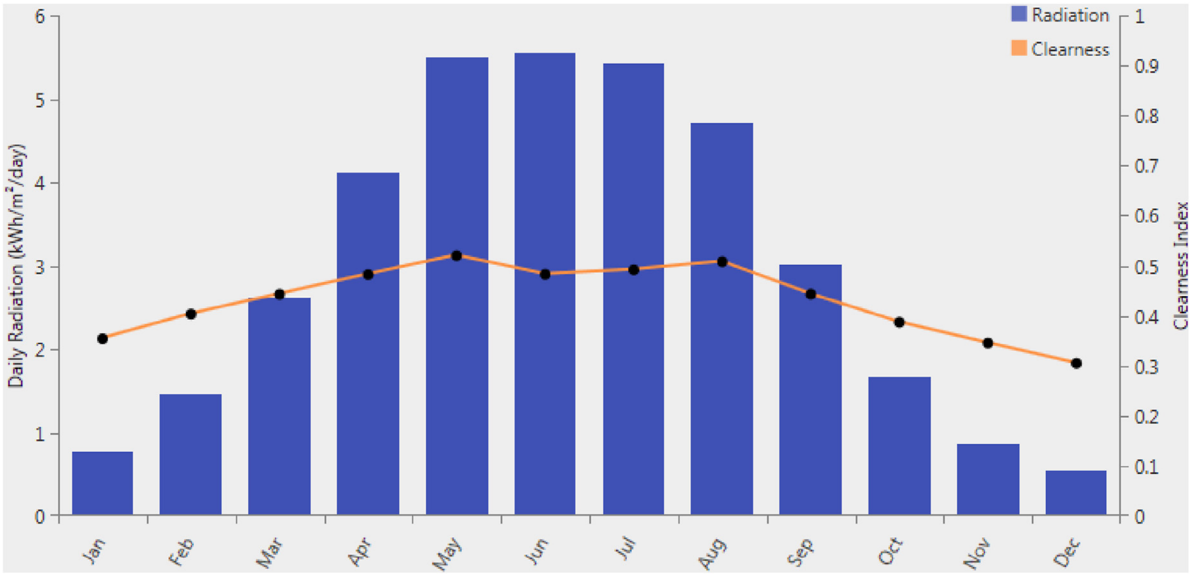

Fig. 7 – Monthly average solar global horizontal irradiance.

Temperature. Temperature has a direct effect on the output power of PV cells, the monthly average temperatures for this case study being shown in Fig. 8. The lowest monthly average temperature was 4.34 °C, and the average annual temperature was 10.735 °C.

Wind. To identify an effective turbine, wind speed must be known, as the amount of power produced by a wind turbine is directly related to wind speed. Fig. 9 shows that the average wind speed in the area where the platform is located is 7.041 m/s, with no significant variation from month to month.

Components

Different technologies can be compared in HOMER. The priority of technologies in this study was the type of energy used in Norway and the North Sea. This was discussed in the last chapter on typical renewable energy in the North Sea and Norway. Table 9 shows a summary of the costs of components.

Grid. A 'simple rate grid' was chosen for convenience in the software, with constant grid power and a sell-back price being used in this model [58]. It is also possible to calculate total emissions production (gr) and tax.

Electrolyser. The PEM electrolyser in this study was a 1-MW model from NEL. This measure of energy should be added to the measure of energy required for desalination, to give the total energy for the processes [59].

Table 10 shows the specifications of this electrolyser. More detailed specifications are presented in Appendix 5.

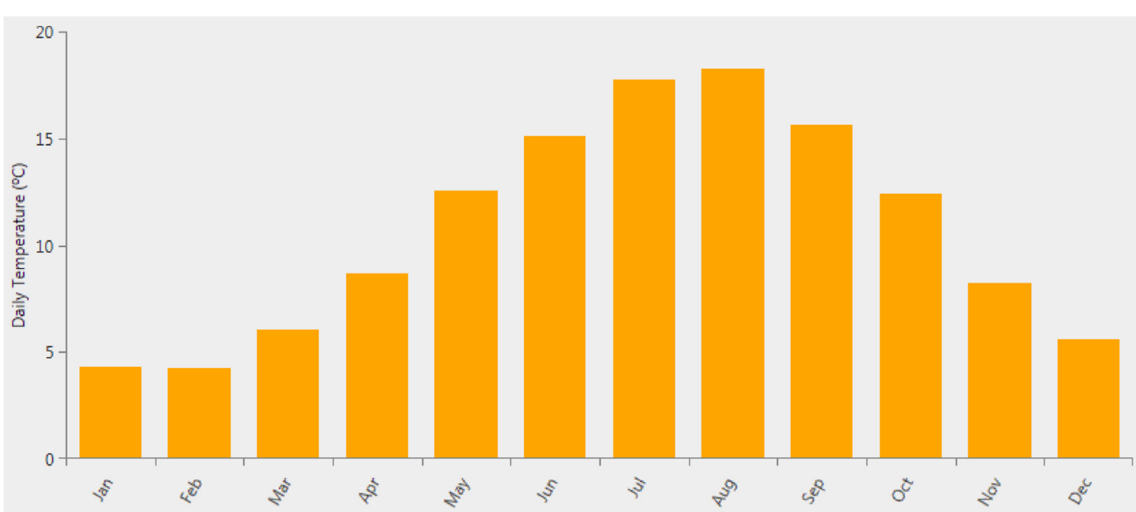

Fig. 8 – Monthly average temperatures for case study.

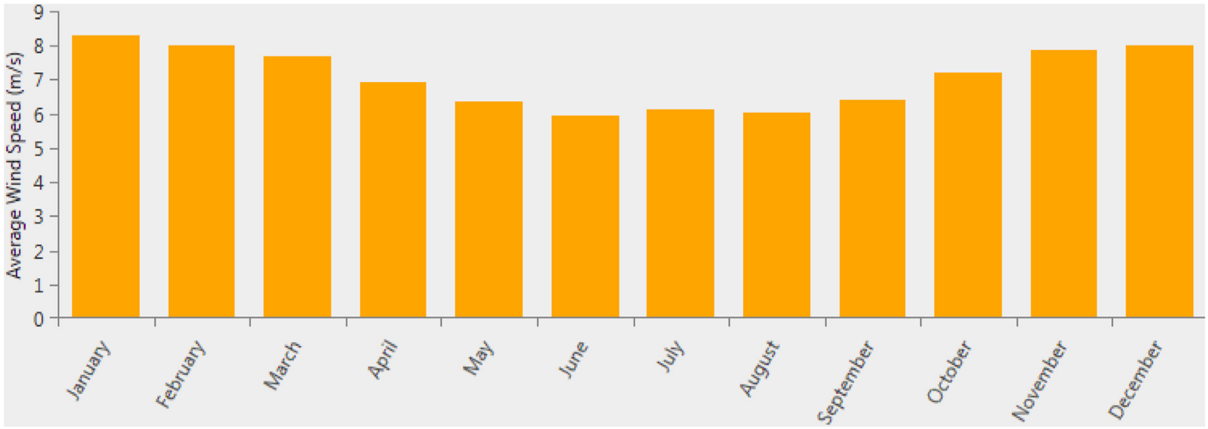

Fig. 9 – Average wind speed.

Table 9 – Component costs.

	Capital cost $	Replacement cost $	O and M costs $[a]
PV module ($/kW)	1200	1200	18
Wind turbine	1,666,670	1,666,670	35,000
Power converter (per kW)	94	94	10
Battery (per kW)	15,000	15,000	1000

[a] Operation and Maintenance.

Economic aspects

The economic assessment and comparison of alternatives conducted in HOMER are based upon the levelised cost of energy (LCOE) and the net present cost (NPC).

Net present cost (NPC). NPC is a function of the lifetime, interest rate, year and net cost. The NPC of each component is calculated from the following equation [9,58,60]:

$$C_{NPC,co} = \sum_{t=0}^{T} \frac{X_t}{(1+r)^t} \quad 1$$

In this equation, t is the year of calculation, T is the lifetime of the project, r is the interest rate and X_t is the cash flow in year t.

Levelised cost of energy (LCOE). LCOE is the average price of energy that will be provided by the system. Based upon Equation (2), to calculate the levelised cost of energy (LCOE), we need to calculate the system's annual costs.

$$LCOE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \quad 2$$

In this equation, E_{prim} is the amount of primary load for the system, E_{def} is the amount of deferrable load and $E_{grid,sales}$ is the amount of electricity sold to the grid.

Table 10 – Specifications of electrolyser MC250 [59].

Model	MC250
Net Production Rate	531 kg/24 h

System's annualised cost. The system's annualised cost is directly related to the capital recovery factor (CRF) and the total net present cost of the system.

$$C_{ann,tot} = C_{NPC,sys} \times CRF(i,N) \quad 3$$

The total net present cost of the system is the summation of the NPC of each component.

$$C_{NPC,sys} = \sum_{t=0}^{n} C_{NPC,co} \quad 4$$

The capital recovery factor (CRF) is a function of the lifetime and interest rate:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad 5$$

Interest rate, inflation, and project lifetime. In the present study, the nominal interest rate, inflation and project lifetime were taken to be 5.5%, 2% and 25 years, respectively [9]. Table 11 shows a list of the parameter values used in the economic analysis of the system [8,9].

Carbon emission cost. To calculate the carbon emission cost, we must first know the amount of CO_2 produced by the powerhouse. In Norway, the amount of CO_2 for 1 kWh from the grid is 531 gr [61]. To calculate the carbon emission cost, we must first determine the amount of CO_2 produced by the powerhouse. The total energy required for the whole process is 1010 KW (electrolyser and desalination). The amount of CO_2 emission from the grid in a year is therefore:

Table 11 – Economic analysis parameters.

Parameter	Measure	Unit
Project lifetime	25	year
Inflation rate	2	%
Nominal discount rate	5.5	%
PV lifetime	25	year
Wind turbine lifetime	25	year
Scaled annual average	24,240	kWh/d
Solar-scaled average	2.536	kWh/m/day
Wind-scaled average	2.9	m/s

$$Co_2\ emission\ for\ 1\ year = 1010\ (kWh) \times 8760\ (hr) \times 531.00\left(\frac{g}{kWh}\right) = 4,698,075,600\ g$$

Scenarios

The following 8 scenarios were analysed and optimised in this study, using HOMER. The cost of purchasing electricity and the sellback price were also calculated for each scenario.

1. Grid only
2. Grid and PV cell
3. PV cell and battery
4. Grid, PV cell and battery
5. Grid and wind turbine
6. Grid, PV cell and wind turbine
7. Grid, PV cell, battery and wind turbine
8. Cheapest scenarios with new policy for CO2 tax in Norway

Calculations

Grid only. The electricity need, which is constant for each hour, is 1.01 MW for all days of the year. One feature of HOMER is 'random variability', which allows the daily or hourly variability for creating our data to be defined. The essential component for the system is the grid, which therefore must be introduced to the software. The grid power and sellback prices are 0.58 NOK/kWh ($0.069/kWh) and 1 NOK/kWh ($0.12/kWh), respectively [8]. Based on our calculation, the average energy is, therefore, 24,240 kWh/d with no peak, the amount of energy needed being 1010 KWh/h. All financial aspects and CO_2 emission tax are also defined in the software.

Table 12 shows the optimised results for the first scenario.

Other scenarios. The energy need is the same as for the first scenario. HOMER accesses online data from NASA to extract the following:

1. Solar data: global horizontal radiation
2. Temperature data: air temperature
3. Wind data: speed at 50 m above the surface of the Earth [35].

The platform location is 52°11′28.032" N, 4°8′10.259" E. The required local weather data can therefore be downloaded, based on the location [62]. Global horizontal radiation and air temperature are used for solar cells, and wind speed data is used for wind turbines. The temperature of the PV cell affects the amount of electricity produced [63]. HOMER evaluates different solar and wind power plant options for different electricity production levels, based on the identified amount of energy that the user needs.

HOMER suggested PV and grid as mixed resources in the second scenario, based on the cost of the PV cell and insufficient production at night. A maximum of 5.7% of the total electricity came from PV cells in these scenarios. As seen from the results, Grid has the lowest COE, so the source for last scenario will be checked in grid. Table 13 shows the optimisation results from HOMER for all the scenarios.

Our findings, which are based on a comparison of energy costs, show the best electricity resources choice for the study site is the use of the grid. The onshore grid currently supplies energy to hydrogen production on the platform. It was therefore considered preferable, as the eighth scenario, to analyse the model for 2025, using the same electricity cost but with a new tax rule in Norway (2010.82 NOK/tonne CO_2 = $243.07/tonne CO_2) [64,65].

Discussion

Section Desalination process describes the calculation of the amount of electricity required and the cost of producing the permeate flow for the electrolyser. The amount of electricity required to produce the permeate flow was added to the electricity required to operate the electrolyser, giving the total energy required to produce hydrogen from seawater. HOMER

Table 12 – Optimised results for grid only.

COE ($)	NPC ($)	Operating cost ($/year)	Energy purchased (kWh/year)	Carbon dioxide production (kg/year)
0.104	15.3 M	920,323	8,847,600	4,698,076

Table 13 – Optimisation results for grid and PV cell.

Resource	COE ($)	NPC ($)	Operating cost (US$/year)	Energy purchased (kWh/year)	CO_2 production (kg/year)	CO_2 cost US$	Electricity production from (PV/wind turbine) %
Grid	0.104	15.3 M	920,323	8,847,600	4,698,076	309,838.08	
Grid and PV	0.104	15.3 M	920,323	8,840,969	4,694,555	309,605.90	PV = 0.210
PV and battery	0.773	113 M	2.42 M	60,601,548			
Grid, battery and PV	0.104	15.3	920,176	23,906		309,136.07	PV = 0.27
Grid and turbine	0.117	17.8 M	935,731	8,485,974	4,694,555	297,174.12	Wind = 4.09
Grid, turbine and PV	0.130	19.2	902,025	7,851,781	4,169,295	288,155.00	Wind = 0 PV = 5.73
Grid, wind turbine, PV and battery	0.119	17.4 M	914,497	8,295, 748	4,405,042	290,512.51	Wind = 4.04 PV = 3.33
Grid only (2025 new policy for CO_2 tax in Norway)	0.168	24.7 M	1.49 M	8,847,600	4,698,076	1,141,961,333.32	

Pro was used to analyse the energy source and cost, and to identify the best hybrid plant for supplying energy. The results show that using the grid is the cheapest option for all scenarios. COE is $0.104, and NPC is 29.1 for 25 years. Calculating the new CO_2 cost also showed that COE will increase ($0.168). Other studies have also shown that the grid is the most economical solution for energy resources, based on the financial aspects of sustainable energies [8,9].

Based on the electrolyser specifications, the amount of hydrogen produced per hour is 246 Nm^3. Over 25 years, the average cost of energy to produce 246 Nm^3 of hydrogen is therefore $0.168. This number must be added to the cost of water treatment materials.

Results and discussion

Section Desalination process describes the calculation of the lowest operating cost of producing permeate flow, and Section Optimising microgrids and distributed energy resources using HOMER describes the use of HOMER Pro to calculate the lowest levelised cost of energy for producing hydrogen from seawater. The hydrogen production cost was calculated on the basis of the results obtained, as described in Section Methodology.

Table 14 – Optimised system for seawater desalination.

Case	Total specific water cost ($/m^3)	Total chemical and utility cost ($/d)	Total energy kWh/d
3	1.072	8.84	89.06
15	1.094	9.22	65.12

The two optimised systems for seawater desalination shown in Table 14 were designed based on the analysis results presented in Section Methodology.

The cost of producing hydrogen for different financial options is discussed below.

A simple calculation that does not take into consideration the following financial aspects, CO_2 tax, inflation and project lifetime

There is a simple calculation for this option. All the energy consumed by the system must be measured and its cost calculated. The total chemical and utility costs for producing 1 kg of hydrogen should then be added. Table 14 shows the results for the first option.

Table 15 shows that the total cost of producing hydrogen from seawater is $3.5/kg H_2. It is important to note that the cost of the desalination process is less than 1% of the total cost of producing hydrogen from seawater.

Calculation taking CO_2 tax, inflation and project lifetime into consideration

The above calculation is repeated, taking a nominal discount rate, inflation rate, project lifetime and CO_2 tax into consideration. The electricity cost was calculated by HOMER, as described in Section Methodology, and is equal to the COE. Table 16 shows the results.

The cost of electricity reaches US$0.104/kW/hr when the financial aspects of the project and the CO_2 emission tax on producing electricity are taken into consideration, with the hydrogen production cost reaching approximately US$5.1/kg H_2. Again, the cost of the desalination process is less than 1% of the total cost.

Table 15 – Calculation of the cost of producing hydrogen based on the first option.

	Total chemical and utility cost (US$/d)	Total chemical and utility cost (US$/hr)	Hydrogen production (kg/hr)	Cost of electricity US $/kW/hr	Total energy needs for the whole process kW/hr	Total electricity cost	Electricity cost of producing 1 kg hydrogen for the whole process (US$/hr)	Cost of desalination (US$/kg H_2)	Total cost (US$/kg)
Case 3	8.84	0.3683	22.125	0.069	1010	69.69	3.1498	0.028	3.51
Case 15	9.22	0.3841	22.125	0.069	1010	69.69	3.1498	0.029	3.53

Table 16 – Calculation of the cost of producing hydrogen based on the second option.

	Total chemical and utility cost (US$/d)	Total chemical and utility cost (US$/hr)	Hydrogen production (kg/hr)	Cost of electricity US $/kW/hr	Total energy needs for the whole process kW/hr	Total electricity cost	Electricity cost of producing 1 kg hydrogen for the whole process (US$/hr)	Cost of desalination (kg H_2/US$)	Total cost (US$/kg)
Case 3	8.84	0.3683	22.125	0.104	1010	105.04	4.7475	0.034	5.11
Case 15	9.22	0.3841	22.125	0.104	1010	105.04	4.7475	0.035	5.13

Table 17 – Calculation of the cost of producing hydrogen based on the third option.

Case Number	Total chemical and utility cost (US$/d)	Total chemical and utility cost (US$/hr)	Hydrogen production (kg/hr)	Cost of electricity US $/kW/hr	Total energy needs for the whole process kW/hr	Total electricity cost	Electricity cost of producing 1 kg hydrogen for the whole process (US$/hr)	Cost of desalination (kg H_2/US$)	Total cost (US$/kg)
Case 3	8.84	0.3683	22.125	0.168	1010	169.68	7.6691	0.051	7.720
Case 15	9.22	0.3841	22.125	0.168	1010	169.68	7.6691	0.052	7.721

Calculation in which the 2025 CO_2 tax in Norway, inflation and the project lifetime are taken into consideration

The new CO_2 tax will come into effect in 2025 and will increase the cost of electricity to US$0.168/kW/hr. The hydrogen production cost will then increase to US$7.72/kg H_2 (Table 15). The cost of the desalination process will still be less than 1% of the total cost of producing hydrogen from seawater. The results can be found in Table 17.

Using an electrolyser to produce hydrogen is cleaner and more cost-effective than other hydrogen production processes discussed in Section Literature review. Furthermore, this method gives a lower hydrogen production cost and a lower rate of carbon emissions than the other methods mentioned. With advances in electrolyser manufacturing, the amount of electricity required by electrolysers to produce hydrogen is expected to decrease in the future. The use of electrolysers will become the primary and cleanest option for producing hydrogen.

Conclusions

Energy consumption has grown as a result of population growth and industrial development. The burning of fossil fuels to produce energy results in greenhouse gas emissions and contributes to air pollution. Governments therefore seek ways of dealing with these problems. One of the most promising approaches to minimising fossil fuel consumption is the use of hydrogen as an alternative to fossil fuel. Hydrogen also has one of the highest specific energies of any fuel. Water molecules can be split into hydrogen and oxygen in an electrolyser. This procedure, however, necessitates the use of high-quality water. Approximately 71% of the Earth's surface is covered with water, the bulk being saline in seas and oceans. An electrolyser cannot operate directly with saline water, which must be converted into purified water with low conductivity. Water desalination is therefore critical to the production of hydrogen from seawater, using electrolysers.

This study has explored the economic possibility of producing hydrogen from seawater, the focus being on producing water with conductivity of between 0.1 and 1 μS/cm. Twenty-four processes were designed for water treatment systems, and optimal systems with low operating costs for RO and double-RO (one pass, two passes) were chosen. The cost of water production for 1 kg of H_2 was calculated. The amount of energy required by the electrolyser was then added to the amount of energy required by the water treatment system. The cost of producing 1 kg of H_2 based on existing cables from the grid to the offshore was finally estimated. All estimates were made using the existing connection from the grid to the offshore, and cables and distribution costs were not taken into account. The results show the cost to be US$3.51/kg H_2. The cost of the desalination of water for 1 kg of hydrogen is relatively low, which is why this factor is neglected in some studies. The amount of energy required for desalination is 1% of the energy required for the whole process.

The possibility of generating renewable electricity, from a hybrid power plant consisting of different components (PV, wind turbine and grid), for 25 years was also explored. A nominal discount rate, inflation rate, project lifetime and CO_2 tax were applied. The grid was the type of system with the lowest levelised cost of energy (LCOE), with the cost of producing hydrogen reaching US$5.11/kg H_2 when a tax on CO_2 emissions in Norway from the grid was taken into consideration.

Finally, the cost of hydrogen production was determined based on the only grid, with the new 2025 CO_2 emission tax in Norway being taken into consideration. From 2025, the CO_2 emission tax in Norway will be US$243.07/tonne CO_2, compared to the current 65.95 US$/tonne CO_2. The grid still has the lowest cost when this is taken into consideration, with the cost of producing hydrogen reaching US$7.721/kg H_2.

It must be mentioned that the location of the study was chosen to analyse the first green hydrogen platform. Due to the software's capabilities, however, the location of the study can easily be shifted and extended to other locations. In addition, because electricity from grid was the lowest LCOE the renewable resources in the location do not effect on the hydrogen production cost.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.11.200.

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