Towards techno-economic evaluation of renewable hydrogen production from wind curtailment and injection into the Irish gas network

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Abstract

This paper presents the results of techno-economic modelling of hydrogen production from otherwise wasted wind energy in the Republic of Ireland (ROI), and its transportation to the natural gas network, for injection. The model includes the production of hydrogen by electrolysis powered by curtailed and constrained (wind curtailment) wind energy at every wind farm in the ROI, compression to 300 bar, and transportation by tube trailer to the nearest potential injection point to the natural gas grid. This system is referred to as a wind-hydrogen system (WHS). The model does not currently include the costs of converting the hydrogen to methane or injecting the hydrogen/methane into the grid. The WHS model selects an optimum electrolyser size for each wind farm that minimises levelised cost of hydrogen (LCOH) from that farm. Compressors and storage tanks for each wind farm are scaled to the farm's electrolyser. Central to the WHS model is a correlation that relates optimum electrolyser size to each wind farm's power capacity (CP), annual capacity factor (CF) and percentage wind curtailment (%CW). This correlation was developed from hourly CW time series data for 75 wind farms in the ROI. Capital, operating and other costs were obtained from literature. Results show that not all wind farms in ROI are suitable for WHS, as indicated by high LCOH at farms of capacity <1 MW. However, 6 kilotonnes of hydrogen, equivalent to 204 GWh or 1% of ROI's natural gas demand, are producible from 209 wind farms in the ROI. 76% of WHSs, accounting for 79% of renewable hydrogen capacity, are located less than 100 km from their nearest grid injection point. LCOH for hydrogen production and transportation to the nearest grid injection point are in the range 26-46 €/kg excluding injection tariff.

Keywords:

Wind energy, Hydrogen, Energy system, Energy storage, Geographic information system.

1. Introduction

Global installed capacity of wind energy increased by 450% from 2007 to 2017, accounting for half of the worldwide renewable installed capacity in 2017 [1]. Wind energy installed capacity in the Republic of Ireland (ROI) increased by 320% to 3,368 MW over the same period, and now accounts for 25% of electricity production, the second highest percentage in the world [1]. ROI has the potential to deliver 70% renewable electricity by 2030 [2]. However, 277 GWh (4%) of wind energy was lost in 2017 due to the electricity grid's technical inability to receive all generated wind energy. This figure is projected to rise to 7-14% by 2020 depending on future wind energy penetration [3]. Large-scale, long-term energy storage can help to reduce this figure. Hydrogen can be produced from this otherwise lost renewable electricity via electrolysis and used as a zero-carbon emissions fuel for power generation, heating or transport. It can be injected to the natural gas transmission network at concentrations up to 12% by volume [4]. If produced at wind farms, renewable hydrogen can therefore (1) enable energy storage on site, (2) reduce wasted available wind energy, (3) decrease fossil fuel consumption and carbon emissions, (4) increase clean fuel supply into the gas grid, and (5) enable sector coupling between power, heating and transportation.

The transformation route to produce hydrogen from renewable power is known as power-to-hydrogen [5, 6, 7]. The electricity is used to electrolyse water to hydrogen and oxygen. When hydrogen is used to produce methane, it is described as power-to-gas (P2G) [4, 8]. As illustrated in Figure 1, the wind hydrogen system (WHS) is an integration of each wind farm with an electrolyser, compressor, bundle storage and tube-trailer. A tube-trailer delivers compressed hydrogen to its closest gas grid injection point. Investigation by [9] describes that there are 42 potential locations for injection to gas network in ROI, which are known as above ground installations (AGIs). Thus, the hydrogen production costs from CW and its transportation costs to injection point can be calculated.

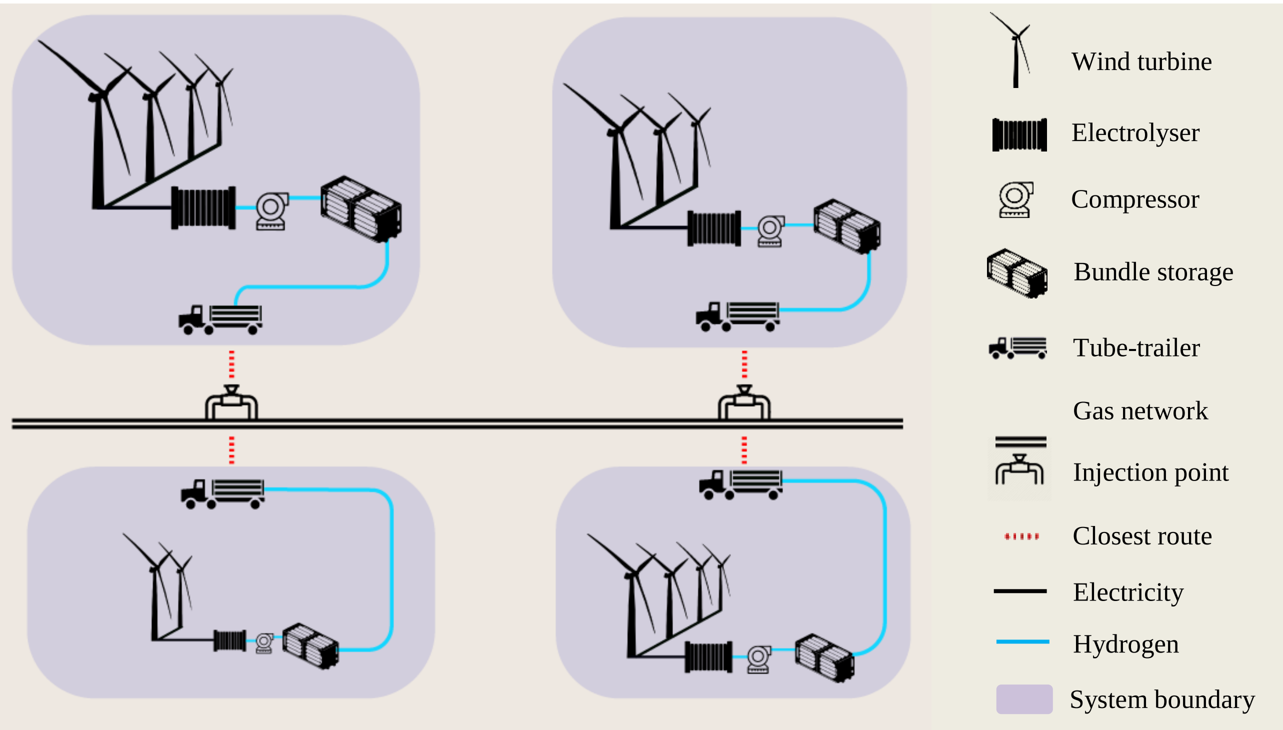

Figure 1. Wind hydrogen system boundary

2. Methodology

2.1 System Description

The WHS is proposed to convert the surplus wind energy to renewable hydrogen. It comprises distribution panel, electrolyser, compressor, storage, and vehicle. The distribution panel manages the input flow of electrolyser power from wind turbine or/and electrical grid. Due to fluctuating CW profiles, additional electricity supply is required and can be delivered by the electricity grid as backup every time the surplus wind energy cannot meet electrolyser minimum input power. The electrolyser system is where water is converted to hydrogen and oxygen. As illustrated in Figure 1, it is an integrated unit of transformer and rectifier (power supplier), safety devices to control the system, inlet pump, treatment, heat exchanger, water circulation pump, proton exchange membrane (PEM) electrolyser stacks, gas water separators, demisters and gas drying (gas purifier) [10]. Then hydrogen is compressed and cooled before it is kept in a storage system. The hydrogen production and storage subsystems are placed at existing wind farms and served by a tube-trailer to transport hydrogen to the nearest gas injection point.

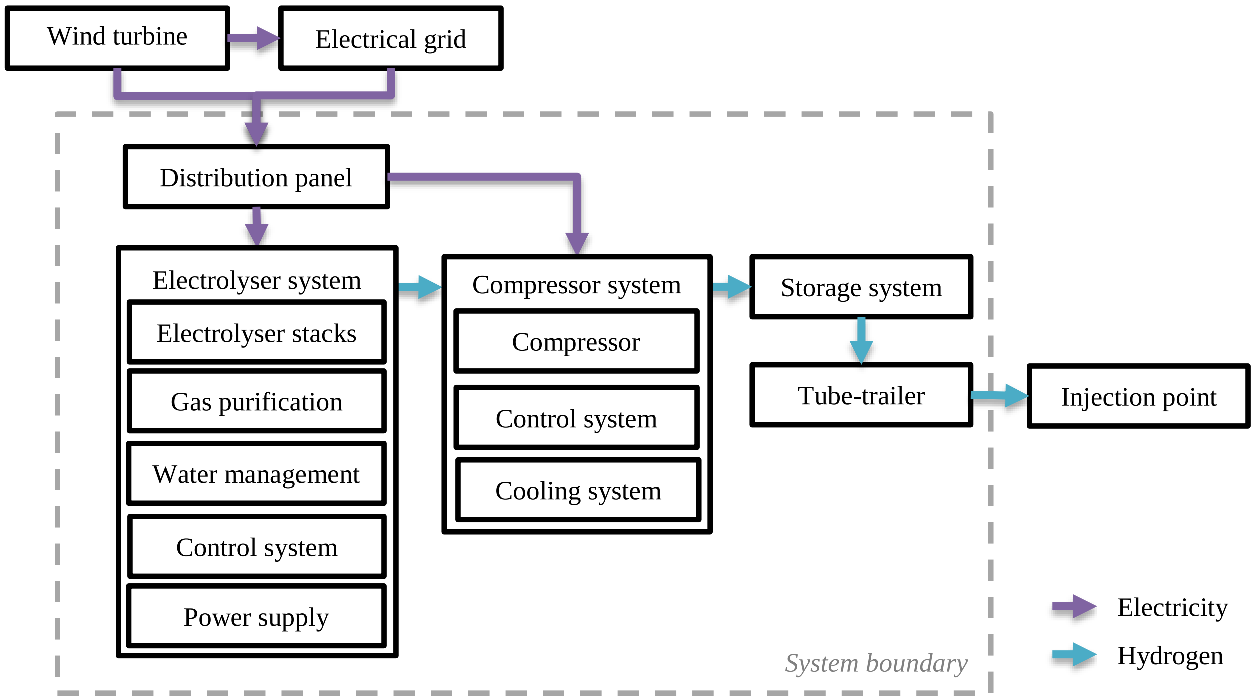

Figure 2. Block diagram of wind-hydrogen system (WHS)

2.2 Technoeconomic submodel

The material in an electrolyser stack can degraded with time [11]. Therefore, a minimum of 5% of the electrolyser nominal rated capacity (P_{nom}) must be maintained to achieve stack's economic lifetime of 5 years. The detailed techno-economic parameters of the electrolyser system are shown in Table 1.

Table 1. Technical parameters of electrolyser system [10, 11, 12]

	Units	PEM (30 bar)	Selected
Nominal input power	kW	1,000 – 20,000	1,000 – 20,000
Minimum input power	% P_{nom}	5	5
Pressure output	Bar	30	30
Power consumption at P nom	kWh_e/kg	63 - 55	55

Water consumption	L/kg	15	15
System economic lifetime	Years	20	20
Stacks economic lifetime	hr	40,000	43,800 (5 years)
System degradation	%/1,000h	0.25	0.25
Annual availability	%/year	>98%	98%

To calculate hydrogen production cost, levelised cost of hydrogen (LCOH) is used as the key economic metric in this evaluation [5, 6, 7]. The equation for LCOH (equation (2)) follows the general variables from levelised cost of energy (LCOE) shown in equation (1).

$$LCOE = \frac{\sum_{t=0}^{t=T} \frac{C_{CAPEX} + C_{OPEX}}{(1+r)^t}}{\sum_{t=0}^{t=T} \frac{E}{(1+r)^t}} \tag{1}$$

$$LCOH = \frac{\sum_{t=0}^{t=T} \frac{C_{inv}}{(1+r)^t} + \sum_{t=0}^{t=T} \frac{C_{FOM}}{(1+r)^t} + \sum_{t=0}^{t=T} \frac{C_{VOM}}{(1+r)^t}}{\sum_{t=0}^{t=T} \frac{M_{H_2}}{(1+r)^t}} \tag{2}$$

Equation (2) requires total investment cost and hydrogen production (M_{H_2}) to calculate hydrogen production cost in € per kg. Total investment cost is the sum of investment capital cost (C_{inv}), fixed (C_{FOM}) and variable (C_{VOM}) operation and maintenance costs. A discount rate (r) of 6% is assumed over a 20-years economic lifetime (T).

$$C_{inv} = (C_{WE} + C_{Comp} + C_{Stor} + C_{Other}) \tag{3}$$

Investment capital cost consists of water electrolyser cost (C_{WE}), compressor cost (C_{Comp}), storage cost (C_{Stor}), and other costs (C_{Other}). Each of C_{WE} and C_{Comp} includes costs for distributed control system, energy management unit, engineering, interconnection, commissioning, and start-up costs. Operation and maintenance cost is divided into fixed C_{FOM} and variable C_{VOM} components. Maintenance of electrolyser ($C_{Main,\,WE}$), compressor ($C_{Main,\,comp}$) and storage ($C_{Main,\,stor}$), together with stack replacement (C_{SR}) are included in C_{FOM}, where C_{VOM} accounts for the electricity (C_{Elec}) and water costs (C_{Wat}) as written in (4) and (5). Expense for electricity is the total purchase of grid electricity and wind curtailment.

$$C_{FOM} = (C_{Main,WE} + C_{Main,comp} + C_{Main,stor} + C_{SR}) \tag{4}$$

$$C_{VOM} = (C_{Elec} + C_{Wat}) \tag{5}$$

Annual hydrogen production (M_{H_2}) can be calculated from input power for the electrolyser system at defined electrolyser size (E_{ES}) multiplied by the efficiency of electrolyser system (η), then divided by lower heating value of hydrogen (LHV_{H_2}). The method used to size electrolysers at each wind farm is described in Section 2.4.

$$M_{H_2} = \frac{\sum_{t=0}^{t=T} E_{ES} \cdot \eta}{LHV_{H_2}} \quad (6)$$

2.3 Wind curtailment submodel

Ireland's Single Electricity Market Operator (SEM-O) provides the data required to calculate CW profile from wind farms in ROI with capacity larger than 10 MW. At least three essential pieces of data can be downloaded from the SEM-O website (www.lg.sem-o.com): actual availability (AA), dispatch quantity (DQ) and metered generation (MG). Each data is in hourly basis within a time-series of one year or 8760 hours. AA is the available power a wind farm can deliver to the grid. MG is the active power exported by a wind farm. To calculate bid offer acceptance on each imbalance settlement period, SEM-O also provides DQ, which is based on dispatch instruction [13]. Finally, the actual CW can be computed by following equation (7) and (8).

$$CW = AA_{(t)} - \left(Max\left(DQ_{(t)} or\, MG_{(t)}\right)\right),\ if\ AA_{(t)} > DQ_{(t)} \quad (7)$$

$$CW = 0,\ if\ AA_{(t)} = DQ_{(t)} \quad (8)$$
$$AA_{(t)} < DQ_{(t)}$$

2.4 Electrolyser sizing submodel

There are several WHS pilot plants operating across Europe. According to [7, 14, 15], LCOH varies from 3 €/kg to 28 €/kg. The electrolyser contributes single largest share of up to 40% of total expenditure, followed by compressor and storage vessels [7, 16]. Therefore, all the cost parameters are set to be functions of electrolyser size (ES), as listed in Table 2. The LCOH is calculated iteratively and started at an ES of 10 kW, increasing in increments of 50 kW to the wind farm rated output. The ES that results in the minimum LCOH for a given wind farm is selected as the optimum ES for that wind farm.

Table 2. Economic parameters in WHS, calculated from [10, 17, 18, 19]

	Symbol	Unit	Parameter
Total investment cost			
Electrolyser system cost	C_{WE}	€/kW	$3872 \cdot ES^{-0.075}$
Compressor cost	C_{Comp}	€/kW	$7670.1 \cdot ES^{-0.34}$
Bundle steel storage	C_{Stor}	€/kg	$470 \cdot (\dot{M}_{H_2} \cdot 48)$
Equipment costs	EC	€	$ES \cdot (C_{WE} + C_{Comp})$
Other cost	C_{Other}	€	$(1.5652 \cdot ES^{-0.154}) \cdot EC$
Fixed operation & maintenance cost			
Electrolyser maintenance	$C_{Main,\,elec}$	$\%C_{WE}$	$167.42 \cdot ES^{-0.305}$
Compressor maintenance	$C_{Main,\,comp}$	€/kW	$2\% \cdot C_{Comp}$
Storage maintenance	$C_{Main,\,stor}$	€/kW	$2\% \cdot C_{Stor}$
Stack replacement	C_{SR}	€/kW	$1355.2 \cdot ES^{-0.075}$
Variable operation & maintenance cost			

Average grid electricity price in ROI	P_{Elec}	€/kWh	0.1263
Average LCOE of onshore wind farm	P_{CW}	€/kWh	0.08
Average water price in ROI	P_{Wat}	€/m^3	2.38

2.5 Compressor and storage submodel

In the hydrogen industry, reciprocating compressors are widely used, so are used in this study. Compression from 30 barg to 300 barg requires two stages to maintain the discharge temperature at 135 °C, with efficiency of 50% and power consumption of 1.7 kWh$_e$/kg [10, 20, 21].

For a long-term storage system with capacity from 10 hours to many months, bundles of steel storage cylinders are selected due to their capability to store up to 300 bar. Depending on the average hydrogen production rate, hydrogen will be kept in the storage system before it is transported to the injection points.

2.6 Transportation submodel

As mentioned in the system description section, there are 42 AGI locations along the ROI natural gas network that can potentially be utilised for renewable hydrogen injection points. Therefore, a transportation cost submodel is created to calculate the additional transportation cost for each WHS in ROI. A tube-trailer with pressure 300 bar is used to transport 500 kg hydrogen per trip. Geographic Information System (GIS) is used to identify the nearest injection point to each wind farm, and the shortest road route. To carry out this, GIS requires the detailed road network in ROI, which can be obtained from [22]. The parameters of transportation cost are calculated from [23, 24] and shown in Table 3.

Table 3. Parameters in transportation cost model

Parameters	**Symbol**	**Unit**	**Value**
Hydrogen trailer cost		€ /kg	464
Vehicle cost	C_v	€ /truck	232,000
Vehicle lifetime		years	10
Salary	C_s	€ /person	38,000
Employers		person	1
Fuel cost	C_f	€ /km	0.20
Other running costs	C_{oc}	€ /km	0.34
Tube-trailer capacity	Cap_v	kg/ trip	500
Average speed		km/h	50
Hydrogen pressure		bar	300
Trip numbers per year	TR_{year}		calculation
Distance between WHS and AGI	$D_{WHS.AGI}$		calculation
Delivered mass per year	M_{H2}		calculation

As an additional cost to existing LCOH, the transportation cost (C_{trans}) must be a ratio of total transportation (C_{tot}) over hydrogen production capacity (M_{H_2}). The equation to calculate transportation cost is shown below.

$$C_{trans} = \frac{C_{tot}}{M_{H_2}} \tag{9}$$

The total transportation cost is the sum of investment cost (C_{inv}) and travel cost (C_{travel}). Investment cost calculates the vehicle cost (C_v) and its operation cost (C_s). On the other hand, travel cost takes into account the shortest distance between WHS and injection points ($D_{WHS.AGI}$), total annual trip numbers (TR_{year}), fuel cost (C_f), other cost (C_{oc}) and return trip as indicated by two as written in the following equation.

$$C_{tot} = C_{inv} + C_{travel} \tag{10}$$

$$C_{inv} = C_v + C_s \tag{11}$$

$$C_{travel} = D_{WHS.AGI} \cdot TR_{year} \cdot 2 \cdot \left(C_f + C_{oc}\right) \tag{12}$$

To obtain the optimum travel cost, the number of trips is calculated based on the average length of storage time (ST_{days}) according to each WHS daily average production ($M_{H_2,ave}$) and tube-trailer capacity (Cap_v), as shown below.

$$TR_{year} = \frac{365}{ST_{days}} \tag{13}$$

$$ST_{days} = \frac{Cap_v}{\dot{M}_{H_2}} \tag{14}$$

2.7 Solution algorithm

To exploit the usage of CW in the entire country, WHSs are designed to be decentralised and sited at each wind farm throughout the island. SEM-O collects hourly power generation data from at least 74 wind farms. Three years of hourly CW from 2015 to 2017 of each wind farm are the data source to calculate the average CW. This CW profile is then used in the electrolyser sizing submodel to calculate LCOH using different ES from 10 kW to 20 MW. The optimum ES is selected at the minimum LCOH. The transportation cost is then added to the minimum LCOH. As depicted in Figure 3, required and calculated values are indicated by square boxes, where mathematical models are shown in round edge boxes. To help understanding the model, preparation data from SEM-O are shown in blue boxes, calculation of technical production with purple boxes and production cost within cream boxes.

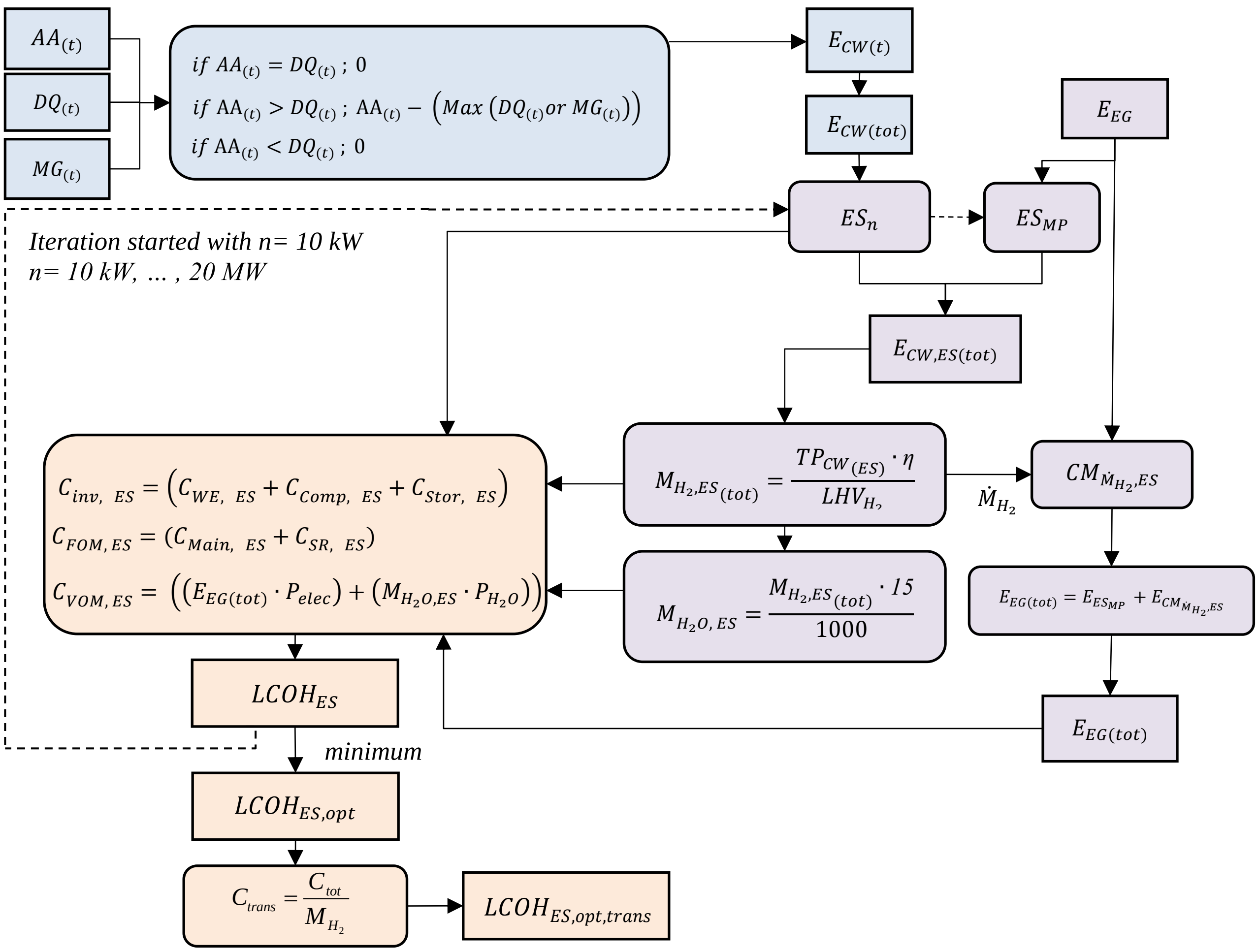

Figure 3. Model to calculate minimum LCOH

3. Results and Discussion

3.1 Electrolyser sizing for a sample wind farm

Figure 4 shows the CW profile of Ballincollig Hill wind farm in 2015. The grey line illustrates the exported power to the grid, where surplus energy is indicated by black line. This 15 MW wind farm runs with 31% capacity factor and 13% CW. As a result, 5204 MWh wind energy is wasted. CW occurs 65% of the time, where half the occurrences are below 2.2 MW and the largest curtailment reaches 11 MW.

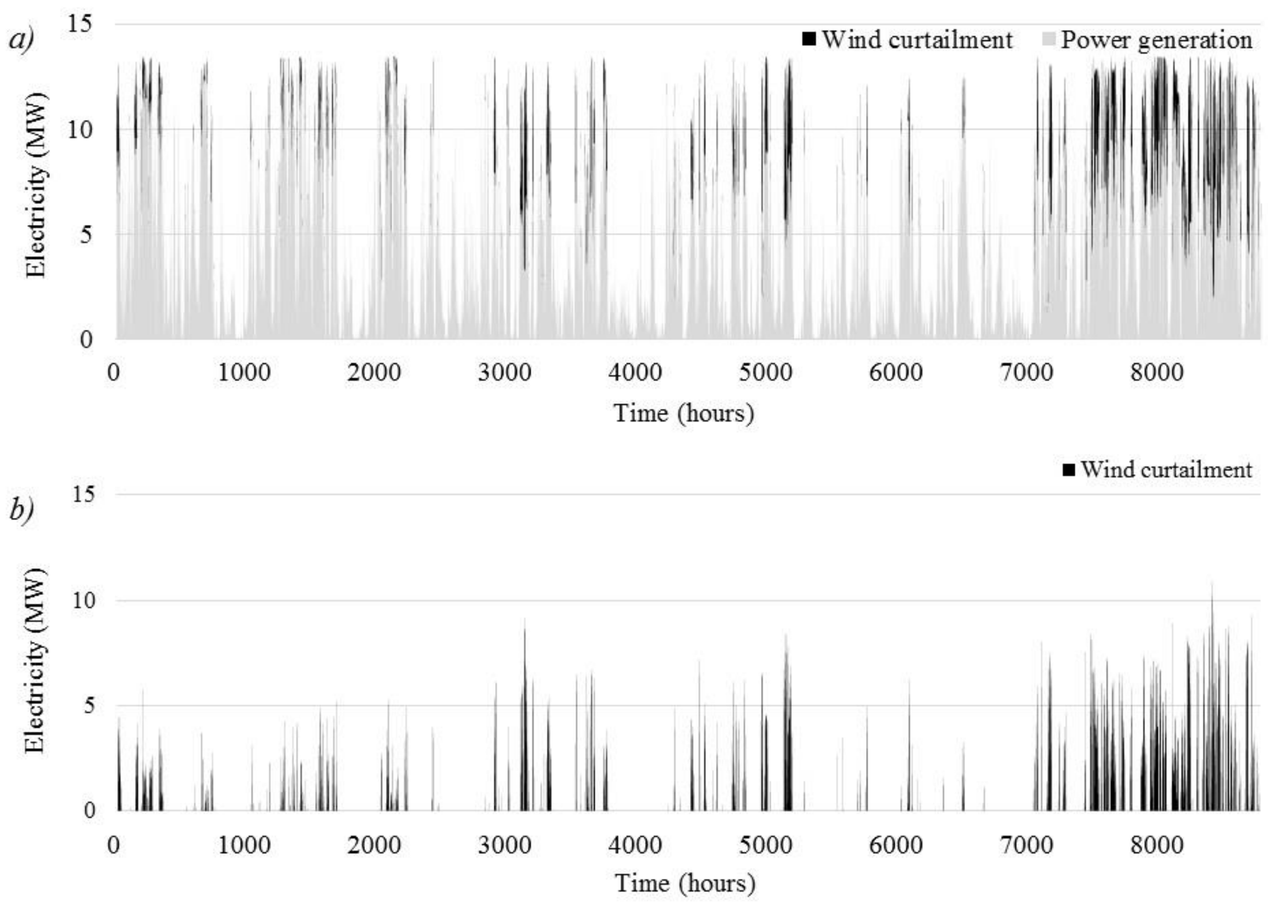

Figure 4. Annual energy profile. a) Power generation profile, b) Wind curtailment profile

From the iterative calculation of LCOH, LCOH falls from 93 €/kg for a 10 kW electrolyser to its minimum level of 20 €/kg for a 2 MW electrolyser as depicted in Figure 5. The maximum CF of the electrolyser reaches 19%. At this condition, 78% of the input electricity is delivered from curtailed wind and the remainder, which maintains minimum electrolyser operation, from electrical grid.

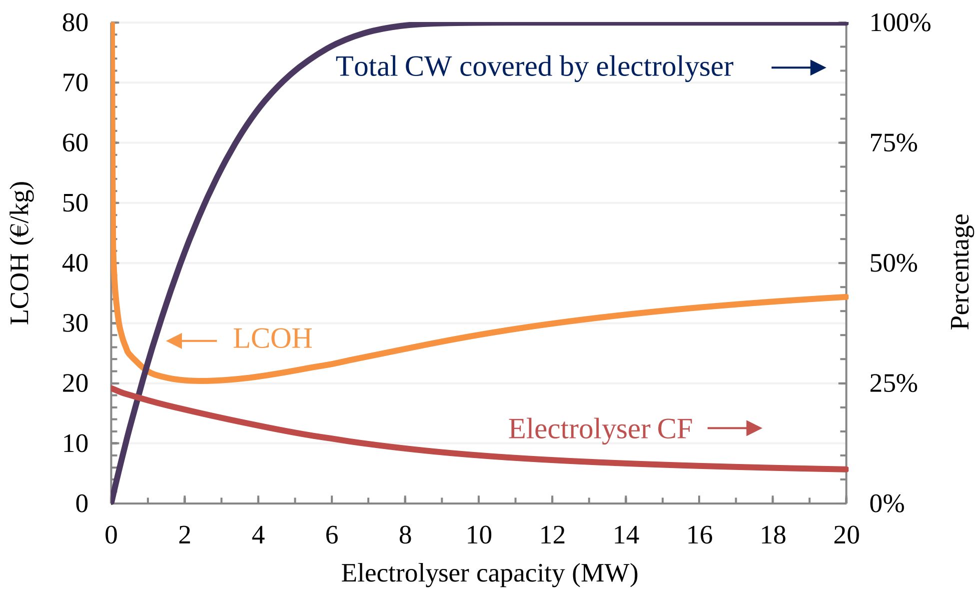

Figure 5. Calculated LCOH for Ballincollig Hill wind farm as a function of electrolyser size

3.2 Optimal electrolyser sizing for all ROI wind farms

A statistical model can be developed for the 74 wind farms in ROI that have detailed hourly data. There are however 238 wind farms in total in ROI, so a method must be developed to size electrolysers and WHSs for these sites. The dependence of optimum electrolyser size for the 74 wind farms at minimum LCOH on total annual CW is shown in Figure 6. Additionally, the strong reliance of hydrogen production on the amount of wasted energy at wind farm also illustrated in the same figure.

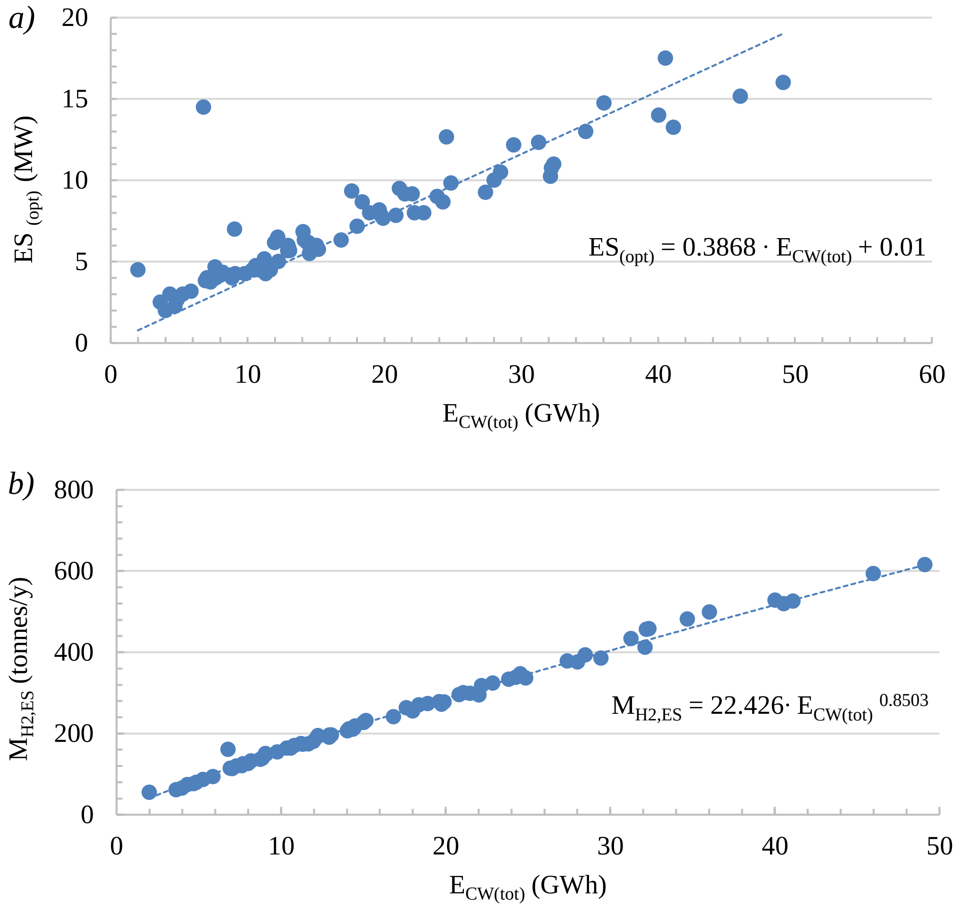

Figure 6. Dependence of (a) optimum electrolyser size and (b) annual hydrogen production, on total wind curtailment volume for detailed wind generation data wind farms in ROI

These statistical models are used to broaden LCOH calculation to all wind farms in ROI where only limited data are available. Instead of using complete data from SEM-O, three important data are taken from Sustainable Energy Authority of Ireland (SEAI) and the Eirgrid annual report [25]. They are ratio of lost energy over available wind energy (%CW), ratio of wind power production over annual wind energy production capacity (%CF) and its wind farm capacity (CP). From these limited data, total CW can be computed for all wind farms in ROI and minimum LCOH at each wind farm can be obtained from the developed statistical model.

3.3 Production-only LCOH at optimum electrolyser size

By using the statistical model, the optimum ES for 238 WHS in ROI can be found. The potential hydrogen production range is from 0.08 to 178 tonnes per year. There are 10 wind farms with capacity lower than 250 kW and each produces less than 1 ton per year. These hydrogen production rates are very low and do not benefit from economies of scale, therefore LCOH significantly increases to more than 50 €/kg. 19 wind farms with capacities between 250 kW and 1 MW have production costs of 30-50 €/kg. All other wind farms in Ireland have capacities greater than 1 MW and have LCOH between 25 and 30 €/kg, as shown in Figure 7.

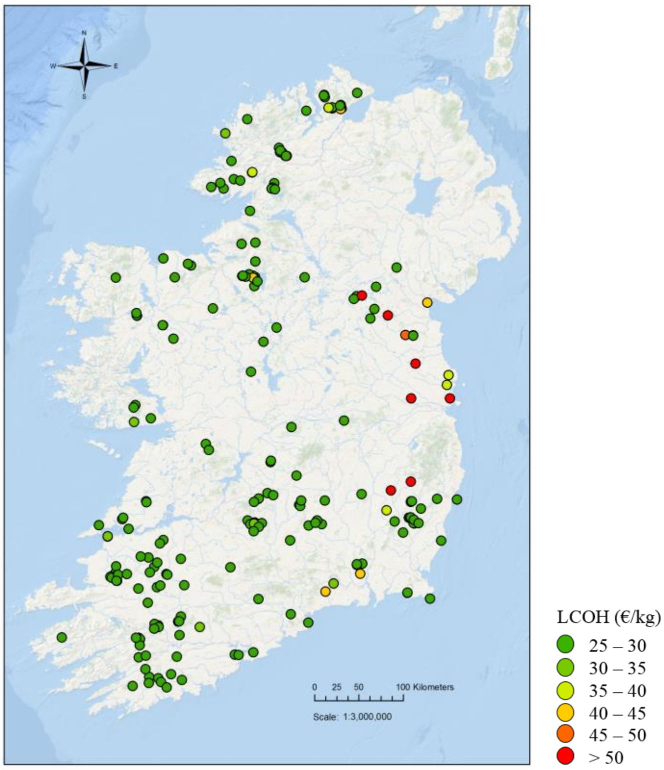

Figure 7. LCOH, excluding transportation costs, calculated by the WHS model for all wind farms in ROI

3.4. Transportation analysis

The duration of storage at each WHS in ROI has to be measured due to the fact that most of the daily hydrogen production from 238 wind farms are less than 500 kg/day. The 11 MW Kingsmountain wind farm produces 108 kg hydrogen per day, therefore the storage system accumulates hydrogen in more or less 5 days until hydrogen can be delivered by a tube-trailer in full capacity of 500 kg, as shown in Figure 8 for 10-days profile. This occurs due to the absence of CW, consequently electrolyser relies on electrical grid during this period and produces minimum hydrogen amount. Total number of trips of tube-trailer is 96 times per year as illustrated in the same figure for annual profile.

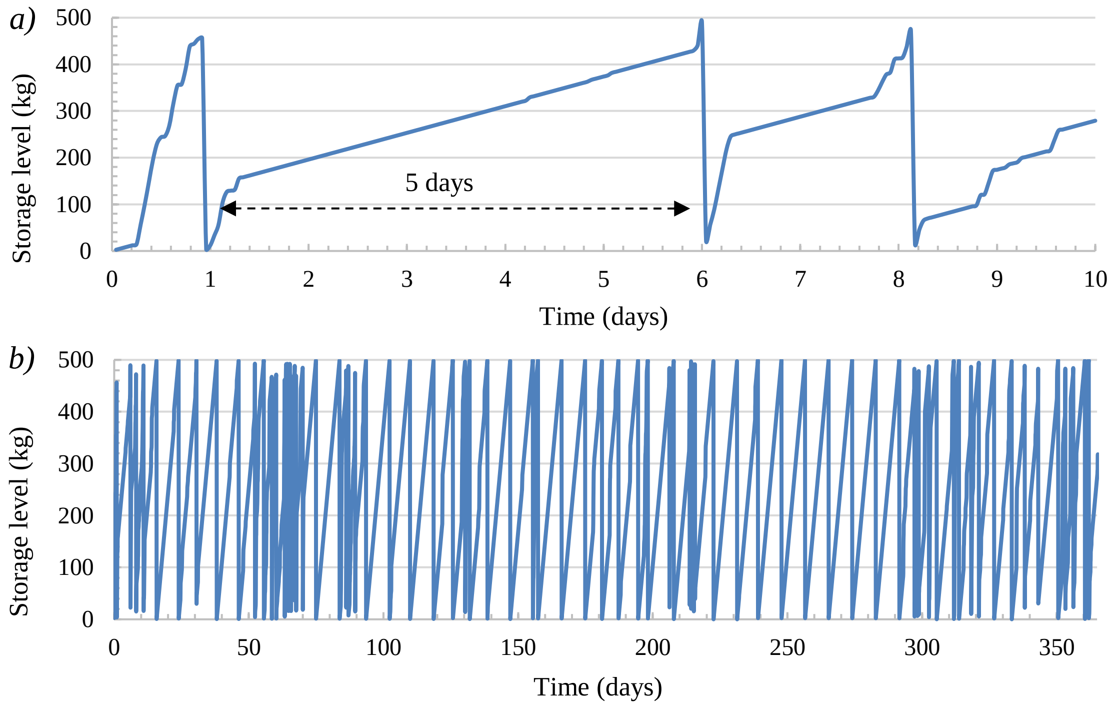

Figure 8. Hydrogen storage profile. a) 10-days profile, b) annual profile

3.5 Production and transportation LCOH

As mentioned previously in transportation submodel, the model accounts for the minimum road distance between each WHS and its nearest injection point, as shown in Figure 9. All wind farms below 1 MW have total production and transportation costs of higher than 50 €/kg. The larger capacity wind farms, at least 209 WHSs, have total costs between 26 and 46 €/kg, with average LCOH of 30.8 €/kg. The results show most of these WHSs are located less than 100 km from their nearest injection point, where the longest distance reaches 343 km. WHSs in the far northwest of ROI have longer distance to reach nearest injection locations compared to WHSs in the middle and southern parts of the island. This is because AGIs in Northern Ireland, which part of the UK, have not been included in the current analysis. Figure 10 shows that at least 76% of WHSs, which deliver 79% of hydrogen capacity, are located below 100 km to the nearest gas injection locations. The total hydrogen production potential from all WHSs reaches 6 kilotonnes. This is equivalent to 204 GWh or 1% of ROI's natural gas demand in 2017 [26]. These costs depend on each WHS's hydrogen production rate, transport distance to injection point. The exclude any injection tariff or costs of conversion to methane in a power-to-gas system.

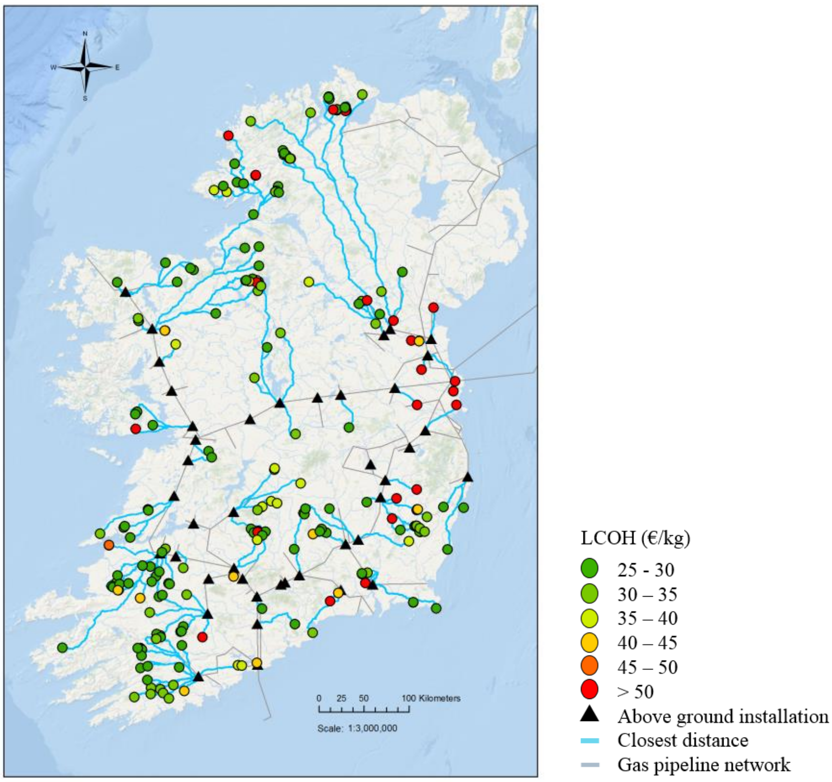

Figure 9. LCOH, including transportation costs to the nearest grid injection points, calculated by the WHS model for all wind farms in ROI

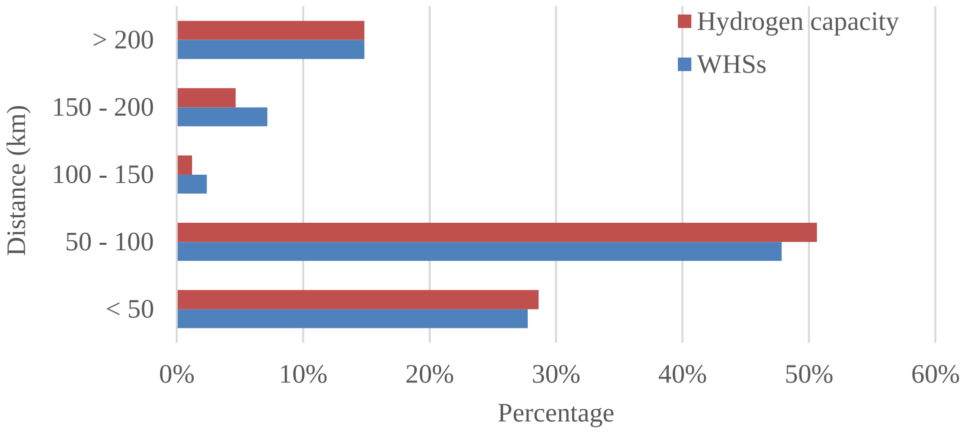

Figure 10. Share of hydrogen capacity and number of WHSs as functions of distance from WHS to injection points

3.6 Limitations and future work

Future work must focus on implementing commercial sizes and costs of electrolyser and compressor. It is also necessary to advance the WHS model and design by developing new arrangement of multiple electrolyser size and battery combination. In the transportation analysis, potential injection points for renewable hydrogen in Northern Ireland must be included in the GIS analysis, so that WHSs in the northern part of the island can have less travel distance to injection points. It is also important to review the potential constraints on hydrogen injection in ROI. These may include maximum hydrogen percentage and the capacities of AGIs. Additionally, there is also an opportunity to study new transportation systems to carry small quantities of hydrogen from small wind farms, so that all hydrogen can be transported efficiently. As complementary work, it is important to evaluate an alternative distribution scenario to cover energy demand in non-grid connected areas.

4. Conclusions

A wind-hydrogen system (WHS) is proposed and designed to harness wasted wind energy to generate renewable hydrogen gas supply and deliver it natural gas network. In designing a WHS, annual CW profile is crucial in the minimum LCOH calculation due to the strong dependence electrolyser sizing has on electrolyser input energy. Based on CW data, statistical models are generated to calculate LCOH for all wind farms in ROI. GIS supports the additional transportation cost calculation at each WHS.

This evaluation shows that minimum LCOH for all wind farms in ROI can be found by using three essential values of %CF, %CW and CP. Afterwards, GIS can be a reliable tool to plot the shortest road route between WHS and injection locations. As a result, wind farms with capacity lower than 1 MW are not suitable to the proposed WHS, as indicated by very high LCOH. On the other hand, results also show 76% of the above 1 MW wind farms in ROI are located below 100 km to nearest injection point and have potential to supply 79% renewable hydrogen potential with average production plus transportation costs of 30.8 €/kg. The total hydrogen production potential reaches 6 kilotonnes which is equivalent to 204 GWh or 1% of ROI’s natural gas demand in 2017.

The future stages of this work is to improve the accuracy of the WHS model based on commercial size and costs of electrolyser and compressor. It also important to broaden GIS analysis to potential hydrogen injection points in Northern Ireland. New distribution mechanism to cover small wind farms and non-gird connected areas is also necessary to be developed and evaluated in the future.

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Nomenclature

C	Cost, €
D	Distance, km
E	Energy generated, MWh
LCOE	Levelised cost of energy, €/ MWh
LCOH	Levelised cost of hydrogen, €/ kg
LHV	Lower Heating Value, kWh/kg
M	Mass, kg
$\dot{M}$	Mass flow rate, kg/h
ST	Storage duration per year, days/y
t	Time, h
TR	Number of trips per year, trips/y

Greek symbols

η	efficiency

Subscripts and superscripts

AA	Actual availability
AGI	Above ground installation
CAPEX	Capital expenditure
CM	Compressor capacity
Comp	Compressor
CW	Wind curtailment
DQ	Dispatch quantity
EC	Equipment cost
Elec	Electricity
Eng	Engineering
ES	Electrolyser size
f	Fuel
FOM	Fixed operation & maintenance
H_2	Hydrogen gas
inv	Investment capital
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
Main	Maintenance
MG	Metered generation
OPEX	Operation and maintenance expenditure
opt	Optimum
Other	Other expenditure
r	Discount rate
s	Operaton expenditure
SR	Stack replacement
Stor	Storage
trans	Transportation
travel	Travel expenditure
v	Vehicle expenditure
VOM	Variable operation & maintenance
Wat	Water
WE	Water electrolyser
WHS	Wind hydrogen system
OC	Operation costs

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