Work Package 7

Deliverable 7.6

Final Environmental Performance Report

Public

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Contents

Tables

Figures

Acronyms and abbreviations

CGH_2: Compressed Gas Hydrogen

CH_4: Methane

CHP: Combined Heat and Power

CO_2: Carbon Dioxide

EU: European Union

FC: Fuel Cell

FCEV: Fuel Cell-Electric Vehicle

GHG: Greenhouse Gas

GWP: Global Warming Potential

H_2: Hydrogen

HHV: Higher Heating Value

ICE: Internal Combustion Engine Vehicle

JRC: Joint Research Centre of the European Commission

kWh: Kilowatt Hours

LBST: Ludwig-Bölkow-Systemtechnik

LCA: Life Cycle Analysis

LHV: Lower Heating Value

MJ: Mega Joule (1 kWh = 3.6 MJ)

MPa: Megapascal (1 MPa = 10 bar)

MW: Megawatt (1 MW = 1000 kW)

Nm^3: Norm cubic metre

RED: Renewable Energy Directive

SMR: Steam Methane Reforming

yr: Year

EXECUTIVE SUMMARY

This document is a deliverable in the context of the HyBalance project.

The methodology for the environmental performance assessment of the HyBalance plant is described. For this final report, technical performance measurements of the HyBalance plant have been combined with different electricity supply cases (grid mix Denmark today and in the future, 100% wind, physical supply), and the resulting greenhouse gas emission balances calculated accordingly.

Electricity from electricity generation mix in 2019 leads to slightly lower GHG emissions from the supply of hydrogen via water electrolysis compared to hydrogen from onsite natural gas steam reforming, and significantly lower GHG emissions compared to hydrogen from central steam reforming in Germany and transport to Denmark.

The GHG emissions from the supply of hydrogen via electricity using the Danish electricity mix will decrease further in the future. Denmark is on a renewable power deployment track to net zero GHG emissions in electricity well before 2050.

Power-to-hydrogen is a key building block for energy system integration, notably via demand side management for grid connected electrolysis plants.

A simple but robust sustainability framework is needed to give stakeholders confidence for building value chains, and for public acceptance. Current policy tracks that could positively shape power-to-hydrogen markets are electricity market regulatory (taxes and levies on storage and other uses), EU RED II national implementation and delegated acts, and EU sustainability taxonomy.

1. Introduction & Approach

1.1 About the HyBalance project

HyBalance is a power-to-hydrogen demonstration project led by Air Liquide and the Copenhagen Hydrogen Network (CHN) together with partners Hydrogenics (electrolyser supplier), Centrica Energy Trading (Danish electricity and natural gas trading company formerly known as Neas Energy), Hydrogen Valley/CEMTEC (Danish business incubator), and Ludwig-Bölkow-Systemtechnik (LBST, research institute and consultancy).

The objective of the HyBalance project is to validate highly dynamic PEM (Proton Exchange Membrane) electrolysis technology and demonstrate this at megawatt-scale (1.2 MW) in an industrial environment. HyBalance has an installed production capacity of about 500 kg of hydrogen per day.

The hydrogen is produced from water electrolysis, enabling the storage of renewable electricity from wind turbines. It helps balance the grid, which is essential for the stability in electricity systems. The hydrogen produced is used to supply industrial customers as well as the network of hydrogen refuelling stations installed and operated by the Copenhagen Hydrogen Network (CHN), an Air Liquide subsidiary in Denmark.

The HyBalance project budget totals € 15 million. The project has received € 8 million in funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2-JU) as well as € 2.6 million in funding from the Danish EUDP program.

1.2 Embedding of this deliverable in HyBalance reporting

This D7.6 Final Environmental Performance Report is one in a row of deliverables that have been developed in the HyBalance project. It builds on D7.1 which has laid out an approach and methodology for the techno-economic and environmental analysis, and D7.3 Intermediary Environmental Performance Report in which nameplate data and actual measurements at nominal production capacity had been used.

For the sake of actuality and completeness, the methodology relevant to the environmental performance assessments has been updated and is included in this report (see the following chapter 1.3).

1.3 Approach

This final environmental performance report builds on actual HyBalance performance data gained from both dedicated measurement regimes (part load behaviour) as well as simulations of plant operation regimes (demand curve, grid carbon intensity). This data is complemented with typical values for value chain elements up and downstream the HyBalance plant, such as the GHG footprint of electricity grid mix or hydrogen transport via truck/pipeline.

1.4 Methodology

The calculation of the environmental performance is based on the life-cycle assessment approach.

According to the funding contract, the following **environmental impacts** are assessed in this report:

- **Greenhouse gas emissions** in terms of global warming potential (GWP) expressed as CO_2-equivalents

- **Cumulated energy efforts** required for the production of hydrogen (as far as data is available)

Generally, in comprehensive life-cycle assessments (LCA) there are sometimes also other impact categories considered, e.g. ozone formation potential, eutrophication, or water consumption. These categories are of no or minor relevance in the setting here (see the following example of water consumption) or are subject to site specific environmental impact assessments demanded by local regulatory authorities for the approval to build and operate a plant.

Excursus: Sustainability impacts other than climate change – Example water consumption

The critical issue of water consumption associated with energy conversion processes is intensively discussed by institutions such as the IEA, IRENA, US-GOA and US-DOE in the context of the so-called water-energy-nexus. According to [LBST & BHL 2018, Table 4], water demand for the production of power-to-hydrogen and power-to-liquids is in the range of 1.3 to 2.6 litre H_2O per litre Diesel equivalent for a range of power-to-X processes. The water footprint of biofuels strongly depends on the cultivated species, agricultural practices, local climatic conditions and soil properties. Nevertheless, the data clearly show that the water footprint of electricity-based fuels is by several orders of magnitude (i.e. 400 to 15000) lower than in case of biofuels.

Further **methodological definitions** have been applied in this study and are documented in the following:

- Functional unit and system boundary

The functional unit for the life-cycle assessment is 1 MJ of hydrogen (lower heating value).

The system boundary for greenhouse gas analysis is well-to-gate (ex industry site in, ex filling station[1] in).

- Greenhouse gases

The greenhouse gas emission balance is performed in general accordance with ISO 14044/67, using principles in accordance with JRC / EU Renewable Electricity Directive (RED) methodology. Greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)[2]. The global warming potential of the various greenhouse gases is expressed in CO_2 equivalents. Table 1-1 shows the global warming potential for a period of 100 years according to the Fourth and Fifth Assessment Reports (AR4 and AR5 respectively) of the Intergovernmental Panel on Climate Change (IPCC).

Table 1-1: Global warming potential (GWP) of variousgreenhouse gases [IPCC 2007], [IPCC 2013]

Greenhouse gases	IPCC Assessment Report 4 (g CO_2 equivalent/g) – used in this study here –	IPCC Assessment Report 5 (g CO_2 equivalent/g)
CO_2	1	1
CH_4	25	30*
N_2O	298	265*

* Table 8.A.1 of the Fifth IPCC Assessment Report

1 This case is subject to the actual supply of H_2 refuelling stations from HyBalance plant and is part of the final environmental performance report at the end of the HyBalance demonstration phase only.

2 Other greenhouse gases are CFCs, HFCs, and SF6, which are, however, not relevant in this context.

Leading research institutions (e.g. Argonne National Laboratory for its tool 'GREET 2014') have already started to use the values of the latest (fifth) IPCC report, i.e. a GWP of 30 g/g for CH_4 and 265 g/g for N_2O [3] [IPCC 2013]. However, in this study the AR4 values have been used because they are also used in the recast of the Renewable Energy Directive (RED II).

The energy requirements and greenhouse gas emissions resulting from the construction and decommissioning of manufacturing plants (so called 'grey emissions') are not considered here analogous to JRC/EUCAR/CONCAWE methodology for well-to-wheel studies.

- Efficiency method

For the calculation of the energy requirements the so-called 'efficiency method' has been used similar to the procedure adopted by international organisations (IEA, EUROSTAT, ECE). In this method the efficiency of electricity generation from nuclear power is based on the heat released by nuclear fission which leads to an efficiency of about 33%. In the case of electricity generation from hydropower and other renewable energy sources that cannot be measured in terms of a calorific value (wind, solar energy) the energy input is assumed to be equivalent to the electricity generated which leads to an efficiency of 100%. The efficiency of geothermal electricity generation is set to 10%.

- Emission allocation

In case emissions of one process have to be allocated to two or more products, the allocation by energy is used where-ever applicable. In the HyBalance case such allocation would be needed only from today's perspective if e.g. the heat from the electrolyser was fed into a district heating grid. The heat case had been investigated by the HyBalance operator but was found not tangible as there is no heating grid in the vicinity of the HyBalance plant.

[3] Without climate-carbon feedback (cc fb).

2. Use Cases

2.1 Overview over pathways investigated

For a comparison of HyBalance environmental performance, several pathways have to be investigated, i.e. taking different energy sources as well as different transport means into account.

Two current HyBalance supply pathways are investigated, i.e. hydrogen for use in industry (ex industry / H_2 refuelling station gate in)

- via H_2 pipeline,
- via H_2 trucking.

It is envisaged to also include the supply of H_2 refuelling stations from HyBalance via trucking as another use case in the final project report. This is, however, subject to actual delivery of hydrogen from the HyBalance plant for the transport sector.

Two fossil reference pathways are considered for comparison of HyBalance results:

- Hydrogen via steam methane reforming of natural gas with truck transport from Germany (current case from Germany for high quality)
- Hydrogen via steam methane reforming of natural gas onsite industry premises[4] (it is assumed that the sites are connected to a natural gas grid)

For the final environmental performance report, the following primary energy supply cases are explored:

- Production grid mix Denmark
- 100 % wind power

For the calculation of the life cycle consumption of primary energy sources data about the fuel input for electricity generation is required. [Energinet 2018, p8], [Energinet 2020a], and [Energinet 2020b] provides data about the overall fuel consumption for electricity generation without any allocation to electricity and CHP heat, and the CO_2 emissions with allocation. From this data the specific primary energy consumption can be derived.

Excursus: Production versus supply grid mix
In this study we have used the production grid mix. It has to be noted though, that the supply grid mix to electricity consumers can deviate from this, subject to imports and exports of physical and virtual electricity or its quality. By means of certificates, such as guarantees of origins (GOs), energy attributes like the low-carbon quality of renewable electricity can be separated from the physical energy flow. This allows inter alia for the import and export of certificates without taking care about the actual physical energy flows. However, with each export of a renewable certificate the (residual) GHG footprint of the destination country would have to be 'imported' to clear the balance. Imports/exports can thus lead to significant differences between the physical production mix of a given country and the calculated mix that is supplied to its population. Reporting regimes using different system boundaries and calculation methodologies – such as national CO2 or GHG emission reporting obligations, EU Member States' reporting obligations towards the EU, and national reporting requirements according to e.g. the UN Kyoto protocol can result in over and

[4] Including (subject to actual delivery) H_2 refuelling stations in the final environmental performance report

under reporting of emissions. Furthermore, besides statistical over/under reporting, 'mental' double-counting may occur as well if both the country of green origin and use, are not netting their trade-relation and disclosing this to public. Often, today, the necessary information is not complete due to untracked consumption attributes. An example often cited for the deviation between production and supply mix is hydro power generation in Norway and exports of renewable electricity certificates from Norway.

Looking at the case of Denmark: According to [AIB 2018], in 2017 Denmark had a renewable electricity production share of 71.6% (2016: 61.7%) and no nuclear power component. Considering imports and exports of renewable electricity certificates the final residual electricity mix comprises a share of renewable power below 15% and an almost 20% nuclear component. The supply mix resulting from this has a split of 26% renewable, 16% nuclear, and 57% fossil (rounded). The corresponding direct CO_2 emissions are 191 g_{CO2}/kWh_e for the production mix and 435 g_{CO2}/kWh_e for the resulting supply mix, respectively.

Figure 1: Production mixes (left bars) and total supplier mixes (right bars) 2017 [AIB 2018, p24]

2.2 Pathway descriptions

2.2.1 H_2 from steam methane reforming of natural gas with truck transport from Germany

Hydrogen is derived from steam methane reforming (SMR) plants in Germany using natural gas as feedstock.

The natural gas is transported via pipeline over a distance of 4000 km from the natural gas fields to the EU where it is distributed over a distance of 500 km via the regional grid to the large natural gas consumers. The GHG emissions and energy use for the supply of natural gas have been derived from [JEC 2014]. Large steam reforming plants are state-of-the art since many decades. The capacity of such plants typically ranges between 50,000 and 300,000 Nm³ of hydrogen per hour. In [Foster Wheeler 1996] a large SMR plant consisting of 3 units with a capacity of about 94,000 Nm³ per hour and unit has been described. The energy related natural gas consumption and emissions of greenhouse gases of this SMR plant shown in Table 2-1 can be considered as typical for large-scale steam reforming plants.

Table 2-1: Large-scale steam reforming plant

Parameter	Value
Natural gas consumption	1.315 $MJ/MJ_{H2, LHV}$
CO_2 emissions	72.4 $g/MJ_{H2, LHV}$
CH_4 emissions	0.016 $g/MJ_{H2, LHV}$

The SMR is self-sufficient regarding electricity. The auxiliary electricity is generated onsite the SMR plant. No import and no export of electricity occur.

The hydrogen is compressed and transferred to a CGH_2 trailer. The hydrogen is transported from a location in Germany via CGH_2 trailer to Hobro. Two distances have been considered. The transport distance from a location in Schleswig-Holstein to Hobro amounts to about 440 km. The transport distance from a location in North Rhine-Westphalia to Hobro amounts to about 720 km.

2.2.2 H_2 from onsite steam methane reforming of natural gas

In this pathway the hydrogen is generated onsite industry premises. The natural gas is transported via pipeline over a distance of 4000 km from the natural gas fields to the EU where it is distributed over a distance of 500 km via the regional grid and 10 km via the local grid to the natural gas consumers. The GHG emissions and energy use for the supply of natural gas have been derived from [JEC 2014].

The GHG emissions and natural gas consumption of the steam reforming plant for onsite H_2 generation have been derived from [Haldor Topsoe 1998].

Table 2-2: Stream reforming plant for onsite H_2 generation

Parameter	Value
Natural gas consumption	1.441 $MJ/MJ_{H2, LHV}$
Electricity consumption	0.0161 $MJ/MJ_{H2, LHV}$
CO_2 emissions	79.3 $g/MJ_{H2, LHV}$
CH_4 emissions	0.021 $g/MJ_{H2, LHV}$

2.2.3 Power-to-H_2 via Electrolysis using Danish grid mix

In this pathway electricity from the Danish electricity generation mix has been used.

The primary energy input and GHG emissions for the Danish electricity generation mix for 2017 and 2019 have been derived from fuel input indicated in [Energinet 2018] and [Energinet 2020b]. In [Energinet 2018] the net CO_2 emissions (194 g CO_2 per kWh of electricity after allocation) and the gross input of fuels for electricity generation (before allocation) have been indicated, but not the net input of these fuels. In [Energinet 2020b] also the net CO_2 emissions (135 g CO_2 per kWh of electricity after allocation in 2019 and 42 g CO_2 per kWh of electricity after allocation expected for 2029) and the gross input of fuels for electricity generation (before allocation) have been indicated, but not the net input of these fuels.

Therefore, the gross CO_2 emissions from gross fuel use have been calculated to get an allocation factor for the net input of these fuels per kWh of electricity. The same approach has been carried out for the calculation of the non-CO_2 GHG emissions (CH_4, N_2O) because only the values before allocation were indicated for these emissions.

The fuel (biomass, natural gas, diesel, fuel oil, coal) used for electricity generation has been connected with upstream processes for the supply of these fuels.

Table 2-3 shows the primary energy input and GHG emissions from electricity generated by the Danish power plant mix.

Table 2-3: Danish electricity mix without transport and distribution

Parameter	Unit	2017	2019	2029
Primary energy input total	kWh/kWh_e	1.7932	1.6911	1.6440
Hydro power	kWh/kWh_e	0.0010	0.0008	0.0006
Wind power	kWh/kWh_e	0.5017	0.5675	0.6564
Solar	kWh/kWh_e	0.0268	0.0339	0.1165
Biomass	kWh/kWh_e	0.4039	0.4107	0.5400
Biogas	kWh/kWh_e	0.0334	0.0334	0.0344
Waste	kWh/kWh_e	0.2034	0.2205	0.1562
Natural gas	kWh/kWh_e	0.1694	0.1465	0.0926
Nuclear	kWh/kWh_e	0.0042	0.0023	0.0001
Hard coal	kWh/kWh_e	0.3855	0.2118	0.0027
Crude oil	kWh/kWh_e	0.0629	0.0633	0.0455
Lignite	kWh/kWh_e	0.0007	0.0004	0.0000
GHG emissions	$g\ CO_{2eq}/kWh_e$	235	165	63
CO_2	CO_2/kWh_e	215	152	56
CH_4	CH_4/kWh_e	0.743	0.467	0.254
N_2O	N_2O/kWh_e	0.0046	0.0022	0.0028

Small amounts of nuclear fuel come from imported fuels for electricity generation such as imported coal from regions where nuclear power is used.

Without upstream GHG emission for the supply of fuels for electricity generation the GHG emissions amount to about 198 g CO_2 equivalent per kWh of electricity in 2017 (CO_2 alone: 194 g/kWh_e), about 138 g CO_2 equivalent per kWh of electricity in 2019 (CO_2 alone: 135 g/kWh_e) and about 47 g CO_2 equivalent per kWh of electricity in 2029 (CO_2 alone: 42 g/kWh_e).

It has been assumed that the electricity is transported to the HyBalance in the same way as in case of electricity from the EU electricity mix. The electricity losses from electricity transport via the high voltage grid (~2.6%) have also been derived from [Moro 2017].

The electricity is transformed to medium voltage and transported to the HyBalance plant via a 15 kV cable (electricity loss 0.7%) where it is transformed to low voltage. For a rated power of 1569 kW of electricity, the transformer losses are indicated with 5 kW leading to an efficiency of about 99.7%. After installation of a new stack the efficiency of the electrolysis plant has increased significantly. Performance tests at the Hobro site from 7 to 8 October 2019 leads to an electricity consumption of 5.08 kWh per Nm³ of hydrogen at full load of the electrolysis plant including all auxiliaries. Table 2-4, Table 2-5, and Table 2-6 shows the different process steps of the HyBalance plant in Hobro for nominal load.

Table 2-4: Electrolysis plant (capacity: 230 Nm³/h)

	kW_e	kWh_e/Nm^3	$kWh/kWh_{H2,LHV}$	Reference/comment
Electrolysis (measured)	1153 @ 227 Nm³/h	5.08	1.683	D3.5

Table 2-5: Compressors C01 (capacity: 230 Nm³/h)

	kW_e	kWh_e/Nm^3	$kWh/kWh_{H2,LHV}$	Reference/comment
MP/HP compression & auxiliaries	117	0.509	0.170	D2.1
Compression cooling system	7	0.030	0.010	D2.1
Total	**124**	**0.539**	**0.180**	

Table 2-6: Plant and shelters lighting and utilities (capacity: 230 Nm³/h)

	kW_e	kWh_e/Nm^3	$kWh/kWh_{H2,LHV}$	Reference/comment
Shelters HVAC & lighting	12	0.052	0.017	D2.1
Plant lighting & utilities	7	0.030	0.010	D2.1
Air compressors	6	0.026	0.009	D2.1
Total	**25**	**0.109**	**0.036**	

As a result, the total electricity input amounts to 5,728 kWh per Nm³ of hydrogen related to the LHV). Including transformer losses, the overall efficiency would be about 52.4% based on the lower heating value (LHV) of the hydrogen stored in the 41 and 90 MPa pressure vessels.

2.2.4 Power-to-H_2 via Electrolysis using renewable electricity

In this pathway 100 % renewable electricity (electricity from wind power) is used for the HyBalance plant. The GHG emissions from electricity generation are zero.

3. Result comparison

Figure 2 shows a comparison of the GHG emissions from the supply of hydrogen 'source to industry / refueling station gate in' for various pathways assessed in this study.

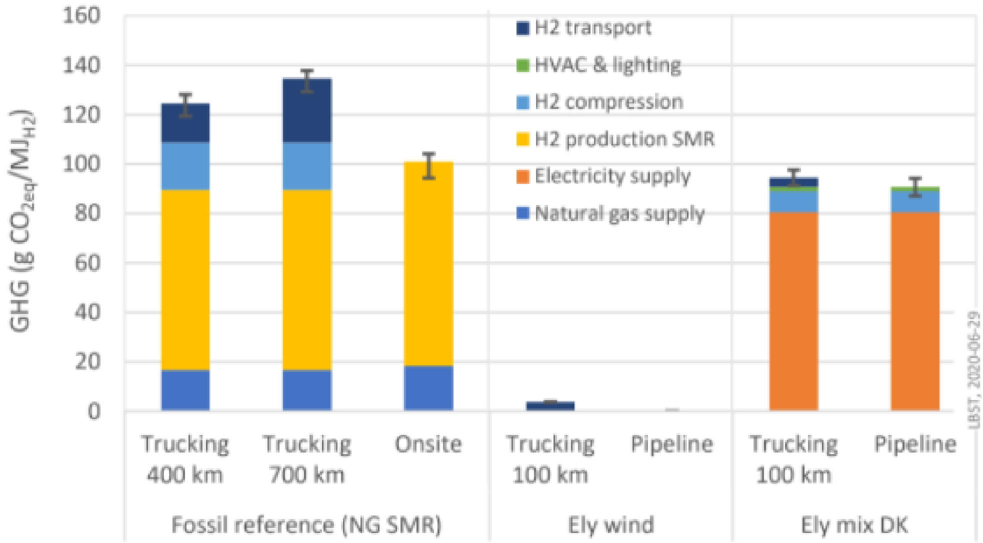

Figure 2: Greenhouse gas emissions from the supply of hydrogen

Electricity from electricity **generation mix** in 2019 leads to slightly lower GHG emissions from the supply of hydrogen via water electrolysis compared to hydrogen from onsite natural gas steam reforming, and significantly lower GHG emissions compared to hydrogen from central steam reforming in Germany and transport to Denmark.

Figure 3 shows a comparison of the GHG emissions from the supply of hydrogen 'source to industry / refueling station gate in' for various pathways assessed in this study including development of the Danish electricity mix.

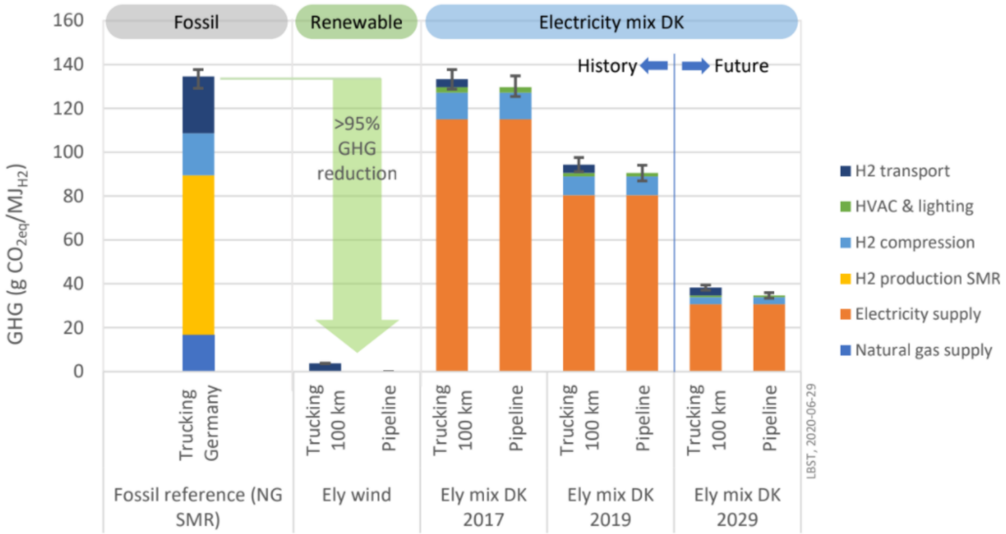

Figure 3: ***Greenhouse gas emissions from the supply of hydrogen including development of Danish grid mix***

The GHG emissions from the supply of hydrogen via electricity using the Danish electricity mix will decrease further in the future.

The GHG emissions from the supply of hydrogen via electrolysis using the **Danish grid mix** is based on an emissions factor for the Danish power plant mix of about 235 g of CO_2 equivalent per kWh of electricity in 2017, about 165 of CO_2 equivalent per kWh of electricity in 2019, about 63 of CO_2 equivalent per kWh of electricity in 2029 including upstream GHG emissions for fuel supply and non-CO_2 GHG emissions.

Increasing the **share of renewable electricity** and increasing the **efficiency of the electrolysis** plant would lead to a further decrease of GHG emissions.

The Danish electricity grid mix is broke-even with GHG emissions “well-to-tank” of conventional hydrogen derived from natural gas steam reforming and trucked in from a location in Germany in 2017, from natural gas steam reforming produced in Denmark in 2019, and from the fossil fuel comparator for gasoline and diesel used in the EU Renewable Energy Directive as reference.

Using **100% wind** power for hydrogen production results in GHG emission reductions of close to 100% compared to the fossil reference pathways.

The **efficiency** of the electrolysis plant amounts to about 59% based on the lower heating value including auxiliaries such as the AC/DC converters. The efficiency potential of water electrolysis technically achievable is significantly higher (more than 70% based on the LHV or more than 83% based on the HHV [DLR et al. 2015]). Further research and development are required to improve the efficiency of the electrolysis plant. Further research and development also are required to improve the efficiency of the compressors.

Hydrogen losses and the associated atmospheric consequences have not been taken into account. Hydrogen is an indirect greenhouse gas because it influences the OH^- concentration in the air leading to an increase of CH_4 concentration. Therefore, hydrogen leakage should be kept below 1 % [Richter 2010]. One measure could be to install emergency flares (similar to the emergency flares at biogas plants) to oxidize hydrogen released e.g. during maintenance procedures or accidental release.

Demand side management: Analyses of Energinet data showed that low grid prices strongly correlate with low CO_2 emissions in Danish grid at current electricity market design (Figure 4).

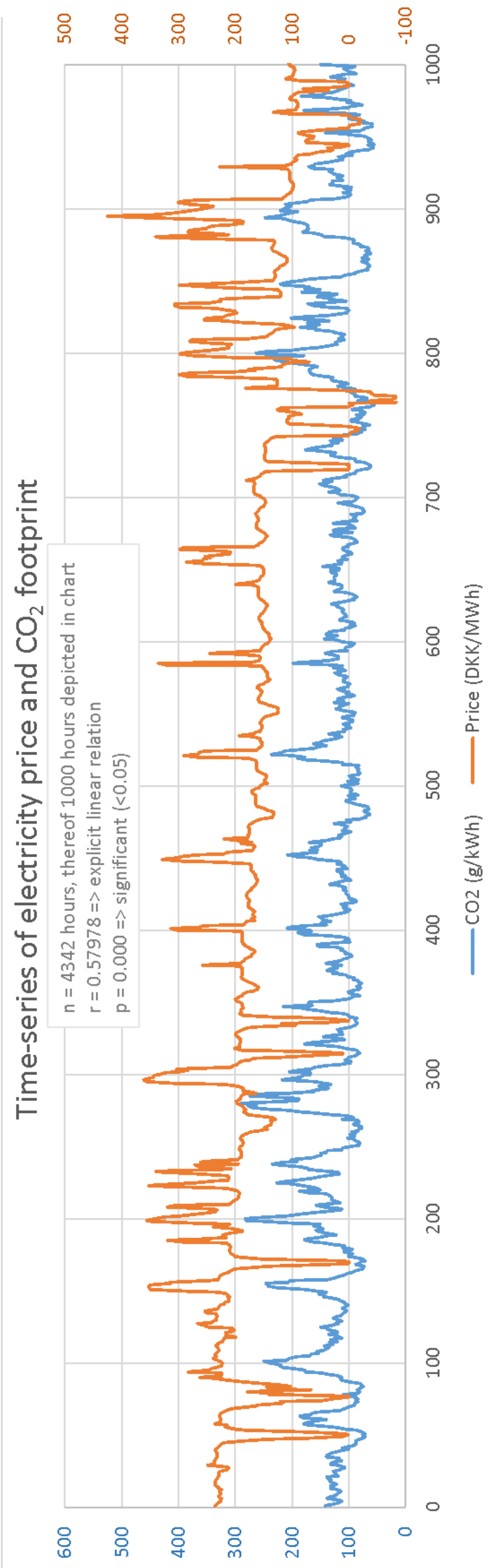

Figure 4: Correlation analysis of 1t half 2020 (thereof1000 h depicted in chart)

Simulation using CO_2 time-series of the Danish grid mix through 1st half 2020 assuming electrolyser operation at times where CO_2 emissions are below 120 g/kWh leads to average GHG emissions of about 40 g CO_2 per MJ of CGH_2 or 70% less CO_2 emissions than for hydrogen from natural gas reforming. The equivalent full load period extrapolated to one year would be about 4750 h per year.

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