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Hydrogen from wind curtailment for a cleaner European road transport system

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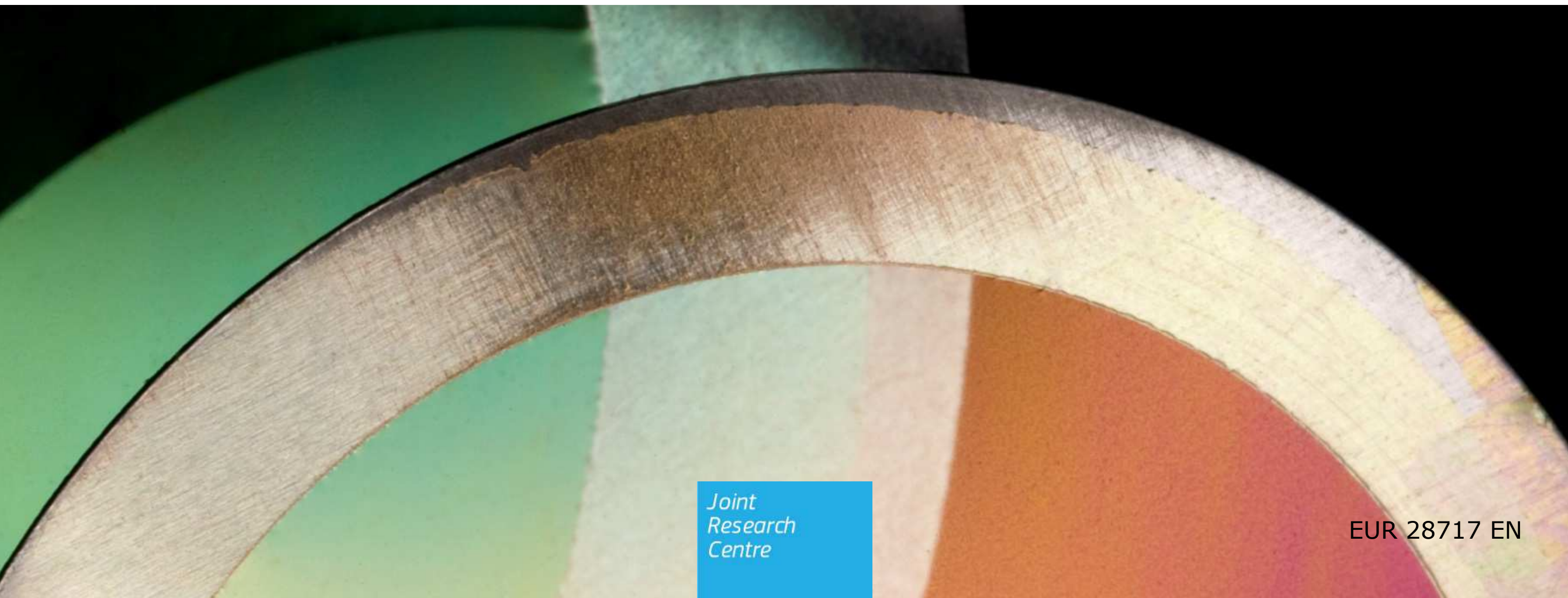

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Title: Hydrogen from wind curtailment for a cleaner European road transport system

Abstract
Wind power is currently curtailed in order to stabilise power systems and due to economic considerations. Using curtailed wind energy to produce hydrogen could fuel hundreds of thousands of new cars. Producing hydrogen from wind curtailment is however still more expensive than buying it at market price.

Contents

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1 Introduction

European power systems are experiencing a significant increase of variable Renewable Energy Sources (RES) in the energy mix. Wind power generation grew from 5.3% in 2010 to 10.4%[1] in 2016 thanks to supportive policies that incentivised market uptake. However, as the share of wind power increases, physical and economic imperatives can force operators of power systems to curtail the production of wind energy.

Wind curtailment has its price: clean energy is wasted, and since it cannot be conveyed to consumers, it has to be substituted with other resources such as fossil fuelled power plants, increasing the costs and carbon footprint of the system.

However, part of this wind curtailment could be recovered by using a chemical process called water electrolysis; by means of an electric current, water is decomposed into its basic components, oxygen and hydrogen. Hydrogen is a key resource for multiple industrial uses[2] but one of the most promising is transportation: hydrogen can be used, for example, in a fuel cell electric vehicle which emits no local pollutants.

Table 1 shows energy curtailed in 2015 in five European countries (Germany, United Kingdom, Ireland, Italy and Spain): with more than 4 terawatt-hours, Germany is the biggest "wind curtailer" in Europe with almost 70% of total wind curtailment in the selected countries.

Table 1. Wind curtailment in selected EU countries

EU country	2015 curtailment [TWh]	Source
DE	4.12	[1]
UK	1.30	[2]
IE	0.35	[3]
IT	0.12	[4]
ES	0.10	[5]

This document explores the amount of hydrogen that can be produced, and number of cars fuelled, using wind curtailment; economic viability of the process is evaluated. Analysing wind curtailment in Germany in 2015, it can be seen that a significant number of private cars can be fuelled. However, at the current cost of technology, producing hydrogen from wind curtailment is still more expensive than buying it at market price.

(1) Percentages refer to EU gross electricity consumption (*Source*: WindEurope)
(2) Chemical, metallurgic, electronics, etc.

2 Hypotheses and input data

Three different technology concepts are currently applied to transform electricity via electrolysis into hydrogen [6]. The most mature technology to split water into hydrogen and oxygen is Alkaline Electrolysis (AE); Proton Exchange Membrane (PEM) is at commercial stage and is suitable for hydrogen production coupled with wind energy due to its high dynamic response: Solid Oxide Electrolysis Cells (SOEC) are still at an early stage of development. This analysis bases its assumptions on the use of PEM electrolysation technology.

Table 2 provides the main techno-economic parameters used in this analysis.

Given its high amount of curtailed energy in 2015, as shown in Table 1, this evaluation focuses on Germany. Germany is recognised as an international leader in fostering the transition to hydrogen for transportation, and several case studies and business cases have assessed the benefits of coupling wind power with the transportation sector [7]. Germany has a number of hydrogen refuelling stations where the hydrogen is locally produced in reaction to energy prices [8].

German curtailed wind energy in 2015 accounted for about 5% of the total annual generation from wind power (about 79 terawatt-hours).

Hourly wind power generation time series have been provided by EMIHIRES, a JRC database providing 30 years (1986-2015) of wind power hourly values for Europe, at country and administrative region levels [9]: this study takes the median wind year (2004) in order to make a conservative assumption.

With regard to the PEM electrolyser technical parameters, a twenty years operative life, 59% efficiency and a 9% minimum load have been considered [11]: an electrolyser rating capacity equal to 5 megawatts has been assumed. When wind curtailment is not enough to cope with minimum load condition, then it is supposed that the remaining amount of energy is purchased in electricity markets, assuming the average price for industrial users in Germany in 2015 [12], increased by a conservative factor. If curtailment is zero, then the electrolyser fleet is shut down without any energy consumption from the grid. It must be pointed out that no taxes or grid fees for electrolysers have been accounted for in this analysis.

Conservative values for techno-economic parameters have been chosen, in order to obtain robust results: since this analysis is related to the use of wind curtailment for generating hydrogen, capital and operational costs in investing in wind farms have not been considered.

Average values in the range for capital investment (CAPEX) and operational (OPEX) costs for the electrolyser, as well as for storing the produced hydrogen, have been considered [10],[11] assuming a storage capacity equal to three days of full hydrogen production; OPEX figures include the annualised cost of two overhauls during the electrolysers' operative life; a 7% discount rate has been considered [10].

In order to evaluate the effect of converting energy from wind curtailment into hydrogen, assumptions on annual distance for private road transportation [13], kilometric consumption for hydrogen cars [14], average CO2 emissions for electricity generation [15] as well as CO2 emission intensity of new cars have been considered [16]. A ten euro per kilogram price for hydrogen has been taken into account [17]. A cost of 3.65 euro per kilogram of hydrogen for transportation and distribution to refuelling stations has been considered.

The economic viability of investing in electrolysers for converting wind energy curtailment into hydrogen has been evaluated, calculating the break-even hydrogen pump price needed to recover total costs of investment: the sum of all costs (CAPEX for electrolysers and local hydrogen storage, OPEX for electrolysers, cost for hydrogen transportation and distribution in refuelling stations and expenses in purchases in electricity markets) has been compared with the expected benefits (selling hydrogen in the market). Currency values are for 2016. It has been assumed that wind curtailment will remain constant for the whole life of the electrolyser fleet: this could be seen as an optimistic hypothesis for the future but it reflects the situation where installed wind capacity is faster than network reinforcement.

Table 2. Main techno-economic parameters

Parameters	Value
Wind curtailment [TWh]	4.12
Installed wind capacity [GW]	43.43
Electrolyser life [y]	20
Electrolyser efficiency [%]	59%
Electrolyser capacity [MW]	5
Electrolyser min load [%]	9%
Electrolyser CAPEX [M€/MW]	1.86 ÷ 2.32
Electrolyser OPEX [M€/(MW x a)]	0.07
Local H_2 storage [h]	72
H_2 storage CAPEX [M€/t]	0.58 ÷ 0.93
H_2 transportation and distribution cost [€/kg]	2.80÷ 4.50
Discount rate [%]	7%
Average electricity price [€/MWh]	100
Annual driving distance – Private car [km/a]	12600
Hydrogen kilometric consumption [km/kg]	≈100
CO_2 emission intensity in electricity gen. [g/kWh]	535
CO_2 emission for new cars [g/km]	≈120
H_2 price at the pump [€/kg]	10

The analysis has been performed without taking into account curtailment reimbursement expenses: as a matter of fact, current RES support schemes foresee a significant reimbursement for any generator that must curtail its production for external reasons.

3 Results

Exploiting wind curtailment to produce hydrogen depends on two main variables: the amount of curtailed energy available (affecting the quantity of hydrogen to be produced) and the maximum amount of wind power to recover (determining the size of the electrolyser fleet).

Two different cases, exploiting different wind curtailment hourly trends retaining the same annual curtailment value (4.12 terawatt-hour) have been considered.

- **Case a)**: 3,000 operating hours of curtailment, with a wind curtailment peak equal to 4.7 gigawatt and 870 equivalent peak hours;
- **Case b)**: 500 operating hours of curtailment, with a wind curtailment peak equal to 19.3 gigawatt and 210 equivalent peak hours.

The size of the electrolyser fleet is based on the recovery of a certain percentage of peak curtailment (from 20% to 100%). Table 3 shows the number of cars that can be fuelled by hydrogen from wind curtailment in Germany, as a function of the recovered peak curtailment in the two cases. This value varies from **230,000 to 606,000 new cars**. Differences arise because of the technical characteristics of the electrolyser[3]; the higher is the number of curtailment hours (e.g. Case a), the higher is the total amount of purchased energy to cope minimum load condition: this has an impact on the hydrogen production and, therefore, on the number of cars that can be fuelled.

Table 3. Thousands of cars that can be fuelled by hydrogen in Germany

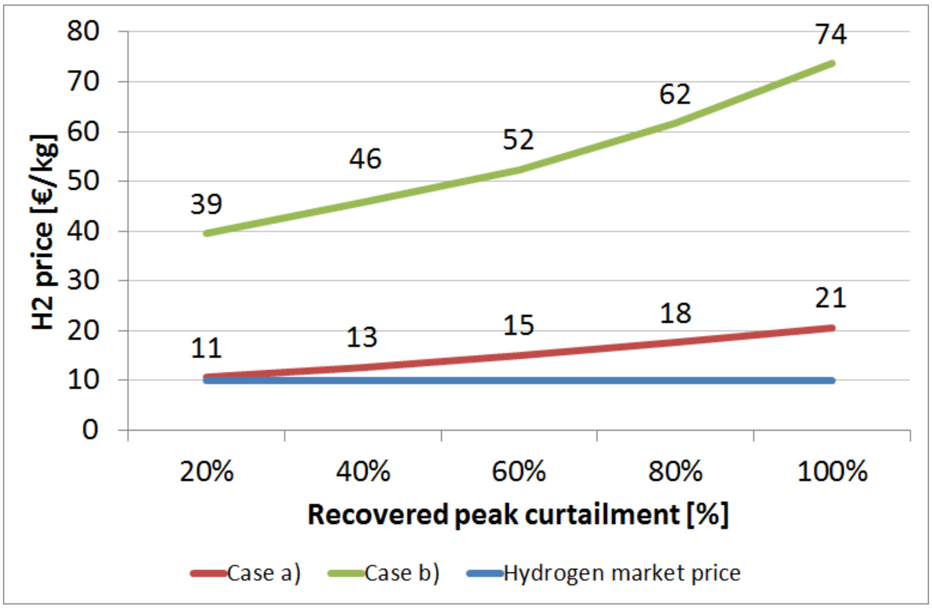
Recovered peak [%]	Case a)	Case b)
20%	294	230
40%	451	392
60%	540	509
80%	586	570
100%	606	590

Source: JRC, 2017

Figure 1 shows the hydrogen break-even prices in the two cases, assuming variable percentages of the recovered peak. Comparing these values to the assumed hydrogen price at the pump (10 euro per kilogram), it can be seen that cost recovery cannot be reached: the total costs incurred are higher than the hydrogen market value.

([3]) As described in Section 2, when curtailment is not enough to cope with minimum load, the remaining amount of energy is purchased in electricity markets.

Figure 1. Hydrogen break-even prices vs. hydrogen market price



Source: JRC, 2017.

Table 4 shows the annual water consumption required to sustain the electrolysation process: assuming it takes around 10 kilograms of water to produce one kilogram of hydrogen, converting 100% of the wind curtailment would require from 730,000 to 750,000 cubic metres of water per year, equivalent to the annual water consumption of about 5,200 to 5,300 families [16]-[17].

Table 4. Water consumption – 100% recovered peak

	Case a)	Case b)
Produced hydrogen [kt/a]	76	74
Water consumption [thousands m^3/a]	750	730
Water consumption [families/a]	5,300	5,200

Source: JRC, 2017

Table 5 shows the number of electrolysers needed to recover wind curtailment in the two case analyses, considering different shares of recovered peak: as already pointed out, the rating capacity of each electrolyser has been assumed equal to 5 megawatts. Since the criterion adopted to fix the size of the electrolyser fleet is the recovery of a certain percentage of the peak curtailment, it is straightforward to note how the shape of the wind curtailment time series affects the number of devices producing hydrogen: this is reflected in the different break-even hydrogen prices shown in Figure 1.

Figure 2 shows the balance of CO_2 emissions avoided – thanks to the substitution of fossil-fuelled vehicles with fuel cell electric ones – in the two cases, assuming a 100% recovered peak. Net CO_2 emissions avoided vary from about 0.82 million of tonnes per year in Case a) to 0.86[4] million of tonnes per year in Case b).

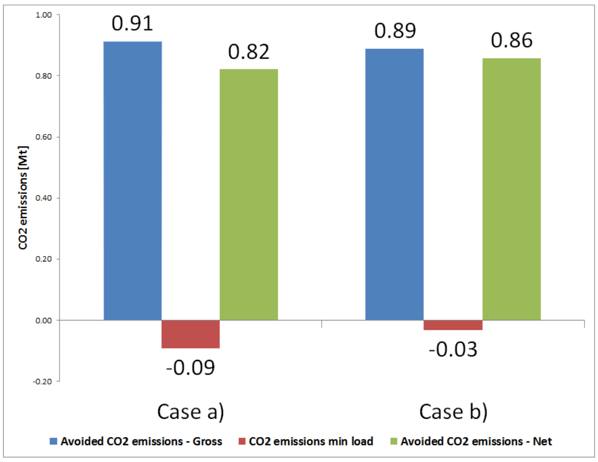
([4]) To give an order of magnitude, this quantity is equal to the CO_2 emission of more than 3,200 round trips on full commercial planes from Brussels to New York [18].

In absolute terms, gross CO_2 emissions avoided (blue) are higher with higher wind curtailment hours, but this difference is offset by the higher CO_2 emissions related to the energy purchased with respect to minimum load condition (red), so the net CO_2 emission avoided (green) are higher with lower wind curtailment hours.

Table 5. Number of electrolysers to recover peak curtailment

Recovered peak [%]	Case a)	Case b)
20%	190	771
40%	379	1542
60%	568	2313
80%	757	3083
100%	946	3854

Figure 2. CO2 emissions – 100% recovered peak



Source: JRC, 2017.

4 Conclusions

Converting wind curtailment into hydrogen has some advantages: hydrogen is useful for various industrial processes and can also fuel vehicles. Two cases were analysed, based on different wind curtailment hourly trends. Results showed that **between 230,000 and 606,000 cars could be fuelled by the hydrogen produced**.

The hydrogen production chain (from electrolysis to refuelling station) is yet to reach cost competitiveness, but investment in R&D could help to reduce the capital and operational costs of electrolysers, especially where those technologies have yet to reach maturity.

The potential of RES generation to sustain the European transportation sector of the future is also related to the value of RES in future European electricity markets: according to the evolution of RES financial support schemes, generators could focus part of their production on hydrogen in order to recover their investments when electricity market revenues are weak. This would result in a stronger synergy between the electricity and transportation sectors, fostering the decarbonisation of the European economy.

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List of figures

List of tables

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