Green hydrogen - a promise of success: How green does it really have to be to play a leading role in the energy transition?

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Overview

Low-carbon hydrogen is considered a key element for achieving the EU's climate ambitions. As it has played only a minor role as energy carrier so far, a successful uptake of a low-carbon hydrogen economy is important to meet the overarching decarbonization goal in a timely and socially acceptable manner. The production of electrolytic hydrogen through the electrolysis process is one possible upstream route. In addition to the production of hydrogen, the process can offer valuable flexibility to the power system to overcome challenges in integrating higher shares of renewable energies into the energy system. Currently, regulatory conditions for the production of electrolytic hydrogen are framed, suggesting the closely linked operation of electrolysis systems and contracted renewable energy facilities to ensure adequate contributions to carbon emission reductions. However, while a strict coupling of renewable energies to electrolyser systems ensures the "greenness" of the produced product, it is likely to be accompanied by increasing production costs. On the contrary, operating the units freely at power markets unfold their flexibility, allows to benefit from price signals and can reduce overall hydrogen production costs. However, the carbon intensity in the system and in the produced hydrogen might rise. Consequently, there is a trade-off between environmental integrity and economic viability which affects social welfare and the decarbonization process. For the case of Germany, we assess the impact of various regulatory options that restrain the sourcing of electricity for the production of hydrogen from electrolyser systems on social welfare and overall carbon emissions.

Methods

Various aspects such as the decided nuclear and coal phase-out, the country's ambition to reduce carbon emissions, missing acceptance for the production of blue hydrogen and the massive foreseen integration of renewable energies into the system in the coming decades make Germany an ideal study case. We developed an electricity market model formulated as partial equilibrium model that minimizes overall system costs to assess the effect of various regulatory options for the sourcing of electricity and the operation of electrolyser systems during the up-scale phase of a hydrogen economy. The model is calibrated for the German case in 2030. It contains both an optimal capacity expansion and the economic dispatch of all considered generating units. We model the electricity market in an hourly resolution over the entire year to capture seasonal effects. Furthermore, all electricity markets of neighbouring countries that are directly connected to Germany are modelled to account for the exchange of electricity among the individual markets.

On the hydrogen downstream we consider the replacement of all fossil-based hydrogen demand in the industry, which is seemed to be one of the first sectors for the use of low-carbon hydrogen. As there won't be any meaningful hydrogen infrastructure developed by 2030 (e.g., dedicated country wide hydrogen pipeline network), the production of the electrolytic hydrogen is assumed to take place in a captive manner and hence directly at the industrial side. The electrolyser systems as well as the renewable energy facilities are sized endogenously within the model in a cost optimal manner to supply the evenly distributed hydrogen demand profile throughout the year. Beside the latter two system components, the model is also allowed to invest in both hydrogen and electricity storage facilities at the industrial side to balance the sourcing of electricity and the supply of hydrogen in a cost minimizing way.

Two extreme cases are defined for the electricity sourcing namely (i) a strict case with a 100% renewable hydrogen production where the sourced electricity must come directly from an onsite renewable facility and (ii) a loose setting where electricity can be freely sourced at the wholesale market without any conditions to the greenness or the timing of the sourcing. These extreme cases span a range of various intermediate regulatory options, that are part of our analysis. They are based on the three dimensions proposed in the ongoing regulatory discussions:

(1) **Temporal correlation of the production of hydrogen and renewable electricity,** which refers to the period in which the produced renewable electricity and the sourced electricity for the production of electrolytic hydrogen are balanced. While in strict cases the produced renewable electricity is sourced at the same time, in loose settings the amount of produced renewable electricity and the sourced volumes only must be balanced over a certain period.

(2) **Spatial correlation of the production of hydrogen and renewable electricity**, which refers to the location of renewable energies with respect to the hydrogen demand location. It can be either directly onsite or in the same or even in another bidding zone.

(3) **Requirements for the origin of the electricity and the 'additionality' of renewable electricity**, which refers to the aspect whether the sourced electricity must come from newly build renewable energies, renewable energies that run out of their current subsidy scheme and hence that are seeking for new business models or a mixture of the latter two possibilities combined with grid electricity.

For each of the dimensions we analyse various scenarios that consider different levels of their strictness/looseness. Each analysed scenario is assessed with respect to the hydrogen production costs, the overall carbon emissions at a system level and their impact on consumer as well as producer welfare. The individual scenarios are then compared among each other.

Results

A variety of insights result from the analysis:

First, the costs of hydrogen decrease significantly (up to 55% from above 9 EUR/kgH_2 to less than 4 EUR/kgH_2) with increasing relaxations of the sourcing constraints. We find that in cases with strict constraints, the need for storage facilities at the demand side account for more than 20% of the overall costs and hence contribute significantly to overall levelized costs of hydrogen. Furthermore, allowing for relaxed temporal correlations enabling operators to trade electricity at the market and to offer flexibility to the market, helps to reduce the production costs of hydrogen drastically (-30%).

Second, the looser the constraints, the higher the overall welfare gains (Up to 7.5 Billion EUR). The results show that the gains in welfare are mainly, but not entirely driven by cost reductions of the hydrogen production. Relaxations of the spatial correlation are important contributors. Allowing for installations of renewable energies in the same bidding zone instead of a strict onsite production shows major steps in welfare gains. However, the relaxation of the temporal correlations is even more important. Balancing the sourced and the produced renewable electricity in the course of a week, instead of a strict hourly balancing, increases overall welfare already significantly. However, going further and allowing the balancing over an even longer period (month, quarter, one year) results in additional substantial increases in welfare.

Third, the results show that CO_2 emissions at the system level do not increase for most analysed cases compared to the case of an off-grid setting, where the production of electrolytic hydrogen does not have any interaction to the wider electricity system (100% renewable hydrogen). For most of the analysed light relaxations, the CO_2 emissions at system level even decrease. This is due to surplus renewable electricity that is not used for the production of hydrogen and hence that is sold to the market, injected into the system and that replaces some fossil generation. Even in the loosest case, the extreme case where electricity is freely sourced at the market without requirements for the greenness, overall carbon emissions increase only by less than 9 kgCO_2/kgH_2, staying below the levels of today's hydrogen production (Grey hydrogen: Natural gas + Steam Methane Reforming). Allowing to balance the produced renewable electricity and the sourced electricity in the course of a quarter year still stays below the level of 3 kgCO_2/kgH_2, that serves currently as threshold for low-carbon hydrogen.

Conclusions

The production of electrolytic hydrogen is accompanied by a trade-off between environmental integrity and economic viability. Within this study we analyse this trade-off and assess various regulatory options of electricity sourcing constraints for the production of electrolytic hydrogen. This work contributes to the ongoing discussions (e.g., EU Renewable Energy Directive - RED II) on the setting of appropriate regulatory conditions for the production of electrolytic hydrogen. For the case of Germany in 2030 we find that strict regulations cause significant higher hydrogen production costs, while loose requirements not only reduce these, but also improve overall social welfare. A relaxation of sourcing constraints results in less needs of costly storage facilities, the provision of valuable flexibility to the power system and the injection of surplus electricity into the grid which replaces some fossil generation. Consequently, looser constraints not only result in lower hydrogen production costs and welfare gains but potentially also in additional CO_2 emission reductions. The given importance of a successful uptake of a hydrogen economy in the decarbonization process suggest that electrolytic hydrogen produced strictly from 100% renewable electricity should not be envisaged, as it results in a "luxury good" that rather hinders its market introduction and hence its timely contribution to climate goals. Therefore, the resulting key policy recommendation of this study is to ensure adequate constraints for the production of 'green' hydrogen. Allowing for both installations of renewable energies in the same bidding zone rather than in close proximity to the demand location and the balancing of the sourced and the produced renewable electricity in the course of quarter year are adequate regulatory setting to address the trade-off between environmental integrity and economic viability of an electrolytic hydrogen production.