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Commentary

Electrolytic hydrogen has to show its true colors

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CO_2-neutral hydrogen may play a pivotal role in a decarbonized energy system as an energy carrier and feedstock in hard-to-abate sectors such as industry (e.g., iron and steel, chemicals) and long-haul transportation (e.g., aviation and shipping). Hydrogen, however, comes in many metaphorical "colors," depending on its source of production, like "gray" from steam methane reforming (SMR) of natural gas, "black" from coal gasification, "blue" from SMR or gasification with carbon capture, or "green" from electrolytic conversion using renewable electricity.[1] Yet, from the perspective of the global transition to climate neutrality, what matters is the impact of hydrogen on aggregate CO_2 emissions. As all hydrogen molecules are physically identical, irrespective of their source of production, it is clear that a careful definition of CO_2-neutral hydrogen—and associated monitoring, verification, and certification—is needed to start building the global production, transport, and market of CO_2-neutral hydrogen.

Electrolytic hydrogen has received most attention from policy makers and industry as a potential production route for CO_2-neutral hydrogen. This, however, creates two challenges related to the electricity used in this process. First, electrolytic hydrogen competes for CO_2-neutral electricity with direct electrification of end-energy services such as space heating or personal mobility. Although we do not focus on this issue in this commentary, it is important to stress that direct electrification should be prioritized where possible, such as in road transport or space heating.[2,3] Direct electrification requires less primary energy for the same end-energy service as it avoids conversion losses in the electrolytic process and enables more efficient end-use technologies (e.g., electric heat pumps or electric vehicles).[3] To capture distant renewable energy resources or in some hard-to-abate sectors, however, electrolytic hydrogen and its derivatives may be essential to reach CO_2 neutrality.[3] Second, electrolytic conversion shifts CO_2 emissions from the direct production of hydrogen to the CO_2 emissions associated with the generation of the electricity required for electrolysis.[2] When the required electricity is generated from renewable energy sources or by nuclear power plants, these emissions are near zero, but when it comes from a gas- or a coal-fired power plant, electrolytic conversion yields approximately two or five times more CO_2 emissions than SMR.

Because the CO_2 intensity of the electrolytic hydrogen depends on the CO_2 intensity of the electricity used, it is clear that more regulation is needed to ensure the CO_2-neutrality of electrolytic hydrogen. Various governments are proposing different definitions of low-CO_2 hydrogen. For example, under

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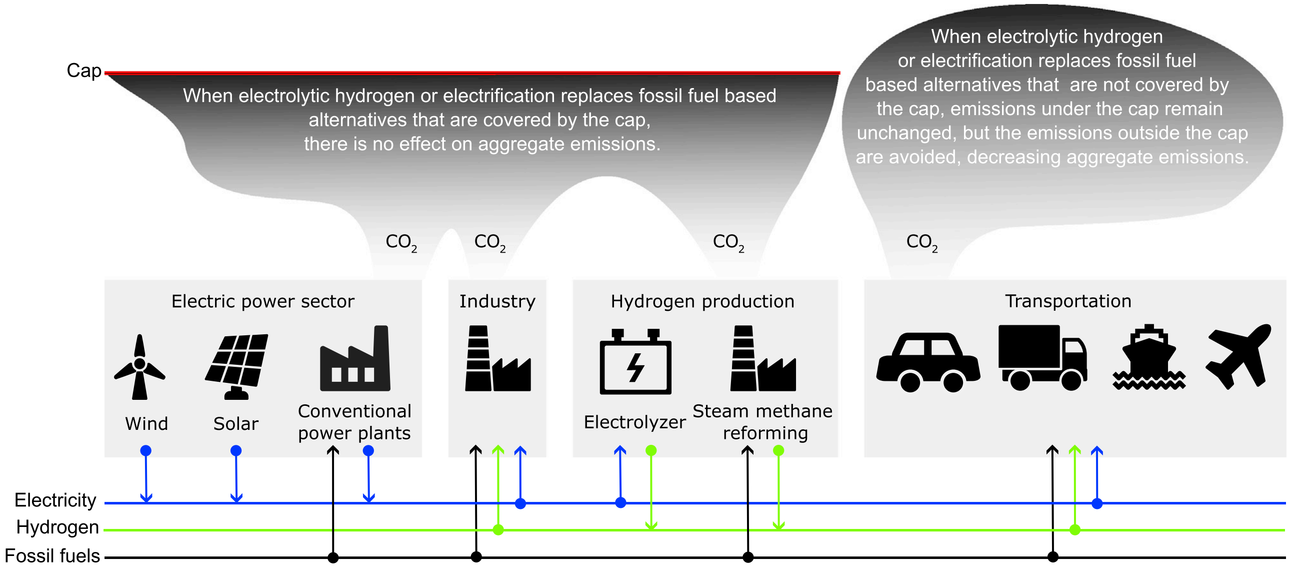

Figure 1. Illustration of a cap-and-trade system with a fixed cap covering the electric power sector, industry, and hydrogen production

The transportation sector is used an example of a sector not covered by this cap-and-trade system. An accelerated deployment of renewables does not affect aggregate CO_2 emissions (left). Similarly, regardless of its CO_2 intensity, electrolytic hydrogen produced under a fixed cap leaves aggregate CO_2 emissions unchanged if it replaces a fossil-fuel-based alternative under the fixed cap (left) but reduces CO_2 emissions when it replaces a fossil-fuel based in a sector not covered by the cap-and-trade system (right).

the EU Taxonomy, hydrogen is a sustainable investment if its life-cycle carbon intensity is below 3 $kgCO_2eq/kgH_2$. In the United States, the Bipartisan Infrastructure Law defines a hydrogen production standard of 2 $kgCO_2eq/kgH_2$, while the Chinese standard for clean hydrogen is set at 4.9 $kgCO_2eq/kgH_2$. The current draft of the UK Low Carbon Hydrogen Standard sets the threshold at 2.4 $kgCO_2eq/kgH_2$, using a "point of production" system boundary. In this commentary, however, we focus on CO_2-neutral (or in EU terminology, renewable or green) hydrogen. Europe's Hydrogen Strategy[4] and REPowerEU plan,[5] which put forward a 80 GW electrolyzer and a 20 million tonnes of renewable hydrogen target by 2030, stress that CO_2-neutral hydrogen must be produced by "additional renewable electricity."[4] More recently, the European Commission specified this additionality requirement in a draft delegated act for renewable fuels of non-biological origin, such as hydrogen, in the transportation sector,[7] as required in the Renewable Energy Directive.[6] In short, this proposal states that hydrogen is fully renewable only when it is (1) produced from renewable electricity that is generated at the same time (hourly temporal correlation or simultaneity), (2) by renewable assets that have been constructed, without subsidies, specifically for this purpose (additionality), and (3) without congestion in the electricity transmission system between the electrolyzer and the renewable asset (geographical congruence).[7] This proposal defines, for the first time, in detail under which conditions electrolytic hydrogen will be considered renewable by the EU, and, hence, can be considered to meet the policy targets in the European Hydrogen Strategy[4] and REPowerEU.[5]

There is a consensus that these requirements indeed ensure the CO_2 neutrality of the hydrogen produced and that this may lead to an accelerated deployment of renewables in the electric power sector, unless the speed of renewable capacity additions is constrained by the availability of materials and labor or by permitting issues. However, some authors argue that the hourly temporal correlation unnecessarily increases the cost of hydrogen by requiring overinvestment in renewable capacity and should thus be replaced by a yearly additionality requirement.[8] Others argue that relaxing the simultaneity constraint will lead to increased emissions.[9]

The current debate, however, fails to recognize that CO_2 emissions of the electric power sector in many jurisdictions are capped by an emissions trading system (ETS), such as EU ETS in Europe, China's national cap and trade, RGGI in the Northeast of the United States, or California's cap and trade. For the jurisdictions that employ a fixed cap, the potential accelerated deployment of renewable electricity generation does not change total emissions: it only changes the timing and/or the sector from which the emissions originate (Figure 1, left).

Similarly, when electrolytic hydrogen replaces fossil-fuel-based alternatives that are also covered by the fixed cap, like the production of gray hydrogen in EU ETS, there is no effect on total emissions (Figure 1, left). Replacing gray hydrogen with electrolytic hydrogen potentially reduces emissions from the hydrogen production process and the electric power sector, depending on the CO_2 intensity of the electricity used and whether the principle of additionality is enforced. Cumulative emissions from within the fixed ETS cap, however, remain unchanged.

On the other hand, when hydrogen replaces fossil-fuel based alternatives that do not fall under the fixed cap, e.g., replacing fossil fuels in the transportation sector in Europe (Figure 1, right), aggregate emissions do go down. This observation holds regardless of the principle of additionality or the CO_2 intensity of the hydrogen used. By using hydrogen instead of a fossil fuel-based alternative, one places the emissions associated with the end-energy service at hand under the fixed emissions cap. Emissions from within the ETS cap remain unchanged, but the emissions from the fossil fuel-based counterpart not covered by the cap are avoided, lowering aggregate emissions. This type of reasoning may be used to motivate the European Commission's decision to consider a battery electric or fuel cell vehicle as a zero-emission vehicle in its CO_2 emission performance standards for cars and vans, without any requirements on the electricity used directly or indirectly in these vehicles.[10]

This is, however, not the full story in cap-and-trade systems where the cap is not fixed, like EU ETS[11] or California's cap and trade.[12] EU ETS, e.g., features a supply adjustment mechanism, the market stability reserve (MSR), which lowers the future supply of emission allowances based on the observed cumulative difference between supply of emission allowances and emissions. As exposed in our previous work, any policy that changes the timing of emissions may now affect the cumulative cap, hence, emissions under EU ETS via the supply adjustments of the MSR.[13] For announced policies affecting emissions in the future, such as the additionality requirement, the effect on cumulative emissions may be counterintuitive and more than proportional. Signaling a policy-driven decrease in demand for allowances by mandating additional renewable electricity production may depress emission allowance prices in the future and today, which promotes less abatement efforts early on. This in turn reduces the downward supply adjustments of the MSR, increasing cumulative emissions under EU ETS.[13] This effect is sometimes referred to as a new green paradox as a policy designed to reduce emissions in the future may increase cumulative emissions under EU ETS and vice versa.[13] Whether this unintended effect materializes, as well as its direction and magnitude, remains uncertain.

In summary, we argue that the discussion on the definition of CO_2-neutral hydrogen should go beyond its "colors" or means of production, recognizing the interaction with and impact of other policy instruments, such as emission trading systems and CO_2 (border) taxes. We here define carbon neutrality as not increasing system-level CO_2 emissions. From an energy system perspective, hydrogen should thus be considered CO_2-neutral when produced from a carbon-neutral electricity source *or* under an emissions cap. In technology- or sector-specific policies, such as vehicle efficiency standards,[10] it remains a semantic discussion whether or not to include upstream in addition to downstream emissions in the definition of an energy carrier's carbon neutrality (e.g., well-to-tank vs. tank-to-wheel or tailpipe emissions in the context of transport). When direct and indirect electrification compete, (CO_2) prices and energy efficiency should guide the choice between hydrogen and electricity. Failing to recognize these interactions may lead to a cost-inefficient development of and an unlevel playing field for CO_2-neutral hydrogen without any impact on CO_2 emissions. Glenk and Reichelstein, e.g., show that the economics of electrolytic hydrogen improve considerably if power can be drawn from the grid without restrictions on its carbon intensity.[14]

This commentary is not a call against hydrogen, renewables, or decarbonization targets, nor does it intend to favor one technology or energy carrier over another. On the contrary, it is a call for ambitious decarbonization strategies, supported by a coherent mix of policies promoting both cost efficiency and effectiveness on a level playing field. A remaining open question is the optimal mix of policy instruments to kick-start the CO_2-neutral hydrogen industry and market. This relates to, e.g., the use of R&D subsidies, research partnerships, and carbon contracts for differences, as well as the choice between and calibration of cost-based targets (e.g., \$1/kgH_2 by 2030 in the United States) and quantity-based targets (e.g., 10 million tonnes of renewable hydrogen produced in the EU by 2030).

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AUTHOR CONTRIBUTIONS

K.B., J.A.M., and M.O. conceptualized the article. K.B. and M.O. wrote the initial draft. K.B. coordinated the reviewing and editing process. All authors contributed to reviewing and editing the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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