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Cost reduction in low-carbon hydrogen: effective but insufficient to mitigate carbon emissions

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Abstract

Many countries have announced hydrogen promotion strategies to achieve net zero CO_2 emissions around 2050. The cost of producing low-carbon (green and blue) hydrogen has been projected to fall considerably as production is scaled up, although more so for green hydrogen than for blue hydrogen. This article uses a global computable general equilibrium (CGE) model to explore whether the cost reduction of green and blue hydrogen production can mitigate the use of fossil fuels and related carbon emissions. The results show that cost reduction can raise low-carbon hydrogen consumption markedly in relative terms but marginally in absolute terms, resulting in a modest decrease in fossil fuel use and related carbon emissions. The cost reduction of low-carbon hydrogen slightly lowers the use of coal and gas but marginally increases the use of oil. If regional CO_2 taxes are introduced the increase in green hydrogen production is considerably larger than in the case of low-carbon hydrogen cost reduction alone. However, if cost reduction in low-carbon hydrogen is introduced in addition to the CO_2 tax the emissions from fossil fuels are only marginally reduced. Hence, synergy effects between the two measures on emissions are practically absent. A low-carbon hydrogen cost reduction alone is effective but insufficient to have a substantial climate impact. This study also calls for modeling development to capture special user preferences for low-carbon hydrogen related to climate mitigation when phasing in new energy carriers like hydrogen.

Keywords Green hydrogen · Energy transition · Climate change · Net zero · CGE model · Fossil fuels

1 Introduction

Hydrogen is considered one of the vital energy carriers to realize net zero CO_2 emissions by the mid-century [1, 2]. Hydrogen was first identified in the late 1700s, but its economic role has remained limited to selected industrial processes [3, 4]. In recent years, hydrogen has obtained new momentum as an energy carrier to realize green energy and reduce CO_2 emissions in hard-to-abate sectors, like steel production and transportation transition [1, 5–7].

Many countries have announced ambitious strategies to scale up hydrogen production and consumption in the coming decades [8–10]. Hydrogen can be generated by several technologies. Green hydrogen is produced by the electrolysis of water using renewable electricity. Hydrogen can also be generated from coal, oil, or natural gas, with or without carbon capture and storage (CCS). The most appealing alternative in the climate context is blue hydrogen generated by reforming natural gas with CCS. Although blue hydrogen uses CCS, green hydrogen is the crucial alternative for climate mitigation.

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For hydrogen to play its expected role in climate mitigation, a substantial cost reduction in green hydrogen production is seen as an essential factor [5] throughout the supply chain, from production and storage to delivery and end-use [1, 11]. As the high cost of low-carbon hydrogen supply is expected to decline markedly in the coming decades [5, 6, 12] to make green hydrogen more competitive to fossil fuels, it is unclear if hydrogen will replace fossil fuel and reduce emissions or mainly add to the total energy supply, which will be addressed by using a global computable general equilibrium (CGE) model in this study.

Taxes on CO_2 emissions from fossil fuels can promote hydrogen consumption by increasing the user cost of fossil fuels and making hydrogen more competitive [14]. This article also explores if the effects of green hydrogen cost reductions could be enhanced with carbon pricing by a CGE model, involving sectoral and regional interactions in the global economy.

An earlier study used a general equilibrium economic model to assess how hydrogen could help Taiwan meet the Kyoto Protocol's mitigation target without sacrificing economic growth [13]. The study concluded that the hydrogen potential in Taiwan was sensitive to industrial structure as well as technical progress but did not explicitly conclude on the role of cost reduction of hydrogen production and carbon taxes at the global level, as will be examined by the present study.

Our study indicates that cost reduction in low-emission hydrogen alone can only marginally reduce CO_2 emissions from fossil fuels in the case of low and high CO_2 prices. Higher CO_2 prices can raise green hydrogen production and use but still not enough to induce sufficient substitution for fossil fuels to reduce emissions. This is consistent with a recent study [15], which shows that even if green hydrogen follows similar growth in capacity and cost reduction as wind and solar power experienced in the past years, it does not necessarily lead to a large supply of green hydrogen.

2 Methods and data

2.1 The global CGE model—GRACE

The global CGE model GRACE [16, 17] is used for this study. GRACE has been used for studies on climate impact, adaptation, mitigation, and assessment of energy and climate policies e.g. [18–23]. In this study, we adopt a recent version of GRACE as specified in Cappelen, et al. [24] that has been used to study the effect on energy markets of achieving a 1.5 °C scenario [25]. More details about the GRACE model can be found in Aaheim, Orlov, Wei and Glomsrød [16]. Below we focus on the newly introduced hydrogen module in this study.

A new industry producing hydrogen is introduced in the GRACE model as the composite of four technologies: two technologies of grey hydrogen (coal-based without CCS (coal-noCCS) and gas-based without CCS (gas-noCCS)), one technology of blue hydrogen (gas-based with CCS (gas-CCS)), and one technology of green hydrogen (renewable-electricity-based (Renewable)). While coal-based hydrogen with CCS can be used as a transition technology in some regions like China, we do not consider it a separate hydrogen production technology in this study. One reason is its relatively high cost of carbon capture, environmental damage, and social risk associated with extraction. The other reason is that it is not expected to be a key option to achieve the ambitious climate target of net-zero emissions by 2050 [26]. The green and blue technologies produce low-emission hydrogen and are expected to dominate in the medium to longer term. As this study mainly focuses on low-emission hydrogen in the long term, we abstract the coal-based hydrogen with CCS technology, although this technology could be important for regions like China during energy transition.

Figure 1 illustrates the four hydrogen technologies and how they aggregate to total hydrogen production as a nested constant elasticity of substitution (CES) function. There is a substitution between capital and labor generating value-added which combines with the energy carrier in a fixed proportion, thus generating the associated type or "color" of hydrogen. The total production of hydrogen is the CES aggregate of the four technology outputs where prices and costs of technologies determine the mix of colors in the total supply of homogeneous hydrogen.

The equations between levels starting with a small "e" indicate the elasticity of substitution between the inputs. At the top level, the elasticity of substitution across hydrogen color products is 2 (eH2 = 2), which is relatively high due to the almost perfectly homogeneous hydrogen supply. At the middle level, fuel used by each technology is combined with Value Added through a Leontief function (eM = 0, i.e., the elasticity is set to 0), which implies constant efficiency to transform other energy to hydrogen in terms of energy values. At the bottom level, Value added for each technology is a CES combination of labor and capital with an elasticity of 0.3 (eVA = 0.3), which is the same as for other production sectors in the model.

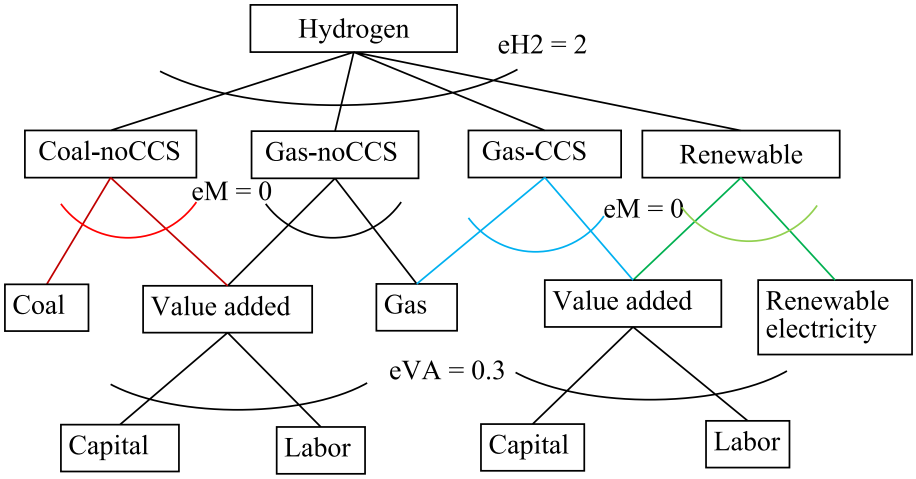


Fig. 1 The production of hydrogen in GRACE

We assume no direct CO_2 emissions from green hydrogen production. The CO_2 emissions from blue hydrogen production (0.9 kg /kgH2) are less than 10 per cent of emissions from gas-based technology without CCS (10.2 kg /kgH2) according to IEA [2]. The CO_2 emissions from coal-based technology (20.2 kg/kgH2) are almost double that of gas-based technology without CCS.

After adding a transport cost, hydrogen can be used as an energy carrier to substitute for electricity and fossil fuels. Hydrogen input in user sectors is treated in the same way as electricity in GRACE as an imperfect substitute for fossil fuels. We do not expect that hydrogen-driven cars will be widely used by households as electric cars in the coming decades. Hence, this study assumes no hydrogen used by households although there is an increasing number of hydrogen-driven cars in some regions for instance Norway.

For hydrogen users, hydrogen is depicted in this model as a homogenous and equally priced product independent of technology of origin. Hence, the users have no possibility to follow their own preferences with respect to the choice of technology and emission impacts or other non-market implications.

Hydrogen can be further transformed to ammonia (NH3), by combining hydrogen with nitrogen. The production of ammonia is also divided into four technologies, corresponding to the four hydrogen production technologies but now with hydrogen as an input and with higher cost of other inputs. So far this study only tracks the use of ammonia as intermediate input in two industries of agriculture and manufacturing, as its current use in other industries such as ocean transportation is negligible. This is obviously a shortcoming since ammonia is expected to be used for ocean transportation to reduce carbon emissions in the future.

2.2 Data and scenarios

GRACE is calibrated around the 2014 global economy as described by the Global Trade Analysis Project (GTAP) database v10 [27]. In the GTAP database, country-level national accounting data are organized into a balanced multi-regional input–output matrix for a specific year like 2014 based on economic data collected by national and international organizations. To calibrate the hydrogen module newly developed in this study, we have collected and compiled data on supply, demand and unit cost of production for both hydrogen and ammonia in 2014. The original GTAP data are then adjusted to include the hydrogen and ammonia data. For details on the collection and treatment of the hydrogen and ammonia data, see the Appendix.

We simulate a *business-as-usual (BAU)* scenario by following the yearly growth rates of GDP and consumption of coal, oil, and gas by region implicated by the Stated Policies Scenario (STEPS) in IEA [28] based on an approach specified in Wei [29]. More details about the BAU scenario can be found in Cappelen, Glomsrød, Lindholt, Rosendahl and Wei [24] and a recent study on how a 1.5 °C scenario may affect the energy market [25]. We then modify the BAU scenario by adding a hydrogen module as described above to simulate hydrogen production and consumption over time until 2050. As a result, hydrogen production increases by only 61 per cent from 2020 to 2050, corresponding to a yearly growth rate of 1.6 per cent, indicating limited interest to use hydrogen at current cost level and without implementation of specific measurements.

Building upon the BAU scenario, we design a *low-cost-of-hydrogen scenario (LowCost)* by introducing cost reductions in blue and green hydrogen production over time. These cost reductions are simulated as a yearly rise in productivity of primary factors (labor and capital) and a reduction in transport cost in supply. The unit costs (excluding cost of energy inputs) are assumed to decrease yearly by 1 per cent and 4 per cent in blue and green hydrogen respectively from 2020 to 2050. This efficiency gain adds to that assumed in the BAU level, based on a report on future hydrogen development [30].

To examine if a mitigation policy could influence the effect of cost reduction in low-carbon hydrogen production, we consider a *carbon-tax scenario (Ctax)* by introducing regional carbon taxes in the BAU scenario. We let regional carbon taxes follow the carbon taxes implied by the Net Zero Emissions by 2050 (NZE) scenario in IEA [26] as indicated in Table 2 of Cappelen, et al. [31]. We then combine the two scenarios to obtain the last scenario (BothIn). The key differences between the scenarios are summarized in Table 1.

In the next section, to highlight the impact of the low-emissions hydrogen cost reduction alone, we present the effects on certain indicators in both the case of no carbon taxes (BAU) and the case with carbon taxes (Ctax). In the BAU case, the effect on an indicator is calculated as the difference in the indicator value between the LowCost and BAU scenarios. In the Ctax case, the effect is calculated as the difference in the indicator value between the BothIn and Ctax scenarios.

3 Results and discussion

3.1 Hydrogen production and consumption

As shown in Fig. 2, the cost reduction in blue and green hydrogen production raises the global supply of green hydrogen to over 4 times the BAU level in 2050, corresponding to 1.7 Mt H2 or two per cent of total hydrogen production in 2020 [26]. Although the relative change in green hydrogen production is considerable, the absolute value of the change in green hydrogen is modest as the BAU level of green hydrogen is quite low.

In comparison, if carbon taxes are introduced separately the use of green hydrogen is only 42 per cent above the BAU level. However, if cost reductions and carbon taxes are implemented jointly as in the scenario BothIn, the green hydrogen supply reaches 5.4 times the BAU level, indicating certain synergy effect of these joint measures over time. The increase in blue hydrogen is about 50 per cent in the LowCost scenario as well as in the Ctax scenario but ends up at more than double the BAU-level in the BothIn scenario, with a push of synergies.

Grey hydrogen supply (coal- and gas-based without CCS) is only slightly reduced in the LowCost scenario, compared with the effect of an increase in carbon taxes where supply falls by 42 per cent for coal-based and 20 per cent for gas-based, both without CCS. This result is roughly repeated in the combined scenario BothIn and thus unaffected by synergies. Similar patterns can be observed at the regional level, although deviations from BAU in relative terms differ across regions.

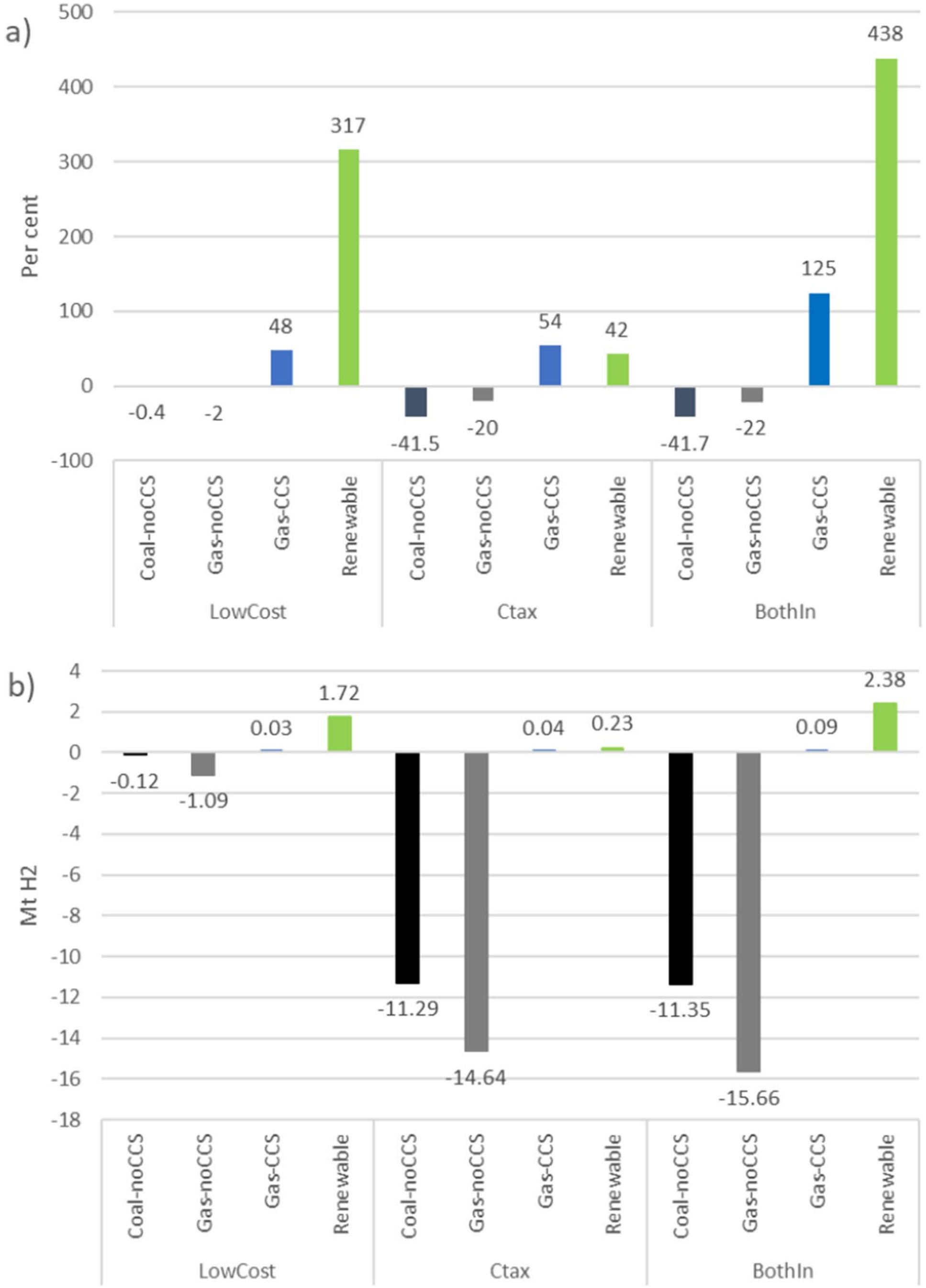
The growth in green hydrogen consumption seems substantial but is modest due to its low BAU level. Notice that the share of green hydrogen in total hydrogen production is very low in BAU, still less than one per cent in 2050. The cost reduction of low-carbon hydrogen increases this share to 3.5 per cent, further reaching 6.1 per cent with the joint effect of carbon taxes. In comparison, the carbon pricing alone increases the share of green hydrogen in total hydrogen use to 1.7 per cent only.

Although green hydrogen is affected to various degrees across scenarios, total hydrogen production and consumption does not increase in the Ctax scenario, as the introduced carbon taxes imply additional cost of using the aggregate energy carrier in production sectors. The low-carbon hydrogen cost reductions induce additional hydrogen use in the Ctax case, at an increasingly higher rate without the carbon taxes (Fig. 3). In both cases, the induced additional

Table 1 Key differences between scenarios

Scenario	Cost reduction yearly 2020–2050: 4 per cent for green hydrogen and 1 per cent for blue hydrogen	Implementation of regional carbon taxes
BAU	No	No
LowCost	Yes	No
Ctax	No	Yes
BothIn	Yes	Yes

Fig. 2 Global hydrogen production. Deviations from BAU in 2050: **a** in Per cent, and **b** in Mt H2



hydrogen supply increases relatively over time. In 2050, the hydrogen consumption in the BAU case is 0.3 per cent above the level without the cost reduction (BAU). In the Ctax case, the induced hydrogen consumption is 0.36 per cent above the Ctax scenario level. This indicates that measures such as carbon taxes might relatively enhance the effects of low-carbon hydrogen cost reduction in promoting hydrogen consumption.

However, with a CO2 tax, the additional hydrogen consumption induced by the cost reduction in low-carbon hydrogen is not larger than in the BAU case in absolute terms. This can mainly be attributed to reduced demand from the two sectors of refineries and ammonia production (Fig. 4). Still, in the Ctax case, the induced hydrogen consumption is higher in two sectors of Iron&Steel and Other manufacturing (excluding Iron&Steel and ammonia) than in the BAU case.

Hydrogen is expected to be widely used in transport sectors in the coming decades. However, this does not show up in our simulation as indicated in Fig. 4, mainly due to the assumption that large-scale adaptation of hydrogen

Fig. 3 Additional global hydrogen consumption induced by cost reduction in blue and green hydrogen. Deviation from without the cost reductions. Without carbon tax (BAU) and with carbon tax (Ctax). Per cent

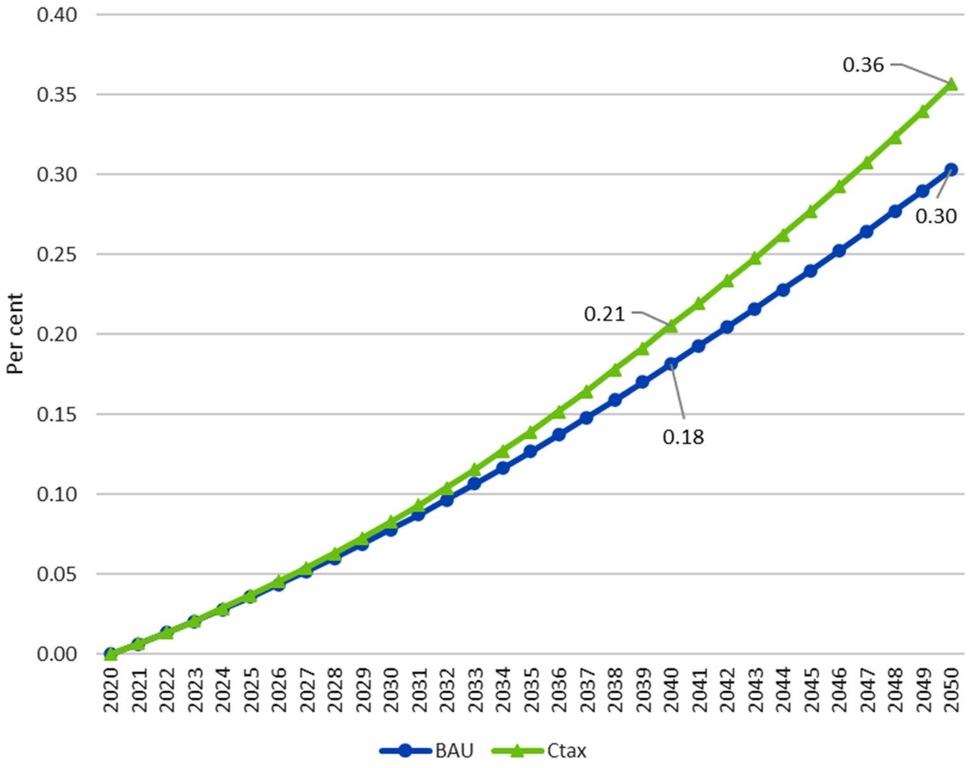
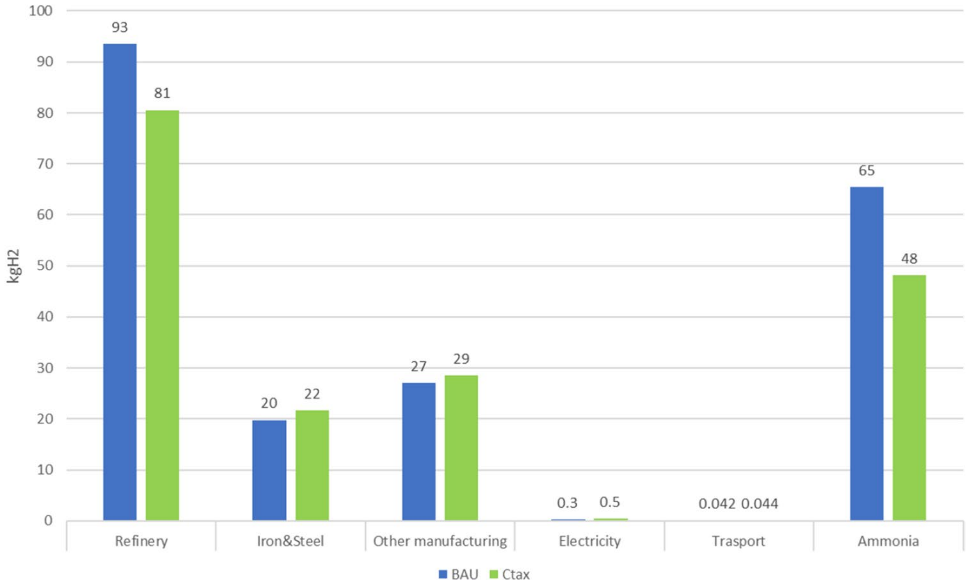


Fig. 4 Sectoral hydrogen consumption induced by cost reduction in blue and green hydrogen production with carbon taxes (Ctax) and without carbon taxes (BAU). 2050. kgH2



in transport sectors would not happen automatically under current user preferences even with cost reductions implemented in this study. Policies and measures to build infrastructure seem necessary to motivate potential hydrogen users to gradually phase out fossil fuels. Hence, global growth of hydrogen use can be expected to be slow, although some economies such as Japan have initiated large programs for phasing in hydrogen vehicles [32].

3.2 Consumption of fossil fuels

When cost reduction of blue and green hydrogen is added to one of the BAU or Ctax scenarios, the consumption of oil is modestly increased, although slightly more so in the Ctax case. Coal use tends to be reduced by low-carbon hydrogen cost reductions alone but shows market decline of 0.02 per cent if regional carbon taxes are already implemented (Fig. 5). Gas consumption is also negatively affected by the cost reductions, responding with a decline of 0.02 per cent from the BAU level in 2050, doubling to 0.04 per cent decline if the Ctax scenario is in place.

This limited response to the cost reduction is understandable as the increase in hydrogen consumption is small in absolute terms. Notice that the decline in fossil fuels induced by the hydrogen cost reduction is negligible in comparison with the effect of carbon pricing alone, except for gas demand, which in Ctax is reduced twice as much as in the BAU case without carbon taxes. This indicates that the expected level of low-carbon hydrogen cost reduction is not sufficiently effective in reducing fossil fuel use since users stick to the fossil-fuel-intensive technologies as calibrated in the model. However, it is important to remember that coal is supplying 27 percent of global energy [28] and that a small relative reduction might contain a large absolute reduction (nearly 0.5 mtoe in the Ctax case in 2050).

3.3 *CO_2 emissions and GDP*

In line with the effects on consumption of fossil fuels, the effect on associated CO_2 emissions from the cost reduction is not large, only around 0.01 percent reduction in 2050 in the BAU scenario and 0.03 percent in the Ctax scenario (Fig. 6), corresponding to around 6 Mt CO_2. In contrast, the effect of low-carbon hydrogen cost reductions on global GDP is positive but negligible at 0.002 per cent, corresponding to 2.5 billion USD2014. This positive effect is somewhat lower when carbon taxes are already implemented as in Ctax scenario. The introduced carbon taxes alone (Ctax minus BAU) lead to GDP losses by nearly 2 per cent of the BAU level but reduce CO2 emissions roughly by one third.

In our simulations we do not take into account the cost of realizing the technological improvements behind the cost reduction of low-carbon hydrogen, thus the economy receives a sort of resource injection that raises GDP slightly. However, there is a question if this assumption is realistic. The assumption can partly be justified by that a

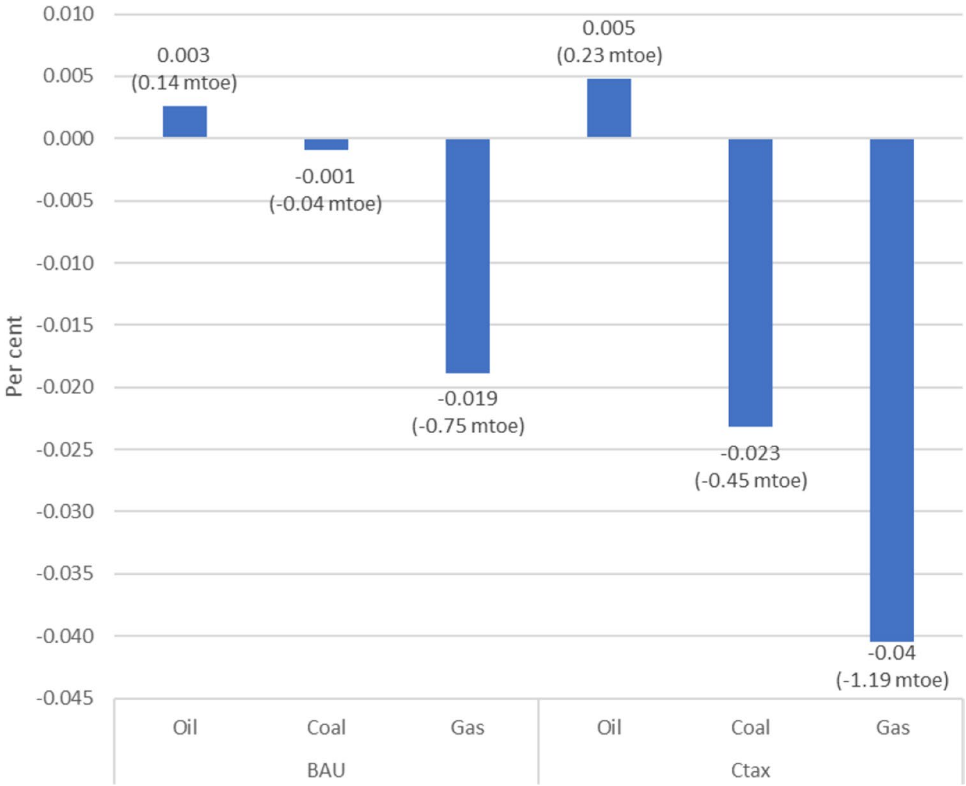


Fig. 5 Effect of low-carbon hydrogen cost reductions on global use of fossil fuels. 2050

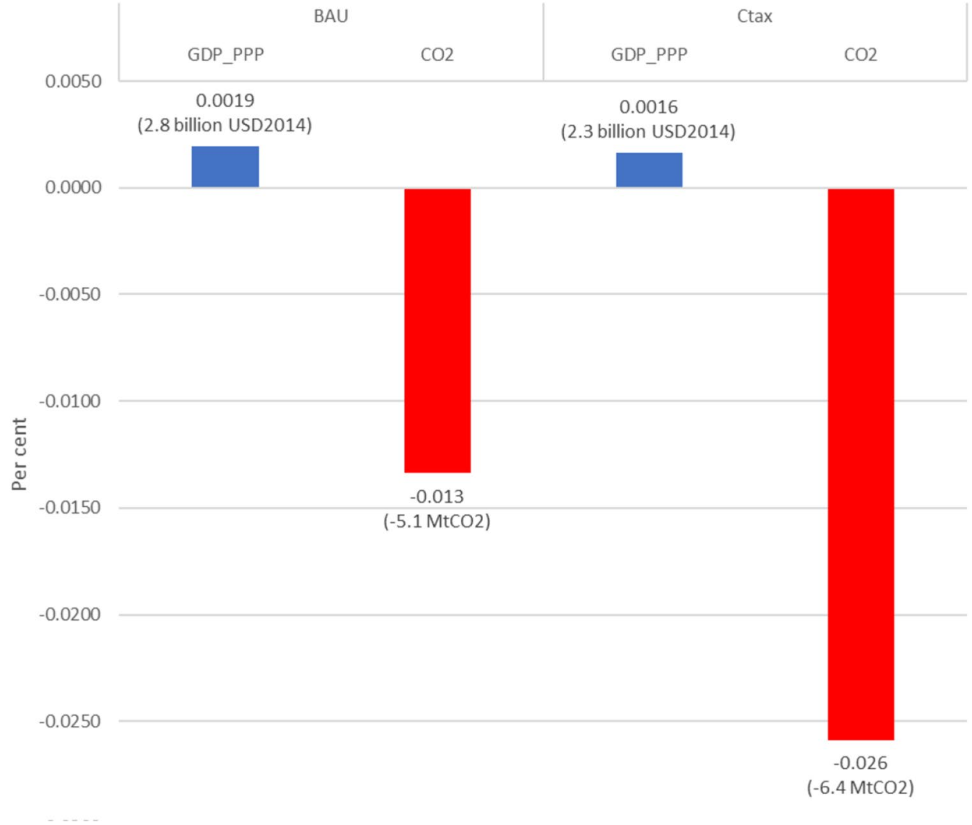


Fig. 6 Effect of low-carbon hydrogen cost reduction on global GDP and CO_2 emissions in 2050

high share in cost reduction of low-carbon hydrogen production is expected due to economies of scale [15], similar to experience with the emerging wind and solar power industries.

4 Discussion

The modest effect of blue and green hydrogen cost reduction in this study is driven by the market mechanism through price changes. Table 2 shows the impact on global energy prices of alternative energy carriers due to the cost reduction, depicted as deviations from BAU. With low-carbon hydrogen cost reduction all energy prices become lower than the corresponding BAU levels, except for oil. The hydrogen price is lowered the most, followed by gas and electricity. The decline in the coal price is negligible. The reduced green and blue hydrogen prices stimulate all types of hydrogen use and total energy demand. However, there are substitution effects between green, blue and grey hydrogen and between hydrogen in general and other energy carriers, tending to reduce demand for other energy carriers. In our simulations, the substitution effect dominates the use of coal, gas and electricity but not the use of oil. Hence, we arrive at higher oil prices and lower prices of other energy carriers.

The introduction of carbon taxes discourages fossil fuel use and encourages electricity and hydrogen use, resulting in lower prices of fossil fuels and higher prices of electricity and hydrogen in the Ctax scenario. When the cost reduction

Table 2 Producer prices of energy in 2050: Deviations from BAU. Per cent

Scenario	Coal	Oil	Electricity	Gas	Hydrogen
LowCost	– 0.0002	0.0081	– 0.0098	– 0.0336	– 0.8071
Ctax	– 27.5616	– 17.8893	45.0357	– 14.1280	58.2199
BothIn	– 27.5675	– 17.8831	45.0110	– 14.1590	56.6144

in blue and green hydrogen is introduced in the carbon tax case in the BothIn scenario, the additional price changes follow the same pattern as the price deviations from BAU in the LowCost scenario.

There are several drawbacks of this study besides the common limitations of a typical CGE model such as profit maximization of producers and utility maximization of final consumers. First, we assume no direct trade of hydrogen between regions although the interregional hydrogen trade might scale up along with lower cost of blue and green hydrogen production. Figure 7 shows considerable differences of hydrogen prices across regions induced by the blue and green hydrogen cost reductions. In Oceania, the hydrogen price is 11 per cent lower than the BAU level, while in several regions the price is not affected by the hydrogen cost reduction, among them "Other regions" including China, Japan, and the OPEC countries. These price differences indicate a large potential for international trade of hydrogen if hydrogen transportation costs become low enough in the future. However, it can be argued that the non-trade setting in this study might be fairly close to realities in the short to medium term.

Further we would highlight that the effect of trade options differs from the effect of hydrogen cost reduction. We have illustrated that with carbon taxes as in the Ctax scenario, the specific additional effect of low-carbon hydrogen cost reduction might not deviate much from in the BAU case. The regional hydrogen potentials unfold through the regional potentials for renewable energy, the fossil reserves and CCS options. As a consequence, hydrogen production might emerge as more evenly dispersed globally than expected today, and thus modify the potential benefits of trade.

Another shortcoming is related to the fossil-fuel-dominated energy system in the GRACE model. The parameters in the energy demand and supply module of the model are calibrated based on the 2014 global economy, when hydrogen use is very limited initially. Given the low share of hydrogen in total energy use, it is hard for the calibrated energy system to adopt hydrogen at a large scale merely through the market mechanism and relative price changes. For example, if the calibrated energy demand functional form is Cobb–Douglas, then the income share of hydrogen in total energy use is constant. If the hydrogen share in total energy use increases from one per cent to 10 per cent, its price needs to drop to 10 per cent of its initial value, which is almost impossible. This mechanism works even in our model with CES energy demand functions. In this sense, our model does not capture the increasing capacity of green hydrogen production and likely shrinking capacity of fossil fuel production in the coming decades. This can largely explain the small effects of the cost reduction in low-emissions hydrogen production on total hydrogen use. To overcome the shortcoming, modeling development is needed to capture special user preferences for low-carbon hydrogen when phasing in hydrogen in a modeling world.

Our study does not consider the role of consumers' confidence in hydrogen use. An additional response associated with higher confidence in hydrogen technology might emerge as a consumer autonomous adjustment, which

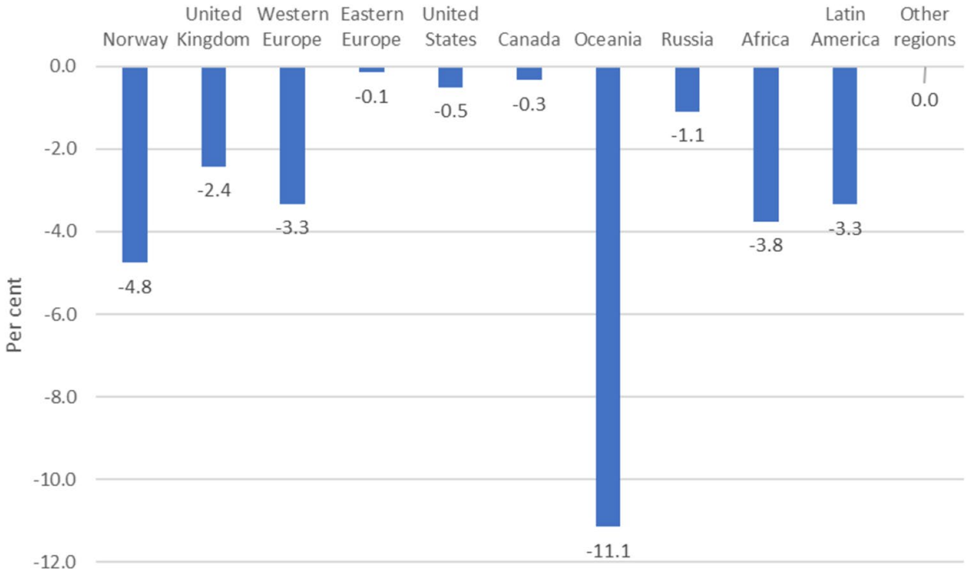


Fig. 7 Effect of low-carbon hydrogen cost reductions on regional hydrogen prices in 2050: Deviations from BAU. Per cent

might be of significance to enhance the effect of a cost reduction in blue and green hydrogen production. There are, however, additional barriers related to lack of equipment and infrastructure associated with the use of hydrogen.

5 Conclusions

Hydrogen is expected to be widely applied in reducing CO_2 emissions in hard-to-abate sectors such as transport. One of the barriers for large-scale use of hydrogen is the high cost of green hydrogen. This study used a macroeconomic model to examine to what extent hydrogen could reduce CO_2 emissions from fossil fuels if the high cost of green and blue hydrogen were lowered.

Our results show that the lower cost of blue and green hydrogen itself reduces CO_2 emissions from fossil fuels only marginally. This conclusion largely holds even if rather high carbon taxes were introduced on fossil fuels. Nevertheless, the reduced cost of low-carbon hydrogen could stimulate green hydrogen production substantially in relative terms, an effect that might be further enhanced if carbon pricing is implemented for fossil fuels.

However, the results need to be interpreted with caution. The limited effect on CO_2 emissions observed in our simulation reflects preferences and behavior of energy users in a current fossil-fuel-based economy, where, e.g., trade in hydrogen is zero and hydrogen demand initially has a very low share within energy use.

In addition, hydrogen use is associated with risk factors and the current level of confidence among users might lag behind technological and security improvements. Increasing confidence among consumers along with a successful increase in scale might generate a future upwards shift in demand beyond the effect of cost reduction. Hence, our results might underestimate the growth in low-carbon hydrogen demand of a cost reduction in the longer run. Thus, the question to what extent low-carbon hydrogen will be enhanced in a world with cheaper green and blue hydrogen falls short of being fully answered in this study.

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Author contributions TW wrote the first draft of manuscript. Both TW and SG commented and revised the other versions. Both the authors read and approved the final manuscript.

Data availability The model code and dataset generated during the current study are available in the Mendeley repository at https://doi.org/10.17632/t56n4dkrmn.1. The GTAP data that used in the GRACE model are available from https://www.gtap.agecon.purdue.edu.

Declarations

Competing interests The authors declare no competing interests.

Appendix

A rough estimate of hydrogen and ammonia demand and supply by sectors and regions

We roughly estimate demand and supply of hydrogen and ammonia by sectors and regions in 2019, which is then proportionally scaled down to the 2014 level used in this study. We start from estimating hydrogen demand data in physical terms by sector and region. By assuming supply equals demand in a region, we obtain total hydrogen supply in a region, which is then divided into different hydrogen production technologies based on relevant studies and documents. By assuming a price of hydrogen equal to unit production cost, we obtain the monetary values of hydrogen demand and supply. A similar approach is used for estimating ammonia demand and supply.

Hydrogen demand

We take the data of hydrogen demand by sector for European countries in metric tons (Mt) per year from FCHO [7]. The data is aggregated into demand by four European regions: Norway, UK, Western Europe (WEU), and Eastern Europe (EEU). The same hydrogen demand by the GRACE sector is obtained by mapping the FCHO sectors to the GRACE sectors. The IEA [2] data have been used to separate hydrogen demand in the steel and iron sector.

To estimate hydrogen demand of regions other than the four European regions, we calculate the hydrogen use per unit output by sectors for the whole Europe by using the sectoral output extracted from the GTAP database. For Ammonia, there is no output data in GTAP. Hence, we aggregate the ammonia production by country [33] to the GRACE regions, which is used as the alternative of output in the ammonia sector.

Assuming the other regions have the same unit hydrogen use in a sector as Europe, we estimate an initial version of all regional hydrogen demand by sector. The initial estimates for four regions (USA, CAN, RUS, and CHI) are then shifted up to be the same as that reported in their national documents and references [8, 9, 34, 35]. The global demand of hydrogen estimated for 2019 is quite close to the IEA [2] estimate.

Hydrogen supply

Currently hydrogen is not traded across countries in significant volumes [1]. Hence, we assume no trade between regions, i.e., production equals demand within a region. Total hydrogen production in European regions is then allocated into different technologies proportional to their capacities from FCHO [36].

For other regions than Europe, we adopt hydrogen shares of different technologies for three regions based on their national documents, i.e., USA [35], Australis and New Zealand [Fig. 6.41 of 10], and China [34]. For the other regions, we simply assume all hydrogen is produced from GAS without CCS. Certain part of the estimated hydrogen supply is further adjusted based on the data reported in IEA [2].

Ammonia demand and supply

We separate a new sector for ammonia in GRACE used in this study. Nowadays, around 90 per cent of ammonia produced globally is used as fertilizer in agriculture. The other ammonia is used for household cleaning products and manufacturing [37]. Hence, we assume that the other 10 per cent of produced ammonia is used by the manufacturing sector. We apply this for all regions in 2019. The regional supply (or production) of ammonia data are from National Minerals Information Center [33] and its trade data from the World Trade Organization (WTO) stats (https://timeseries.wto.org).

Hydrogen and ammonia production cost

We adopt the unit costs of hydrogen production by technology from Figs. 9 and 15 of IEA (2019). We assume the costs of regions not shown in Fig. 9 of IEA 2019 follow one of the regions shown in the figure.

We adopt the unit costs of ammonia production by technology as shown in Fig. 41 of IEA (2019). Almost all the ammonia production in 2019 is assumed by unabated technologies, i.e., coal- and gas-based technology without CCS. For simplicity, we assume the same share of hydrogen produced from natural gas and coal in a region are used to produce ammonia.

Transport cost of hydrogen and ammonia

Based on IEA [2], the total cost of local distribution would be USD 2.9/kgH2 for hydrogen in 2018. For ammonia the equivalent cost would be USD 1.5/kgH2. However, if ammonia is used without the need for reconversion back to hydrogen, the cost of distribution would considerably be as low as USD 0.4/kgH2 [p. 80, 2]. Hence, we assume that the users of hydrogen and ammonia will pay transport costs of USD 2.9/kgH2 and USD 70.8/t NH3 (0.4/kgH2 *177kgH2) respectively.

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