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Short Communication

A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future

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HIGHLIGHTS

- The concept of hydrogen credit is proposed the first time.
- The green hydrogen credit system is closely coupled with the carbon credit market.
- A framework of trading hydrogen credits is designed to stimulate hydrogen economy.
- This work contributes to the global uptake of green hydrogen financially.
- It provides a new pathway towards the net-zero emission/carbon neutral future.

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ABSTRACT

Hydrogen as a low-carbon clean energy source is experiencing a global resurgence and has been recognized as an alternative energy carrier that can help bring the world to a carbon neutral future. However, getting to scale is one of the main challenges limiting the growth of the hydrogen economy. In particular, the high cost of transporting green hydrogen is bottlenecking the international trading and wider adoption of hydrogen for global carbon natural objectives. In order to explore incentives for the global hydrogen economy and develop new pathways towards the carbon neutral future, the concept of hydrogen credit is proposed by this research and a framework of trading hydrogen credits similar to carbon credits in the international market is established. This research aims to contribute to the overall uptake of green hydrogen financially rather than relying on the physical production, transportation, and storage of hydrogen. Case studies are presented to demonstrate the feasibility and efficiency of the proposed hydrogen credit framework, as well as the great potential of a global hydrogen credit market.

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Introduction

DUE to concerns on carbon emission reduction and security of energy supply, renewable energy (RE) technologies are favoured by countries during the past decades. By the end of 2020, global RE generation capacity amounted to 2802 GW in which hydropower accounts for the largest share (1333 GW). In 2020, the installed capacity of solar and wind power expanded by 126 GW and 110 GW, respectively [[1]]. The share of RE in the global electricity generation has increased to 29% in 2020, up from the 27% in 2019 [[2]]. Meanwhile, green hydrogen (H_2) made without fossil fuels has long been identified as the clean energy source that could help bring the world to attain net zero emissions target. The rapid growth of RE worldwide together with the development of green H_2 technology provide a promising solution for achieving the carbon neutral target.

In terms of the key roles of H_2 in the worldwide energy transition, there are already some publications being reported. Since RE sources are featured by the inherent intermittency of output, it is thus challenging to operate energy systems with high renewables reliably and securely. In Ref. [[3]], an energy system with 100% renewables is designed using an iterative approach where the H_2 infrastructures for production and transportation are considered for overcoming the intermittency of RE. Similarly, H_2 is also utilized in Ref. [[4]] to compensate the mismatch between production and demand of RE. It is found that the production of H_2 from RE could change the current energy market paradigms and speed up the transition to H_2 economy. Moreover, the commercial viability of H_2 production from wind power generation is investigated in Ref. [[5]], which can serve as a complete feasibility study on renewable H_2 production and utilization. In particular, the comprehensive reviews of potential roles that H_2 could play in a low-carbon energy system are presented in Refs. [[6],[7]]. The results show that challenges around cost and performance of H_2 remain, and considerable improvements are required for H_2 to become truly competitive.

In practice, there is already a wide application of H_2 in transportation, industrial processing, fuel cell, and heating. Despite these opportunities, there are still challenges and issues related to producing H_2 at scale. In Refs. [[8],[9]], various H_2 production pathways and associated technologies are reviewed, including the green, blue and aqua H_2. In order to promote the development of H_2 economy, the current challenges, future directions and policy recommendations are also investigated in Ref. [[9]]. It is pointed out in Ref. [[10]] that significant levels of new investment are needed to successfully commercialise and scale a global green H_2 industry. To meet the estimates of providing up to 18% of the world's final energy demand by 2050, global annual investments of between US $20 to $25 billion are needed for a total investment of about $280 billion by 2030.

Currently, the storage cost of compressed and liquified H_2 is expensive and the transportation of H_2 over longer distance is economically inefficient [[11]]. While H_2 carriers such as ammonia, methane and methanol are being increasingly considered, there are concerns on their certification and resulting emissions when utilized. In Ref. [[12]], the levelized cost of H_2 distributed to refueling stations while using different carriers are presented. Costs and technical requirements for storage and long-distance transportation are major obstacles for international trading and wider adoption of green H_2 for global carbon natural objectives. A variety of compressed H_2 storage technologies (e.g., the storage vessels, geological storage, and other underground storage alternatives) are investigated in both [[13],[14]]. The theory of operation, limitations, and challenges of each H_2 storage and transportation technology are explored. The analysis confirms that a techno-economic chain analysis is required to evaluate the viability of a specific option over another in the practical application.

Through the literature survey, it can be found that there are still no efficient solutions being proposed on how to stimulate the international green H_2 trading towards a carbon neutral future. Notably, the carbon credit (CC) system has already been proven effective in international emission reduction efforts. To fill in this research gap, a green H_2 credit (HC) system which is coupled with CCs is developed in this work for green H_2 trading. The main contributions of this work are 2-fold:

(1) Be the first research to propose the concept of HC. The HC is defined by the net savings of carbon dioxide equivalent emissions (CO2-eq) when using a ton of H_2. The quantitative relationship between the HCs and CCs is derived and the international regulatory framework of HC issuance is also constructed.
(2) To design an innovative HC trading framework and provide a new pathway towards the carbon neutral future. The proposed framework of trading HCs provides an additional option for reducing carbon emission through stimulating the H_2 industry. The proposed framework enables countries with abundant RE (e.g., solar PV generation in Australia) to trade green HCs financially instead of real local production to contributing to the global emission reduction. For countries with poor RE, the HCs created by this framework will be a new source of CCs, since HCs can be converted into equivalent CCs. The HC framework also enables these countries with less renewables to benefit from the development of RE in other countries as the produced abundant green HCs can help stabilize the price of CCs in the global market.

Key methodologies

Life cycle assessment of hydrogen

Green H_2 has long been identified as the clean energy source with its zero-carbon potential, but most of the H_2 production today falls into the category of grey or brown H_2, which produce H_2 via combustion of fossil fuels (e.g., natural gas and coal). There are four major sources for commercial production of H_2, three of which require fossil fuels: steam methane reformation, oxidation, and gasification. The fourth source is electrolysis, which separates water into its constituent elements using electricity [[15]]. When the electricity for H_2

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production is supplied by RE, the produced H_2 is regarded as zero carbon green H_2. Quantitative assessment models are proposed in Refs. [[16–19]] to evaluate the life cycle environmental performance of various H_2 production technologies, where [[18],[19]] focused on the natural gas steam reforming process H_2 and the biomass staged-gasification H_2, respectively. In particular, the monetized values of environmental impacts of H_2 were obtained to transparently rank the alternative technologies in Ref. [[11]].

Key challenges regarding the delivery and storage of H_2 are yet to be tackled (e.g., the delivery/storage cost, weight and volume of H_2 storage systems, storage efficiency and safety), in order to scale up the H_2 industry. Presently, H_2 is transported from the site of production to the utilization sites mainly through pipeline, over the road in cryogenic liquid tanker trucks or gaseous tube trailers, by rail or barge. In Ref. [[20]], the life cycle assessment for three different H_2 supply chain architectures are carried out, including (*a*) Liquid organic H_2 carriers for transport and storage; (*b*) compressed H_2 storage in salt caverns, together with pipelines; and (*c*) pressurized gas truck transport.

The utilization of H_2 can be categorized into [[15]]: (*a*) Combustion, e.g., blending H_2 into the natural gas network, power generation at a grid scale, and H_2 for heating. (*b*) Fuel cells. Compared with the internal combustion which converts fuel into kinetic energy at an efficiency ranging from 20% to 35% in practice (the efficiency of internal combustion engines is affected by various factors, e.g., the temperature of intake air, compression ratio, air-fuel ratio, and the final drive ratio), H_2 fuel cells have a much higher efficiency in energy conversion and can produce electricity at up to 60% efficiency. The typical application is the fuel cell transportation. (*c*) Utilization in chemical processes (e.g., the petroleum industry, Haber-Bosch process, methanol synthesis and the metallurgical industry et al.). H_2 is essential for material supplies and economy growth considering its significance in numerous chemical processes.

Economic model of the hydrogen credit value

To denote the CO_2-eq of a specific H_2 production technology and a transportation method by C^{prod} and C^{trans}, respectively, namely the production and transportation of 1 ton of (green) H_2 will result in the C^{prod} and C^{trans} tons of CO_2-eq. Under a specific utilization scenario, the reduction of CO_2-eq due to the utilization of H_2 can be indicated by C^{reduc}, which means the utilization of 1 ton of H_2 results in the savings of C^{reduc} tons of CO_2-eq. Meanwhile, the CC is a tradable permit or certificate that provides the holder of the credit the right to emit one ton of CO_2 or an equivalent of another greenhouse gas. Therefore, in the H_2 economy towards a carbon neural future, the value of a HC is defined by the net savings of CO_2-eq when using a ton of H_2. Let r^{CC} (\$/ton CO_2-eq) denote the price of CCs. Then, the value of HCs $r^{v,HC}$ (\$/ton H_2) can be calculated as below.

$$r^{v,HC} = \left(C^{reduc} - C^{prod} - C^{trans}\right) \cdot r^{CC} \tag{1}$$

Eqn. (1) gives a generalized definition of HC value, where C^{prod} differentiates the various H_2 production options, C^{trans} measures the emission savings associated with transporting H_2. For example, for green HC, the emission savings from the corresponding RE is counted by having $C^{prod} = 0$.

For each fuel with a high emission factor, if it can be replaced by H_2, then there will be a reduction of carbon emissions. To evaluate the net savings of CO_2-eq in H_2 utilization, this research proposes to use a heat value-based method. The net savings of CO_2-eq is derived by calculating how much carbon emission is avoided while producing the same amount of heat.

$$C^{reduc} = \left[H^{hydr} \middle/ H^{fuel}\right] \cdot E^{fuel,f} \tag{2}$$

where H^{hydr} (MJ/kg H_2) and H^{fuel} (MJ/kg fuel) is the heat value of H_2 and a specific fuel replaced by H_2. $E^{fuel,f}$ (kg CO_2-eq/kg fuel) is the emission factor of the replaced fuel.

Since the utilization of H_2 can save emissions, under the carbon neutral scenario, the saved emission by H_2 utilization can be traded as an equivalent CCs, without increasing the total net emissions. The concept of HC and the diagram of H_2 economy are presented in Fig. 1 and Fig. 2, respectively.

There are two types of CC markets, namely the compliance market (CM) and the voluntary market (VM). CMs are created and regulated by mandatory national, regional, or international carbon reduction regimes. In a CM, the cap-and-trade or emission trading scheme is usually adopted, where a central authority or governmental body will allocate or sell carbon emission permits. Thus, carbon pricing in the CM is mainly undertaken by governments, but the CC price can also be strongly influenced by the market itself and the changes in supply and demand. Carbon tax is another method adopted in the CM to manage carbon emissions. Differently, carbon tax is fully controlled by policymakers and not subject to marketplace changes. The VM functions outside of CMs and enables companies and individuals to purchase carbon offsets on a voluntary basis with no intended use for compliance purposes. In a VM, the CCs from different carbon offset projects can be selected and thus there is a wide range of CC prices depending on the project itself, including the project quality, size, and location. Compliance offset market credits may in some instances be purchased by voluntary, non-regulated entities, but voluntary offset market credits, unless explicitly accepted into the compliance regime, are not allowed to fulfill CM demand. Similar to the CC market, two types of HC markets are considered in the proposed HC market, as shown in Fig. 2.

Hydrogen tax and hydrogen credit price

In the production and transport of H_2, the quantity of CO_2-eq varies depending on the adopted production technologies and transportation methods. Under the framework of HCs, the H_2 tax is defined as the payment from H_2 production and transportation entities to compensate the emissions. Let $r^{tax,\ prod}$ (\$/ton H_2) and $r^{tax,\ trans}$ (\$/ton H_2) denote the H_2 taxes for production and transportation, respectively. According to the definition, the H_2 tax will be a function of emissions.

$$r^{tax,prod} = f\left(C^{prod}\right) \cdot r^{CC};\ r^{tax,trans} = g\left(C^{trans}\right) \cdot r^{CC} \tag{3}$$

where $f(\cdot)$ and $g(\cdot)$ is determined by the H_2 market operator. For example, when there is no subsidy provided to H_2

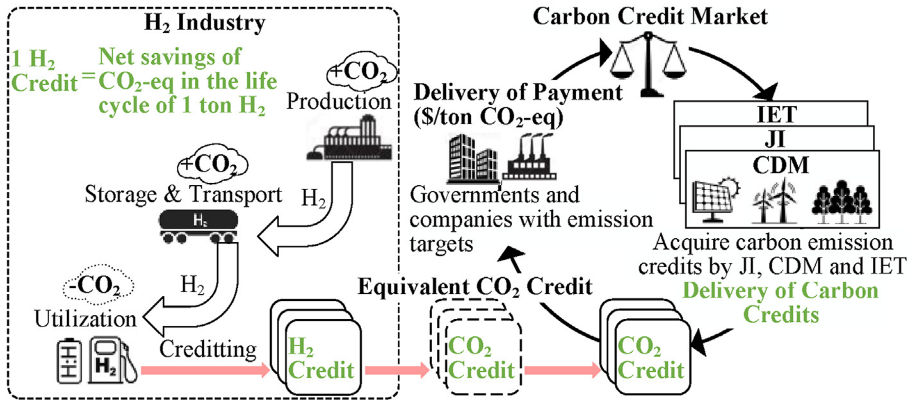

Fig. 1 – The generalized concept of H2 credit and its transactions. Note: IET denotes International Emission Trading; JI is Joint Implementation; CDM indicates Clean Development Mechanism.

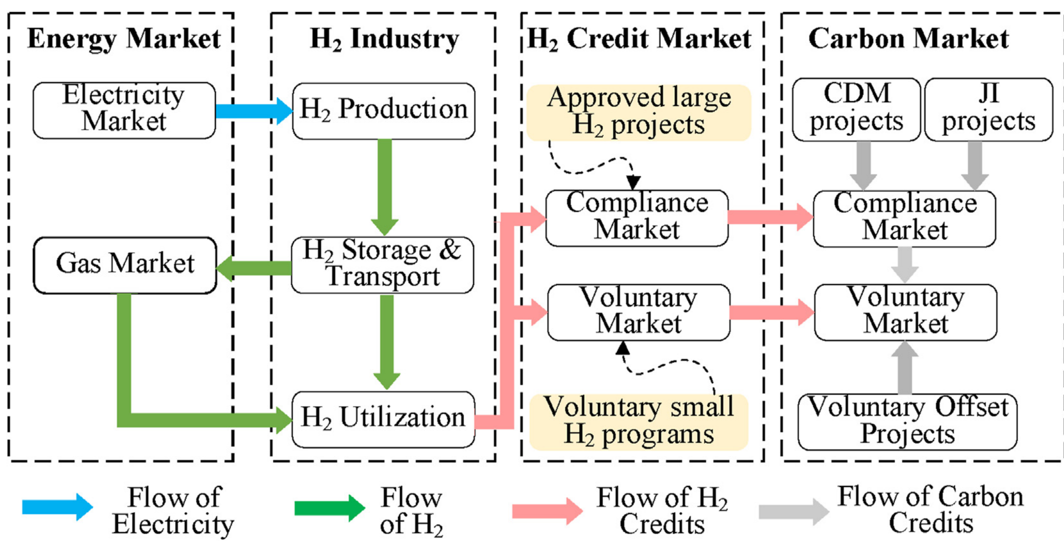

Fig. 2 – Diagram of the H2 economy towards a carbon neutral future.

producers and transporters, these functions can be defined as $f(C^{prod}) = C^{prod}$ and $g(C^{prod}) = C^{trans}$. When subsidy is available, the functions can be defined as $f(C^{prod}) = \alpha \cdot C^{prod}$ and $g(C^{prod}) = \alpha \cdot C^{trans}$ and $0 < \alpha < 1$.

During the process of generating HCs, any tax paid by H_2 producers and transporters can be viewed as costs and will be finally recovered through the transaction of HCs. Without loss of generality, it can be assumed the HC market is operated by a nonprofit operator, and thus there is a balance between its expenses (payment to HC holders) and income (H_2 tax, selling HCs to the carbon market).

$$r^{price,HC} = r^{v,HC} + r^{tax,prod} + r^{tax,trans} \quad (4)$$

where $r^{price,HC}$ (\$/ton H_2) is the price of HCs. $r^{v,HC}$ is the value of HCs, which is defined from the perspective of CO_2-eq savings. The price of HCs can be derived as follows:

$$r^{price,HC} = \left[C^{reduc} - C^{prod} - C^{trans} + f\left(C^{prod}\right) + g\left(C^{trans}\right)\right] \cdot r^{CC} \quad (5)$$

In (5), given the price of CCs r^{CC}, the market operator can stimulate the utilization of H_2 using the income from selling HCs and the H_2 tax. Even without the H_2 tax, the exporting of HCs the carbon market will still benefit H_2 users. Besides, by adjusting $f(\cdot)$ and $g(\cdot)$ for the H_2 taxes ($r^{tax,\ prod}$ and $r^{tax,\ trans}$), the market operator can balance the financial stimulation between the supply and demand sides of H_2. A higher incentive for H_2 utilization can be carried out through improving the H_2 tax. A lower H_2 tax is an incentive for the supply side of H_2. It should be pointed out that the adjustment of H_2 tax will affect both the demand and supply sides of the H_2 industry simultaneously. The choice of tax policy should be made based on a comprehensive evaluation of its impacts on the whole value chain. Besides, although the HC market operator is assumed to collect the H_2 tax on behalf of the government after the authorization, the regulations on tax are still determined by the governments. The practical legislation on tax is a sophisticated process and the assumption here is made for the convenience of discussion.

Framework of hydrogen credit issuance

Carbon emission is recognized as a global issue, under the United Nations framework convention on climate change

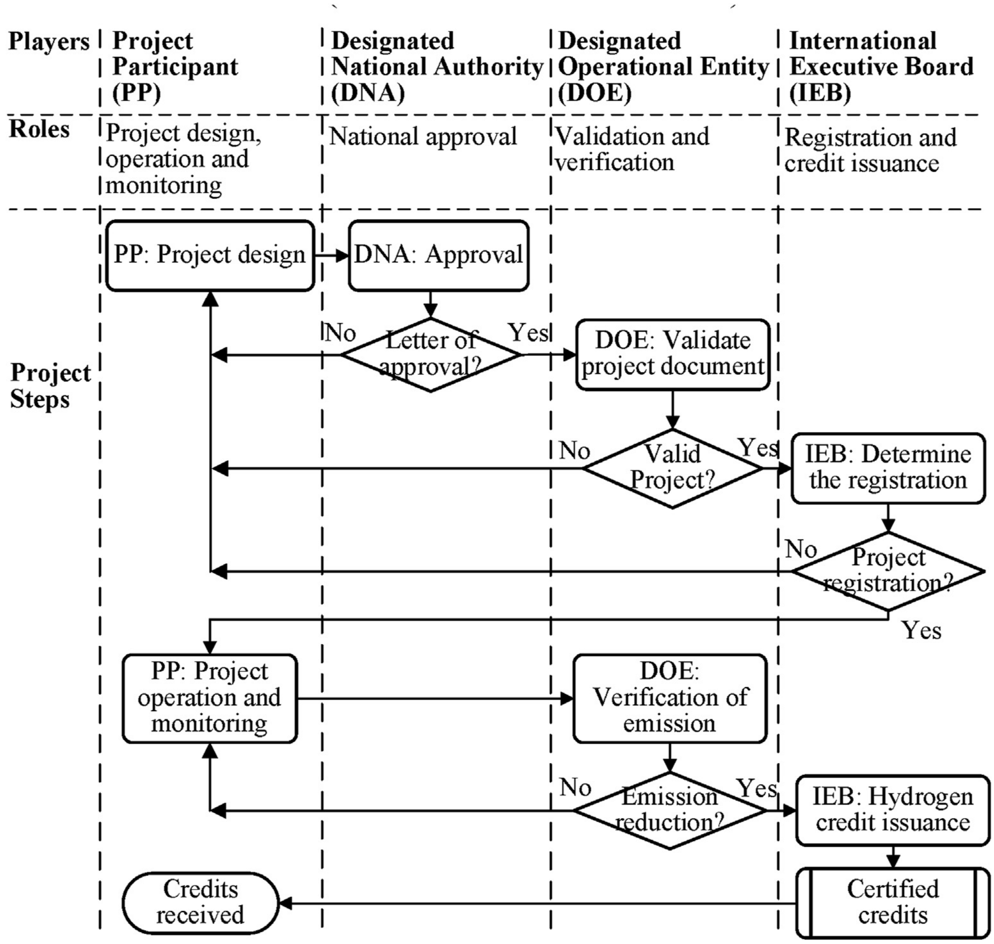

Fig. 3 – The constructed regulatory framework of HC issuance.

Table 1 – CO_2 emissions of H_2 production and delivery options.

H_2 production pathways	CO_2 emission (kg CO_2-eq/ kg H_2)	Options of H_2 Delivery	CO_2 emission (kg CO_2-eq/ kg H_2)
SMR	12.4	LOHC 100 km	3.40
SMR with CCS	4.3	LOHC 400 km	4.28
CG	19.14	Pressure 100 km	1.25
CG with CCS	1.8	Pressure 400 km	3.06
CH_4 pyrolysis	3.72	Pipeline 80 t/d	0.17
E-wind	0.88	Pipeline 40 t/d	0.16
E-solar	2.21	Pipeline 10 t/d	0.35
E-nuclear	0.76		
S–I cycle	1.2		
Cu–Cl cycle	1.08		

Note: SMR is Steam Methane Reforming; CCS is Carbon Capture and Storage; CG is Coal Gasification; E-wind, E-solar, E-nuclear is Electrolysis with wind, solar and nuclear energy; S–I cycle is the Thermochemical water splitting Sulphur–iodine cycle and Cu–Cl is the copper–chloride cycle. LOHC is Liquid Organic H_2 Carriers; 100 km and 400 km represent the transport distance; Pressure indicates high-pressure tanks for transport of H_2. t/d is ton/day.

(UNFCCC), multiple international commitments have been achieved to combat climate change since the UNFCCC took effect in 1994, e.g., the earliest Kyoto Protocol in 1997 and the latest Paris Agreement in 2015. To facilitate Annex I countries in achieving their greenhouse gas (GHG) emission obligations, Kyoto Mechanisms or Flexibility Mechanisms are defined under the Kyoto Protocol. The Kyoto Mechanisms include three new market-based cooperative flexibility mechanisms, i.e., emission trading (ET), joint implementation (JI) and clean development mechanism (CDM). Notably, the ET (also known as cap and trade) is a market-based approach to controlling pollution through the trading of CCs, which give them the

Table 2 – Evaluation of the H_2 credit market.

Fuels replaced by H_2	CO_2 reduction (kg CO_2-eq/kg H_2)	Price of green HCs ($/HC)	Global market size of HCs (billion $)	Global demand in 2019 (ton)	Potential quantity of HCs
Gasoline	8.762	0.26	30.6	4.86×10^8	1.18×10^{11}
Diesel fuel	9.1	0.27	46.1	7.21×10^8	1.71×10^{11}
Natural gas	6.682	0.20	0.0658	2.97×10^6	3.29×10^8
Anthracite	11.7	0.35	418	7.3×10^9	1.19×10^{12}
Lignite	12.155	0.36	18.7	7.96×10^8	5.21×10^{10}

right to emit a specific amount of GHG. Currently, CDM and JI projects are the main sources of CCs. In practice, the issuance of CCs is required to follow either the UNFCCC procedures (for CC traded in the CM) or local governmental regulations on emission reductions (for CC traded in the VM).

In the proposed HC framework, HCs are tradable in an international H_2 economy environment. Thus, the framework of HC issuance is constructed by considering an international regulatory framework, as is given in Fig. 3. The international executive board (IEB) as the highest authority of credit issuance can ensure the global recognition of credits. The designated operation entity (DOE) and designated national authority (DNA) enable the proposed H_2 project to comply with the domestic laws and carbon reduction regulations. The project participant (PP) as the project developer has the ownership of issued HCs and is also a key player in the HC market.

Case study and discussions

HCs are valued according to their equivalent CCs. Then it is essential to account for the life cycle carbon emissions of the H_2 utilization. In the case study, the life cycle carbon footprint of H_2 production methods and delivery options are surveyed and presented, as is given in Table 1.

Besides, a host of countries have announced commitments to cut carbon emissions, promising to achieve net zero emission targets by 2050. The study of the international RE agency (IRENA) [[21]] shows that by 2050, fossil fuels used for energy would fall to one-third of current levels. Specifically, oil and coal will decline most, 70% and 85% respectively. Natural gas usage will decline by 30% from the level of 2018–2019. Under this scenario, the price, market size, and potential quantity of HCs under the proposed H_2 market are presented in Table 2, where the price of CC is set as 30 $/ton CO_2-eq by referring to European Union emissions trading system carbon market price. According to the International Energy Agency (IEA) data, global energy-related CO_2 emissions in 2019 is around 33 Gigatons. Thus, to achieve the carbon neutral target in 2050, there will be market size of about US $990 billion for CCs. In comparison, the HC market size is significant in the transition of energy systems towards a carbon neutral future.

Conclusions

Due to the current high cost of green H_2, incentives and financial support are needed to accelerate the development of H_2 industry. Around 20 countries have introduced financial incentives for H_2 uptake, including incentives for investment in H_2 technology, incentives for the use of renewable H_2 in industry, financial incentives for vehicle manufacturers, purchase and building H_2 refueling stations. The proposed framework of HC market provided a new form of incentives by taking full advantage of the carbon emission reduction of H_2. The evaluation of future global HC market is also presented to manifest the significance and great potential of the proposed framework.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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