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# Green hydrogen credit subsidized renewable energy-hydrogen business models for achieving the carbon neutral future

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ABSTRACT

The global resurgence of hydrogen as a clean energy source, particularly green hydrogen derived from renewable energy, is pivotal for achieving a carbon-neutral future. However, scalability poses a significant challenge. This research proposes innovative business models leveraging the low-emission property of green hydrogen to reduce its financial costs, thereby fostering its widespread adoption. Key components of the business workflow are elaborated, mathematical formulations of market parameters are derived, and case studies are presented to demonstrate the feasibility and efficiency of these models. Results demonstrate that the substantial costs associated with the current hydrogen industry can be effectively subsidized via the implementation of proposed business models. When the carbon emission price falls within the range of approximately 86–105 USD/ton, free access to hydrogen becomes a viable option for end-users. This highlights the significance and promising potential of the proposed business models within the green hydrogen credit framework.

## 1. Introduction

DUE to growing concerns about climate change and the imperative carbon neutral transition, increased attention has been paid to renewable energy solutions, among which the hydrogen ($H_2$) energy has been acknowledged as a promising clean energy carrier to drive decarbonization. In 2021, global $H_2$ demand reached 94 million tonnes (Mt), and it is projected to rise to 130 Mt by 2030, driven primarily by the refining and industrial factors as well as the accelerated deployment of fuel cell electric vehicles [1].

The adoption of low-emission $H_2$ as a clean industrial feedstock is still in its nascent phase. Research indicates that the availability of green $H_2$ will remain limited in the short term and uncertain in the long term, hindering investments in $H_2$ infrastructures and end-use applications [2]. The main barriers to large-scale $H_2$ utilization lie in the high production costs, a relatively small market size, and inadequate infrastructure [3,4]. Therefore, innovative financial mechanisms and business models are essential to promote the development of the $H_2$ industry, especially for green $H_2$ which generates zero emissions during production.

Several publications have explored the design of $H_2$ markets and pricing strategies for $H_2$ providers. In Refs. [5,6], frameworks of the local energy market are proposed for integrated electricity-hydrogen trading, with the corresponding trading mechanisms designed and the market clearing model established. In Ref. [7], a bi-level strategic bidding model is developed for a power-to-$H_2$-and-methane plant, aiding decision-making for $H_2$ producers. In Ref. [8], the trading strategy for a hybrid-renewable-to-$H_2$ provider is proposed based on the Vickrey auction and Stackelberg game. Ref. [9] presents a credit-based sharing model between coordinators and prosumers of a shared energy storage system for $H_2$ and electricity, allowing both parties to realize benefits in the energy market. However, most of the existing studies treat $H_2$ investors and users as ordinary market participants, which may limit incentives for further development of the $H_2$ industry.

In our previous work [10], the concept of $H_2$ credit (HC) is introduced and a framework to trade HC is proposed, which allows the HC trading income to be used to subsidize $H_2$ prices, thereby promoting the local utilization of $H_2$ energy. Building upon the HC framework, the main contributions of this paper are 2-fold.

(1) Practical business models for $H_2$ investors/developers are presented within the $H_2$ credit framework, offering different

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approaches to incentivize and facilitate green $H_2$ uptake. The pricing of $H_2$ and HC as well as the benefits of stakeholders are derived. These business models cater to the diverse participants involved in the $H_2$ value chain.

(2) Analysis of $H_2$ pricing strategies and assessment of stakeholders' revenue under each business model are conducted. The results demonstrate the feasibility and effectiveness of the green $H_2$ credit framework in promoting the $H_2$ industry and fostering collaboration among stakeholders.

## 2. Green hydrogen business models

### *2.1. Framework of green hydrogen credits*

Incentives and financial support are needed to expedite the development of the $H_2$ industry, especially considering the current high cost of green $H_2$ production. These incentives and financial support mechanisms include providing direct subsidies or grants to companies involved in green $H_2$ production, implementing investment tax credits for businesses, and offering low-interest loans or loan guarantees to companies. Meanwhile, financial and $CO_2$ reduction are closely interconnected in the context of sustainable practices, via implementing carbon emission markets, improving environmental awareness of consumers, and ensuring regulatory compliance in environmental matters. Entities that align financial decisions with sustainability goals can achieve both economic benefits and $CO_2$ emission reduction. Particularly, our previous work [10] introduces the concept of HC, leveraging carbon emission reductions from $H_2$ and establishing a framework for trading HC internationally, similar to carbon credits (CC). The HC is defined by the net reduction of carbon dioxide equivalent emissions ($CO_2$-eq) throughout the life cycle of a ton of $H_2$. (See Fig. S1 in the supplementary materials for illustration of the green hydrogen credit framework). However, in order to effectively implement the proposed HC framework, practical business models are needed, which are discussed in detail in the following sections.

### *2.2. Business models for green hydrogen industry*

#### *2.2.1. Business model 1: investment for emission reduction*

The Greenhouse Gas Protocol [11], currently the world's most widely used greenhouse gas (GHG) accounting standard, categorizes carbon emissions produced by an entity into three distinct scopes (i.e., scope 1, 2, and 3). These scopes encompass emissions from the entity's own operations as well as its broader value chain, involving suppliers and customers.

In this business model (see Fig. 1), the entity invests in $H_2$ projects and sells $H_2$ to users for revenue. As $H_2$ utilization results in a reduction of fossil fuels consumption, the energy consumers can save costs in the CC market, since fewer CC are required to meet its overall emission target (including scope 1, 2, and 3). In this context, the term "energy consumers" primarily refers to large-scale entities with assigned emission quotas/targets rather than small-scale end-users. Thus, the implication is that it is the larger energy consumers, not small-scale users, who will directly pay the cost of purchasing carbon credits. Users' savings in the CC market, which come from the net reduction of $CO_2$-eq, is paid to the entity for cost recovery. Given the rate of return as $\eta^{ror}$, the price of $H_2$ is derived below.

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left( \alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}} \right) \tag{1}$$

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left( \alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}} \right) \tag{2}$$

where $r^{price,HH}$ (\$/ton) is the price of $H_2$; $M^{cost,HH}$ (\$/ton) denotes the investment cost of $H_2$ projects; $M^{save,CM}$ is the cost saving in the CC market, measured by the value of net $CO_2$-eq savings when using a ton of $H_2$. The $CO_2$-eq of a specific $H_2$ production technology and transportation method is given by $C^{prod}$ and $C^{trans}$ (ton $CO_2$-eq). $C^{reduc}$ (ton $CO_2$-eq) is the reduction of $CO_2$-eq due to the usage of $H_2$ under a specific utilization scenario. $r^{CC}$ (\$/ton $CO_2$-eq) is the price of CC.

It can be found (via (1)–(2)) that the net savings of $CO_2$-eq resulted from the $H_2$ utilization will further reduce the $H_2$ price. When the CC price (i.e., $r^{CC}$) is higher than the threshold given by (3), $H_2$ users can even receive subsidies for using $H_2$ (i.e., the $H_2$ price is negative).

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left( \alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}} \right) \tag{3}$$

#### *2.2.2. Business model 2: investment for HC*

In this model (see Fig. 2), the entity invests in $H_2$ projects to acquire HC and sells $H_2$ to users for revenue. The entity takes charge of the operation and monitoring of the $H_2$ project and will apply for HC accreditation based on the life cycle emission data of the delivered $H_2$. The accredited HC are fully tradable within the carbon emission market. Assuming the rate of return as $\eta^{ror}$, the price of $H_2$ is derived below.

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left( \alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}} \right) \tag{4}$$

where $r^{price,HC}$ (\$/ton $H_2$) is the price of HC.

Particularly, the HC price is calculated by (5) using the life cycle emission of $H_2$, the $H_2$ taxes for production and transportation, and the price of CC. Please refer to Ref. [10] for the detailed formulation of $r^{price,HC}$.

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left( \alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}} \right) \tag{5}$$

where $f(\bullet)$ and $g(\bullet)$ denote $H_2$ taxes for production and transportation, respectively.

Eqn. (4) shows that the income from HC can help reduce the $H_2$ price for users. When $r^{CC}$ exceeds the threshold given by (6), $H_2$ users will receive subsidies.

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left( \alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}} \right) \tag{6}$$

Unlike model 1 where the entity earns benefits from users' savings in the CC market, model 2 allows the entity to trade surplus HC, offering greater flexibility.

#### *2.2.3. Business model 3: benefit sharing*

In this benefit-sharing model (see Fig. 3), compared to model 2, the entity still invests in $H_2$ projects and sells $H_2$ for revenue, but it does not possess the HC. The HC ownership is distributed among different stages of the $H_2$ life cycle, including production, transportation, and utilization. Each stakeholder is assigned a proportion of the HC based on their contribution to the net savings of $CO_2$-eq. This shared ownership can also incentivize collaboration among stakeholders in recording $H_2$ life cycle emission data. Finally, the revenue of trading HC in the CC market

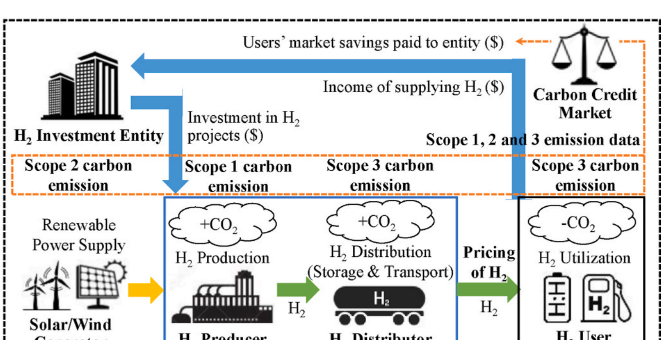


**Fig. 1.** Schematic of business model 1 - investment for emission reduction.

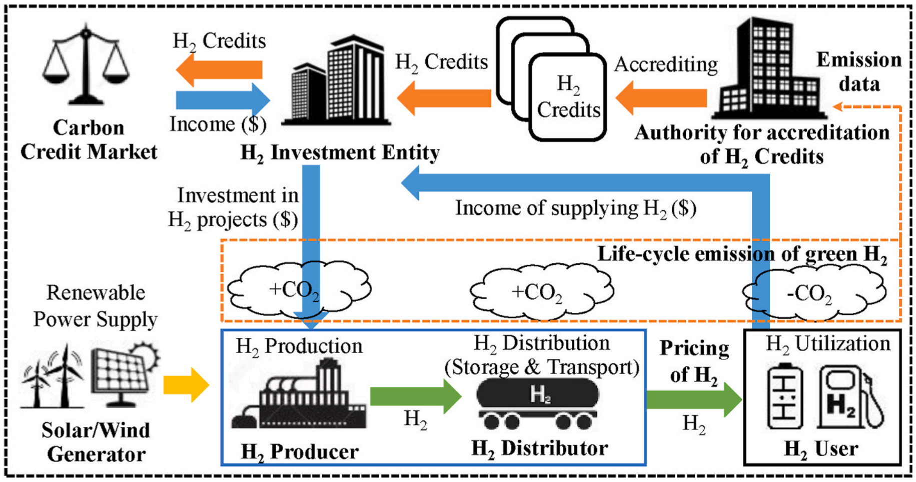


**Fig. 2.** Schematic of business model 2 - investment for HC.

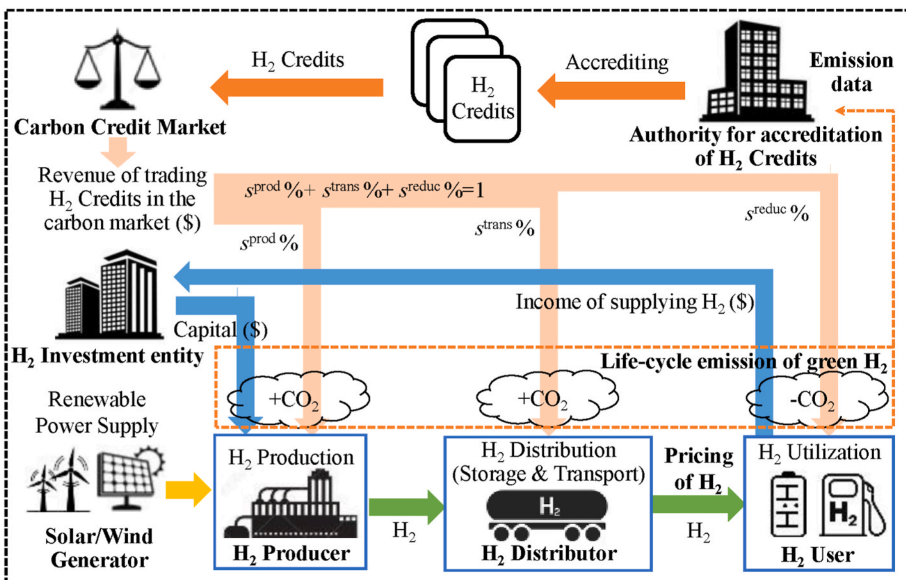


**Fig. 3.** Schematic of business model 3 - benefit sharing.

is shared by the producer, distributor, and users according to their respective proportions of HC ownership.

Different from previous models, the $H_2$ price is only determined by the entity's expected rate of return as well as the investment cost of the $H_2$ project:

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left(\alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}}\right) \tag{7}$$

The allocation of HC ownership among stakeholders is a crucial aspect. A feasible benefit-sharing model should reflect stakeholders' contributions to the HC value, which is the net savings of $CO_2$-eq throughout the life cycle of $H_2$, and should incentivize stakeholders to upgrade their technology and further reduce carbon emissions. Considering that users' emission reduction $C^{reduc}$ contributes positively, while distributors' and producers' emission $C^{trans}$ and $C^{prod}$ contribute negatively, we propose to determine the HC shares based on their exponentiation as given by (8)-(10).

$$s^{reduc} = \alpha^{C^{reduc}} \Big/ \left(\alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}}\right) \tag{8}$$

$$s^{trans} = \alpha^{-C^{trans}} \Big/ \left(\alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}}\right) \tag{9}$$

$$s^{prod} = \alpha^{-C^{prod}} \Big/ \left(\alpha^{C^{reduc}} + \alpha^{-C^{prod}} + \alpha^{-C^{trans}}\right) \tag{10}$$

where $s^{reduc}$, $s^{trans}$ and $s^{prod}$ are the proportions of HC ownership for the user, distributor, and producer. Thus, their revenues from HC trading will then be $s^{reduc}.r^{price,HC}$, $s^{trans}.r^{price,HC}$ and $s^{prod}.r^{price,HC}$, with the price of HC $r^{price,HC}$ given by (5). The exponentiation base $\alpha$ ($\alpha > 1$) can be adjusted by the market operator to tune the HC shares among stakeholders. A larger $\alpha$ gives more shares to the stakeholder with a larger emission saving, providing a stronger incentive for emission reduction efforts.

While the $H_2$ price is not directly subsidized in (7), the income from HC trading is compensated to $H_2$ users, resulting in an equivalent $H_2$ price given by (11). Similarly, when $r^{CC}$ exceeds the threshold given in (12), $H_2$ users can receive subsidies for using $H_2$.

$$r^{eq\ price,HH} = (1+n^{ror}).M^{cost,HH} - S^{reduc}\%.\ r^{price,HC} \tag{11}$$

$$r^{cc} \geq \frac{(1+n^{ror})M^{cost,HH}}{\left[C^{reduc} - C^{prod} - C^{trans} + f(C^{trans})\right] s^{reduc}\%} \tag{12}$$

In summary, a comparison of models 1, 2, and 3 is presented in

**Table 1**
Comparison between proposed business models.

| | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| **$H_2$ credit** | × | ✓ | ✓ |
| **HC ownership** | × | Investor | Shared ownership |
| **Flexibility** | Low | Medium | High |
| **$H_2$ price** | Low | Low | High |

Table I below.

### 2.3. *Tracking life-cycle emission of green hydrogen*

The blockchain technology offers promising opportunities for tracking the life cycle emissions of green $H_2$ in a transparent and secure manner [12,13]. With a shared and tamper-proof ledger, blockchain enables real-time recording of transactions and emission data. This provides stakeholders, including producers, distributors, and users, with access to accurate and reliable information regarding the carbon footprint of $H_2$. Implementing a blockchain-based tracking system enhances transparency, accountability, and traceability, fostering collaboration and incentivizing emission reduction efforts across the entire green $H_2$ value chain. In particular, the monitoring and management of Scope 3 GHG emissions, which have traditionally been challenging, can be effectively addressed. Thus, the substantial emission reduction potential in Scope 3 can be utilized to offset the emissions from Scope 1 and Scope 2 sources.

## 3. Case study and discussions

### 3.1. *Pricing analysis of $H_2$ and HC*

To investigate the relationship between $H_2$ and carbon prices, case studies are carried out with the following parameter configurations: $\eta^{\text{ror}} = 0.1$, $f(C^{\text{prod}}) = 0.3\bullet C^{\text{prod}}$, $g(C^{\text{trans}}) = 0.3\bullet C^{\text{trans}}$, $\alpha = 1.15$, $M^{\text{cost,HH}} = 900$ \$/ton $H_2$ for hydrogen project using renewable energy [1], $C^{\text{reduc}} = 13.93$ ton $CO_2$-eq/ton $H_2$ for replacing anthracite coal with $H_2$ [14], $C^{\text{prod}} = 2.21$ ton $CO_2$-eq/ton $H_2$ for electrolysis with solar energy [10], and $C^{\text{trans}} = 1.25$ ton $CO_2$-eq/ton $H_2$ for 100 km transportation with high-pressure tanks [10]. The results of $H_2$ prices and HC prices as a function of CC prices are presented in Fig. 4.

With the increase in CC prices, the benefit obtained via the utilization of green $H_2$ because of the emission reduction also rises. This can be verified by the higher CC market savings in model 1 and the increased HC prices in models 2 and 3. Specifically, in model 1, the entity's savings in the CC market brings down its $H_2$ price supplied to users. Model 2 further subsidizes the $H_2$ prices through $H_2$ taxes for production and transportation. In model 3, the users' equivalent $H_2$ price is compensated with the HC trading income, although the price is slightly higher

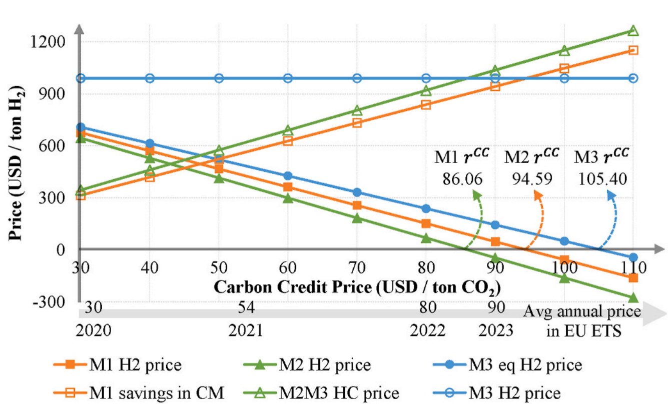


**Fig. 4.** Pricing analysis of $H_2$ and HC.

due to the benefit sharing with producers and distributors. The critical CC prices, at which $H_2$ users can consume $H_2$ for free, are approximately \$86~\$105, which is comparable to the CC price of \$90 observed in the European Energy Exchange (EEX) European Allowance (EUA) market in April 2023. With the recent surge of CC prices (from \$30 in 2020 to \$90 in 2023 in the EEX EUA market [15]), it can be anticipated that the proposed HC framework and business models hold significant promise in driving the growth of the green $H_2$ industry.

### 3.2. *Revenue analysis of stakeholders*

To examine the revenue of stakeholders in proposed business models, further case studies are conducted with the same HC framework parameters as mentioned earlier. Meanwhile, the CC price is assumed to be 80 \$/ton $CO_2$-eq. The case study involves an entity investing in a $H_2$ project with a total capacity of 1000 tons, among which 700 tons are supplied to user 1, and 300 tons are supplied to user 2. User 1 is a steel company using anthracite coal as its original fuel (HHV 29.18 MJ/kg, $CO_2$ factor 2.87 kg$CO_2$-eq/kg, price 0.12 \$/kg [14–16]). User 2 is a transportation company using motor gasoline (HHV 46.44 MJ/kg, $CO_2$ factor 3.09 kg$CO_2$-eq/kg, price 0.85 \$/kg [14–16]). Four scenarios (S1–S4) are considered, and the results are presented in Table II:

**S1:** Users purchase original fuels for their energy demand and purchase CC to cover their emissions.

**S2:** The entity invests in a $H_2$ project, supplies $H_2$ to users, and recovers costs with users' savings in the CC market.

**S3:** The entity invests in a $H_2$ project, supplies $H_2$ to users, obtains HC accreditation, and recovers costs in HC trading.

**S4:** The entity invests in a $H_2$ project and supplies $H_2$ to users. The benefits from HC trading are shared among $H_2$ users, producers, and distributors.

For energy users, the proposed HC framework offers them the benefits of cleaner and more affordable fuels while reducing their emission costs. In the baseline scenario, users have to purchase CCs to meet their emission targets, which can be costly when CC prices rise. In model 1, by paying their CM savings to the entity, users gain access to $H_2$ at a low price. Model 2 provides users with even lower prices with subsidies from $H_2$ taxes. In model 3, with shared HC ownership, users have greater flexibility in trading within the CC market, enabling long-term investment decisions. Since the $H_2$ price is lower when $H_2$ is used to replace fuels with higher emissions (user 1 in this case), the proposed HC

**Table 2**
Revenue analysis of stakeholders.

| Stakeholders | Revenue components ( × $10^3$ \$) | S1 | S2 | S3 | S4 |
|---|---|---|---|---|---|
| Entity | $H_2$ investment cost | 0 | −900 | −900 | −900 |
| | $H_2$ selling income | 0 | 261 | 178 | 990 |
| | Users' CM savings paid to the entity | 0 | 729 | 0 | 0 |
| | HC trading income | / | / | 812 | 0 |
| | **Total income** | **0** | **90** | **90** | **90** |
| User 1 | Fuel cost | −401 | −107 | −49 | −693 |
| | Emission cost | −780 | 0 | 0 | 0 |
| | Users' CM savings paid to the entity | 0 | −586 | 0 | 0 |
| | HC trading income | / | / | 0 | 526 |
| | **Total income** | **−1181** | **−693** | **−49** | **−167** |
| User 2 | Fuel cost | −774 | −154 | −129 | −297 |
| | Emission cost | −226 | 0 | 0 | 0 |
| | Users' CM savings paid to the entity | 0 | −143 | 0 | 0 |
| | HC trading income | / | / | 0 | 118 |
| | **Total income** | **−1000** | **−297** | **−129** | **−179** |
| Producer | HC trading income | / | / | 0 | 78 |
| Distributor | HC trading income | / | / | 0 | 90 |

Note: CM denotes the carbon market.

framework incentivizes high-emission enterprises to transition their energy usage. As for the $H_2$ investment entity, the proposed HC framework allows it to participate in the market, and its costs can be recovered in various ways in different business models. $H_2$ producers and distributors also benefit from the proposed HC framework, as the whole green $H_2$ industry is promoted, and more commercial opportunities are created. Notably, in business model 3, shared HC ownership allows them to participate in the CC market and obtain benefits.

## 4. Conclusions

The current high costs associated with green $H_2$ hinder its adoption as a clean energy source, calling for financial support and incentives for $H_2$ investors, manufacturers, users, etc. The $H_2$ credit framework, leveraging the emission reduction potential of $H_2$ and coupled with the carbon credit market, is designed to stimulate the global uptake of green $H_2$. In this paper, practical business models under the $H_2$ credit framework are proposed, and the prices of $H_2$ and HC are defined accordingly. Analysis of $H_2$ prices and stakeholders' revenue demonstrates that the $H_2$ industry can be subsidized effectively under these business models. The presented case study highlights the significance and promising potential of the proposed business models within the green HC framework. Besides, under the proposed business models, the realization of a robust and efficient $H_2$ industry development can be greatly expedited with the support of various government initiatives, including the supportive regulations and efficient procedures for accrediting HC, the introduction of carbon pricing systems, and fostering international collaborations.

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## 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.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.02.152.

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