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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 η^{ror}, the price of H_2 is derived below.

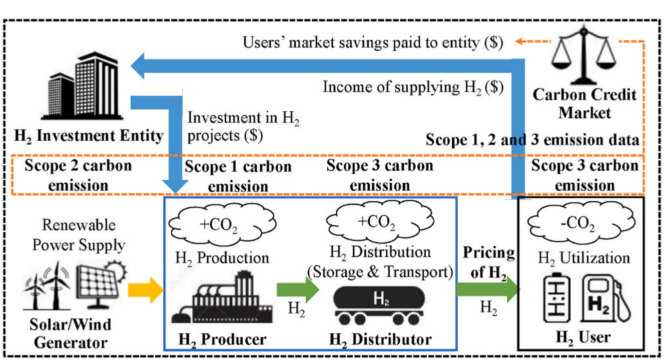

Fig. 1. Schematic of business model 1 - investment for emission reduction.

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

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

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 η^{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

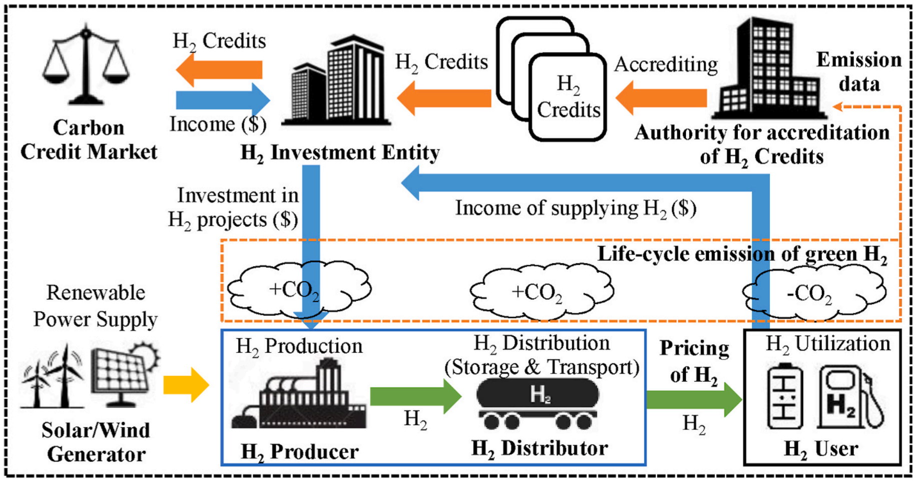

Fig. 2. Schematic of business model 2 - investment for HC.

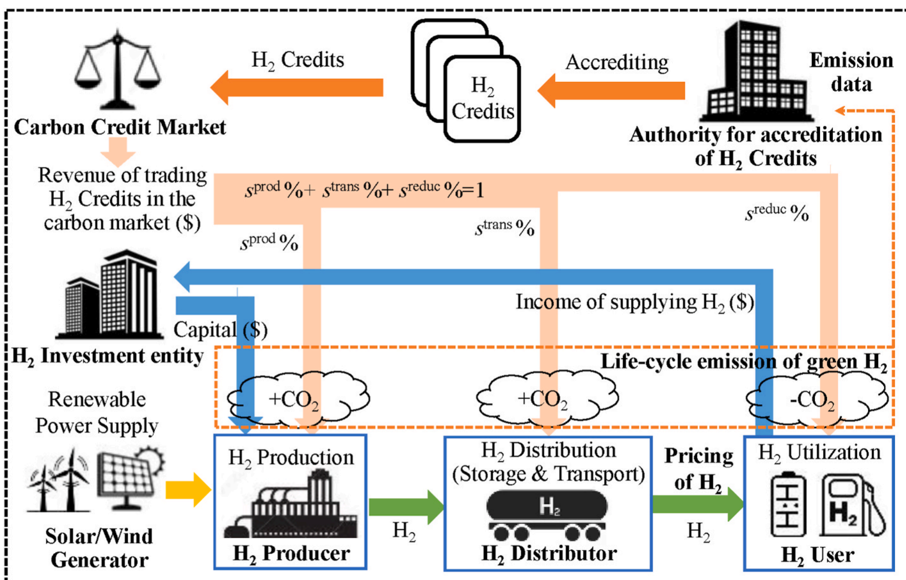

Fig. 3. Schematic of business model 3 - benefit sharing.

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 α ($\alpha > 1$) can be adjusted by the market operator to tune the HC shares among stakeholders. A larger α 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.

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

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

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: $\eta^{\mathrm{ror}} = 0.1$, $f(C^{\mathrm{prod}}) = 0.3 \bullet C^{\mathrm{prod}}$, $g(C^{\mathrm{trans}}) = 0.3 \bullet C^{\mathrm{trans}}$, $\alpha = 1.15$, $M^{\mathrm{cost,HH}} = 900$ \$/ton H_2 for hydrogen project using renewable energy [1], $C^{\mathrm{reduc}} = 13.93$ ton CO_2-eq/ton H_2 for replacing anthracite coal with H_2 [14], $C^{\mathrm{prod}} = 2.21$ ton CO_2-eq/ton H_2 for electrolysis with solar energy [10], and $C^{\mathrm{trans}} = 1.25$ 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

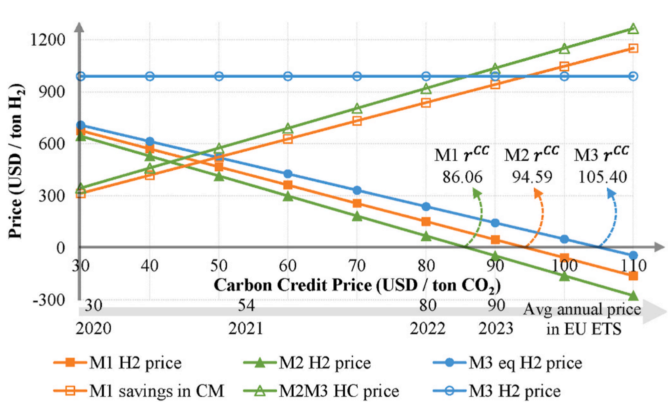

Fig. 4. Pricing analysis of H_2 and HC.

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 kgCO_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 kgCO_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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