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A Review of Emerging Revenue Models for Low-carbon Hydrogen Technologies

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Abstract

Adoption of Low-Carbon Hydrogen (LCH) technologies is considered promising to curtail carbon emissions in the industrial sectors and substitute high carbon-intensive fuels. However, LCH technologies are still evolving and face several technical & commercial barriers. On the commercial side, they face economic viability and financial risks and, therefore, fail to attract investments. Recently, some countries have developed policy support to incentivize LCH technologies, but their reward mechanisms and design vary widely and lack a standardized approach. The paper aims to contribute to the current knowledge by discussing the theoretical underpinning of LCH revenue models. It reviews emerging revenue models for LCH technologies in Germany, the Netherlands, and the UK. The review covers CCfD (Carbon Contract for Difference) in Germany, SDE++ (Stimulation of Sustainable Energy Production and Climate Transition) in the Netherlands, and HPBM (Hydrogen production Business Model) in the United Kingdom (UK). The review highlighted CCfD acts as simple hedging instrument against CO2 market price fluctuations without any visibility on hydrogen prices in the market. In contrast, SDE++ and HPBM are found to more comprehensive incentive schemes for LCH development.

Keywords: Low-carbon Hydrogen, economic viability, revenue, financial risks

1. Introduction

1.1 Background

Hydrogen has emerged as a promising option for energy transition and an effective means to decarbonize hard-to-abate sectors due to its physical and chemical properties. Hydrogen, as a high-intensity energy carrier, is expected to play a critical role in industries such as steel, chemicals, transport, and shipping, where direct electrification is challenging (IRENA, 2020). Given the net-zero 2050 target, the hydrogen demand is expected to increase by almost six holds, from 90 million tonnes (Mt) in 2020 to 530 million tonnes (Mt) in 2050 (IEA,2021). The hydrogen produced from water electrolysis powered by renewable electricity sources (wind or solar) is considered "green" with zero emissions. While the hydrogen produced from SMR (Steam Methane Reforming), where by-product CO2 is captured using Carbon Capture Utilization and Storage (CCUS), is considered "Blue'. Both green and blue hydrogen face technical and commercial barriers. Green hydrogen technologies are still evolving and have not yet matured, and the production cost is 2-3 times higher than blue hydrogen. The production cost for blue hydrogen is 1.5 to 2.5 US$ per kg, while green hydrogen production costs range from 2.0 to 7.0 US$ per kg depending on renewable electricity costs and electrolyzer load factors (IRENA, 2020). The blue hydrogen produced through the SMR+CCUS route also faces challenges. SMR is a mature technology with decades of experience and learning process, but CCUS has technical and commercial issues. First, the carbon capture rate of CCUS technology is typically 65-90%, which means a sizable portion of CO2 generated during the methane reforming process still escapes into the environment (Joy & Al-Zaili, 2021). A carbon capture rate of up to 90% can be achieved in the SMR process. However, a higher carbon capture rate increases blue hydrogen's LCOH (Levelized Cost of Hydrogen) (Collodi et al., 2017). Second, the commercialization of CCUS technologies requires project-specific financial support from governments (IEA, 2019).

Electrolyzer and CCSU technologies face various risks related to policy, technology, and market. On one side, the uncertain market demand and lack of guaranteed revenue streams impact the bankability of the new project. On the other side, high Capex (capital expenditure) and uncertainties in Opex (operating expenditure) due to evolving technologies raise concerns about economic viability. Therefore, LCH technologies fail to attract investments. One way to ensure a revenue stream for LCH projects is to provide a long-term off-takers agreement or implement support schemes like CfD (Contract for Difference); such policy instruments can improve bankability. Also, technology-specific support policies in short to intermediate terms can help improve economic viability through demonstration projects and innovation funding. Another way to improve the economic viability of LCH projects is to address market failures in the energy sector and make “polluters pay” for the carbon emissions by implementing carbon pricing or carbon tax. There is a common agreement that regulations like carbon trading or carbon tax with sufficiently high carbon floor prices will be able to reduce carbon emissions. However, experts caution that carbon pricing alone does not guarantee that LCH technologies can scale up and remain economically viable without additional policy support (Rosenbloom et al., 2020). Further, the free carbon allowance or special carbon quota in the heavy industrial sectors and volatile carbon prices with much lower floor levels in the cap-and-trade system do not encourage private investors to set up LCH projects.

At the beginning of the 21st century, many European countries implemented technology-specific support schemes for solar and wind electricity generation; such initiatives helped solar and wind technologies to scale up energy generation and reduce the cost compared to conventional energy systems. Learning from past success and recognizing technical and commercial barriers in green hydrogen and CCUS technologies, many EU countries selected LCH pathways as part of national hydrogen strategy leveraging private investment potential. In intermediate terms, instead of solely relying on a specific technology, the EU hydrogen strategy support both electrolyzers and CCUS technologies using LCH support schemes (Erbach & Jensen, 2021). The rationale behind selecting an LCH pathway by Governments with a technology-neutral approach is to promote both blue and green hydrogen options and leave market users to decide about technology adoption (IEA, 2019). Further, to set a policy direction on LCH and bring clarity to future investment, the EU initiated the development of the LCH standard and certification scheme (Erbach & Jensen, 2021). Similarly, The UK aims to develop LCH standards to promote technology neutrality, allowing multiple production routes to deliver LCH targets (BEIS, 2022).

In recent years, there have been debates on ways to incentivize low-carbon hydrogen production while limiting the subsidy burden on the treasury and taxpayers. In general, incentive schemes can be broadly categorized as a) fixed feed-in-tariff (FIT) model, b) premium-based model, and c) revenue stabilizing model. All schemes are performance-based and valid for a fixed term, aiming to help producers achieve break-even points and remain profitable throughout the contractual duration. These support schemes have different remuneration mechanisms. Under the fixed FIT scheme, the producer is remunerated with a guaranteed payment for a fixed duration independent of market price, therefore improving bankability and lowering investment risks for new projects. The Fixed FIT schemes are generally focused on technological push without any visibility on market conditions. At the same time, remuneration under the premium-based model and revenue stabilizing model are linked to market price. In a premium-based model, producers receive a subsidy on top of the market price from the sales. In contrast, the revenue stabilization model provides a guaranteed return to producers with a topped-up when the market price is below the agreed strike price, or the procedure pays back up when the market price is above the strike price (Thornhill & Deasley, 2020). According to Schallenberg-Rodriguez and Haas (2012), in a premium-based model, there is a risk of overcompensation to producers when market price rises, leading to undermining market conditions for renewable energy. In contrast, the revenue stabilizing model, such as the CfD (Contracts for difference) scheme, is perceived as effective in reducing overcompensation and mitigating investment risks (Joy & Al-Zaili, 2021). Also, the revenue stabilizing model can be applied to all technologies. In contrast, the premium-based model is challenging to implement due to the complexity of forecasting the correct premium amount to avoid overcompensation (Thornhill & Deasley, 2020).

A few countries, such as Germany, the Netherlands, and the UK, have proposed support schemes for LCH. However, their schemes have some commonalities and distinct differences in scope, revenue stream, and cost components. Germany proposed CCfD (Carbon Contract for Difference), and the Netherlands proposed SDE++ (Stimulation of Sustainable Energy Production and Climate Transition); both are based on the CfD concept and directly link remuneration with the cost of carbon emission avoided. Germany's CCfD aims to decarbonize the industrial sector, while SDE++ in the Netherlands focuses on both energy production and decarbonization of the industrial sector. Like Germany and the Netherlands, HPBM proposed by the UK also uses the CfD concept. However, remuneration in HPBM is based on the cost of energy production instead of the cost of carbon emission avoided, and the scheme primarily focuses on energy production. Still, many countries aspiring to scale up LCH have neither proposed any support scheme nor initiated consultation within the industry. There is a need to create a consensus among policymakers on how to implement these support schemes; also, there is no best way to implement them, as these support schemes depend on a country's geo-political factors. Recognizing the possible variability in the LCH support schemes, the paper reviews emerging revenue models for LCH technologies and accentuates their essential elements.

2. Aim and Method

This paper aims to review emerging revenue models for LCH technologies in Germany, the Netherlands, and the UK. The review covers CCfD (Carbon Contract for Difference) in Germany, SDE++ (Stimulation of Sustainable Energy Production and Climate Transition) in the Netherlands, and HPBM (Hydrogen Production Business Model) in the UK. The paper uses a compare-and-contrast approach to accentuate key similarities and differences between these revenue models. I conducted a literature review to conceptualize the revenue model applicable to LCH technologies. Using the conceptual framework as a lens, I reviewed individual support schemes and discerned key similarities and differences.

I started section 1 with a brief discussion on the LCH technology-related commercial barriers and investment risks. It also highlighted why LCH-specific policy support schemes are imperative to improve the economic viability and bankability of LCH projects. Section 2 discusses the aim, methodology, and data source used. Section 3 conceptualized the revenue model applicable to LCH technologies. In section 4, using the conceptual framework, I reviewed support schemes a) CCfD (Carbon Contract for Difference), b) SDE++ (Stimulation of Sustainable Energy Production and Climate Transition), and c) HPBM. In section 5, I compared and contrasted support schemes to accentuate key similarities and differences. Section 6 concludes the paper by highlighting key takeaways from the paper. LCH technology support schemes and policy papers by policymakers in respective countries are used as data sources.

3. Literature Review

The revenue model explains how the company gets monetized in return for the services it provides; the economic viability and profitability of a business are determined by its revenue model (Osterwalder, 2004). A business must maintain healthy revenue flows based on a robust revenue model to remain profitable and economically viable. The business model is sometimes interchangeably used with the revenue model, especially in commodity markets without much focus on customer value creation. However, scholars have differentiated the revenue model from the business model and suggested the revenue model as a subset of the business model concept. Osterwalder et al. (2004) presented the revenue model as one of the nine building blocks of the business model, which deals with the financial aspects of a business. According to Remenova et al. (2020), the revenue model is an element of a business model that specifies how revenue streams are managed while other elements of the business model are involved in creating values.

The revenue models depend on the business type and services it offers as cost structure and revenue streams vary with business type. In the energy sector, the revenue model consists of the cost structure of energy production and revenue collection from selling energy. The revenue model in the energy sector explains the relationship between the total cost incurred to produce energy units and the total revenue generated from selling the energy units to the customers (Richter, 2012). Due to mature technologies and well-established market demands within the energy sector, conventional energy systems have stable and clearly defined revenue models compared to low-carbon energy systems. On the contrary, the revenue model for LCH systems is evolving and yet to be established.

The revenue model for LCH faces two issues. First, the cost structure of low-carbon energy systems is uncertain and technology-dependent. The cost structure represented by LCOH is a metric that indicates average per unit cost of green hydrogen that is produced over the lifecycle of the plant, it accounts for all of the Capex and Opex of the asset involved in green hydrogen production. LCOH is expressed as total lifetime cost (Capital investment + Operating & Maintenance cost) incurred divided by green hydrogen produced from plant. The LCOH of an electrolyzer-based green hydrogen unit is complex; It is driven by several parameters, including the selection of renewable electricity sources and electrolysis technology (IRENA,2020). Similarly, the LCOH of CCS technologies depends on complex cost structures due to uncertainties around technological performance, Capex, and Opex (Durusut & Mattos, 2018). Second, the revenue stream projections from current market configurations are unfavorable for LCH technologies. A lack of LCH market demand does not guarantee sustained revenue visibility and makes LCH projects unprofitable (Durusut & Mattos, 2018; IEA,2022). In simple terms, as shown in Figure-1 profitability of LCH technologies, $P(x)$ can be expressed in terms of revenue collected $R(x)$ from the sales and related services and $LCOH(x)$ cost incurred in the production.

P(x)= R(x) - LCOH(x)	
Elements of R(x)	***Elements of LCOH(x)***
• Market Price • Demand Volume • Carbon Emission Avoidance Credit • Tradable LCH Certificates	• Capital Expenditure (Capax) • Operating Cost (Opex) • Unit performance (Capacity factor / Capture rate) • Technological Limitations

Figure 1. Factors influencing revenue model

R(x)= *f* (Market price, Demand volume, Carbon Emission Avoidance Credit, Tradable LCH Certificates)

C(x) = *f* (Cost of capital, Operating cost, Unit performance, Technological Limitations)

To have an economically viable and profitable LCH-producing unit, the total estimated revenue collection R(x) from various streams should be reasonably high and stable, while LCOH(x), the cost incurred in the production should be lower and predictable. However, LCH-producing units face different types of risks and uncertainties. On the cost side, high Capax, Opex, performance-related issues like capacity factor / or carbon capture rate, and technological limitation are the main causes of higher and unpredictable expenses. On the revenue side, the absence of an LCH market and clarity on value proposition, non-recognition of positive externalities related to carbon emission avoided, and lack of transportation and storage infrastructure are some issues that give rise to financial risks.

The cost of blue hydrogen produced via CCUS from the SMR process ranges between US$2 and US$6 per kg (Limpach et al., 2023). Moreover, blue hydrogen cost is correlated to natural gas, and its contribution to the blue hydrogen production cost is around 70-80 percent (ESMAP, 2020). Therefore, any variation in natural gas cost will have considerable variation in blue hydrogen production cost (Limpach et al., 2023). The LCOH of blue hydrogen also depends on plant size, process configuration, and selected CO2 extraction technology. As shown in the figure-2, the blue hydrogen production using the SMR process can typically have three different CO2 capturing configurations, from (1) shifted syngas, (2) PSA tail gas, or (3) SMR flue gas (Collodi et al., 2017).

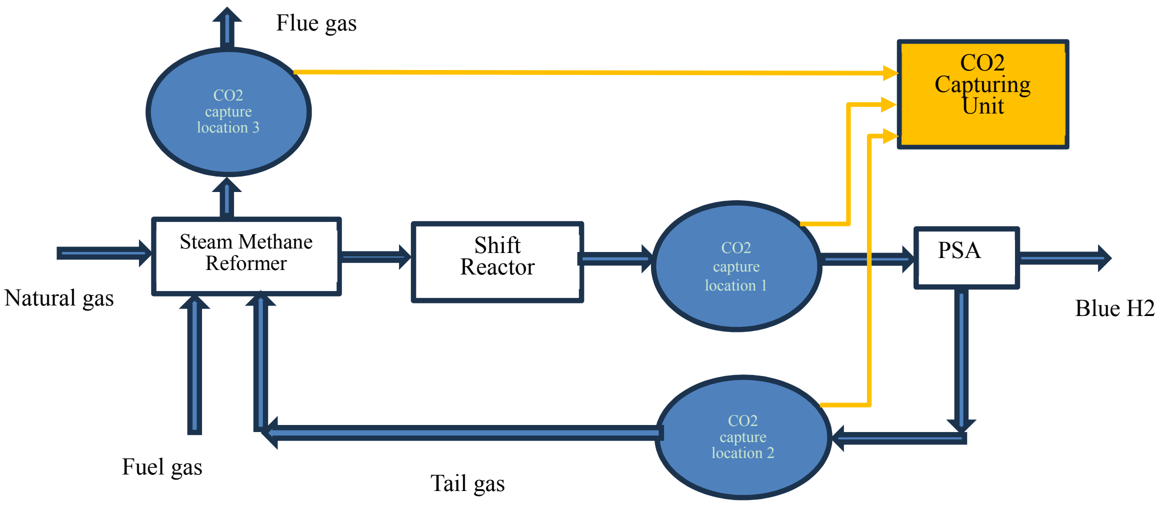

Figure 2. CO2 capture locations in SMR process

Recovering CO2 from any three locations is possible using CO2 capturing technologies. However, CO2 capturing technologies are still evolving and they are at different development and commercialization stages (Collodi, 2010). The energy footprint and associated GHG emissions could vary depending on the selected location and CO2 extraction technologies (van der Meer et al., 2020). The recovery rate also depends on the CO2 extraction technology used. In the SMR+CCUS process, CO2 is extracted from a gas stream using amine-based liquid solvents when a gas stream is passed through an absorbing column (scrubber). Generally, Monoethanolamine (MEA) or Methyldiethanolamine (MDEA) are the most commonly used amine solvents used in scrubbing applications, their CO2 absorbing capacity is dependent on the solvent concentration, the composition of the gas stream, and the operating temperature (Huertas et al.,2015). Around 55% of the capture rate can be achieved when CO2 is captured from the shifted syngas using MDEA solvent; CO2 can also be captured from the flue gas using MEA solvent, resulting in a higher % capture rate of 90% (Lyons, Durrant & Kochhar, 2021). Typically, CO2 capture rates range from 55% to 90% in the SMR+CCUS process; a higher capture rate of 90% could be the most desirable configuration. However, a higher capture rate will result in higher LCOH due to higher energy consumption and increased carbon emission footprint (Collodi et al.,2017). In the post-combustion configuration, MEA solvent can provide up to 90% CO2 capture rate, but it will impact both energy consumption and cost. In recent years, a hybrid system utilizing more than one capture technology (amine solvents and membrane-based separation) seems to be a new direction in CO2 capture process design (Wang et al., 2017).

Unlike the SMR+CCUS process, hydrogen production from electrolyzers has no carbon emission. However, if electricity-feeding electrolyzers are from non-renewable sources, they can indirectly contribute to carbon emissions. The green hydrogen produced from the electrolysis process is 2-3 times more expensive than blue hydrogen produced from the SMR+CCUS process; the most significant contributor to the green hydrogen production cost is the cost of renewable electricity (IRENA, 2020). Renewable electricity is the major cost driver, accounting for around 70-80% of green hydrogen production costs (ESMAP, 2020). Renewable costs widely vary between available technologies (offshore wind, onshore wind, solar) depending on the meteorological condition of the project site. The load factor of renewable electricity also influences the green hydrogen LCOH. The lower load factor of renewable electricity results in higher LCOH as the electrolyzer capacity factor is reduced. The LCOH decreases with increasing load factor; the grid-connected renewable electricity can produce a 100% capacity factor for electrolyzer compared to on-site intermittent renewable electricity (Christensen, 2020). However, grid-connected electricity can only be claimed to be green by implementing green origin tracking and certification schemes.

In addition to electricity cost, other parameters such as electrolyzer cost and its performance largely influence the green hydrogen LCOH. As electrolyzer technologies are still evolving, incurring higher capex on electrolyzer units without certainty of green hydrogen demand in the market poses an investment risk to developers (IRENA, 2020). ALK and PEM are commercially available electrolysis technologies, but their performance parameters vary widely. A comparison between ALK and PEM is shown in Table 1. Another technical issue is the non-availability of larger electrolyzer module sizes. Commercially available module sizes are in the 1 to 10 MW range; electrolyzer module size must be scaled up to 100s of MW. However, manufacturers need more R & D support, engineering knowledge, and long-term business visibility to increase module size. The economies of scale with increased module size will help reduce CAPEX costs by around a third (Cammeraat et al.,2022).

Table 1. Comparison between ALK & PEM Electrolyzer **(**IRENA, 2020)

Key parameters	*ALK*	*PEM*
Unit footprint	Large	Relatively smaller
Electrolyzer Lifetime [thousand hours]	80	50-80
H2 producing cell pressure [bar]	Atm. to <30 bars	> 30 bars
Flexibility in operation	Not flexible to demand changes	Flexible to demand changes
Stand-by mode	Not possible	Possible
Startup time	1-10 minutes	1-5 seconds
Ramp up / ramp down	0.2 to 20% per seconds	100% per seconds
Shutdown	1-10 minutes	1-5 seconds
Maintenance	Regular	low
Electricity Efficiency [kWh consumption /Kg of H2]	51	58
Efficiency (system) [kWh consumption /Kg of H2]	50-78	50-83
Capital costs estimate for stack-only, > 1 MW [US$/kW]	270	400
Capital cost range estimate for the entire system, >10MW [US$/kW]	500-1000	700-1400

The absence of a value proposition and market demand for LCH are fundamental barriers impacting revenue streams. Lack of clarity on the value proposition in LCH technology adoption is a challenge from an investor's perspective (Muslemani et al., 2023). The value proposition explains how LCH as a product could fulfill market needs with added benefits to support industrial decarbonization. Clarity on the value proposition in the LCH business is crucial for economic viability. Durusut and Mattos (2018) highlighted that insufficient value proposition in LCH business is the biggest challenge in identifying revenue streams. Issues like lower carbon pricing, the absence of a reward scheme for CO2 emission avoidance, and the lack of earnings through LCH tradable certification schemes do not provide impetus for private investments in LCH business. Due to insufficient financial benefits in LCH adoption, polluters would rather pay carbon taxes or find buying additional carbon allowances more cost-effective. Market demand risk is another issue that could lead to financial losses due to the gap between forecast and actual demand for LCH products. Instead of creating the LCH market and transferring demand risks away from LCH producers, several countries provide end-user subsidies on carbon emission abatement measures that limit emissions in the short run; however, this could be ineffective in achieving decarbonization objectives in the long run. According to Thornhill and Deasley (2020), when the end-user subsidy is provided for abatement instead of increasing the LCH consumption, the market demand for LCH remains uncertain, and the demand risk for LCH would remain with the producer, making it difficult for producers to manage. There is a need for a paradigm shift in LCH policymaking from the current focus on carbon emission abetment to adopting LCH and creating future market demand (Durusut & Mattos, 2018).

The market failure in the energy sector is another barrier that makes LCH costlier compared to fossil fuels; thus, consumption of LCH fails to pick up. The factors contributing to market failures are 1) environmental externalities and 2) information asymmetry. The negative environmental externalities arise when the market price of fossil fuels does not reflect the social cost of climate impact for carbon-intensive activities. Rosenbloom et al. (2020) cautioned that carbon pricing to make polluters pay for the social cost of climate impact alone could not solve market failure in the energy sector; instead, policymakers must reform key system elements to address market failures. Also, information asymmetry on products could lead to market failures when economic transactions are made without considering the accurate information about that product. LCH product labeling, tracking, and origin certification schemes can differentiate LCH products from other high carbon-intensive fuels and reduce information asymmetry to consumers (Cheng & Lee, 2022).

Overall, on the revenue side, LCH technologies face barriers related to the value proposition and hydrogen demand uptake. On the cost side, LCH technologies still have higher production costs and performance-related issues such as capacity factor / or carbon capture rate. The higher LCH production cost and performance limitations discourage LCH market development. However, without a significant increase in LCH demand from the current level, the financial risks in LCH investment remain high, and LCH technologies fail to benefit from an "economy of scale'. This situation creates a chicken-and-egg dilemma for policymakers. In order to scale up the LCH development, policymakers need to make more sector-specific and tailored policy incentives for LCH technologies.

4. Emerging Revenue Models

4.1 CCfD Scheme

The concept of carbon contracts was proposed by Helm and Hepburn (2007) to help policymakers enhance carbon policy credibility and also provide carbon price certainty to private investors interested in decarbonization projects. Utilizing CCfD schemes on pilot basis, the German federal government supported the climate-neutrality target of 2045 under the Climate Protection Act 2021; the act mandates CO2 emissions must be reduced by 65 % by 2030 and by 88 % by 2040 compared to 1990 (Lösch et al., 2022). Under Climate Protection Act 2021, Germany selected *Carbon Contract for Difference (*CCfD) as primary policy instrument to scale up LCH development to replace fossil fuels and produce low carbon steel. According to Gerres and Linares (2020), CCfD can address two problems. First, CCfDs act as a hedging instrument for future carbon prices and stabilize revenue streams for low emission projects, therefore reducing financing costs. Second, act as a support instrument by addressing concerns related the valley of death for emerging technologies.

$$P_{CCfD} = (C_{Strike} - C_{Effective})*E_{Realized} \qquad (1)$$

$C_{Effective} = f(C_{Market}, E_{Reference}, E_{Project})$; it is effective CO2 price in a project

C_{Market} = Carbon price in market

$E_{Project}$ = Emission from project

$E_{Reference}$ = Emission from a reference installation

$E_{Realized}$ = Emission reduction realized from project

C_{Strike} = Strike carbon price in CCfD contract agreed between the private investors and government

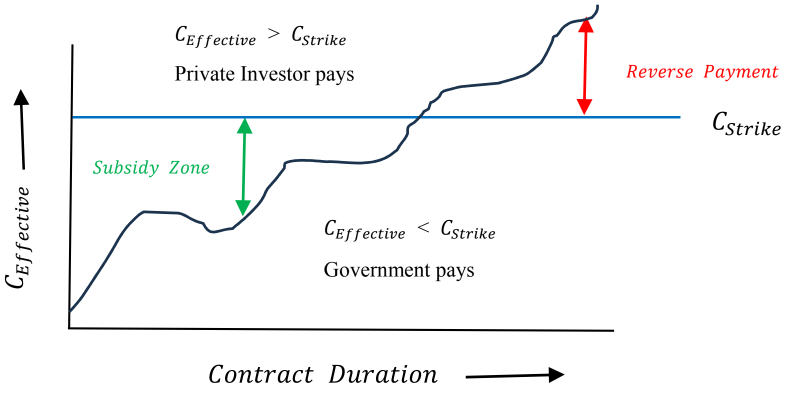

Figure 3. CCfD revenue model

4.2 SDE++ Scheme

The SDE++ in the Netherlands stands for The Stimulation of Sustainable Energy Production and Climate Transition (SDE++) scheme focusing on the roll-out of renewable energy production and other technologies that reduce carbon dioxide (CO2) emissions. In 2020 the SDE+ which focused only on renewable energy technologies was upgraded to the SDE++ to include carbon emission reduction technologies. The main difference between the SDE++ and the previous edition (SDE+) is that the former covers carbon emission-reducing technologies, such as CCS (Fuentes, 2022). The SDE++ is an operating subsidy, valid for the operational period (12 to 15 years) which compensates the difference between the cost price of the sustainable energy (or the reduction in CO2 emissions) and the revenue generated (Netherlands Enterprise Agency, 2023). The SDE++ is a technology neutral scheme where the amount subsidized depends on the technology selected and the verifiable level of CO2 reduction achieved (Fuentes, 2022). The SDE++ scheme is based on revenue stabilizing mechanism that aims to provide a reliable and robust support carbon price for decarbonization projects (Hydrogen Council, 2022). Under the LCH production option both electrolyzer and CCU technologies are eligible to receive subsidy when technology specific criteria are fulfilled (Netherlands Enterprise Agency, 2023).

Subsidy under the SDE++ scheme depends "subsidy intensity" which implies the subsidy amount requested per tonne of CO2 reduction using a specific technology. Subsidy intensity is driven by the following elements a) application amount, b) the long-term price, and c) the emissions factor.

$$\text{Subsidy Intensity [€/tonne CO2]} = (\text{Application amount [€/kWh]} - \text{Long-term price [€/kWh]}) / (\text{Emissions factor [kg CO2/kWh]} / 1{,}000) \quad (2)$$

Where,

a) Application amount is the amount requested for the project using specific technology (Fuentes, 2022).

b) Long-term price is unweighted average of the actual hydrogen price over the subsidy period based on estimated price movements (Netherlands Enterprise Agency, 2023).

c) *Emissions factor is emissions avoided by implementing the specific technology* (Netherlands Enterprise Agency, 2023).

Technologies with lower subsidy intensity have better chances of receiving a subsidy, as projects with lower subsidy intensities will receive priority when evaluated (Fuentes, 2022). SDE++ scheme is planned to be implemented in phased manner and subsidy eligibility will gradually be increased during subsequent phases. SDE++ scheme has five phases and during each phase, the technologies can get subsidy only up to a predetermined subsidy intensity per tonne of CO2 emissions reduction (Netherlands Enterprise Agency, 2023). In 2022, the maximum subsidy intensity for which your SDE++ technology may be eligible is €300 per tonne of CO2 reduction; technologies with a subsidy intensity higher than €300 per tonne of CO2 is not eligible and considered not cost effective for this subsidy phase (Netherlands Enterprise Agency, 2023). The subsidy intensity for green hydrogen producing electrolyzer units and blue hydrogen producing CCS units was estimated to be €300 per KWh and €214 KWh respectively, thus making LCH technologies eligible for SDE++ application in year 2022 (Netherlands Enterprise Agency, 2023).

SDE++ scheme covers the unprofitable component of each technology which is the difference between the cost of technology that reduces CO2 emissions (base amount) and the market values of energy produced (correction amount). As shown in the below figure-4, base amount is the estimated cost price for the production of renewable energy, it is different for each technology. The application amount is the amount required for the project to remain economically viable. Both base and application are fixed for the entire duration of the subsidy. The correction amount is partly determined by the energy market price and is revised and updated annually (Fuentes, 2022). The SDE++ subsidy is equal to the application amount minus the correction amount when correction amount is equal or greater than base amount. In case the correction amount is higher than the application amount driven by higher energy price in the market, the project will not receive any SDE++ subsidy. The correction amount is set annually and has a lower limit usually set at base amount level therefore avoiding any revenue gap at any point in a year.

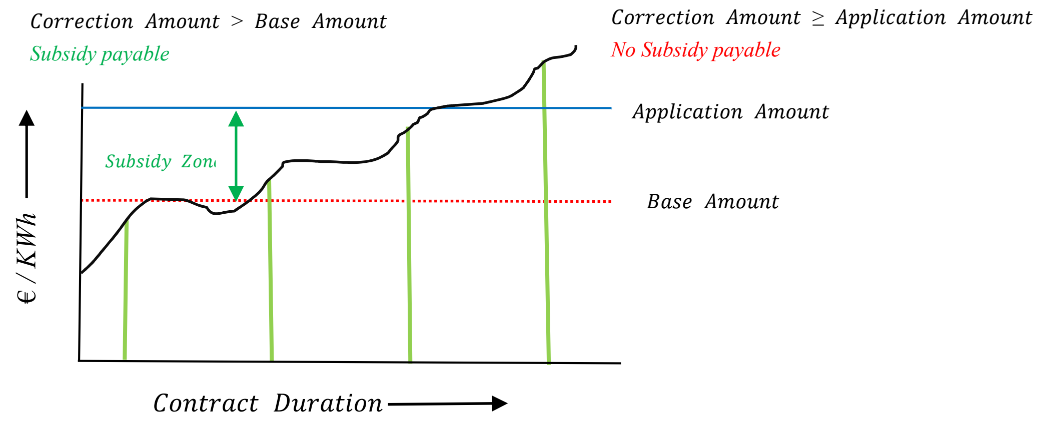

Figure 4. SDE++ revenue model

4.3 HPBM Scheme

UK's hydrogen strategy outlines 10 GW of LCH producing capacity by 2030 with at least half of this will be produced from electrolyzing units (DESNZ, 2023). Aiming at both energy transition and net-zero, the UK supports electrolyzer technologies for green hydrogen and carbon capture technologies retrofitted with SMR units to produce blue hydrogen (DESNZ, 2023). The Hydrogen Production Business Model (HPBM) revenue support scheme is designed in such a way that LCH producers are paid an amount equal to the difference between: (i) the price the producer needs to cover its cost and remain profitable (the strike price); and (ii) the actual achieved sales price (the reference price). As shown in the below figure-5, the cashflow in the HPBM is based on the traditional CfD mechanism where the payment is difference between a strike price [SP] and reference price [RP], when the RP is below SP, the producer is entitled to receive a payment and if RP is above SP, the producer pays back the difference (Heyworth & Chesser, 2023). Essentially HPBM is a revenue stabilization mechanism tailored for renewable energy projects that are highly capital intensive and required to operate in a market which could have price volatility.

HPBM aims to make payouts to producers cost-effective and avoid any over subsidization by incorporating three elements which are related to market price and volume. First, reference prices are adjusted on a regular basis and capped at the natural gas price floor to reduce the subsidy amount. The reference price is intended to represent the market price for each unit of hydrogen sold, however, it becomes challenging due to lack of observable hydrogen market price (Heyworth & Chesser,2023). Second, the HPBM scheme also incentivizes producers to sell at a higher achieved sales price through PDI (Price Discovery Incentive) and this component would help prevent over subsidizing during contract period. Third, HPBM mitigates volume risk through a "sliding scale" mechanism, however, keeps the onus on producers to seek out qualified offtakers as defined in HPBM. Under the mechanism, if volumes of hydrogen sold fall below specified levels, the producer is eligible to receive a top up payment on the hydrogen sold. However, if the producer does not sell any hydrogen no support will be received (Heyworth & Chesser,2023).

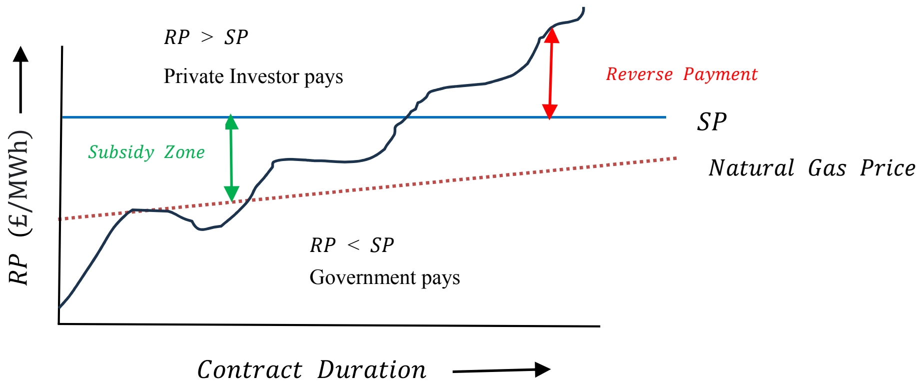

Figure 5. HPBM revenue model

5. Discussion

This section presents key similarities and differences in revenue models for LCH Technologies. I used seven criterion 1) Purpose 2) Objective, 3) Economic model, 4) Contract basis, 5) Reward mechanism, 6) Market price visibility & 7) Perceived effectiveness to analyze each revenue model. A comparison highlighting key similarities and differences between CCfD, SDE++ and HPBM is shown in Table-3.

All three schemes have different purposes. The CCfD aims to decarbonize the heavy industrial sector by replacing high-carbon intensity fuels with low-carbon alternatives such as LCH. The purpose of SDE++ is to support energy transition and achieve decarbonization through large-scale roll-out of renewable energy systems, a technology-neutral approach supporting electrolyzers and CCUS technologies. In comparison, the primary purpose of HPBM is to achieve energy transition by supporting electrolyzers, while the indirect goal is to achieve decarbonization in the long term.

The objectives of SDE++ and HPBM were found to be similar, aiming to make hydrogen production economically viable; in contrast, CCfD's objective is to cover the cost of carbon reduction measures in a project. SDE++ and HPBM are more comprehensive models that aim to cover key aspects of cost and revenue elements; in comparison, CCfD covers the difference between the strike carbon price and market carbon price for project developers.

The economic model of HPBM enables the payment for the cost of hydrogen (£/MWh) produced from electrolyzer units only meeting pre-qualified volume and specified LCH standard requirements. On the other hand, in the SDE++ the economic model the payment for the cost of hydrogen (€ /KWh) depends on the technology selected (electrolyzer / CCUS) and the verifiable level of carbon reduction realized, the main difference between HPBM and SDE++ payment is that no verification in carbon reduction level under HPBM, but the producer must deliver pre-qualified volume, making HPBM a support scheme for energy transition. On the contrary, payment under CCfD is based on a verifiable volume of carbon reduction realized aligned with the purpose of decarbonization similar to SDE++.

There is a clear distinction between CCfD, SDE++, and HPBM in terms of contract basis. The CCfD is a technology-neutral scheme designed to support decarbonization projects for an agreed contractual terms and duration. In contrast, SDE++ and HPBM schemes are tailored for specific technologies. SDE++ is designed for both electrolyzer and CCUS for agreed contractual duration according to subsidy intensity requirements for each technology. While HPBM funding only supports LCH projects based on electrolyzers for agreed contractual delivery terms, which includes producing pre-qualified volume and meeting hydrogen quality according to LCH standards.

A striking similarity is observed in reward mechanism for CCfD, SDE++, and HPBM. All three schemes are found to be based on a revenue-stabilizing mechanism. In all three schemes, the producers get a top-up payment for the difference between the strike and market prices. Understandably, these schemes are designed to incentivize low-carbon hydrogen production technologies, minimize the subsidy burden on the treasury and taxpayers, and avoid overcompensation to producers.

The CCfD scheme has no provision to reflect the hydrogen price in the market; instead, the payout is based on the carbon market price. In contrast, SDE++ and HPBM aim to reflect the current market price in the scheme using correction factors that are reviewed annually. Due to the lack of an established hydrogen market, policymakers face challenges in representing an accurate market price of LCH; therefore, they use different correction factors and reference prices.

Among the three schemes, SDE++ distinctly covers parameters related to CCUS technology and is the only scheme focusing on LCH production through electrolyzers and the SMR+CCUS process. Germany's CCfD scheme was initially designed to support green hydrogen via electrolyzers; however, in 2023, Germany extended the CCfD scheme to cover industrial blue hydrogen production via the SMR+CCUS process. In the UK, HPBM only covers green hydrogen via electrolyzers, while in 2023, the UK proposed a separate scheme, the "Industrial Carbon Capture business model," to support blue hydrogen via the SMR+CCUS process.

From a perceived effectiveness perspective, which denotes how scheme is likely to help LCH technologies overcome commercial barriers and improve economic viability, it is observed that CCfD is a much more basic scheme. The CCfD scheme acts as a hedging instrument against future carbon prices. It aims to cover the difference between strike cost and the effective cost of carbon reduction as a means to provide a revenue stream to cover the cost of hydrogen production, and the scheme has no visibility on hydrogen market price. In contrast, SDE++ and HPBM apply a more comprehensive and realistic approach to cover production costs and market price. Additionally, HPBM scheme mitigates volume risks for producer in case volumes sold fall below specified levels, also the producer is eligible to receive a top up payment on the hydrogen sold at a higher price.

Overall, it is observed that the CCfD scheme is a basic tool for decarbonization, acting as a hedging instrument against carbon price fluctuation in the emission trading system. However, due to two issues, some scholars are skeptical about CCfD's effectiveness in supporting energy transition. First, CCfD based on subsidy schemes could lead to carbon market distortions in the short term, as CCfD requires a higher carbon price to be effective in the decarbonization process. Second, the CCfD scheme is a simple hedging instrument to mitigate carbon price risk, and it does not represent the LCH economic model. In contrast, SDE++ and HPBM are more complex and primarily focused on supporting LCH technologies. They are found to be comprehensive and more realistic in incorporating elements of cost structure and hydrogen market price proxies to delineate an economic model.

Table 3. Comparison between revenue models

Criteria	*CCfD Scheme* Germany	*SDE++ Scheme* *Netherlands*	*HPBM Scheme* *UK*
Purpose	Decarbonization of Industrial Sector	Decarbonization & Energy Transition	Primary focus on Energy Transition
Objective	Cover the cost of carbon reduction measures; in 2023, Germany extended CCfD scheme to cover blue hydrogen production via CCUS	Make hydrogen production economically viable	Make hydrogen production economically viable
Economic Model	Payout based on effective volume of carbon reduction realized	Payout based on cost of hydrogen production (€ /KWh), where the payout amount depends on technology selected (electrolyzer / CCUS) and the verifiable level of carbon reduction realized.	Payout based on cost of hydrogen production (£/MWh), only payable to electrolyzer units producing qualified volume and adhering to LCH standard requirements.
Contract Basis (Project or specific technology)	Technology Neutral (both electrolyzer / CCUS covered) with agreed contractual duration	Technology Neutral, tailored for specific technologies (both electrolyzer / CCUS covered) with agreed contractual duration	Technology Specific, only electrolyzers covered with agreed contractual duration. In 2023, UK proposed a separate scheme "Industrial Carbon Capture business model" to support blue Hydrogen via CCUS
Reward Mechanism	Subsidy based Revenue stabilization mechanism, currently no proposal for regular adjustments to avoid overcompensation	Subsidy based Revenue stabilization mechanism with regular adjustments in key elements to avoid overcompensation	Subsidy based Revenue stabilization mechanism with proposal of regular adjustments in key elements to avoid overcompensation
Market Price Visibility	No visibility on Hydrogen market, only focused on carbon price in market.	The correction price is partly determined by the energy market price and is revised and updated annually	The reference price is intended to represent the market price for each unit of hydrogen sold.

Perceived Effectiveness	Acts as a hedging instrument against future carbon prices and ensures a revenue stream for projects to cover the cost of hydrogen production. Although CCfD is linked with market carbon price but does not have any visibility on hydrogen market price. A much simpler scheme.	Compensates for the difference between the application amount (Producer's unit cost of hydrogen production) and the correction amount (revenue generated from sale of hydrogen). The parameters are adjusted annually based on the market price. A more realistic approach to cover production costs and market price. Producers must meet a complex set of criteria to qualify for the scheme.	Compensates for the difference between a Strike Price (Producer's unit cost of production) and a Reference Price (the selling price of hydrogen, with a floor at the natural gas price). The scheme also has a reward mechanism to incentivize Producers to achieve higher sales prices that will reduce the size of the support payouts. The scheme mitigates volume risks for producers in case volumes sold fall below pre-agreed levels. Also, producer is eligible to receive a top up payment on the hydrogen sold at higher price.

6. Conclusions

The LCH scaling up faces two commercial barriers. First, the cost structure of LCH production is uncertain and technology-dependent. Second, the revenue stream projections from current market configurations are unfavorable for LCH technologies; also, the absence of LCH market demand does not guarantee sustained revenue visibility and makes LCH projects unprofitable. Although some countries have developed policy support to incentivize LCH technologies, their reward mechanisms and design vary widely and lack a standardized approach. This paper compares and contrasts CCfD, SDE++, and HPBM emerging revenue models for LCH technologies.

The paper highlighted some key similarities and differences in these revenue models. The paper observed that all three revenue models are based on revenue stabilizing mechanisms. It is also observed that all three revenue models are performance-based and valid for a fixed term, aiming to help producers achieve break-even points and remain profitable in the contractual duration. The selection of a performance-based revenue stabilizing reward mechanism is understandable as, in recent years, policymakers have focused on limiting the subsidy burden on the treasury and taxpayers while developing incentive schemes for the energy transition. The paper highlights a clear distinction between the three schemes. The CCfD is basically a hedging instrument against CO2 market price fluctuations without any visibility on hydrogen prices in the market. In contrast, SDE++ and HPBM are more comprehensive incentive schemes for LCH development. Additionally, HPBM focuses on demand-side elements to reduce volume risks and incentivize producers to sell qualified volumes at higher prices.

Having provided a theoretical underpinning for scholarly discourse on LCH revenue models, the paper recommends a qualitative study involving policymakers and LCH producers who are part of design and implementation of these schemes. The implication of observations from this paper includes new knowledge for policymakers in countries where the LCH development is at a novice stage.

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