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Feasibility study of renewable e-methanol production: A substitution pathway from blue to green

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ABSTRACT

Producing renewable e-methanol from e-hydrogen and diverse carbon sources is an essential way for clean methanol preparation. Despite this, the technical and economic feasibility of different e-methanols has yet to be thoroughly compared, leaving the most promising pathway to achieve commercialization yet evident. This paper reports a preliminary analysis of the lifecycle greenhouse gas (GHG) emissions and costs of four renewable e-methanols with different carbon sources: bio-carbon, direct air capture (DAC), fossil fuel carbon capture (FFCC), and fossil. The results indicate that renewable e-methanol costs (4167−10250 CNY/tonne) 2−4 times the market rate of grey methanol. However, with the carbon tax and the projected decline in e-H_2 costs, blue e-methanol may initially replace diesel in inland navigation, followed by a shift from heavy fuel oil (HFO) to green e-methanol in ocean shipping. Furthermore, the e-H_2 cost and the availability of green carbon are vital factors affecting cost-effectiveness. A reduction in e-H_2 cost from 2.1 CNY/Nm³ to 1.1 CNY/Nm³ resulting from a transition from an annual to a daily scheduling period, could lower e-methanol costs by 1200 to 2100 CNY. This paper also provides an in-depth discussion on the challenges and opportunities associated with the various green carbon sources.

KEYWORDS

Renewable energy, e-methanol, e-hydrogen, green carbon source, chemical process flexibility.

Methanol is a potential clean energy carrier, green fuel, and essential chemical feedstock in the global context of decarbonization[1]. For example, methanol is considered the most promising alternative fuel for shipping in the short term[2,3]. Approximately 70% of the world's 98 million tons of methanol produced annually is used to make chemicals, and the other 30% is utilized for fuel purposes[4]. A vast potential for methanol demand and production growth is expected. Methanol is currently produced almost exclusively from fossil feedstock, like coal and natural gas, the former with extremely high greenhouse gas (GHG) emissions. It accounts for about 10% of overall GHG emissions from the chemical industry[5,6]. For the goal of decarbonization, renewable methanol with low and net-zero carbon emissions has received wide attention. In contrast, only a few industrial and experimental facilities worldwide generate less than 0.2 million tons of renewable methanol annually[7].

Renewable e-methanol based on renewable energy and e-hydrogen has become one of the most influential preparation approaches with the rapid growth and popularization of renewable energy[8]. It's reported that there are more than ninety renewable methanol projects in China[9]. Besides pilot programs, extensive research efforts have been dedicated to exploring renewable e-methanol development. Aramco and Methanol Institute assessed the potential of e-fuels, including e-methanol, in China's road transport[10]. Fasihi and Breyer[11] assessed the global production potential of e-methanol from variable renewable electricity. Kauw et al.[12] analyzed the potential of renewable e-methanol from hydrogen and carbon dioxide using excess renewable electricity in Germany. Gu et al.[13] eported a case study on Techno-economic analysis of e-methanol plants with renewable hydrogen production.

Despite the abundance of renewable e-methanol preparation pathways with diverse carbon sources, there is yet to be a consensus among industry and academia on the most promising way towards scale-up. To this end, the technical and economic feasibility of various renewable e-methanols needs to be thoroughly compared and revealed. This paper reports preliminary feasibility analysis results of four types of renewable e-methanol and shares views on the development pathways of renewable e-methanol. Two primary obstacles, including the e-hydrogen cost and the availability of green carbon, are discussed in depth.

1 Classification of renewable methanol

Hydrogen and carbon sources are the primary feedstock of methanol. IRENA's proposition indicates that the emission intensity of methanol is contingent upon the types of hydrogen and carbon sources utilized[14]. Figure 1 illustrates the taxonomy of methanol varieties, which are differentiated based on their hydrogen and carbon sources. These sources are classified into renewable, termed 'green,' and non-renewable, labelled as 'grey'. Methanols are designated as 'green' or 'grey' depending on whether their sources are totally renewable. 'Blue methanol' occupies a middle ground between these two classifications. Additionally, Figure 1 uses crossed grids to denote typically considered infeasible schemes.

Hydrogen is primarily derived from biomass, renewable energy, and fossil feedstock, referred to as bio-H_2, e-H_2, and fossil-H_2, respectively. As depicted in Figure 1, renewable e-methanol is defined as green and blue methanol with e-H_2 as its hydrogen

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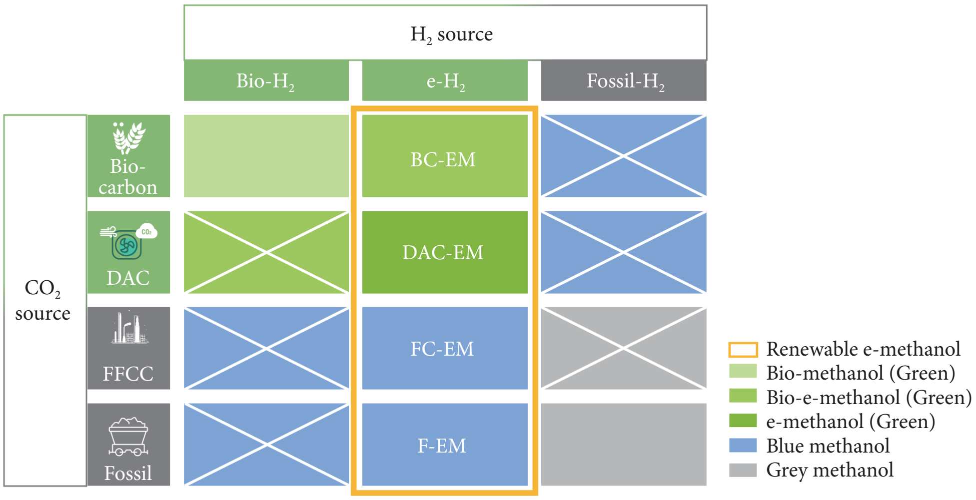

Figure 1 **The proposed classification of methanol from diverse hydrogen and carbon sources.**

source is from renewable power. Furthermore, renewable e-methanols that incorporate carbon from bio-carbon, direct air capture (DAC), fossil fuel carbon capture (FFCC, e.g., carbon capture form coal power plants), and fossil sources (e.g., direct coal-to-methanol) are abbreviated as BC-EM, DAC-EM, FC-EM, and F-EM, respectively.

2 Life-cycle GHG emissions and production cost assessment

2.1 Assessment framework

Figure 2 presents a life-cycle assessment (LCA) framework of GHG emissions associated with renewable e-methanol production. This assessment includes indirect emissions from sourcing carbon and hydrogen, which are attributed to the production phase at the 'well' level. The calculation of GHG emissions is based on the global warming potential matrix defined in the IPCC fifth assessment report, in g CO_2 equivalent per heat value (g CO_2e/MJ), which can be referred to Ref. [10]. The analysis delves into the production costs of the four types of renewable e-methanol previously discussed. The cost components, including expenses for e-H_2, carbon sourcing, synthesis processes, and transportation, are detailed. Building upon a model from our earlier research[15,16], we've adapted it to assess the levelized cost of methanol (LCOM). The relevant details can be referred to Appendix.

2.2 Assessment results

2.2.1 Life-cycle GHG emission

Figure 3(a) illustrates the life-cycle assessment of the four types of renewable e-methanol. Green e-methanols significantly reduce GHG emissions, 90% and 70% lower than coal-based methanol and conventional fossil fuels like diesel and heavy fuel oil (HFO). Blue e-methanols, while still more eco-friendly than coal-based methanol, remain near the emissions from diesel and HFO. The GHG emissions from BC-EM and DAC-EM carbon sources are negative. This phenomenon occurs because the green carbon sources effectively introduce a negative carbon footprint, which counterbalances the GHG emissions from end-use. Nevertheless, the GHG emissions associated with the carbon sources of FC-EM and F-EM are non-negative, as the grey carbon source is inherently from fossil fuels and does not contribute to carbon reduction. The

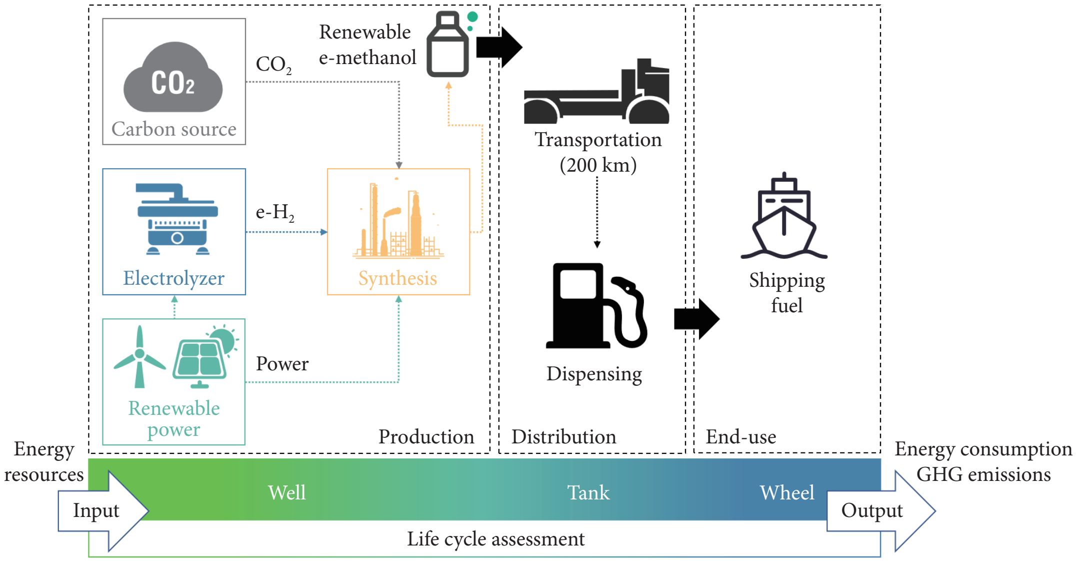

Figure 2 **System boundary of life-cycle assessment and framework for production cost analysis.**

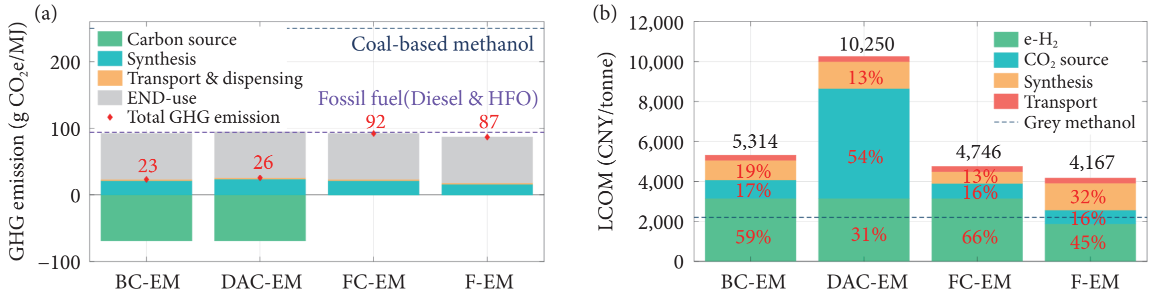

Figure 3 Assessment results of the four types of renewable e-methanol. (a) Life-cycle GHG emissions, **(b)** LCOM.

variance in emissions between FC-EM and F-EM is predominantly attributed to differences in energy consumption during the synthesis processes[17,18].

2.2.2 Production cost

The metric of the levelized cost of methanol (LCOM) is used to assess production costs. As depicted in Figure 3(b), renewable e-methanol costs 2–4 times the market rate of conventional coal-based methanol. Specifically, the LCOMs of BC-EM, DAC-EM, FC-EM, and F-EM are 5314, 10250, 4746, and 4167 CNY/tonne, respectively. Notably, the cost of e-H$_2$ constitutes a significant slice of the total production expense, ranging from 31% to 66%. Additionally, the cost associated with methanol synthesis deserves attention, primarily subject to the high energy input required for this process. It's also important to highlight that the carbon source cost is disproportionately high for DAC-EM, reaching up to 54% of the overall cost. It is attributed to the current technical challenges and DAC's substantial investment and energy demands.

3 Economic competitiveness in shipping fuel application

3.1 Comparison of cost per heat value

Methanol stands out as one of the most promising shipping fuels, with leading maritime companies actively seeking green methanol globally. A prime example is A. P. Moller–Maersk, which is leading this application and used green methanol for the inaugural journey of the world's first container vessel designed to operate on methanol[19]. Conventional fossil shipping fuels —diesel for inland navigation and heavy fuel oil (HFO) for ocean shipping —are counterparts to renewable e-methanol fuels. To assess and compare the economic viability of these fuels with varying characteristics, we've calculated the cost per unit of heat value (CpHV). Figure 4 presents this comparative analysis, providing insight into the financial competitiveness of each fuel option.

All four types of renewable e-methanol are currently 1 to 4 times more expensive than HFO, which suggests that a swift substitution of HFO with e-methanol in ocean shipping is unlikely in the near term. Nonetheless, the cost per heat value (CpHV) of FC-EM and F-EM varieties are comparable to diesel, positioning blue e-methanol as a viable alternative for inland navigation. However, there is still a cost gap of between the green e-methanol and the rest of the counterparts, showing strong competitiveness of the later in near terms.

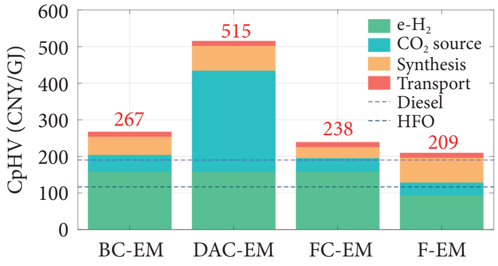

Figure 4 Economic competitiveness of the four types of renewable e-methanol compared with diesel and HFO.

3.2 Sensitivity analysis of carbon tax and e-H$_2$ cost

3.2.1 Sensitivity analysis of carbon tax

More than simply raising the carbon tax is required to drive the adoption of renewable e-methanol over fossil fuels, particularly in the ocean shipping realm. As shown in Figure 5(a), the green e-methanols, BC-EM and DAC-EM, enjoy a lower sensitivity to carbon tax fluctuations due to their inherently low greenhouse gas (GHG) emissions, which could bolster their competitiveness with a higher carbon tax. However, their already substantial costs make the tax rate needed to make them competitive with diesel and HFO prohibitively steep. It would require a carbon tax exceeding 1080 CNY/tonne to position BC-EM competitively against diesel and 2120 CNY/tonne to rival HFO. Blue e-methanol faces a similar challenge with high carbon tax thresholds due to its comparable GHG emissions to those of conventional fossil shipping fuels, as summarized in Table 1. For F-EM to become a contender with diesel, the carbon tax would need to surpass 2640 CNY/tonne. Even then, dislodging HFO from its dominant position may prove to be a difficult task.

3.2.2 Sensitivity analysis of e-H$_2$ cost

Reducing the e-H$_2$ cost is anticipated to be crucial in enhancing the economic viability of renewable e-methanol. As Figure 5(b) and Table 1 demonstrate, BC-EM, FC-EM, and F-EM could become competitive with diesel if the e-H$_2$ cost drops to 1.20 CNY/Nm^3, 0.77 CNY/Nm^3, and 1.04 CNY/Nm^3, respectively. Nevertheless, to rival HFO, even lower e-H$_2$ costs are required, at 0.03 CNY/Nm^3, 0.35 CNY/Nm^3, and 0.08 CNY/Nm^3. Further discussion will highlight that e-H$_2$ costs are projected to decrease to 1–1.2 CNY/Nm^3. With this reduction and an appropriate carbon tax, blue e-methanol is poised to become a frontrunner as an alternative fuel for inland navigation. BC-EM deserves special consideration in ocean shipping due to its significant emission reduction potential and comparatively reasonable costs.

4 Discussion

4.1 Feasibility of e-H$_2$ cost reduction

Given that e-H$_2$ constitutes a substantial share of the renewable e-methanol cost, the potential for reducing e-H_2 costs is pivotal in shaping the commercial viability of e-methanol. Based on the insights from our prior research, we can delineate the e-H_2 cost as comprising two main components: power cost and storage cost.

The power cost is defined as the levelized cost of hydrogen (LCOH) that results from the operation of electrolyzers following renewable power sources without configuration of energy storage. It generally depends on the endowment and installation cost associated with wind and solar energy resources, as well as the efficiency of the electrolyzers. Figure 6(a) shows a preliminary case study that explores a direct solar-to-hydrogen conversion. Specifically, the LCOH decreases by 35% with a reduction in photovoltaic (PV) installation costs from 4 CNY/W to 2 CNY/W and by an additional 25% if the electrolyzer efficiency is enhanced from 60% to 80%. It demonstrates that the primary strategies for reducing the power cost are further reducing installation costs for renewable energy and advancing high-efficiency electrolysis technologies, such as solid oxide electrolysis cells (SOEC).

The storage cost is the expense incurred to ensure a steady supply for downstream chemical synthesis processes, encompassing energy and hydrogen storage solutions. Figure 6(b) illustrates a sensitive analysis of the e-H_2 cost to chemical synthesis flexibility. This analysis is grounded in the optimized sizing and operation of an isolated renewable power-to-hydrogen system integrated with ammonia synthesis. The scheduling period, ΔT_{syn}, is a critical parameter that reflects the flexibility of the chemical synthesis process: a longer scheduling period indicates lower flexibility. As depicted in Figure 6(b), the e-H_2 cost escalates from 1.1 CNY/Nm^3 to 2.1 CNY/Nm^3, consequently driving up the ammonia cost by 2000 CNY as the scheduling period extends from a daily to an annual basis. It is primarily due to the expanded capacity of hydrogen storage (HS). In the context of ammonia production, the fact that air separation can be decoupled from the downstream Haber-Bosch process implies that chemical synthesis has a restricted degree of flexibility. Similar inspiration can be borrowed for methanol production with the potential to significantly reduce e-methanol costs by 1200–2100 CNY. Decoupling the carbon source's acquisition from the synthesis stage may introduce greater flexibility and potentially decrease the costs of e-methanols. In this vein, a process based on post-combustion carbon capture could offer superior techno-economic performance than those that do not allow for such decoupling (e.g., biomass or coal gasification).

4.2 Availability barrier of green carbon sources

Blue e-methanol has limited carbon reduction capacity compared to fossil fuels and should mainly play its role as a transition fuel. For instance, the EU stipulated in ACTS related to renewable fuels of non-biological origin and recycled carbon fuels (RFNBO & RCF) that fossil CO_2 is only allowed for RFNBO and RCF production until 2040[20,21].

The primary challenge hindering the advancement of renewable e-methanol lies in the availability of green carbon sources. Two leading options for such sources are direct air capture (DAC) and bio-carbon, and each faces its own unique dilemmas.

DAC is still in its infancy and faces high capital and energy costs. Due to the lack of economically feasible medium and energy resources at the industrial scale, the literature estimates that liquid solvent DAC's net removed cost projection ranges from 200 to 780 USD/tonne CO_2[22,23], which makes DAC-EM exceedingly costly. Meanwhile, compared with separating CO_2 from concentrated sources, the kinetics of directly capturing from the air is less favorable, and the thermodynamics challenges are heightened[24,25]. Thus, the operational energy cost required for separation, concentration, and thermal regeneration increases dramatically.

Bio-carbon is fraught with more uncertainty, primarily limited by its availability. Acquiring bio-carbon demands substantial inputs, including land, water, and resources from agriculture, forestry, and livestock sectors. For instance, using marsh gas from dairy farming as a bio-carbon source, it would require 400,000 cows and 2,000 ha of farming land to produce 0.1 million tons of methanol annually. Similarly, capturing CO_2 from biomass power plants would take 5,400 ha of arable land to provide 81,000 tons of corn straw, as illustrated in Figure 7. These requirements bring the complexities and difficulties associated with collecting bio-carbon.

Furthermore, the challenges associated with varied bio-carbon sources vary from case to case. For example, a 10MW-scale biomass plant could potentially satisfy the bio-carbon needs of a methanol plant with an annual yield of 10,000 tons. However, the costly biomass power generation makes it difficult to make a profit. In China, for instance, the levelized cost of bio-electricity is generally above 0.5 CNY/kWh, while the benchmark on-grid tariff of biomass power is on a downward trend. Since 2022, the on-grid price of newly approved biomass power projects in Shandong province has been implemented according to the benchmark price of coal-fired power (0.394 CNY/kWh). Additionally, biomass power plants rely heavily on subsidies and face the subsidy removal risk, which could further squeeze the living space. Inno-

Table 1 The thresholds of the carbon tax and LCOH so that e-methanols have the same cost-effectiveness as the benchmark fossil fuels

e-methanols (kg)	Fossil fuels (days)			
	Carbon tax (CNY/tonne CO_2e)		LCOH (CNY/Nm^3)	
	Diesel	HFO	Diesel	HFO
BC-EM	1080	2120	1.20	0.03
DAC-EM	–	–	–	–
FC-EM	–	–	0.77	0.35
F-EM	2640	–	1.04	0.08

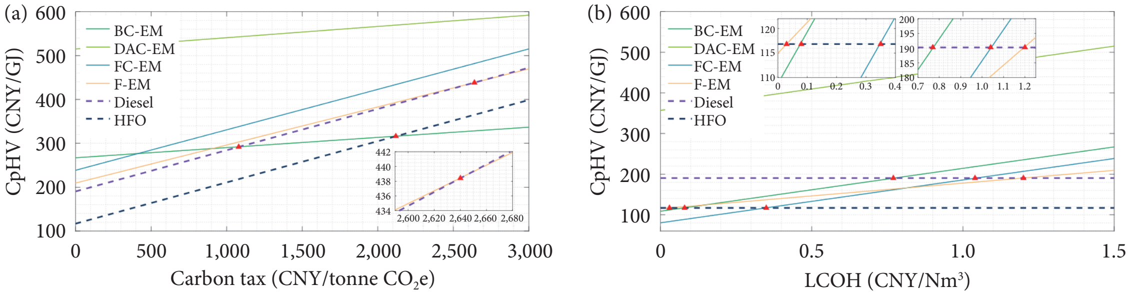

Figure 5 Sensitivity analysis results. (a) Carbon tax, **(b)** e-H_2 cost.

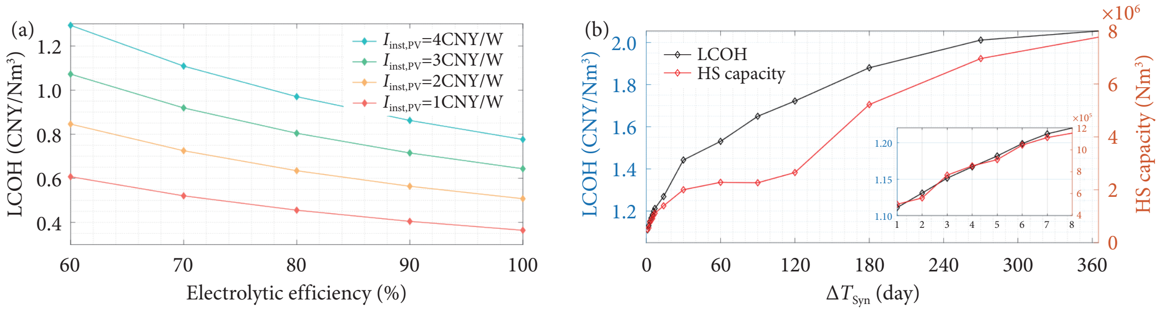

Figure 6 Sensitivity analysis of e-H_2 cost to various factors. (a) LCOH in the direct solar-to-hydrogen scenario, **(b)** LCOH of an isolated power-to-hydrogen system with ammonia synthesis.

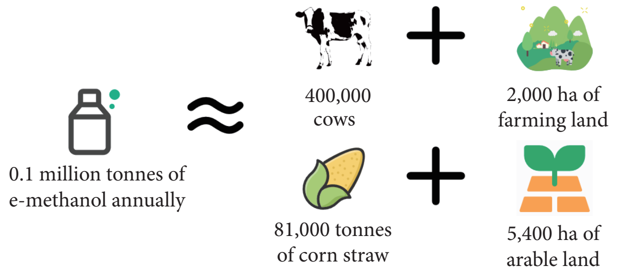

Figure 7 Resources required by annual production of 0.1 million tonnes of e-methanol.

vative business models are essential to expand its revenue streams. One such opportunity could be the integration of e-H_2 with biomass power to produce e-methanol, which may offer potential for industrial chain extension and profitability growth.

Biomass gasification stands as another potential alternative source of bio-carbon. However, in China, biomass gasification currently remains at the pilot stage and is not yet capable of fulfilling the demand for large-scale production reaching millions of tons annually. Additionally, the storage cost, as discussed above, can be high due to the rigid coupling between biomass gasification and methanol synthesis processes. Moreover, bio-methanol derived directly from biomass gasification (as shown in the upper left corner of Figure 1) has the potential to be a formidable competitor in the market. It is because bio-H_2 and CO replace e-H_2 and CO_2 in methanol synthesis to save cost significantly if industrial scale-up is achieved.

Marsh gas, approximately 40% CO_2, is another potential bio-carbon source. However, it comes with its own set of challenges. On the one hand, marsh gas depends on a steady feedstock supply. When the feedstock is dispersed and challenging to collect, both the quantity and quality of mash gas will be affected, hindering the establishment of large-scale, centralized production facilities. On the other, the demand for marsh gas is decreasing with the development and popularization of alternative energy sources. The industry is in search of new avenues for growth, and e-methanol production could offer such an opportunity.

5 Conclusions

This work sets out to assess the feasibility of renewable e-methanol production. Life-cycle GHG emissions and levelized costs of the various renewable e-methanols are evaluated. Renewable e-methanol has significantly lower GHG emissions than coal-based methanol. Nevertheless, it now costs (4167–10250 CNY/tonne) more than twice the market price of their grey counterparts. However, renewable e-methanol has a promising prospect as a shipping fuel, especially blue e-methanol, as an alternative fuel for inland navigation to replace diesel. While for ocean shipping, BC-EM has potential to gain a place for its carbon reduction capacity and relatively reasonable costs. The e-H_2 cost and the availability of green carbon are the two vital factors considered to improve cost-effectiveness and promote the commercialization of renewable e-methanol. The e-H_2 cost declines from 2.1 CNY/Nm^3 to 1.1 CNY/Nm^3 as the scheduling period changes from yearly to daily level, which could drive down the e-methanol cost of 1200–2100 CNY. Thus, the chemical process flexibility should be valued in the same way as renewable power sources and electrolytic efficiency regarding reducing the e-H_2 cost. As for the availability of green carbon sources, large-scale production will bring difficulties collecting feedstock. An annual output of 0.1 million tons of e-methanol needs 400,000 cows with 2,000 ha of farming land or 810,000 tons of corn straw with 5,400 ha of arable land. The challenges and opportunities of three typical bio-carbon sources, biomass power plants, biomass gasification, and marsh gas, are also discussed in depth. The following five to ten years are pivotal for the maturation and demonstration of renewable e-methanol technology. Within the next two to three decades, a steady progression for renewable e-methanol is anticipated, starting with the initial introduction of blue e-methanol and eventually securing a significant market presence with green ones.

Appendix

As depicted in Figure A1, the model adopted in this work envisions a renewable e-methanol facility, that integrates renewable energy sources —both wind and solar plants —along with energy storage such as batteries, fuel cells, and hydrogen storage systems, as well as the electrolyzers and methanol synthesis units. It's important to note that the carbon sources vary by case, aligning with the distinct attributes of each renewable e-methanol variant.

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Additional information

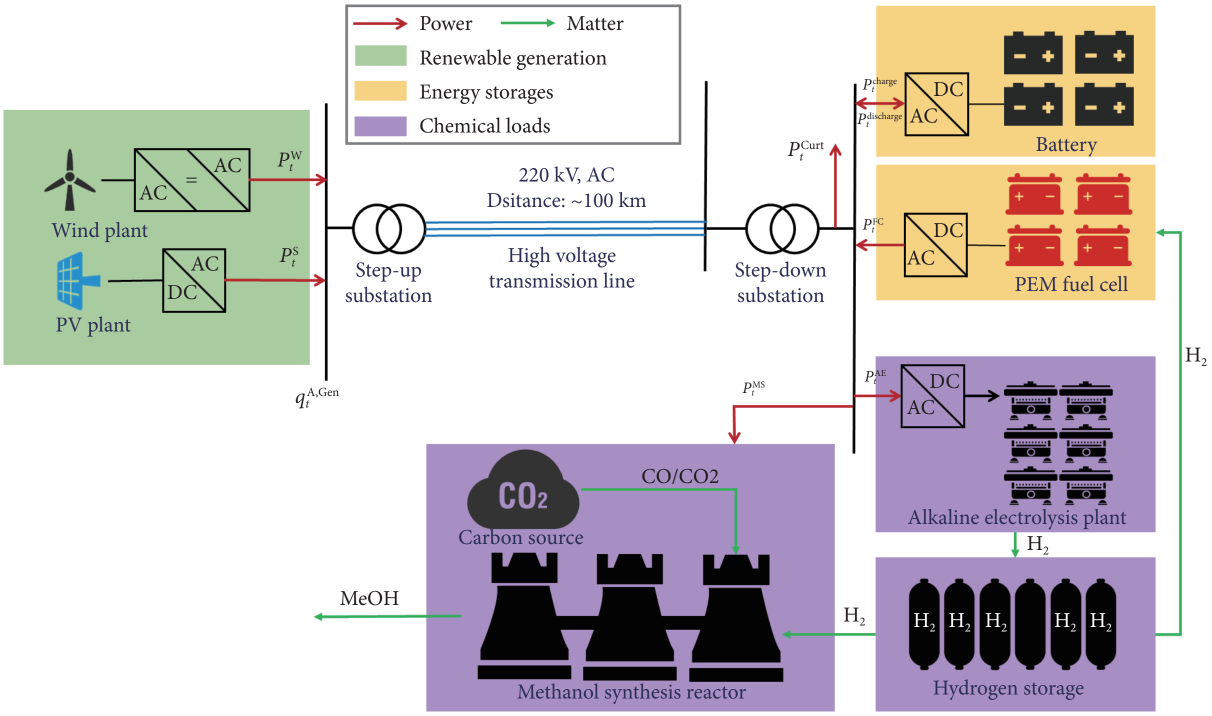

Figure A1 Isolated renewable e-methanol plant.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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