Engineering 29 (2023) 32–34

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

Roles of Bioenergy and Green Hydrogen in Large Scale Energy Storage for Carbon Neutrality

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1. Roles of biomass and bioenergy in solar energy storage

Biomass comprises plant-based material, for example, wood, microalgae, energy crops, and agro-forestry residues, as well as organic waste from industries, farms, and households, and plays a key role in solar energy capture and storage. Globally, an estimated 8500 EJ (1 EJ = 10^{18} J) of solar energy is captured/stored naturally in biomass each year, thereby contributing to fixing approximately 220 billion tonnes of carbon per year ($\mathrm{Gt \cdot a^{-1}}$) [1], which is approximately 15 times the world's current total energy consumption (580 EJ) [2].

Biomass can be used for producing bioenergy (fuel, heat, or electricity) via thermochemical conversion technologies (combustion, pyrolysis, gasification, hydrothermal liquefaction (HTL), etc.) and bioconversion technologies (anaerobic digestion, fermentation, etc.), in which CO_2 is emitted. The amount of CO_2 emitted is balanced by the amount of CO_2 captured from the atmosphere by the biomass through a photosynthetic mechanism that converts solar energy and CO_2 into biomass. Thus, biomass is a carbon-neutral energy source with inherent net zero carbon emissions. However, in the context of a full supply chain, attention should be paid to the harvesting, transportation, and processing of raw biomass, as they involve fossil fuel energy use, thereby making the biomass/bioenergy application not truly carbon neutral. Nevertheless, analysis has shown that the fossil fuel energy used in the supply chain is usually a small fraction of the energy content of the bioenergy product, even in the case of woody biomass transported over long distances, for example, between North America and Europe [3].

Besides the immense natural storage of solar energy in biomass, recently developed bioenergy technologies capture and store solar energy. A few examples are as follows:

(1) Solar-to-algal biomass conversion. Iluz and Abu-Ghosh [4] developed a novel tubular photobioreactor and demonstrated that its application for large-scale solar energy harvesting to microalgae is feasible and promising. The reactor generated fluctuating light of controlled successive high and low intensities from sunlight, thereby promoting microalgal growth, increasing the cell doubling rate and algal biomass productivity by more than 55%, and achieving a light-to-biomass conversion efficiency higher than those of conventional photobioreactors.

(2) Co-production of biomass and electricity from solar energy. Parlevliet and Moheimani [5] presented a novel method for the co-production of algal biomass and electricity from solar energy by combining these energy production processes and utilizing the full sunlight spectrum. The proposed system allows the production of both chemical and electrical energy from one facility, and electrical power generation of up to 151 $\mathrm{W \cdot m^{-2}}$.

(3) Solar photovoltaic (PV)–biomass gasifier. Macías et al. [6] developed a solar PV–biomass gasifier system comprising a biomass gasification module coupled to a 30 kilowatts of electricity (kWe) motor generator and a 5 kWe solar PV system with inverter charging and battery storage systems, which realized even output to the grid.

(4) Solar and biomass-based system for integrated production of fresh water, H_2, CH_4, electricity, and ethanol. Oner and Dincer [7] proposed a novel solar and biomass energy-based integrated system for producing electricity, heating, freshwater, and ethanol, attaining overall energy and exergy efficiencies of 53.4% and 41.0%, respectively. In this highly integrated system, food waste is digested anaerobically to generate biogas for electricity. Simultaneously, solar energy is collected via a conventional concentrating solar power system to generate power in an organic Rankine cycle and desalinate seawater. Hydrogen is further generated by utilizing part of the electricity produced through an alkaline electrolyzer and then converted to ethanol by direct CO_2 hydrogenation.

(5) Hybrid solar–biomass thermochemical conversion systems. Ling et al. [8] proposed a high-temperature hybrid solar–biomass system comprising a solar power tower (SPT) coupled with a circulating fluidized bed (CFB) biomass gasifier in a beam-down configuration. Although the operation of the proposed system is challenging in terms of operating temperature, continuous supply/syngas production, and scaling of the reactor, particularly for the CFB, the development of a high-temperature hybrid solar–biomass system is anticipated for more efficient solar-to-fuel conversion, minimized direct combustion of biomass, and reduced greenhouse gas (GHG) emissions.

2. Promising roles of bioenergy in large-scale electricity and energy storage

According to the *World Energy Outlook 2022* of the International Energy Agency (IEA) [9], with 83 countries and the European Union

https://doi.org/10.1016/j.eng.2023.08.007

(EU) targeting net zero carbon emissions by 2050, the utilization of renewable resources (particularly solar and wind) for electricity generation will rise drastically, and is projected to go from 28% in 2021 to approximately 50% by 2030 and 80% by 2050. Solar PV capacity additions are projected to expand from 151 GW in 2021 to 370 GW in 2030 and almost 600 GW in 2050, whereas wind capacity additions are projected to double to 210 GW in 2030 and further increase to 275 GW by 2050. Unlike traditional power plants, where outputs can easily be adjusted to match the power requirements of the consumers, a major challenge with renewable electricity systems is that they are intermittent and subject to naturally fluctuating energy flows. Therefore, the cost-effective storage of excess or surplus electricity at a large scale has become a pressing need and an obstacle for the rapid and continuous development of renewable electricity, although large-scale electricity and energy storage has been realized by pumped hydro storage, compressed air, batteries, flywheels, as well as cryogenic, thermal, and hydrogen (by electrolysis) storages [10,11].

In recent years, driven by the hydrogen and low-carbon economies, there has been great interest in producing green hydrogen by water electrolysis using renewable electricity, and many scientific studies have highlighted the advantages of using hydrogen as a renewable energy carrier for the storage of surplus electricity. However, the development of the hydrogen economy faces many major issues: ① Hydrogen has a low volumetric energy density, ② the existing infrastructure is insufficient for long-term storage, ③ H_2 storage on a transportation vehicle as its own motive power involves cost and safety issues, and ④ the conversion of H_2 into electricity in fuel cells has unresolved durability and cost issues. To address these issues, various hydrogen storage technologies have been investigated, including the development of novel adsorbents (activated carbon, nanostructured carbons, metal–organic frameworks (MOFs), and hydrogen clathrate hydrate), liquid organic hydrogen carriers (LOHCs), and liquid hydrogen carriers (hydrocarbons, methanol, formic acid, and ammonia) [12]. Nevertheless, thus far, no hydrogen storage technology has achieved a satisfactory level of performance [12]; therefore, continued efforts for new hydrogen storage technologies are required.

Given all the above, a new technical route to incorporate excess electricity (via green hydrogen generation by electrolysis) into a biorefinery to produce modern bioenergy (advanced biofuels) is proposed as a promising alternative to the aforementioned conventional approach. This new route involves storing hydrogen for mobile and stationary applications, and can be a three-bird–one-stone solution for the storage of excess electrical energy, storage of green hydrogen, and high-value utilization of biomass. On the one hand, green hydrogen is generated by electrolysis using excess electricity or electricity from renewable sources, thereby addressing the issue of excess electricity storage. On the other hand, the produced green hydrogen is used in a biorefinery for production of multiple advanced biofuels (e.g., renewable natural gas (RNG), Fischer–Tropsch (F–T) fuels, methanol, "drop-in" biofuels, bio-aviation fuels (BAFs)) that can be cost-effectively transported using existing pipelines, roads, rails, or waterways, thereby addressing the green electricity and green hydrogen storage issue and realizing high-value utilization of biomass. The proposed biorefinery, which incorporates excess electricity and green hydrogen into the production of multiple advanced biofuels, is illustrated in Fig. 1. In this scheme, excess electricity is first converted into green hydrogen and oxygen by electrolysis. The oxygen generated is then used to produce syngas by biomass oxygen/steam gasification, while the green hydrogen is used to produce multiple advanced biofuels: RNG by methanation of H_2 with CO_2 in the syngas; methanol or F–T fuel by catalytic conversion of the syngas, whose H_2/CO ratio is adjusted to appropriate levels with the green H_2; and "drop-in" biofuels or BAFs by catalytic hydrotreatment of biocrude oils from fast pyrolysis or HTL of biomass.

RNG can be produced by methanation of H_2 with CO_2 in the syngas from biomass gasification via the Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$, $\Delta H^\circ = -167\ \text{kJ}\cdot\text{mol}^{-1}$) [13], catalyzed by nickel and ruthenium catalysts [14]. Based on a case study by Jürgensen et al. [15], surplus electricity from wind power (to generate H_2) can be effectively utilized for the production of CH_4 by methanation of H_2 with CO_2 through the Sabatier process, leading to the conversion, storage, and transport of surplus electricity from fluctuating renewable energies to bioenergy without long transport pathways.

Methanol and F–T fuels are commercially produced by the catalytic conversion of syngas (at suitable H_2/CO ratios). Methanol can be used directly as a fuel for solid oxide fuel cells (SOFCs), chemicals (methanol-to-olefins (MTO) technology), or as a liquid hydrogen carrier. Clausen et al. [16] presented a technoeconomic

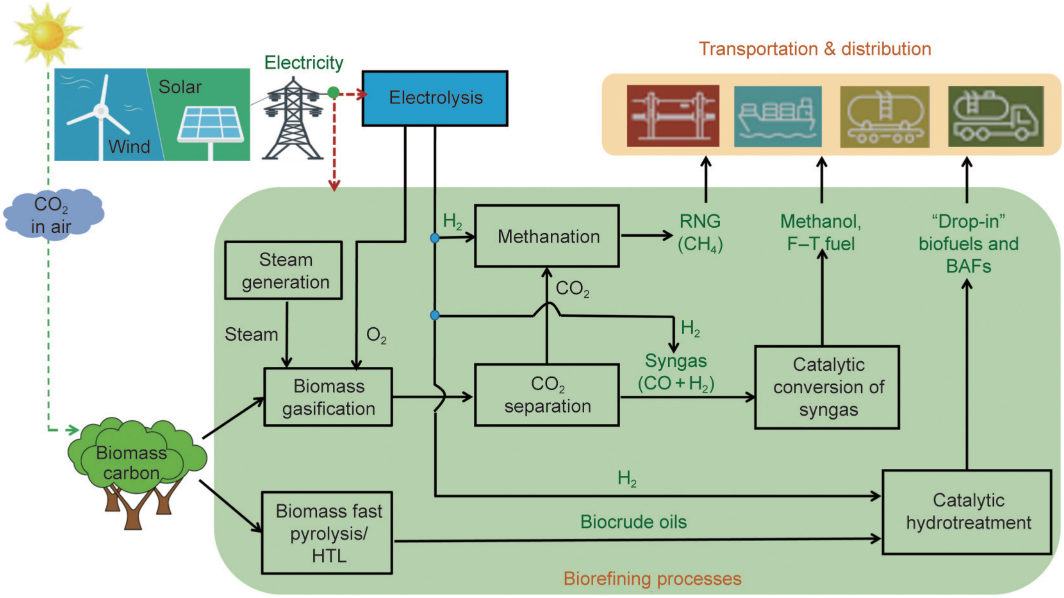

Fig. 1. Promising roles of bioenergy in large-scale electricity and energy storage: a biorefinery for producing multiple advanced biofuels from biomass using excess electricity from fluctuating renewable energy sources.

analysis of a methanol plant based on biomass gasification and water electrolysis, in which the lowest production cost (0.2 EUR·L^{-1}) was obtained.

The aviation sector is the second largest transportation sector, responsible for approximately 3.6% of the global GHG emissions. The number of flights between 2014 and 2017 increased by approximately 8% and is projected to further increase by over 40% by 2040 [17]. Commercial aviation fuels (Jet A-1 in the EU and Jet A in the United States) are kerosene derived from crude oil and consist primarily of a mixture of alkanes, alkenes, and aromatics (mostly alkylbenzenes and naphthalenes). Morgan et al. [18] presented various technical routes to produce "drop-in" biofuels or BAFs from biomass, including hydrotreatment of plant oils/animal fats or biocrude oils from fast pyrolysis or HTL of lignocellulosic biomass.

3. Prospects and challenges

According to the IEA, bioenergy is the most important source of renewable energy, and the current bioenergy deployment rate is well below the levels required for future low-carbon scenarios. In IEA's Net Zero Emission (NZE) by 2050 scenario, the conversional bioenergy (e.g., heat and electricity generation from biomass by combustion) should phase out by 2030, while the share of modern bioenergy, for example, production of 2nd or 3rd generation biofuels (methanol, F–T biofuel, "drop-in" biofuels and BAFs, RNG, and renewable H_2, etc.) in the total energy supply is expected to increase from 6.6% in 2020 to 13.1% in 2030 and 18.7% in 2050 [19]. The production and use of hydrogen and hydrogen-based fuels will increase drastically, particularly in heavy industries (steel and aluminum sectors, where they can be used as reducing agents to substitute coke/coal) and long-distance transport. Driven by sustainability, energy security, and NZE targets, many countries (including the EU countries, the United States, Canada, China, and Japan) are developing clean hydrogen strategies/programs and implementing various types of carbon prices/taxes. For instance, in December 2020, the Natural Resources of Canada (NRCan) published "Hydrogen strategy for Canada—seizing the opportunities for hydrogen: a call to action" [20], according to which hydrogen consumption in Canada is expected to reach 20 Mt·a^{-1} in 2050, meeting 30% of the delivered energy and abating up to 190 Mt CO_2 emission in the country. As for carbon prices/taxes, the EU countries expect to increase carbon prices from the current 120 to 150 EUR·t^{-1} by 2030. In Canada, on December 11, 2020, Prime Minister Justin Trudeau announced a bold strategy to increase carbon pricing from 50 USD·t^{-1} in 2022 to 170 USD·t^{-1} in 2030 in 15 USD·t^{-1} annual increments. All of the above should shift the global energy supply from fossil fuels to renewable sources (solar, wind, and biomass, etc.). Therefore, the technical route illustrated in Fig. 1 for incorporating excess electricity into biorefineries to produce advanced biofuels that can be transported or distributed by roads, railways, waterways, and pipelines is a promising alternative to the conventional approach involving storing hydrogen for mobile and stationary applications. However, to develop biorefineries for large-scale production of modern bioenergy or other high-value bioproducts (bio-based chemicals/materials), the following challenges need to be addressed: ① The supply of biomass feedstock is usually unstable (biomass is abundant; however, it is spread over large and remote areas); ② the biorefining processes are usually capital- and energy-intensive; ③ some biomass conversion and refining technologies (e.g., biomass HTL, biomass gasification, CO_2 methanation, and catalytic hydrotreatment) are still at the research and development stage.

The proposed biorefinery technology (Fig. 1) integrates several technologies, including biomass gasification/liquefaction, catalytic syngas conversion, and bio-oil hydrotreatment. These technologies have been investigated intensively by many researchers in academia and industries worldwide. Given the carbon neutrality or NZE goals of many countries and continued support from governments/industries, such an integrated biorefinery technology should be realizable in 5–10 years if not earlier.

4. Summary

Biomass and bioenergy play key roles in solar energy capture and storage. Modern bioenergy also plays a promising role in large-scale electricity and energy storage. Utilizing green hydrogen (generated by electrolysis with the excess electricity or electricity from renewables) to produce advanced biofuels—RNG, F–T fuels, methanol, "drop-in" biofuels, BAFs, and so on—can be a three-birds–one-stone solution for the storage of excess electrical energy, green hydrogen storage, and high-value utilization of biomass.

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