THE UNIVERSITY OF BRITISH COLUMBIA

Clean Energy Research Centre (CERC)

# Part II

# Clean Energy Strategies for Mitigating Greenhouse Gas Emissions in British Columbia

**Haoqi Wang, Roland Clift, and Xiaotao Bi**

**University of British Columbia**

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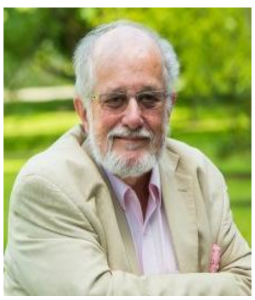
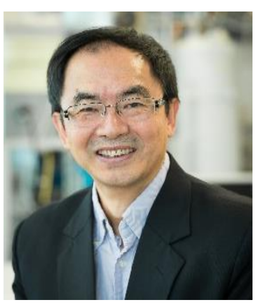
## Biographies

**Haoqi Wang** worked on life cycle environmental analysis and techno-economic analysis of bioenergy systems in British Columbia during his PhD study as a PICS fellow and postdoctoral research at the Department of Chemical and Biological Engineering, University of British Columbia, under the supervision of Xiaotao Bi and Roland Clift. He is now an assistant professor in the College of Materials and Environmental Engineering, Hangzhou Dianzi University, China.



**Roland Clift** is emeritus professor (founding director) in the Centre for Environment and Sustainability, University of Surrey, UK, and an adjunct professor at the Department of Chemical and Biological Engineering, University of British Columbia. His research interests are in life cycle assessment, industrial ecology and sustainable energy systems. He is a fellow of the Royal Academy of Engineering, UK, and a past member of the UN Intergovernmental Panel on Climate Change (IPCC).



**Xiaotao Bi** is a professor in the Department of Chemical and Biological Engineering and the director of UBC's Clean Energy Research Centre. His current research focuses on particle technology and fluidized bed reactors for biomass thermo-catalytic conversion, green and sustainable engineering, and integrated assessments of clean energy systems. He is a fellow of the Canadian Academy of Engineering and Engineers Canada.

**UBC Clean Energy Research Centre**
2360 East Mall
Vancouver, BC Canada V6T 1Z3
Phone: 604-827-4342
Email: cerc@cerc.ubc.ca
Website: www.cerc.ubc.ca

## Executive Summary


The potential in BC for increasing use of biomass, generation and use of renewable electricity, and using hydrogen as an energy carrier have been assessed. As demonstrated in Part I of this paper series, both bioenergy and electricity will be in short supply, as further decarbonization efforts are made. Therefore, all renewable energy sources must be used in the ways that give greatest mitigation of Greenhouse Gas (GHG) emissions at the lowest cost.

Waste biomass in BC could provide about 20% of the energy currently provided by fossil fuels, mainly wood residues from logging and sawmilling. Energy crops could also be grown in BC. Lignocellulosic (woody) biomass can be used to generate electricity and heat, gasified to produce Renewable Natural Gas (RNG) or liquid fuels, or pyrolyzed to produce a range of liquid biofuels including aviation fuel. Direct use for district and industrial heating gives greatest GHG mitigation at lowest cost. Pre-gasification combustion generates lower health impacts. Converting biomass to refined biofuels leads to energy losses and increases overall costs. Manure and food waste can be converted into biogas by anaerobic Digestion (AD). Biogas can be used directly to generate electricity and heat or upgraded to RNG. The digestate residue can displace synthetic fertilizers. Integrating AD with agricultural operations gives the greatest GHG mitigation at the lowest cost. Upgrading to RNG has the highest cost.

Even with Site C completed and operating, BC will not have surplus renewable electricity. Other primary energy sources must therefore be explored. Wind energy could be significant. Solar photovoltaic production is less favourable in BC but could be deployed in niche applications. Increasing wind and solar will greatly increase the proportion of intermittent generation but at least 20% should be readily manageable. Cogeneration of heat and power, providing dispatchable electricity and steam/heat for industrial operations, should be retained and possibly increased.

The most effective use of electricity for land transport is to power electric vehicles. Using electricity to produce liquid fuels (“electrofuels”) is much less efficient. For industrial applications, replacing natural gas and diesel engines by electric motors is the preferred use. In buildings, the preferred use is in heat pumps to replace resistive and gas-fired heaters.

Hydrogen can be produced from different energy sources: electricity, by electrolysis of water; biomass, by gasification; or natural gas, by steam methane reforming. Hydrogen produced from renewable energy sources is termed “green” hydrogen, but its application is limited due to scarcity of future renewable electricity and biomass supply. “Blue” hydrogen is made from natural gas with carbon capture, which represents the only major use for natural gas in a low-carbon economy. It should be used in fuel cell vehicles, to replace internal combustion engines which are inherently less efficient. Combustion of hydrogen loses the advantage of fuel cells and is less efficient than direct use of the energy from which the hydrogen is produced.

## Table of contents

# 1. Bioenergy

## 1.1 Bioenergy potential in BC

BC has enormous potential for bioenergy production from waste biomass: existing wastes and byproducts of existing economic activities do not require additional resources and therefore constitute sustainable bioenergy feedstock. Figure 1 shows the estimated total primary energy in currently unused waste biomass in BC, totaling 190 PJ per year [1], equivalent to 20% of fossil fuel consumption. BC's primary source of waste biomass is its forestry sector. During logging and sawmilling, millions of tonnes of wood residues are generated; most are used domestically for energy production (135 PJ) [2] or exported as pellets (40 PJ) [3], but a considerable amount (80 PJ) remains unused. To prevent wildfires, unused wood residues must be destroyed by slash burning, which generates $CH_4$, a potent GHG, and other hazardous emissions [4]; converting the residues to bioenergy avoids these emissions as well as displacing fossil fuels. Trees killed by mountain pine beetle infestation are another source of forestry waste biomass [5], but future availability is unpredictable. Waste biomass is also available in animal manure, crop residues, and the organic fraction of municipal solid waste (MSW). The total waste biomass resource could supply a significant part but not the whole of BC's energy demand. The priority for developing the available bioenergy resource is therefore to maximize GHG mitigation while keeping the total costs as low as possible.

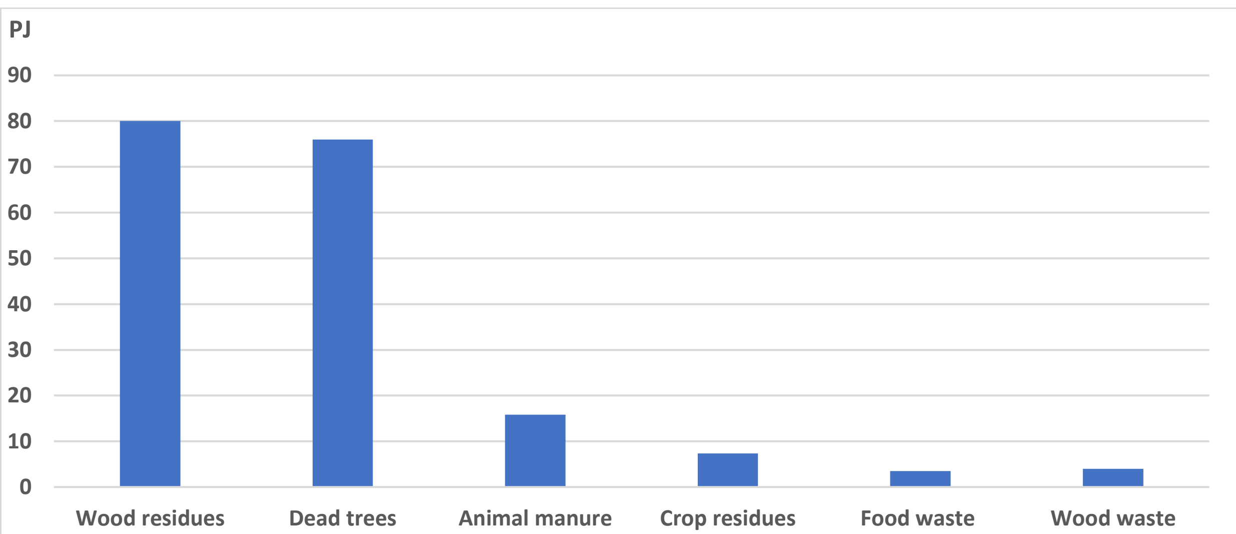



**Figure 1 Primary energy in unused waste biomass in BC** [1]

Beyond waste biomass streams, additional primary bioenergy could be obtained by expanding timber harvesting and growing energy crops. Short-rotation coppice (SRC) production of biomass should give an annual yield of 16-23 ODT/ha in Canada [6], [7]. However, producing 100 PJ of primary bioenergy would require roughly 250,000 ha, equivalent to 10% of BC's agricultural land [8]. Because the sustainability of these sources is contentious – they involve land-use change and potentially a conflict between food and energy production – they are not considered further here. However, they might be considered in future given that SRC is tolerant of flooding.

Most biomass resources in BC, including wood logs and residues, crop residues, and the woody fraction of MSW, and also SRC product, are lignocellulosic, composed of cellulose, hemicellulose, and lignin. The material can be converted to biofuels and energy by thermochemical processing (see Section 2.1.2). On the other hand, animal manure and food waste contain much more mixed constituents with higher moisture contents and are thus not suitable for thermochemical conversion; instead, anaerobic digestion (AD) should be employed (see Section 2.1.3).

## 1.2 Utilization of Lignocellulosic biomass

As illustrated in Figure 2, many thermochemical bioenergy conversion technologies start with gasification, a partial oxidation process that converts biomass into syngas, a mixture of mainly $H_2$, CO, $CH_4$, and $CO_2$ [9]. Biomass or biomass-derived syngas can be combusted for heat generation or cogeneration (CHP). Syngas combustion provides higher-grade heating, which can be used to replace natural gas for industrial use, such as in lime kilns in the pulp and paper industry. It also generates lower health impacts [10]. Alternatively, syngas can be synthesized into different biofuels, including methanol, ethanol, and methane (RNG). Biomass can also be pyrolyzed to produce hydrocarbons. An emerging pyrolysis technology is hydrothermal liquefaction (HTL), which turns biomass into a mixture of liquid biofuels including aviation fuel. Due to the nature of biogenic carbon cycle, bioenergy generally has lower GHG emissions than its fossil fuel counterpart [11]. Converting wood residues to bioenergy in BC can achieve additional reductions of GHGs and health impacts by avoiding slash burning [12].

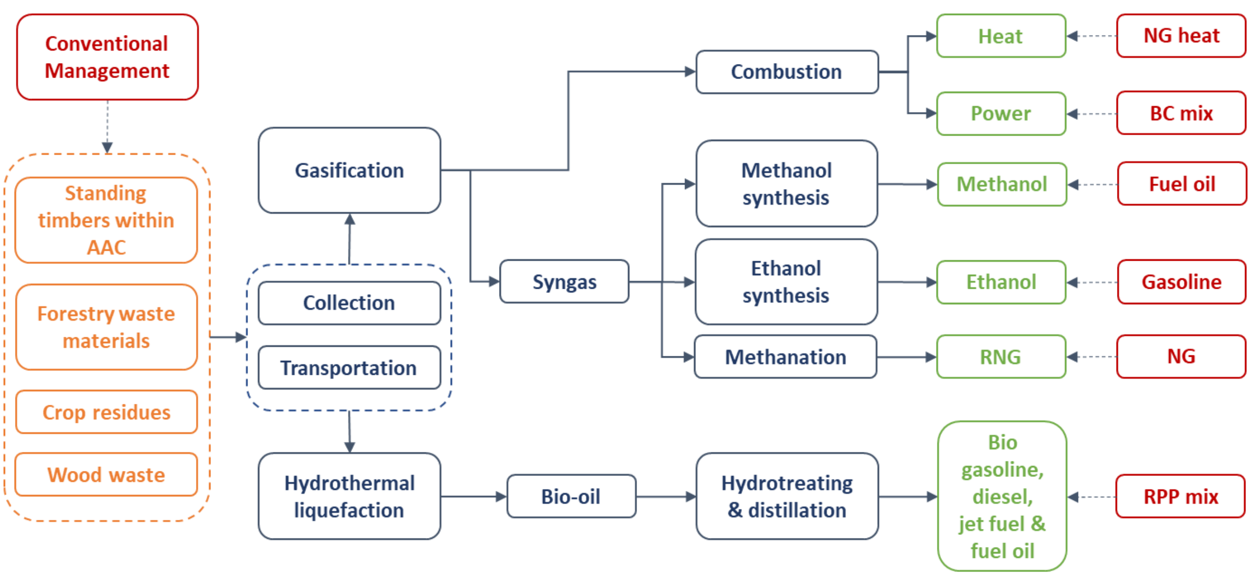



**Figure 2 Systems for energy production from lignocellulosic biomass** [12]

Conventionally, the carbon footprint of bioenergy is reported per GJ, which underplays the importance of conversion efficiencies. In Figure 3, GHG reduction potential of bioenergy derived from wood residues is compared per ODT biomass, which properly reflects the GHG benefit of utilizing limited biomass supply allowing for conversion efficiency [12]. GHG reduction cost ($/tCOeq) is shown in the ordinate of Figure 3, which represents the total carbon pricing (such as carbon tax and low-carbon fuel credit) needed to make bioenergy economically viable. Biomass-fired heating gives the highest GHG reduction per ODT, with negative reduction cost. Liquid biofuels and RNG have lower GHG mitigation benefits, due to extra energy losses in the conversion processes, but higher reduction costs. Typically, the conversion efficiency of biomass-fired heating can exceed 75%, whereas efficiencies of refined biofuels are below 60% [12]. Biomass-fired CHP has the lowest GHG reduction potential, due to the low carbon intensity of electricity in BC, but this could change in the long term (see Section 2.2.1). For other lignocellulosic biomass, the ranking of bioenergy options remains the same [13]. Overall, biomass-fired heating, in applications including high-pressure steam, kilns, and district heating, should be prioritized.

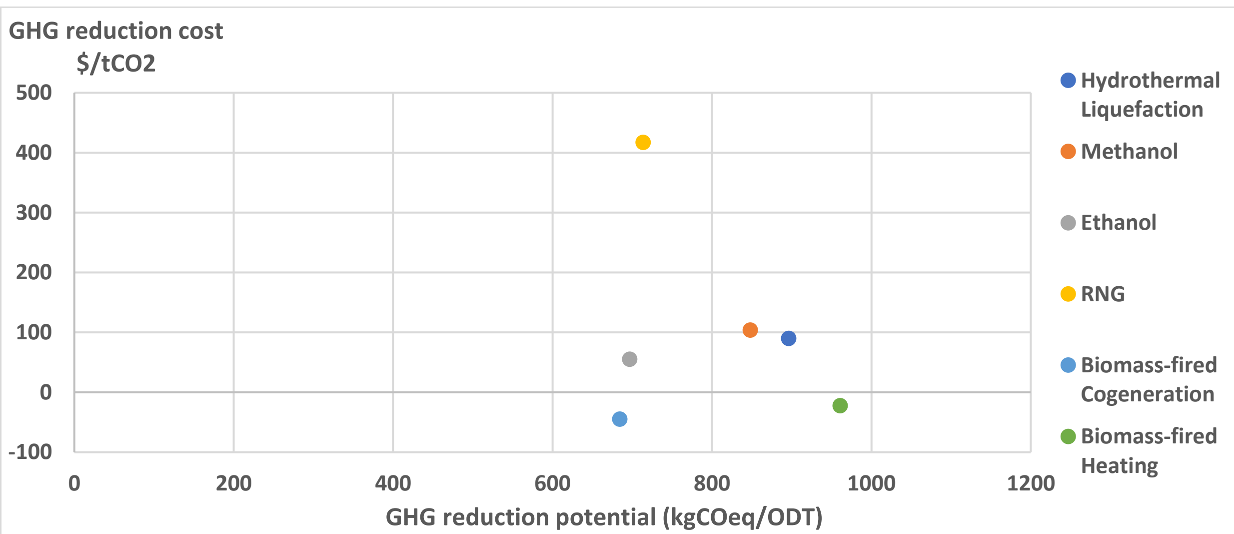



**Figure 3 GHG reduction potential and costs of bioenergy produced from wood residues** [12]

## 1.3 Anaerobic digestion

AD can decompose animal manure and food waste into biogas, which typically consists of 60% $CH_4$, 40% $CO_2$, and traces of other components. As shown in Figure 4, biogas can be directly combusted for heat production or CHP. Alternatively, it can be upgraded to RNG by removing $CO_2$ and trace gases. Thus AD can produce renewable energy and reduce the volume of waste. Furthermore, the organic residue of the AD process, namely digestate, retains nutrients in the feedstock. Using digestate as organic fertilizer can achieve additional environmental benefits by displacing synthetic fertilizers and improving nutrient management [14].

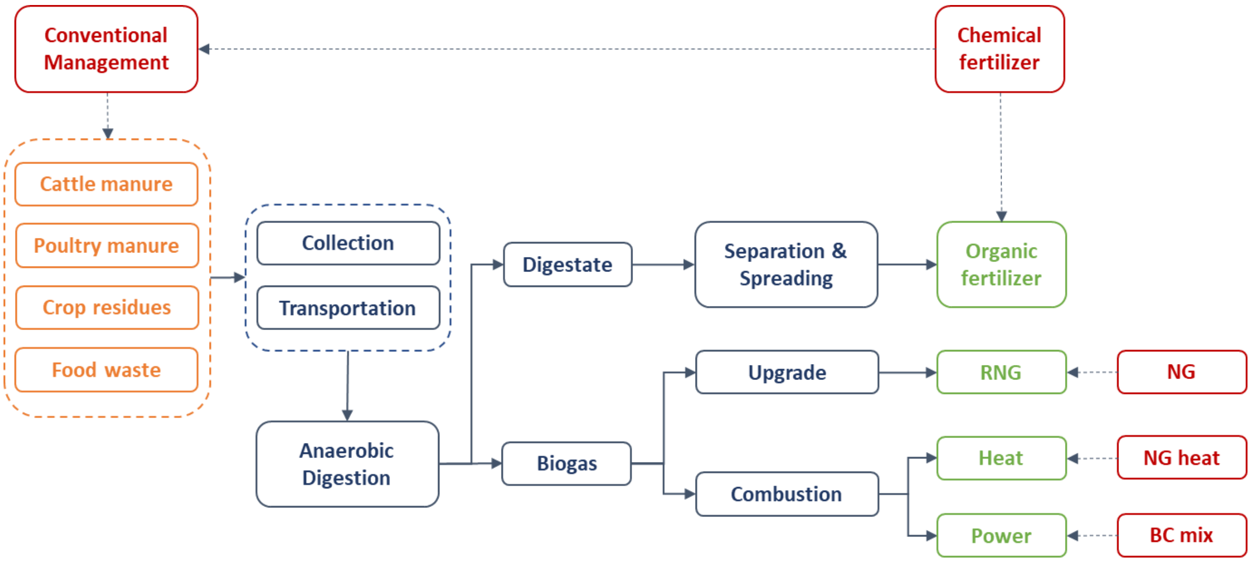



**Figure 4 Systems for anaerobic digestion of organic wastes** [15]

Figure 5 compares GHG reduction potential and costs of different biogas utilization options. Biogas-fired heating has the highest GHG mitigation potential and the lowest costs. RNG has slightly lower GHG benefits, due to extra energy losses and fugitive $CH_4$ emissions, but significantly higher costs. Biogas-fired CHP has the lowest GHG benefits but, like direct use of biomass for CHP, this could change in the long term (see Section 2.2.1). Economically, the GHG reduction costs of AD for standalone applications are higher than \$200/t$CO_2$, well above an ambitious future carbon tax level of \$170/t$CO_2$ (currently \$45/t$CO_2$). Such high GHG mitigation costs call for strong financial support from policy measures. Full utilization of the waste streams can generate 5.9 PJ of biogas and RNG [13], which is a small yet indispensable step towards reducing GHG emissions from natural gas consumption.

## 1.4 System integration for byproduct utilization

Utilization of byproducts from bioenergy conversion enhances the overall GHG mitigation potential and economic viability. For example, digestate residue from AD is rich in nutrients and can be used to substitute synthetic fertilizers [16]. Biochar generated by thermochemical conversion of biomass contains residual carbon and nutrients [17], [18] and can be used as a soil improver. Byproduct utilization may potentially improve the GHG benefits of AD and HTL by 100% and 50%, respectively, and also lead to cost savings [13].

A novel type of AD-centered system can effectively integrate animal, greenhouse, mushroom, and crop farming [15], [19], which are all common agricultural activities in BC. Biogas from AD of animal manure is combusted to heat participating farms. Biogenic $CO_2$ from combustion of biogas and ventilation of the mushroom farm replaces natural gas consumption for $CO_2$ enrichment in greenhouses. Digestate is used as growing medium in greenhouse and mushroom farming, in addition to fertilizers for crop farming. Co-digestion can further increase biogas yield and thus improve overall performance of the system. As shown in Figure 5, such integrated AD systems have substantially higher GHG benefits and lower GHG reduction costs than standalone AD options (Section 2.1.3) [15]. They represent an application of agricultural carbon sequestration and circular economy and so fit perfectly into BC's GHG mitigation roadmap [20].

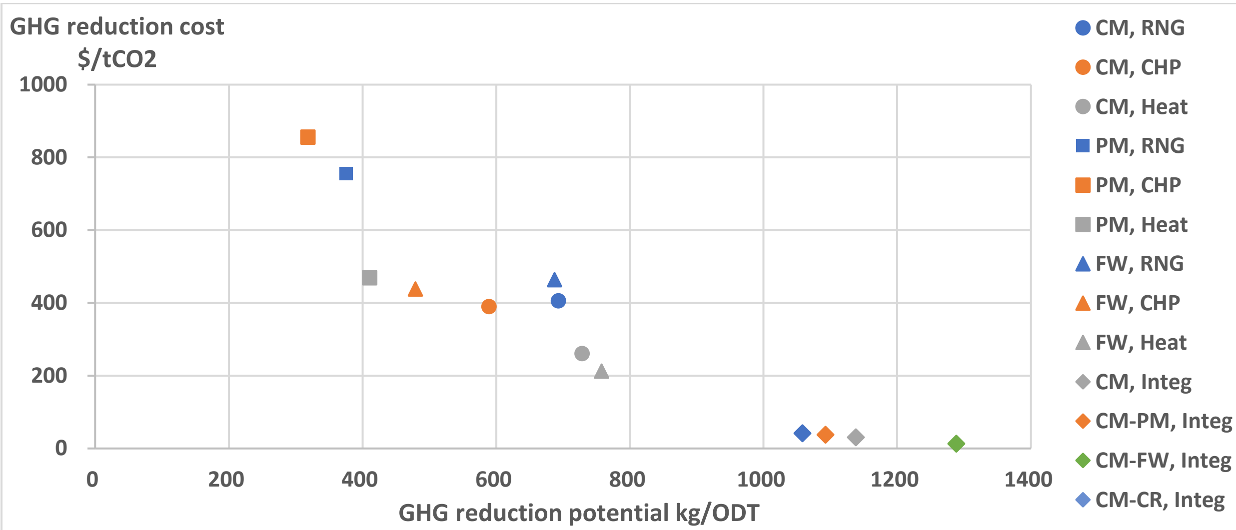



**Figure 5 GHG reduction potential and costs of anaerobic digestion of organic wastes in BC** [1], [15]**. CM = cattle manure, PM = poultry mature, FW = food waste.**

## 2. Renewable electricity and electrification

### 2.1 Renewable electricity sources

Hydroelectric generation is the main electricity source in BC, providing 90% of total supply [21] and expected to grow significantly. The Site C project currently under construction should provide an additional 18.4 PJ annually upon completion, expected in 2025. However, hydroelectric resources are limited, and no data are available on BC's total hydroelectric generation potential. Therefore, electricity from other renewable sources in BC should also be considered.

Biomass, mainly wood residues, fuels 5.5% of total generation in BC [21]. Section 2.1.1 identified the scope to expand the use of biomass, but power generation must compete with other uses of the feedstock. In the near term, with hydroelectricity dominating the mix of sources and the added capacity of Site C, biomass generation yields low GHG benefits and thus attracts little interest in BC [12]. In the long term, the position of biomass generation depends on whether other renewable sources can meet demand.

Wind energy is the third largest source of renewable electricity in BC and is growing: in 2019, .capacity reached 6.1 PJ, providing 2.5% of total generation in the province [21]. The average capacity factor, defined as output divided by maximum capacity, is about 33% in BC. Typical capacity for one wind turbine is 2.5 MW so, to match the output of Site C, about 700 turbines will be needed. Permanent direct land use for onshore turbines is about 3000 $m^2$/MW capacity, so 2.1 $km^2$ of land would be required. BC's location enables use of offshore wind turbines, which are more expensive although the additional cost is compensated at least partially by higher capacity factors. Assuming that wind generation in BC grows in line with the annual rate of 14% predicted globally by the IEA [22], annual output could reach 26 PJ in 2030, a substantial addition to future renewable electricity supply.

Solar photovoltaic (PV) generation is a major source of renewable electricity world-wide, but its contribution in BC is nugatory (0.043%) [21]. BC does not have strong solar radiation: average annual output of PV panels in BC is 1200 kWh/kW capacity (corresponding to an average capacity factor of 14%), and each kW capacity requires more than 7 $m^2$ of panel area [23]. To match the output of Site C would require as much as 30 $km^2$ of panels so that, if PV is to make a significant contribution in BC, distributed rooftop collectors and large-scale solar farms will all be needed.

Wind and solar generation are intermittent, i.e. not continuous or controllable. The possible proportion of intermittent generation in the grid depends on matching supply and demand, using dispatchable sources – hydroelectric (including pumped storage), biomass, and conventional fossil fuel-based generation. In many European countries, including Germany, Spain, and UK, the total share of wind and solar electricity has approached or exceeded 30% [24], [25], and may realistically increase to 45-50% by 2040 [26]. In US, EU, and China, the share of intermittent electricity is also expected to exceed 20% by 2026 [22]. It is therefore reasonable to expect BC's grid to be able to accommodate far more than the current 2.5% of intermittent generation; 20% appears to be a modest target for 2030, and 40% for 2050.

### 2.2 Efficiencies of electrification technologies

The most efficient ways to use electricity differ between the applications targeted in CleanBC: buildings, transportation, and industrial production. Energy demand in buildings is mainly for low-grade heat, which can be provided by electric heat pumps or resistance heaters. Heaters merely convert electrical input, whereas output from a modern heat pump can be at least three times the electrical input, giving an efficiency at least three times that of a resistance heater.

For transportation, the immediate option is the electric vehicle (EV). EVs use less than 30% energy per km than internal combustion engine vehicles (ICEVs) of similar size [27]. Electricity can also be used to produce other energy carriers, such as hydrocarbons for ICEVs from captured carbon (Carbon Capture and Utilization, CCU) and hydrogen for fuel cell vehicles (FCVs) by water electrolysis. ICEVs using synthesized hydrocarbons have similar efficiency to those using fossil fuels while FCVs have about twice the energy efficiency of ICEVs [27]. However, converting electricity to other energy carriers involves significant energy losses so that these options have much lower overall efficiency than EVs.

Electrification can reduce industrial energy consumption in two main ways: replacing natural gas and diesel engines by electric motors for motive power, and replacing fossil fuel boilers by electric resistance heaters for high-grade thermal energy. The efficiency of electric motors, defined as motive power output divided by energy input, can reach 85%, whereas the efficiency for natural gas engines is 30-40% [28]. Electric resistance heaters can approach 100% efficiency, whereas the efficiencies of modern natural gas furnaces and boilers are typically around 90% [29]. The efficiency advantage of electric motors is notably higher than that of electric heaters. However, both these applications depend on the availability of low-carbon electricity; if the electricity is generated from fossil fuels, the comparison depends on the application, with direct firing usually preferred for furnaces and boilers due to the inefficiencies in power generation.

# 3. Hydrogen

## 3.1 Hydrogen production pathways

Hydrogen is an energy carrier that can be derived from various primary energy sources. In BC, potential hydrogen production pathways include water electrolysis using renewable electricity, biomass gasification, and steam methane reforming (SMR) with or without carbon capture and storage (CCS). Hydrogen produced from low-carbon electricity and biomass is considered as "green hydrogen", which inherits the low carbon intensity of these renewable energy sources. Hydrogen produced by SMR of fossil natural gas coupled with CCS also has low carbon intensity and is termed "blue hydrogen". Hydrogen produced from fossil natural gas without CCS has high carbon intensity and is thus labeled "grey hydrogen". To ensure effective GHG mitigation, BC intends to set a gradually declining carbon intensity threshold for hydrogen [30], which means only green and blue hydrogen should be considered.

In principle, green hydrogen has the advantage of being renewable. However, green hydrogen suffers from additional energy losses during the conversion process and competes with alternative applications for the same renewable energy sources: in the context of limited renewable energy supply (see Section 3), energy used to produce hydrogen is diverted from more beneficial uses. Blue hydrogen is therefore more practical for BC, giving BC's abundant natural gas resources a role in a future carbon-neutral economy and helping relieve the pressure to expand renewable energy supply. However, a low carbon intensity for blue hydrogen depends on curtailing methane emissions from natural gas supply and hydrogen conversion.

## 3.2 Hydrogen utilization options

Like bioenergy and electricity, the most efficient uses of hydrogen must be identified and prioritized. The two main potential applications are (1) fuel-cell vehicles (FCV) replacing internal combustion engine vehicles (ICEV); and (2) direct combustion for thermal energy replacing combustion of fossil fuels, primarily natural gas for low-grade heating in buildings or high-grade thermal energy in industrial processes. FCVs are twice as efficient as ICEVs of similar size (see Section 2.2.2). On the other hand, combustion of hydrogen has similar efficiency as fossil fuels Therefore, using hydrogen in FCVs displaces more fossil fuels and achieves significantly higher GHG mitigation, and is therefore preferable to direct combustion.

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