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Removing the Bottleneck on Wind Power Potential to Create Liquid Fuels from Locally Available Biomass

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Abstract: In order to reduce global greenhouse gas emissions, renewable energy technologies such as wind power and solar photovoltaic power systems have recently become more widespread. However, Japan as a nation faces high reliance on imported fossil fuels for electricity generation despite having great potential for further renewable energy development. The focus of this study examines untapped geographical locations in Japan's northern most prefecture, Hokkaido, that possess large wind power potential. The possibility of exploiting this potential for the purpose of producing green hydrogen is explored. In particular, its integration with a year-round conversion of Kraft lignin into bio-oil from nearby paper pulp mills through a near critical water depolymerization process is examined. The proposed bio-oil and aromatic chemical production, as well as the process' economics are calculated based upon the total available Kraft lignin in Hokkaido, including the magnitude of wind power capacity that would be required for producing the necessary hydrogen for such a large-scale process. Green hydrogen integration with other processes in Japan and in other regions is also discussed. Finally, the potential benefits and challenges are outlined from an energy policy point-of-view.

Keywords: green hydrogen; biofuel; kraft lignin; wind power; Japan

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1. Introduction

Society has become highly reliant on fossil fuels to meet its energy needs, such as for electricity generation, transportation, and industry. However, considering our current understanding of climate change and greenhouse gas (GHG) emissions, society is faced with the challenge of finding energy alternatives to replace fossil fuels [1]. This situation, fortunately, is starting to change. Renewable energy technologies such as solar photovoltaics (PV) and wind power have been largely developed in the past decades. These have reached a level of technological feasibility that makes them realistic alternatives to fossil fuel generated electricity in many cases [2]. These developments correlate with a large decrease in implementation costs because of technological improvements, economies of scale, and support policies [3] that have led them to outcompete with fossil fuel generated power in various instances.

While these technologies offer the possibility of producing electricity with low GHG emissions, they also bring new challenges to the table. The intermittent nature of the phenomena these technologies depend on results in fluctuating electricity generation that must be managed by grid operators [4]. Additionally, while many sectors of the economy can be electrified, the transportation and industrial sectors largely still require hydrocarbon based liquid fuels [5].

Furthermore, restrictive existing infrastructure and planned fossil-fuel-powered energy projects further deter the possibility of implementing renewables in meaningful, larger, magnitudes [6]. This can be further complicated depending on the country in question. The legal arrangement of production and distribution of electricity varies by country, with most countries having different power companies operating in each region, which may cooperate to a limited extent outside of their core region. Because of these issues, even in geographical areas that have larger potential for further renewable energy development, they may often go unexploited.

One of the methods to exploit renewable energy's potential while avoiding these issues is the use of power-to-fuel (PtF) processes, that to some extent function as a way to "store" electricity as chemical compounds. PtF processes have been in development recently, allowing for transformation of electricity to storable fuels, with the production of "green hydrogen" taking the spotlight [7]. Green hydrogen is produced via electrolysis of water in a relatively simple process, and has attracted great interest due its lack of GHG emissions upon combustion, compatibility with fuel cells [8], and wide applications in industry such as steel production [9], chemical production [10], and oil refining [11].

The overall aim of this paper is to explore how to eliminate or reduce the curtailment of renewable energy for geographical locations in Japan that possess large wind power potential that is unexploited due to geographic and economic factors. We propose this may be achieved by integrating the production of hydrogen with readily available biomass to produce high energy content bio-oil. Analyses of the potential benefits of this process' integration are highlighted and calculations are drawn for the magnitude of renewable energy capacity required for a given amount of biomass.

For this study, we selected Kraft lignin from the Kraft pulp industry as the targeted biomass due to its year-round availability and large production in geographic areas that possess large wind power potential. The northernmost regions of the world above the equatorial line comprise the majority of the total available onshore wind power potential [12]. Simultaneously, Kraft pulp producing countries, with the exception of Brazil, are largely located in north America, Europe and east Asia [13], thus being viable candidates for the previously outlined process.

2. Background Analysis

2.1. The Role of Hydrogen in Renewable Energy Systems Design

Given that hydrogen can be readily produced from renewable energy sources, it can utilize excess electricity produced from solar PV and wind turbine electricity production to be stored in the form of hydrogen gas [14], or be used entirely for that purpose in an off-grid arrangement [15]. Proton exchange membrane (PEM) technology allows for high purity hydrogen to be produced at efficiencies ranging from 60 to 80% [16], can respond faster to increased operation than other electrolysis methods [17], and has been steadily getting closer to reaching economic feasibility [18].

Hydrogen gas could, in theory, replace many of the applications currently served by fossil fuels, allowing for processes that normally emit large amounts of CO_2 to operate at drastically reduced emission levels [19]. Despite this, little progress has been made toward achieving this, with the reasons cited often relating to the nature of hydrogen itself; hydrogen possesses high gravimetric energy density, but low volumetric energy density at standard conditions [20], unlike common liquid hydrocarbon fuels. For this reason, transportation of hydrogen in large quantities requires low temperatures and high pressures, requiring infrastructure with higher specifications when compared to, for example, natural gas.

To overcome hydrogen's disadvantages, many studies suggest the possibility of reacting hydrogen with different chemical species for the purpose of transforming it into more easily transportable fuels. Examples include CO_2 hydrogenation to methanol [21] and methane [22], as well as ammonia production [23]. Yet, these technologies are still under development or are not compatible with current infrastructure. A more practical short-term alternative would be the hydrogenation of a biomass-derived bio-oil whose high oxygen content can be greatly reduced to obtain a high-energy-density liquid hydrocarbon mixture, and for this reason, we discuss the conversion of Kraft lignin into bio-oil in a subsequent section.

2.2. Kraft Lignin Bio-Oil as a Renewable Energy Carrier

Lignin is found in woody biomasses, which are composed 15–30% lignin, 40–50% cellulose and 15–25% hemicellulose depending on the source, its chemical structure is made of phenolic units that, when combined, form a complex three-dimensional polymer, containing ether and carbon-carbon bonds. Kraft lignin is considered a waste product of Kraft paper pulp production; the lignin in wood along with the spent pulping chemicals is left over in a solution denominated "black liquor", which is burned in the recovery boiler of the pulping mill to recover heat and regenerate the spent pulping chemicals, and a fraction as high as 36% can be potentially removed without compromising the operation of the mill [24].

Depolymerization of Kraft lignin to produce bio-oil has been extensively studied in the past decades, and various methods have shown excellent results [25]. This depolymerization process is shown in Figure 1, where the chemical bonds of lignin are severed, usually in presence of a catalyst and a solvent at relatively high temperatures.

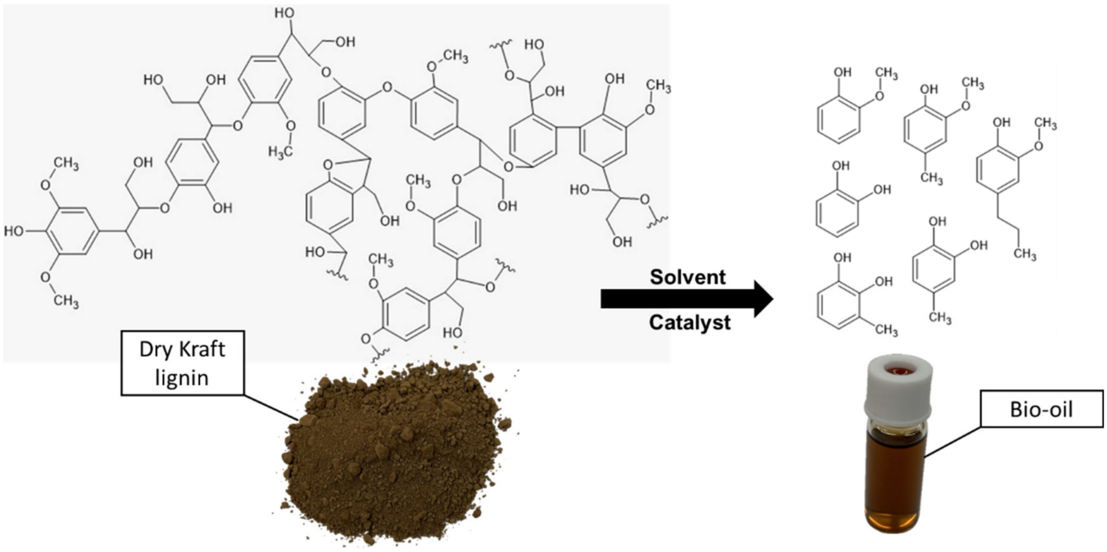

Figure 1. Lignin depolymerization process. Shown in the left side is the structure of lignin and a picture of dry Kraft lignin powder. On the right some of the chemicals contained in the resulting bio-oil after depolymerization and a sample of said bio-oil.

Lignin derived bio-oil contains about 27% oxygen by weight, depending on the production method [26], compared to crude oil's 1% [27]. Oxygen-containing species in bio-oil result in higher viscosity, worse stability, and lower heating value. Because of this, it is necessary to remove the oxygen content through a hydrodeoxygenation (HDO) process. HDO processes employ molecular hydrogen in presence of a transition metal catalysts at relatively high temperatures.

2.3. Renewable Wind Energy Potential in Hokkaido and Challenges for Wind Power Expansion

Hokkaido, the northernmost island of Japan, is sparsely populated, yet holds the highest onshore wind power potential among all prefectures of Japan, followed by Tohoku and Kyushu, as illustrated in Figure 2.

Despite this extensive potential, as of 2017, Hokkaido has only installed 441 MW of wind power capacity [28], relying almost entirely on imported fossil fuels for electricity generation [29], which Japan lacks any meaningful reserves of. Furthermore, 2011's Fukushima Daichi disaster, pushed for further regulations on nuclear energy and a change in the population's attitude toward nuclear power, resulting in a small increase in renewables since then.

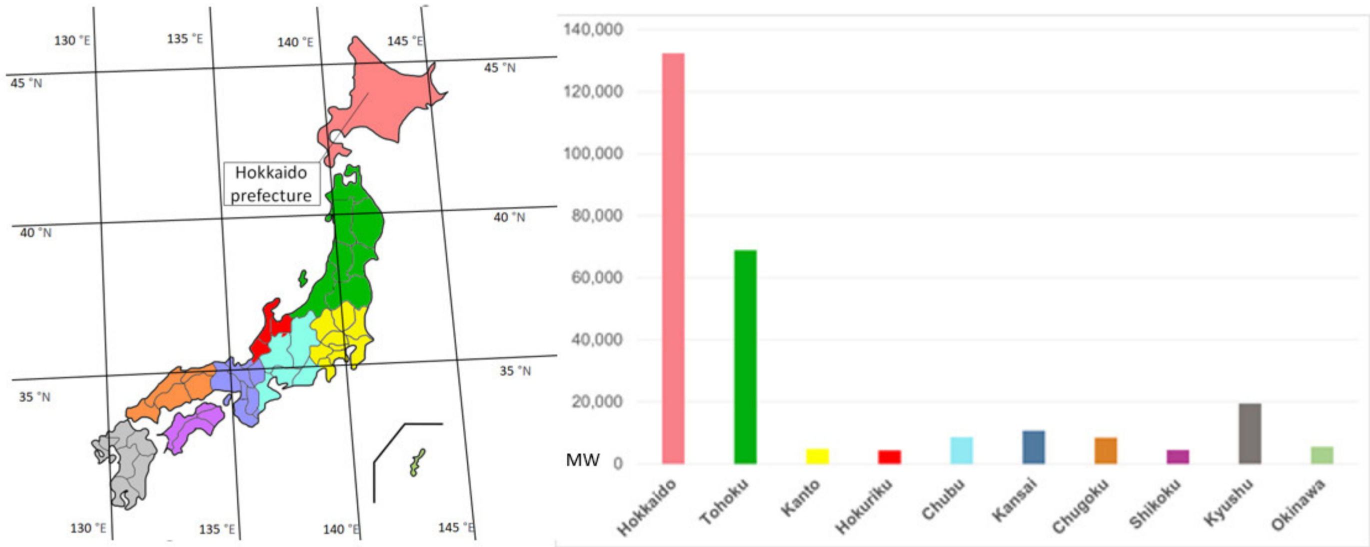

Figure 2. Geographical location and onshore wind power potential of Hokkaido (MW). Renewables 2017 Japan status report, Institute for Sustainable Energy Policies.

Even if these renewable energy potentials were completely exploited, due to the magnitude and intermittent nature of these natural phenomena, generation will exceed the demand, leading to a surplus that must be redirected, stored, or simply disconnected from the grid (curtailed). Redirection of electricity among countries is well-known and studied, as seen in many European countries [30], although despite this, Japan does not currently possess any connections to other countries, with South Korea currently being the most feasible candidate for interconnection with west Japan [31]. Owing to Hokkaido's geographical location at the northernmost of Japan, the only possible connection would be with east continental Russia and Sakhalin Island, which are also sparsely populated.

The Hokkaido area has low population growth and a relatively stable energy consumption from its industries in the last decade [32], meaning that there is little incentive to exploit the wind power potential that exists. In a given scenario where a significant quantity of wind power capacity was implemented in Hokkaido, the current forecast for 2030 reveals that it is likely that this wind power would not be able to be used unless major changes in the planned energy developments were done, or electrical grid capacity was expanded to trade electricity with the Tohoku region. This would require Tohoku to enable a sufficient grid capacity extension with Tokyo to efficiently make use of the electricity and minimize power losses. In 2019, the grid capacity was expanded [33] from 0.6 GW to 0.9 GW between Hokkaido and Tohoku and recent investment for developing further 0.6 GW grid extension from northern Hokkaido has been confirmed [34]. Additionally, the possibility of undersea cable projects originating in Hokkaido to the greater Tokyo region have been recently proposed [35], though it must be kept in mind that the available onshore wind power potential far surpasses the extensions carried out so far.

It is important to note that each region within Japan has its own regional electrical power company, thus further complicating the trading, planning and implementation of such an extended grid. This situation, along with the fact that power companies would rather not invest in renewable energy so as not to further deteriorate the economic value of their existing assets, has resulted in very slow expansion of renewables, despite the seeming urgency.

3. Concept Description and Methodology

This study aims to highlight the possibility of exploiting this large renewable energy potential to produce hydrogen, which in turn would allow the production of other valuable products such as fuels, commodity chemicals and raw materials that can result in economic growth and a reduced dependency on imports.

The scenario described below points to the possibility of using Kraft lignin from paper pulp mills in Hokkaido as a year-round source of biomass that can be reliably transformed to bio-oil that is then upgraded with wind-power-derived hydrogen, allowing for the constant production of a high-quality hydrocarbon mixture and aromatic chemicals.

The integration of hydrogen production from a wind farm and lignin depolymerization process is illustrated in Figure 3. Where wind power-derived electricity would be directly used for the producing hydrogen, this would then be used in upgrading Kraft lignin derived bio-oil from a paper pulp mill on a year-round basis.

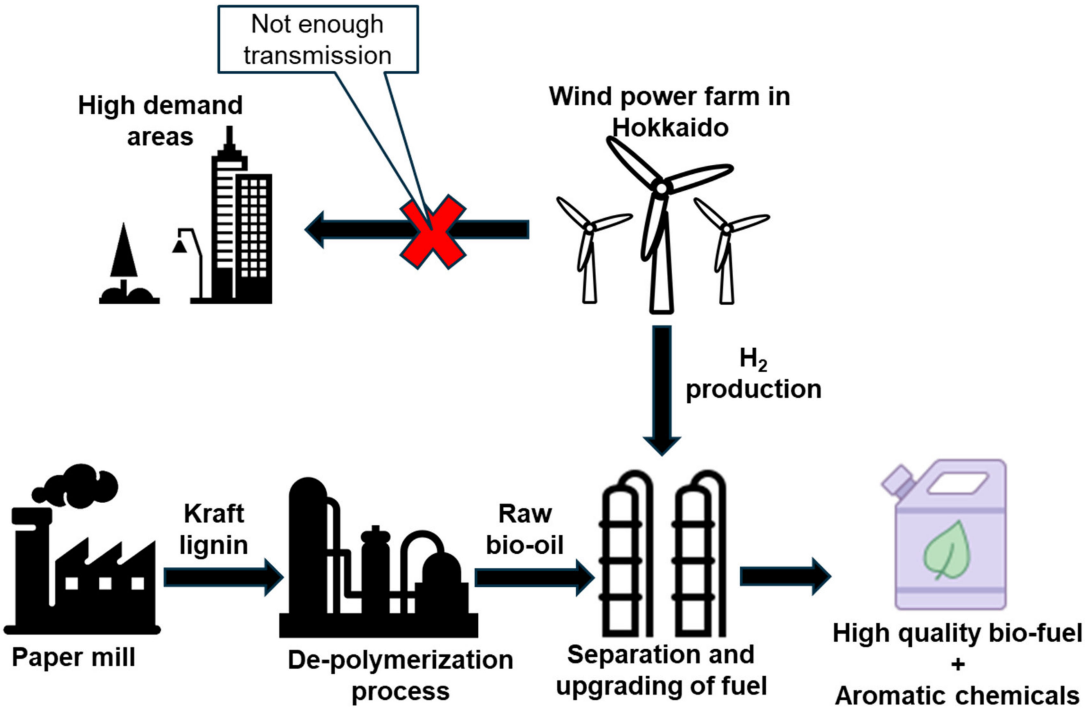

Figure 3. Integrated hydrogen production from wind power and lignin depolymerization for biofuel production.

The proposed lignin depolymerization process is based on a techno-economic assessment by [36], where estimations for the economic feasibility of implementing a hydrothermal lignin depolymerization process were carried out. This study provided insight about the production of bio-oil, BTEX (benzene, toluene, ethyl-benzene and xylene) and char from the excess lignin produced in Swedish Kraft pulp mills. The process consists of removing the excess lignin from black liquor through a non-specified process, wet lignin is fed into a lignin slurry tank along with an alkali catalyst and then into a near critical water (NCW) plug flow reactor, while the bio-oil phase produced is separated for upgrading in a later part of the process.

Bio-oil upgrading through HDO was based on a study conducted by [37], where anisole and guaiacol were used as model compounds for lignin bio-oil and hydrodeoxygenated in presence of molecular hydrogen and a NiMo/SiO_2 in a fixed bed reactor. This study was used to estimate the hydrogen required to successfully remove the oxygen from the bio-oil. Tables 1 and 2 describe the operating conditions of the NCW and HDO processes.

Table 1. Operating conditions of NCW lignin depolymerization process.

Temperature	350 °C
Pressure	25 Mpa
Residency time	11 min
Recycle ratio	3:6
Alkali salt catalysts	K_2CO_3 or KOH
Amount of alkali catalyst required per amount of reactant	0.1 kg catalyst/kg lignin feed
Solid catalyst substrate	0.5 kg catalyst
Mass flow of feed/mass of catalyst	5 kg/hr/kg catalyst
Mass of desired product/mass of total product (wt %)	88%
Water soluble aromatics (wt %)	20%
Mass of reactant feed/total influent mass (wt %)	5.50%

Table 2. Operating conditions of HDO process.

Temperature		410 °C
Pressure		1 atm
Weight hour space velocity		1.5 h^{-1}
H_2/guaiacol equivalents (mol/mol)		5
Conversion %		99.79
Product yield %	Gas (CH_4)	6.28
	Condensable organics	62.96
	Water	26.34
Selectivity to aromatic hydrocarbons (%)		97.53

While the original NCW study [36] delves into techno-economic analysis of a standard Kraft pulp mill, here we do not provide such estimations, as we exclusively focus on the potential for the conversion for all available Kraft lignin in Hokkaido. Japan produces a significant portion of the world's Kraft pulp at around 5% yearly, whereas Hokkaido accounts for 10.76% of this total production amount as of 2018 [38]. To this end, we assume that the amount of lignin removable from the Kraft pulping mills is either 30%, which is currently viable, and 100%, under the possibility that lignin becomes a valuable commodity, which would require innovations in Kraft pulp processing. It is assumed that 0.3 MT of lignin is produced per MT of Kraft pulp produced.

For the wind power capacity required for hydrogen production, it was assumed that hydrogen's specific energy is 142 MJ/kg and is produced with an efficiency of 70% from PEM electrolysis [39], thus producing 202.85 MJ/kg of hydrogen. Wind turbines are in operation 365 days of the year, 24 h a day, with a capacity factor of 20%. All of which are in line with known values from literature and reports.

4. Results and Discussion

4.1. Scenario Results

Considering Hokkaido's total Kraft pulp production of 1,326,000 MT, according to the 2018 prefectural report [38], the total production of crude bio-oil and char is summarized in Table 3 for both scenarios.

Table 3. Products from NCW lignin depolymerization process.

Product	Kraft Lignin Removed from Pulp Mill (wt %)	
	100%	30%
Char (MT/yr)	47,736.0	14,320.8
Crude bio-oil (MT/yr)	350,064.0	105,019.2

In this crude bio-oil, there is a 20% water soluble fraction of aromatic monomers that can be upgraded to BTEX in the HDO process [40]. The remaining bio-oil is comprised of larger, oxygen-containing poly aromatic structures without a definitive structure. Char produced by the NCW process could be burned as fuel to generate power, however, there is significant research in the use of lignin derived chars to produce high-quality microporous activated carbons which has potential applications as pollutant absorbents [41].

The properties of crude lignin bio-oil produced by a similar process were studied by [42], suggesting that the oxygen-containing species found in the bio-oil resemble guaiacol. The crude lignin bio-oil produced by the NCW process contains 15% oxygen by weight, which is notably low when compared to bio-oils obtained from pyrolysis processes [43]. This fact was used as the basis for the calculations of the HDO process. The products obtained from the HDO process are shown in Table 4.

Table 4. Products from HDO process.

Product	Kraft lignin Removed from Pulp Mill (wt %)	
	100%	30%
Upgraded bio-oil (MT/yr)	219,689.5	65,906.9
BTEX (Ton/yr)	54,922.4	16,476.7

Aromatics in this upgraded bio-oil, along with cycloalkanes if further hydrogenation is carried out, could provide essential properties for elastomeric swelling, material compatibility, and lubricity that are not found in other current bio-jet fuels, which until now have required blending with traditional petroleum oils [44]. The primary advantage of lignin bio-oils is that their chemical composition is comparatively simple, being comprised almost entirely of aromatic hydrocarbons, which would allow easier blending with other biofuels such as fatty acid methyl ester (FAME) or fossil fuel-derived stocks.

In addition, the consistent production of BTEX chemicals boosts the economy of the process by guaranteeing some income and reducing the impact of the volatility of bio-oil prices, which are affected by the price of other fossil fuels. Decoupling the price of BTEX from oil prices might play an important role in the future as the production of aromatics is directly tied to gasoline production via catalytic reforming, obtaining aromatics from lignin may allow for more competitive prices and reduce emissions associated with their production.

For comparison, the lower heating value (LHV) of Kraft lignin, crude bio-oil and upgraded bio-oil were estimated by using Dulong's formula (1), where mC, mH, mO and mS are the weight fraction of carbon, hydrogen, oxygen and sulfur, respectively, with the calculated values reported in Table 5. The elemental composition of Kraft lignin and crude bio-oil were taken from [42].

$$\mathrm{LHV(Mj/kg)} = 33.8\ \mathrm{mC} + 122.3\ (\mathrm{mH} - \mathrm{mO}/8) + 9.4\ \mathrm{mS} \quad (1)$$

Removal of oxygen by the HDO processing resulted in a 30% increase in LHV from crude bio-oil, resulting in 40.5 MJ/kg, which is close to the value of conventional gasoline or diesel. During the calculations it was assumed that the sulfur and nitrogen content in Kraft lignin would not be removed by the HDO process, however, the values for both are similar to those seen in regular crude oil feedstocks, indicating that their removal should not pose a particular challenge, but must be done to prevent the formation of contaminants upon combustion.

Table 5. Elemental composition and LHV of Kraft lignin, crude bio-oil and upgraded bio-oil.

Elemental Composition (%wt)	Kraft Lignin	Crude Bio-Oil	Upgraded Bio-Oil
Carbon	65.6	75.3	89.6
Hydrogen	5.7	6.4	8.3
Oxygen	26.0	15.0	0.001
Nitrogen	0.9	1.1	1.4
Sulfur	1.8	0.4	0.5
Dulong's formula LHV (MJ/kg)	25.3	31.0	40.5

Upgrading of crude bio-oil by HDO would require hydrogen, which can be produced by exploiting unused wind power potential. Bio-oil's high oxygen content is often cited as the biggest wall in implementation. Given that hydrogen production is currently strongly dependent on methane reforming, which is prohibitively expensive for small and medium sized applications, the prospect of cheap green hydrogen from water electrolysis could be the key for the implementation of technologies that until now have been curtailed by the necessity of using fossil fuel-derived hydrogen.

The calculated values for the necessary hydrogen production and by extension the required wind power capacities are shown in Table 6.

Table 6. Calculated necessary wind power capacity for hydrogen production both scenarios.

Energy Requirements	100% Case	30% Case
Hydrogen production (MWh)	924,615.7	277,384.7
Required wind power capacity (MW)	527.7	158.3

The magnitude of required wind power capacity for the 100% case equals over 10% of the current installed capacity in Japan [28]. It must be noted that hydrogen storage would be necessary up to a certain point, as even if the consumption of hydrogen takes place year-round consistently, as, due to the intermittency of wind, hydrogen production will show peaks and valleys.

4.2. Energy Efficiency and Economic Aspects

From the perspective of energy efficiency, it is hard to draw a definitive conclusion for the overall process, but in terms of renewable energy usage a few key conclusions can be drawn. Based on the previous LHV calculation using Dulong's formula, we can observe that by spending 9.5 MJ worth of hydrogen to upgrade the produced crude bio-oil we obtain a LHV increase of the same magnitude in the upgraded bio-oil.

It is important to keep in mind that crude bio-oil cannot be used directly as fuel in most conventional engines due to its high oxygen content, requiring upgrading by hydrodeoxygenation before being usable. Under this assumption, the energy efficiency from the hydrogen production perspective approaches 100% if used for upgrading crude bio-oil, however, this does not take in to account the energy needs for the Kraft lignin depolymerization process, nor the loss in mass in the bio-oil due to hydrodeoxygenation.

Although a concrete economic analysis for the feasibility of the overall process cannot be done at this stage, it is possible to calculate the required investment and maintenance costs for the necessary wind power capacity. In a report by Renewable Energy Institute of Japan [45] the average investment costs per MW of wind power capacity, as well as the necessary operation and maintenance costs was calculated, pointing at an investment cost of 2.87 million USD/MW and 18,181 USD/MW/year, respectively. Based-off these values the costs for the wind power capacity required for the 100% and 30% scenario area described in Table 7.

Table 7. Wind power capacity and investment required for presented cases.

-	100% Case	30% Case
Required wind power capacity (MW)	527.7	158.3
Required investment cost (Million USD)	1312.6	393.92

Assuming a turbine lifetime of 20 years and the previously mentioned operation and maintenance costs, electricity can be produced at 0.1675 USD/kWh.

The profitability of this process depends heavily on the market price for upgraded bio-oil, which would arguably be at least as valuable as FAME biodiesel, possibly more in the case of jet fuel blends, as they require a minimal aromatics content, which until now required blending with oil-derived fuel [44]. The process used is based on [36], where the production cost of the biofuel is 0.41 USD/L compared to price of gasoline in Japan at 1.16 USD/L, however, it must be kept in mind that the value from this study does not rely on green hydrogen to upgrade the biofuel, making this value only an estimate. It should be noted that gasoline purchased at a gasoline stand is heavily taxed in Japan.

Additionally, the produced BTEX chemicals could offer a consistent source of income, as their demand continues to rise and is forecasted to continue in this manner.

4.3. Energy Policy Perspective

From the point of grid operators, "priority dispatch order" dictates the order in which energy sources are used to supply electricity by giving priority to long-term base-load energy sources such as nuclear, hydropower and geothermal. In practice, this means that renewable sources of energy are only considered after these other sources are utilized. In turn, this results in power companies not having to give priority to renewable power use nor improve the grid capacity to make room for greater renewable energy transmission.

The enactment of the feed in tariff (FIT) act in 2012 in Japan [46] was originally intended to strongly incentivize the implementation of renewable energy projects by investors. If a renewable energy producer requests a power company to sign a contract to purchase electricity at a fixed price and for a long-term period guaranteed by the government, the electric utility company is obligated to accept this request. However, according to a recent report by the Renewable Energy Institute [47] one of the biggest factors in the curtailment of renewables in Japan is the fact that under the FIT act grid operators can enforce curtailment of renewable energy producers, without compensation, for up to 30 days per facility per year for purposes of balancing supply and demand. Additionally, power companies can refuse contracts that would require curtailment for over 30 days. In the case of Hokkaido, these issues are further exacerbated by the fact that local electricity demand is low, and as explained before, transmission to other regions is severely limited.

Implementing renewable energy projects explicitly for the purpose of green hydrogen production could break the bottleneck in wind power potential and in the national context, it could contribute to the recently declared goal of achieving carbon neutrality by 2050 in Japan [48]. Though detailed discussion must be carried out about the legal and economic arrangement of these green hydrogen projects, in our opinion, two overall scenarios could take place;

- Renewable energy project investors operate off-grid, produce hydrogen within the facility (wind or solar farm) and then transport it to costumers, thus potentially overcoming the need for reaching an agreement for expanded transmission capacity with the power company.

- Renewable energy project investors operate on-grid, reach an agreement for expanded transmission capacity with the power company and customers buy electricity for hydrogen production at a discounted rate.

Both scenarios can take place at the same time to some extent, but may be ultimately dependent on policy enacted. In the international context, examples of hydrogen related policy exist in western Europe and US [49], usually in tandem with other policies aimed toward decarbonization that incentivize industry to use green hydrogen and rely more on renewable energy where possible to meet their demands.

The push for expanding renewable energy adoption by companies is not new, with examples seen around the world from various private enterprises [50,51], where chemicals and fuels are produced by using renewable energy, biomass or carbon emissions as feedstocks; however, examples of this are not yet found in Japan in any meaningful significance.

5. Conclusions

In this article, the wind power potential of Hokkaido and the bottleneck inherent to its exploitation were outlined. Integration of green hydrogen production via electrolysis of water with Kraft pulp mills was suggested, and calculations were drawn to highlight the potential of producing economic value from renewable energy.

The cases presented in previous sections serve as example of a possible way to generate value off renewable energy in way that is not coupled to electricity demand. For Hokkaido, which holds an extensive share of Japan's agricultural output, post-harvest waste could represent a viable feedstock that could be transformed into fuel and chemicals similarly to that described in this study. The production of ammonia fertilizers in Hokkaido could be of interest, as their production normally requires the availability of natural gas for hydrogen production and could show a synergy with the production of energy crops [52].

Green hydrogen production locally could be the key for decoupling the economic value of renewable energy potential from electricity demand. At the same time, the production of hydrogen in Hokkaido could allow for hydrogen-relying industries that would otherwise not be economically viable to take place in the region, resulting in a positive socio-economic impact by creating jobs and incentivizing migration to less populated areas of the country.

Further techno-economic analysis for various industrial sectors needs to be carried out to accumulate proof of the viability of this kind of integrated processes, as well as detailed study of the possible energy policy that could serve to incentivize the private sector companies to develop processes that take advantage of the large available wind power potential in the region.

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