Chapter 10

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Chapter 10

Curtailed Electricity Surplus from Renewables for Hydrogen: Economic and Environmental Analysis

Youngho Chang[13] and Han Phoumin[14]

This study examines how well producing hydrogen via electrolysis from curtailed electricity from renewables could fulfil environmental benefits against the cost of producing hydrogen via electrolysis in the context of the Association of Southeast Asian Nations (ASEAN) and the East Asia Summit (EAS). The cost of producing hydrogen via electrolysis ranges from less than US$2 per kgH_2 when the electrolyser load factor is 1,500 hours or above to US$10 per kgH_2 or even higher when the electrolyser load factor is 500 hours or lower. The amount of CO_2 emissions abated by hydrogen produced from curtailed electricity from renewables ranges from about 130 million tonnes to about 150 million tonnes for ASEAN and from about 18,000 million tonnes to about 19,000 million tonnes for EAS. Applying prevailing carbon prices to the CO_2 emissions abated, the possible monetised benefits of hydrogen produced via electrolysis from curtailed electricity from renewables range from about US$0.25 per kgH_2 to about US$9.00 per kg H_2 for ASEAN and from about US$0.50 per kgH_2 to about US$15.00 per kg H_2 for EAS. The results of the cost-benefit analysis suggest that the price of carbon needs to be about US$10 per tonne of CO_2 to justify hydrogen produced via electrolysis from curtailed electricity from renewables for both ASEAN and EAS. The results also suggest that high electrolyser load factors make hydrogen produced via electrolysis from curtailed electricity from renewables cost-competitive even under low carbon prices.

Keywords: Hydrogen, Curtailed electricity, Cost-benefit analysis, Carbon price, Electrolyser load factor, CO_2 emissions; ASEAN; EAS.

1. Introduction

Hydrogen can be a reliable source of energy provided a dependable supply at a reasonable price. Hydrogen is not found in nature and is classified as, grey (or brown), blue, and green depending on how it is produced.

The two methods to produce hydrogen are reformation, as with natural gas, and electrolysis. The former is still based on fossil fuels, making it not a sustainable solution. The latter can be sustainable if a reliable and environmentally friendly source of electricity is secured. Electricity generated from fossil fuels may not be desirable for electrolysis in the long term, but electricity generated from renewable sources could be desirable.

There are currently various methods of large-scale hydrogen production, namely steam reforming with carbon capture sequestration (CCS), alkaline electrolyser with stable or

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fluctuating power, lignite gasification and woody biomass generation (IEA, 2019). Steam reforming with CCS presents the lowest cost followed by lignite gasification with CCS and woody biomass gasification. The cost of alkaline electrolyser with stable power is almost three times that of steam reforming with CCS, while alkaline electrolyser with fluctuating power costs almost six times of that of steaming reforming with CCS. For the alkaline electrolyser, feed cost is the main source of the high cost and followed by CAPEX and OPEX (IEA, 2019).

When electricity generated from renewable sources does not have corresponding demand, it causes negative net load. Net load is defined as the difference between forecasted load and expected electricity production from variable generation sources. The load structure of a typical spring day in California shows there are four typical ramping possibilities, namely at 4:00 a.m., 7:00 a.m., 4:00 p.m. and after sunset (or around 6:00 p.m.). The 4:00 p.m. possibility is the most significant daily ramp (CAIS), 2017).

Curtailing renewables is one way of solving the oversupply problem, despite electricity being wasted (CAISO, 2017). To utilise this opportunity is using cheap or free 'otherwise curtailed' electricity (IRENA, 2019).

One of the ways to mitigate oversupply is to increase demand; in other words, to offer consumers time-of-use rates, to increase energy storage, and to increase the ability of power plants to respond more quickly to changes in generation levels. The inherent variability of renewables such as wind or solar is an impediment to their effective use. Hydrogen fuel and electric power generation could be integrated at a wind farm. This allows flexibility of shifting production to best match resource availability given system operational needs and market factors. In times of excess electricity production from wind farms (i.e., the Belly of the Duck curve), instead of curtailing the electricity as is commonly done, this excess electricity can be utilised to produce hydrogen through electrolysis.

This study evaluates whether curtailed electricity from renewables, in the context of the Association of Southeast Asian Nations (ASEAN) and the East Asia Summit (EAS), can be used to produce hydrogen and how well it could serve these objectives in terms of economic and environmental perspectives. It estimates how much hydrogen is to be produced from curtailed electricity from variable renewables in the ASEAN and EAS regions.

The hydrogen produced would replace fossil fuels and, hence, reduce CO_2 emissions in the region. The amount of CO_2 emissions abated is treated as possible environmental benefits to be monetised by applying a prevailing carbon price in the US, the European Union (EU), or Singapore to the amount of emissions abated per unit of hydrogen produced from utilising curtailed electricity generated from renewables. This study surveys the cost of producing hydrogen through electrolysis in the literature and adopts a few estimates to examine the monetised environmental benefit against the cost of producing hydrogen via electrolysis.

There seems to be no study that applies a cost-benefit analysis to curtailed electricity for producing hydrogen against possible monetised benefits accrued from abated carbon dioxide emissions due to the produced hydrogen replacing fossil fuels. A few studies present the cost of producing hydrogen (Proost, 2019 and IEA, 2019), but there are no extensions to compare the cost of producing hydrogen from curtailed electricity to possible monetised benefits from abated carbon dioxide emissions. Such a novel application of a cost-benefit analysis is to be the contribution of this study to the literature.

The rest of this study is structured as follows. Section 2 reviews the types of hydrogen production, various cost estimates of hydrogen production from variable renewables, and environmental implications of hydrogen production from variable renewables via electrolysis. Section 3 presents details of methodology applied in the study such as the cost estimation of producing hydrogen from curtailed electricity from variable renewables via electrolysis, the benefit estimation of producing hydrogen from curtailed electricity from renewables via electrolysis in the ASEAN and EAS regions, and estimates of carbon prices. Section 4 discusses results and draws policy implications based on the results of the cost-benefit analysis conducted. Section 5 concludes this study.

2. Hydrogen: Variable Renewables and Environmental Implications

2.1. Hydrogen and Variable Renewables

There are three types of hydrogen by production methods: grey or brown, blue, and green hydrogen. Grey hydrogen is typically produced in a process called steam methane reformation, while brown hydrogen is produced from the coal (or ignite) gasification. Blue hydrogen is produced mainly from natural gas but with CCS technology. Green hydrogen is produced by a process called electrolysis in which a unit called an electrolyser that is powered splits water into hydrogen and oxygen using non-carbon-emitting electricity (DNV GL, 2020). Electrolysers can assume various sizes, such as a small, appliance-size piece of equipment to a large-scale, central production facility. The former is good for small-scale distributed hydrogen production, while the latter is good for an electricity grid that is directly linked to renewable or non-carbon-emitting electricity generation technology (US Department of Energy, n.d.).

Apart from the types of hydrogen by production methods, there are various methods of large-scale hydrogen production, namely steam reforming with CCS, alkaline electrolysers with stable or fluctuating power, lignite gasification, and woody biomass generation (IEA, 2019). Steam reforming with CCS presents the lowest cost, followed by lignite gasification with CCS and woody biomass gasification. The cost of alkaline electrolysers with stable power is almost three times that of steam reforming with CCS, while using alkaline electrolysers with fluctuating power costs almost six times that of steaming reforming with CCS. For the alkaline electrolyser, feed is the main source of the high cost, followed by capital and operation expenditure (IEA, 2019). For making electrolysis a viable source of hydrogen, it is critical to reduce the capital cost of the electrolyser unit and the balance of the system, and to improve energy efficiency for converting electricity to hydrogen. Cost is the key determinant for the wide adoption of electrolysers. However, electrolysis could be a promising option for hydrogen production where renewable resources are used as the sources of electricity.

Hydrogen can play two key roles in the global economy, namely as a booster that accelerates more usage of renewable electricity and a channel that helps the global economy decarbonise. First, hydrogen can boost renewable energy by functioning as storage and a reliable source of cleaner energy. Second, hydrogen production via electrolysis can lead to zero carbon dioxide emissions depending on how electricity is generated, which could present a pathway to a net zero future. Green hydrogen has huge implications for storing energy generated from renewables such as wind and solar energy. Green hydrogen has been active in a few states in the US, such as California and Utah (Mitsubishi Heavy Industries, 2020). Considering the sheer volumes of decarbonising needed in the electricity sector, however, green hydrogen is not expected to be fully utilised in the near future. As a result, blue hydrogen must be fully developed and utilised before green hydrogen works at full scale (Dickel, 2020).

Hydrogen has been cost-competitive and hailed as a low-carbon option. The Hydrogen Council pegs the 2020 cost of producing hydrogen via electrolysis from dedicated offshore wind in Europe to be on average US$6/kg$H_2$; it projects the cost to be US$2.6/kg$H_2$ in 2030. The breakdown of the drop in the cost is as follows: decreases in the capital cost (US$2.6), improvement in efficiency (US$0.4), decreases in the operations and maintenance cost (US$0.2), and decreases in the levelised cost of electricity of offshore wind (US$1.3) (Hydrogen Council, 2020).

Table 10.1 presents the estimated costs of producing hydrogen by various sources in the EU.

Table 10.1: Estimates of Hydrogen Production Costs in the European Union

Types of Hydrogen	Costs (EUR/kgH_2)	Costs (EUR/MWh)
Grey (Fossil Fuel Hydrogen)	1.5	44.9
Blue (Low-Carbon Hydrogen)	2.0	59.9
Green (Clean Hydrogen)	2.5 – 5.5	74.9 – 164.7

Source: Authors' compilation of data from Barnes and Yafimava (2020), Lambert (2020).

Compared to grey hydrogen, green hydrogen is still more expensive, as shown in Table 10.1. Green hydrogen in the EU is expected to cost-competitive by 2030, but it depends on not only the capital cost of electrolysers but also the electrolyser load factors, along with the cost of electricity from renewable sources (Barnes and Yafimava, 2020).

Hydrogen fuel can be integrated with electric power generation at the site of variable renewables, such as a wind farm. This allows production to be shifted to best match resource availability under system operational needs and market factors. When excess electricity is produced, it is possible to use it to produce hydrogen through electrolysis rather than curtailing it (US Department of Energy, n.d.).

The source of the required electricity has become critical in determining the benefits and economic viability of producing hydrogen via electrolysis. This includes the cost and efficiency of the electrolysis along with the amount of emissions coming from electricity generation. The current power grid of most countries is not suitable for providing the electricity needed to run the electrolysis sustainably because carbon dioxide and other greenhouse gases are released as long as fossil fuels are used. When hydrogen is produced via electrolysis with renewable sources from the grid or separate from the grid, such pathways will lead to virtually zero emissions of carbon dioxide and other greenhouse gases.

The pathway to hydrogen competitiveness requires developing more efficient fossil fuel-based electricity production with CCS as a short-term goal and decreasing the cost of generating electricity from renewable sources as a long-term goal. Using curtailed electricity to produce hydrogen via electrolysis is a solution to meet the long-term goal.

The Hydrogen Council identified seven roles hydrogen can play in providing the sustainable pathway to the transformation of energy sector in the global economy. First, it enables large-scale renewable energy to be integrated in power generation. Second, it helps energy be distributed across sectors and regions. Third, it spurs energy system resilience. Fourth, it decarbonises transportation. Fifth, it decarbonises industrial energy use. Sixth, it promotes the decarbonisation of heat and power in the building sector. Seventh, it provides clean feedstock for industry (Hydrogen Council, 2017). Hydrogen works as an energy carrier and storage facility in energy transition (DNV GL, 2018). Hydrogen is expected to be a transformative role in energy transition as a catalyst to decarbonise natural gas and accelerate uptake of CCS in producing blue hydrogen (DNV, 2020). Solar photovoltaic and wind energy are expected to dominate in power generation and capture 62% of variable renewable share by 2050. Natural gas is expected to be the largest energy source in this decade and remain as the dominant source until 2050. These confirm the place of hydrogen in energy transition and the status of hydrogen in the energy system (DNV, 2020).

2.2. Hydrogen and Environmental Implications

Apart from helping the energy transition of the global economy, hydrogen is suggested as a key factor in the global economy to meet the temperature target set by the Paris Agreement (DNV, 2020). As mentioned in section 2.1, hydrogen can bring environmental benefits in providing a sustainable pathway to the transformation of energy sector in the global economy. First, hydrogen enables large-scale renewable energy to integrate in power generation so that it helps the global economy abate carbon dioxide emissions by displacing fossil fuels in power generation. Second, hydrogen helps decarbonises transportation, industrial energy use and heat and power in the building sector so that it displaces carbon-emitting fuels in sectors like transportation, industry, and the building sector (Hydrogen Council, 2017).

The variable nature of renewable energy sources causes surplus in electricity supply at certain times and makes wasting the excess supply inevitable (CAISO, 2017; IRENA, 2019). The production of hydrogen from curtailed electricity via electrolysis is expected to replace power generation from fossil fuels with renewable energy and hence reduce carbon dioxide emissions. Compared to the baseline case, the amount of carbon emissions in ASEAN countries can be reduced from 28% to 64% following the rates of fossil fuels replaced (Phoumin et al., 2021).

There are many studies on how hydrogen will help the global transition to a non-carbon emission economy with good cost estimates of hydrogen production via electrolysis. Along with cost studies, there are a few studies that present how hydrogen produced from variable renewables can help reduce carbon dioxide emissions. However, whether the expected reduction in carbon emissions by producing hydrogen via electrolysis from variable renewables is cost-effective against the accrued environmental benefits is not extensively studied.

Hydrogen produced from curtailed electricity from variable renewables abates carbon dioxide emissions, which can be monetised by a carbon price. By utilising a cost-benefit analysis, this study examines the cost-effectiveness of producing hydrogen from curtailed electricity from variable renewables via electrolysis and takes the ASEAN hydrogen study (Phoumin et al., 2021) and extends it to the EAS region as a basis for estimating environmental benefits. Such an analytical framework can be applied to other regions provided a similar hydrogen production study exists. This would give at least some indication of the cost-competitiveness of producing hydrogen from curtailed electricity via electrolysis.

3. Methodology

The costs for using curtailed electricity from renewables for producing hydrogen are estimated using itemised cost inputs such as capitalisation expense (CAPEX), operating expense (OPEX), and feed cost, while the estimation of benefits is done by expected abatement of carbon dioxide emissions due to reduced usage of fossil fuels in the energy mix. The expected abatement of carbon dioxide emissions is monetised by applying current prices of carbon in the US, the EU or Singapore to the abated amount.

The cost-benefit analysis constructs a few scenarios with different costs of producing hydrogen via electrolysis in the market and discusses how carbon prices affect using the curtailed electricity surplus from renewables for producing hydrogen.

3.1. Cost Estimates of Producing Hydrogen from Curtailed Electricity via Electrolysis

There are various technical and economic factors in determining the cost of producing hydrogen via electrolysis. The electrolyser stack bears 50% and 60% of the CAPEX costs of alkaline and polymer electrolyte membranes, respectively. The power electronics, gas-conditioning, and plant components bear most of the rest of the costs. Apart from these factors, conversion efficiency, electricity costs, and annual OPEX are other key factors (IEA, 2019).

With more load hours of operation, the impact of CAPEX on the costs decreases but the electricity becomes the key cost component. For example, with CAPEX of US$450/kWe and a zero cost of electricity, the levelled cost of hydrogen could be about US$5/kg$H_2$ to less than US$1/kg$H_2$ over full load hours (IEA, 2019). This illustrates how the curtailed electricity from renewable can be a competitive way of producing hydrogen.

Running the electrolyser at high full load hours and paying for the additional electricity can actually be cheaper than just relying on surplus electricity with low full load hours. The relationship between electricity costs and operating hours becomes apparent when looking at electrolysers that use grid electricity for hydrogen production (IEA, 2019). Very low cost electricity is generally available only for a few hours within a year, which implies a low utilisation of the electrolyser and high hydrogen costs that reflect CAPEX costs. With increasing hours, electricity costs increase, but the higher utilisation of the electrolyser leads to a decline in the cost of producing a unit of hydrogen up to an optimum level at around 3,000 to 6,000 equivalent full load hours. Beyond that, higher electricity prices during peak hours lead to an increase in hydrogen unit production costs. With all these considerations, IEA (2019) asserts that ‘in the near term, hydrogen production from fossil fuels will remain the most cost-competitive option in most cases.' This study aims to show producing hydrogen using curtailed electricity from renewables is a good alternative to fossil fuel-based hydrogen production.

A detailed economic assessment by the IEA, based on hourly solar and wind data over a year in five locations across different provinces, suggests hydrogen can be produced at a cost of US$ 2–2.3/kgH2. In some provinces, the lowest production costs are reached by using only solar (Qinghai) or wind (Hebei and Fujian), while in Xinjiang and Tibet performance is best with a combination of the two (IEA, 2019).

IEA (2019) has provided various cost estimates for producing hydrogen by electrolysis. As this study uses curtailed electricity for producing hydrogen, it assumed the cost of electricity is zero. The electrolyser load factor is the key determinant of the cost of producing hydrogen. If the electrolyser load factor is about 1,500 hours or higher, then the production cost could be less than US$2/kg$H_2$. If the electrolyser load factor is about 1,000 hours, then the cost could be US$2/kg$H_2$. If the electrolyser load factor becomes very low such as about 500 hours, then the cost could be higher than US$10/kg$H_2$ (Proost, 2019).

This study takes two scenarios of cost estimates following two most plausible cases of the electrolyser load factor, namely 1,000 hours and 1,500 hours. The corresponding cost estimate is US$2/kg$H_2$ and US$1/kg$H_2$, respectively. Table 10.2 presents the cost estimates of producing hydrogen from curtailed electricity from variable renewables via electrolysis that this study adopts.

Table 10.2: Cost Estimates of Hydrogen Production by Electrolysis Load Factors

Electrolyser Load Factors (hours)	Costs (US$/kg$H_2$)
1,500	1
1,000	2

Source: Authors' compilation of data from Proost (2019), IEA (2019).

With more load hours of operation, the impact of CAPEX on the costs decreases but the electricity becomes the key cost component. This illustrates how the curtailed electricity from renewables can be the case of a competitive way of producing hydrogen. Running the electrolyser at high full load hours and paying for the additional electricity can actually be cheaper than just relying on surplus electricity with low full load hours.

3.2. Estimation of Benefits from Producing Hydrogen from Curtailed Electricity in ASEAN

The power generation mix in ASEAN is estimated for business-as-usual (BAU) and various scenarios based on renewables-shares in the energy mix using the countries' energy models by applying the Long-range Energy Alternative Planning System (LEAP) software, an accounting system to project energy balance tables based on final energy consumption and energy input and/or output in the transformation sector. Final energy consumption is forecast using energy demand equations by energy and sector and future macroeconomic assumptions.

The expected reduction of carbon dioxide emissions is monetised by current carbon prices in the US, the EU, or Singapore. This study takes hydrogen production from curtailed electricity in the ASEAN and EAS regions as the basis of calculating the possible amount of the emissions of carbon dioxide abated. Applying the LEAP software to ASEAN, Phoumin et al. (2021) presented various estimates of how much hydrogen can be produced from curtailed electricity. This study also estimates how much hydrogen will be produced from curtailed electricity by extending the ASEAN study to the EAS region. Section 3.3. presents details of how much hydrogen will be produced from curtailed electricity in the EAS region.

The study constructs scenarios of how much renewables would replace total combined fossil fuel generation, i.e. by 10%, 20%, and 30% by 2050 and labels them Scenario1 for 10% replacement, Scenario2 for 20% replacement and Scenario3 for 30% replacement. Each scenario further assumes the rate of curtailed electricity is utilised to produce hydrogen, namely at 20% to 30%. Following these assumptions, the three scenarios are renamed Scenario1H_2, Scenario2H_2, and Scenario3H_2.

The formulas to calculate potential hydrogen production in the renewable scenarios are as follows:

Scenario1H_2 (Mt-H_2) = [Scenario1 (TWh) x (Percentage of curtailed electricity) / 48 (TWh)]

Scenario2H_2 (Mt-H_2) = [Scenario2 (TWh) x (Percentage of curtailed electricity) / 48 (TWh)]

Scenario3H_2 (Mt-H_2) = [Scenario3 (TWh) x (Percentage of curtailed electricity) / 48 (TWh)]

Mt-H_2 stands for million tonnes of hydrogen; TWh is terawatt-hour; the percentage of curtailed electricity is 20% or 30% of total generation from renewables. The study also applies the conversion factor of 48 kilowatt-hours (kWh) of electricity needed to produce 1 kg H_2 (ISES, 2020).

The potential emissions abatement is the difference between the BAU scenario and various renewable-share scenarios such as Scenario1, Scenario2, and Scenario3. Table 10.3 shows the amount of hydrogen produced from curtailed electricity by various replacement scenarios in ASEAN.

Table 10.3: Hydrogen Produced from Curtailed Electricity in ASEAN

(unit: million tonnes)

	Scenario1H_2	**Scenario2H_2**	**Scenario3H_2**
Of 20% curtailed renewables	4.23	5.10	5.97
Of 30% curtailed renewables	6.35	7.65	8.96

ASEAN = Association of Southeast Asian Nations.

Source: Authors' compilation of data from Phoumin et al. (2021).

Table 10.4 presents the amount of carbon dioxide emissions that can be abated by different renewables replacement scenarios in 2050 in ASEAN. The amount of carbon dioxide emissions abated ranges from about 650 million tonnes to around 800 million tonnes.

Table 10.4: Emissions Reduction by Scenarios in 2050 in ASEAN

(unit: million tonnes)

	Baseline (2017)	**Emissions in 2050**	**Abatement in 2050**
BAU	376	1,216	-
Scenario1	376	568	648
Scenario2	376	506	710
Scenario3	376	442	774

ASEAN = Association of Southeast Asian Nations, BAU = business as usual.
Source: Authors' compilation of data from Phoumin et al. (2021).

3.3. Estimation of Benefits from Producing Hydrogen from Curtailed Electricity in EAS

The potential of renewable hydrogen produced using curtailed electricity in Scenario1, Scenario2, and Scenario3 is quantified according to a renewable curtailment rate of 20%–30% for the high share of renewables in 2050 in EAS. Emissions abatement, i.e. the difference between BAU and various scenarios such as Scenario1, Scenario2, and Scenario3, is calculated. The higher share of renewables under Scenario1, Scenario2, and Scenario3 could only happen if hydrogen is developed as energy storage by utilising curtailed renewable electricity. Utilising unused electricity and/or curtailed renewable electricity to produce hydrogen could be ideal to tap the maximum potential of renewables.

The higher share of renewables under various scenarios such as Scenario1, Scenario2, and Scenario3 will see a large reduction in carbon dioxide emissions, which could result in decarbonising emissions and contribute to Conference of the Parties (COP) commitments. The potential emissions abatement is the difference between the BAU scenario and various renewable-share scenarios such as Senario1, Scenario2, and Scenario3. Table 10.5 shows the amount of hydrogen produced from curtailed electricity by various replacement scenarios in EAS.

Table 10.5: Hydrogen Produced from Curtailed Electricity in EAS

(unit: million tonnes)

	Scenario1H_2	Scenario2H_2	Scenario3H_2
Of 20% curtailed renewables	72	76	80
Of 30% curtailed renewables	108	114	119

EAS = East Asia Summit.

Source: Authors' calculation.

Table 10.6 presents the amount of carbon dioxide emissions that can be abated by different renewable replacement scenarios in 2050 in EAS. Potential emissions abatement is 18,059 million tonnes-carbon (Mt-C), 18,527 Mt-C, and 18,994 Mt-C in Scenario1, Scenario2, and Scenario3, respectively.

Table 10.6: Emissions Reduction by Scenarios in 2050 in EAS

(unit: million tonnes)

	Baseline (2017)	Emissions in 2050	Abatement in 2050
BAU	18,623	22,266	-
Scenario1	18,623	4,207	18,059
Scenario2	18,623	3,739	18,527
Scenario3	18,623	3,272	18,994

BAU = business as usual, EAS = East Asia Summit.

Source: Authors' calculations.

3.4. Carbon Prices

This study constructs a few cases with different hydrogen prices in the market. It adopts three carbon prices, namely, the Regional Greenhouse Gas Initiative (RGGI), European Union Emissions Trading System (EUETS) and a carbon tax in Singapore. For both RGGI and EUETS, the lowest and the highest carbon price are adopted. For the carbon price in Singapore, the current carbon tax is adopted (SGD5 per tonne of CO_2). Table 10.7 presents various carbon prices used in the calculation of potential benefits of producing hydrogen from curtailed electricity via abating the emissions of carbon dioxide.

Table 10.7: Carbon Prices

(unit: US$/tonne-$CO_2$)

	Carbon Price/Tax	Carbon Price/Tax (US$)	Remarks
RGGI (the highest)	7.6	7.6	
RGGI (the lowest)	2.05	2.05	
EUETS (the highest)	49.88	60.15	@1.2059
EUETS (the lowest)	2.59	3.40	@1.3113
Singapore	5	3.77	@0.755

EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.

Source: Authors' compilation of data from RGGI (2009, 2021), Investing.com (2021), National Environmental Agency (2021).

4. Results, Discussions, and Policy Implications

This study carries out a cost-benefit analysis of using curtailed electricity from renewables to produce hydrogen. The costs of this are compared to the possible monetised benefits accrued from the amount of the emissions of carbon dioxide abated due to reduced usage of fossil fuels in energy mix.

4.1. Results

4.1.1. ASEAN

Table 10.8 shows the amount of hydrogen produced from curtailed electricity under 20% curtailed renewables by different scenarios in the second row and the amount of the emissions carbon dioxide abated by different scenarios in the third row. The fourth row presents the amount of carbon dioxide abated per the unit amount of hydrogen produced from curtailed electricity from variable renewables via electrolysis. This is considered environmental benefits and the benefits are monetised by multiplying by carbon prices. In sum, Table 10.8 presents the possible amount of carbon dioxide abated per hydrogen produced in 2050.

Table 10.8: Possible Amounts of CO_2 Abated per H_2 Production in 2050

(unit: million tonnes)

	Scenario1H_2	Scenario2H_2	Scenario3H_2
H_2 production in 2050	4.23	5.10	5.97
CO_2 abated in 2050	648	710	734
CO_2 abated per H_2 produced	153.19	139.22	122.95

Source: Authors' compilation of data from Phoumin et al. (2021).

Using the carbon price (Table 10.7) and the possible amount of carbon dioxide abated per hydrogen produced (Table 10.8), the possible monetised benefits of unit of hydrogen produced from curtailed electricity from variable renewables via electrolysis is estimated. Table 10.9 shows the possible monetised benefits by different carbon prices expressed in US dollars per kgH_2, which accrue from hydrogen that replaces fossil fuels in the energy mix in ASEAN.

Table 10.9: Possible Benefits of Hydrogen Produced from Curtailed Electricity

(unit: US$/$kgH_2$)

	Scenario1H_2	**Scenario2H_2**	**Scenario3H_2**
RGGI (the highest)	1.16	1.06	0.93
RGGI (the lowest)	0.31	0.29	0.25
EUETS (the highest)	9.21	8.37	7.40
EUETS (the lowest)	0.52	0.47	0.42
Singapore	0.58	0.53	0.46

EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

4.1.2. EAS

Table 10.10 shows the amount of hydrogen produced from curtailed electricity under 20% curtailed renewables by different scenarios in the second row and the amount of the emissions carbon dioxide by different scenarios in the third row. The fourth row presents the amount of the carbon dioxide abated per the unit amount of hydrogen produced from curtailed electricity from variable renewables via electrolysis. In sum, Table 10.10 presents the possible amount of CO_2 abated per hydrogen produced in 2050 in EAS.

Table 10.10: Possible Amounts of CO_2 Abated per H_2 Production in 2050

(unit: million tonnes)

	Scenario1H_2	**Scenario2H_2**	**Scenario3H_2**
H_2 production in 2050	72	76	80
CO_2 abated in 2050	18,059	18,527	18,994
CO_2 abated per H_2 produced	250.82	243.78	237.43

Source: Authors' calculations.

Using the carbon price presented in Table 10.7 and the possible amount of CO_2 abated per hydrogen produced (Table 10.10), the possible monetised benefits per unit of hydrogen produced from curtailed electricity from variable renewables via electrolysis are estimated. Table 10.11 shows the possible monetised benefits by different carbon prices expressed in US$ per kgH_2, which accrue from hydrogen that replaces fossil fuels in energy mix in EAS.

Table 10.11: Possible Benefits of Hydrogen Produced from Curtailed Electricity

(unit: US$/kg$H_2$)

	Scenario1H_2	Scenario2H_2	Scenario3H_2
RGGI (the highest)	1.91	1.85	1.80
RGGI (the lowest)	0.51	0.50	0.49
EUETS (the highest)	15.09	14.66	14.28
EUETS (the lowest)	0.85	0.83	0.81
Singapore	0.95	0.92	0.90

EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

4.2. Discussions

As noted in section 3, the electrolyser load factor is the key determinant of the cost estimate of producing hydrogen from curtailed electricity. The production cost is about US$2/kg$H_2$ when the electrolyser load factor is 1,000 hours. Except the case of the highest carbon price in EUETS, the cost appears to be higher than the benefit for all other cases. With the higher electrolyser load factor of 1,500 hours, the cost-benefit ratio could be lower than 1 for the RGGI highest carbon price.

The cost-benefit ratio is calculated by the two cost estimates (Table 10.12) over the possible monetised benefits (Tables 10.9 and 10.11 for ASEAN and EAS, respectively). Table 10.12 presents cost-benefit ratios under the electrolyser load factor is 1,500 hours in ASEAN. Two scenarios of RGGI (the highest carbon price) and EUETS (the highest carbon price) show the cost-benefit ratio is lower than 1, which implies those options are cost-effective and plausible.

Table 10.12: Cost-Benefit Ratios under the Electrolyser Load Factor (1,500 hours) in ASEAN

	Scenario1H_2	Scenario2H_2	Scenario3H_2
RGGI (the highest)	0.86	0.95	1.07
RGGI (the lowest)	3.18	3.50	3.97
EUETS (the highest)	0.11	0.12	0.14
EUETS (the lowest)	1.92	2.11	2.39
Singapore	1.73	1.90	2.15

ASEAN = Association of Southeast Asian Nations, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Table 10.13 presents cost-benefit ratios under the electrolyser load factor is 1,000 hours in ASEAN. Only EUETS (the highest carbon price) shows a cost-benefit ratio of lower than 1, which indicates the options are cost effective.

Table 10.13: Cost-Benefit Ratios under the Electrolyser Load Factor (1,000 hours) in ASEAN

	Scenario1H_2	Scenario2H_2	Scenario3H_2
RGGI (the highest)	1.72	1.89	2.14
RGGI (the lowest)	6.37	7.01	7.94
EUETS (the highest)	0.22	0.24	0.27
EUETS (the lowest)	3.84	4.23	4.79
Singapore	3.46	3.81	4.31

ASEAN = Association of Southeast Asian Nations, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Table 10.14 presents cost-benefit ratios under the electrolyser load factor being 1,500 hours in EAS. Two scenarios of RGGI (the highest carbon price) and EUETS (the highest carbon price) show the cost-benefit ratios are lower than 1, which implies those options are cost-effective and plausible.

Table 10.14: Cost-Benefit Ratios under the Electrolyser Load Factor (1,500 hours) in EAS

	Scenario1H_2	Scenario2H_2	Scenario3H_2
RGGI (the highest)	0.52	0.54	0.55
RGGI (the lowest)	1.94	2.00	2.05
EUETS (the highest)	0.07	0.07	0.07
EUETS (the lowest)	1.17	1.21	1.24
Singapore	1.06	1.09	1.12

EAS = East Asian Summit, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Table 10.15 presents cost-benefit ratios under the electrolyser load factor is 1,000 hours in EAS. Only EUETS (the highest carbon price) shows the cost-benefit ratio is lower than one, which indicates the options are cost effective.

Table 10.15: Cost-Benefit Ratio under the Electrolyser Load Factor (1,000 hours) in EAS

	Scenario1H_2	Scenario2H_2	Scenario3H_2
RGGI (the highest)	1.05	1.08	1.11
RGGI (the lowest)	3.89	4.00	4.11
EUETS (the highest)	0.13	0.14	0.14
EUETS (the lowest)	2.35	2.42	2.48
Singapore	2.11	2.17	2.23

EAS = East Asian Summit, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Unlike ASEAN, the cost-benefit analysis for EAS shows a ratio of close to 1 under the highest carbon price of RGGI. The larger production of hydrogen from curtailed electricity from variable renewables via electrolysis replaces larger amount of fossil fuels in energy mix in EAS. This leads to the larger amount of CO_2 emissions abated from which larger monetised benefits are accrued. Larger potential in hydrogen production in EAS appears to make the cost-benefit ratio close to 1 even under the domain of a low carbon price such as US$10 per ton of CO_2.

The current carbon prices in RGGI appear not to make producing hydrogen from curtailed electricity cost-effective or plausible. The carbon prices need to double the current price levels if the electrolyser load factor is about 1,000 hours. If the electrolyser load factor is about 1,500 hours or higher, then the current carbon prices seem to be cost-effective for producing hydrogen via electrolysis from curtailed electricity.

The carbon prices in EUETS have been above EUR20 per tonne of CO_2 since 2020. The current carbon prices in EUETS appear to make producing hydrogen from curtailed electricity cost-effective or plausible. If such trends in carbon prices in EUETS continue, then producing hydrogen via electrolysis from curtailed electricity seems to be cost effective or plausible in European nations.

The current carbon price in Singapore will not make producing hydrogen via electrolysis from curtailed electricity plausible. Carbon prices should be twice higher than the current carbon tax for the electrolyser load factor of 1,500 hours and more than quadruple the current carbon tax for the electrolyser load factor of 1,000 hours.

Proost (2019) presents the cost could be higher than US$10/kg$H_2$ if the electrolyser load factor is 500 hours or lower. A low carbon price would make the monetised environmental benefits accrued from abated CO_2 emissions low, which in turn makes hydrogen production from curtailed electricity from variable renewables via electrolysis less attractive if not attractive at all.

In sum, producing hydrogen from curtailed electricity from variable renewables via electrolysis could be a plausible option even under low carbon price if the electrolyser load factor is higher than 1,500 hours. If carbon prices are sufficiently high such as higher than US$20/tonne of CO_2, then producing hydrogen from curtailed electricity from variable renewables via electrolysis could be cost effective even under the low level of the electrolyser load factor such as 1,000 hours. If the electrolyser load factor is very low such as 500 hours, then curtailed electricity from variable renewables could be a plausible option for producing hydrogen only if the carbon prices are significantly high, e.g. in the range of US$80 to US$100/tonne of CO_2.

4.3. Policy Implications

The cost-benefit analyses of producing hydrogen from curtailed electricity present the plausible range of carbon prices that make curtailed electricity a cost-effective source of producing hydrogen. This study derives the following policy implications.

First, it is good to grant the abated amount of CO_2 to get carbon credits so that they can be traded in the carbon market. A regional carbon market is expected to promote the utilisation of hydrogen production from curtailed electricity from variable renewables. The hydrogen produced works as an energy storage that would solve the intrinsic intermittency of variable renewables and excess supply of electricity from variable renewables.

Second, the cost of producing hydrogen via electrolysis varies by the electrolyser load factors. It is beneficial to make the electrolyser load factors 1,000 hours or above. With this, producing hydrogen from curtailed electricity from renewables is viable even low carbon prices.

5. Conclusions

This study examines if curtailed electricity can be a cost effective and plausible option for producing hydrogen in ASEAN and EAS region employing a cost-benefit analysis. The cost estimation is based on two scenarios of the electrolyser load factor, namely 1,000 hours and 1,500 hours. The electrolyser load factor appears to be the key determinant of the cost estimate of producing hydrogen from curtailed electricity from renewables via electrolysis. The production cost is about US$2/kg$H_2$ when the electrolyser load factor is 1,000 hours. The benefit of producing hydrogen from curtailed electricity from renewables via electrolysis is estimated by three stages. At a first stage, the amount of fossil fuels to be replaced by the amount of hydrogen produced from curtailed electricity is estimated. At a second stage, the amount of CO_2 emissions to be abated by the reduced usage of fossil fuels in energy mix is estimated. At a third and final stage, the amount of CO_2 emissions abated by the unit amount of hydrogen produced is estimated, which is monetised by multiplying a prevailing carbon price.

The cost of producing hydrogen from curtailed electricity from variable renewables via electrolysis appears to be higher than the benefit accrued from the abated amount of CO_2 emissions for all but the case of the highest carbon price of EUETS for ASEAN and EAS. With the higher electrolyser load factor of 1,500 hours, the cost-benefit ratio could be lower than one for the highest carbon price of RGGI for EAS.

The current carbon prices of RGGI or Singapore appear not to make producing hydrogen from curtailed electricity cost-effective or plausible. The carbon prices of EUETS, which are above EUR20 per tonne of CO_2, appear to make producing hydrogen from curtailed electricity from variable renewables via electrolysis cost effective or plausible. The current carbon price in Singapore appears not to make producing hydrogen from curtailed electricity from variable renewables via electrolysis plausible.

In sum, producing hydrogen from curtailed electricity from renewables via electrolysis could be a plausible option under two occasions, either high carbon prices or the electrolyser load factor is higher than 1,500 hours. If carbon prices are significantly high, such as higher than US$20/tonne of CO_2, then producing hydrogen from curtailed electricity from renewable via electrolysis could be cost effective even under the low level of the electrolyser load factor, such as 1,000 hours. If the electrolyser load factor is very low, such as 500 hours, then producing hydrogen from curtailed electricity from renewables could be a plausible option only if the carbon prices are significantly high, such as in the range of US$80 to US$100/tonne of CO_2.

References

Barnes, A. and K. Yafimava (2020), 'EU Hydrogen Vision: Regulatory Opportunities and Challenges', *Energy Insight*, 73, The Oxford Institute for Energy Studies.

CAISO (2017), *Fast Facts: Impacts of Renewable Energy on Grid Operations*. Folsom, CA: California Independent System Operator.

Dickel, R. (2020), 'Blue Hydrogen as an Enabler of Green Hydrogen: The Case of Germany', *OIES Paper*: *NG* 159, The Oxford Institute for Energy Studies.

DNV GL (2018), *Hydrogen as An Energy Carrier*. Position Paper 2018. Hovik, Norway: DNV GL AS.

DNV GL (2020), *Energy Transition Outlook* 2020. Hovik, Norway: DNV GL AS.

Hydrogen Council (2017), *Hydrogen Scaling Up*. Brussels: Hydrogen Council.

Hydrogen Council (2020), *Path to Hydrogen Competitiveness*: *A Cost Perspective*. Brussels: Hydrogen Council.

International Energy Agency (IEA) (2019), *The Future of Hydrogen*. Paris: International Energy Agency.

International Renewable Energy Agency (IRENA) (2019), *Hydrogen*: *A Renewable Energy Perspective*. Abu Dhabi: IRENA.

International Solar Energy Society (ISES) (2020), 'Renewable Transformation Challenge: Hydrogen production from Renewables', http://www.renewableenergyfocus.com/view/3157/hydrogen-production-from-renewables/ (accessed 27 September 2020).

Investing.com (2021), 'Carbon Emissions Futures Historical Prices', https://www.investing.com/commodities/carbon-emissions-historical-data (accessed 7 May 2021).

Lambert, M. (2020), 'EU Hydrogen Strategy: A Case for Urgent Action towards Implementation', *Oxford Energy Comment*, July 2020, The Oxford Institute for Energy Studies.

Mitsubishi Heavy Industries (2020), *Hydrogen – Powering A Net Zero Future*: *The Technologies to Get Us There*. https://oilandgas.mhi.com/ebooks/hydrogen-powering-a-net-zero-future/ (accessed 27 September 2020)

National Environmental Agency, Singapore (2021), 'Carbon Tax', https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/carbon-tax (accessed 24 April 2021).

Phoumin, H., F. Kimura, and J. Arima (2021), 'ASEAN's Energy Transition towards Cleaner Energy System: Energy Modelling Scenarios and Policy Implications', *Sustainability*, 13, pp.2819.

Proost, J. (2019), 'State-of-the Art CAPEX Data for Water Electrolysis, and Their Impact on Renewable Hydrogen Price Settings', *International Journal of Hydrogen Energy*, 44, pp.4406–13.

RGGI Inc. (2009), *Marker Monitor Report for Auction* 6. https://www.rggi.org/sites/default/files/Uploads/Auction-Materials/06/Auction_6_Market_Monitor.pdf (accessed 7 May 2021).

RGGI Inc. (2021), *Market Monitor Report for Auction* 51. https://www.rggi.org/sites/default/files/Uploads/Auction-Materials/51/Auction_51_Market_Monitor_Report.pdf (accessed 7 May 2021).

U.S. Department of Energy (n.d.), *Hydrogen Production: Electrolysis*. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis (accessed 9 November 2020).