ENABLING MECHANISMS FOR THE ADOPTION OF ENERGY STORAGES AND HYDROGEN FOR RESPONDING TO CLIMATE CHANGE IN SOUTHEAST ASIA

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Abstract

Realizing the countries' Nationally Determined Contributions (NDCs) under the Paris Agreement is one of the critical solutions in accelerating the world's path toward a green future. This article aims to analyze and review enabling technologies adaptations for addressing climate change, particularly within the ASEAN countries. These initiatives seem to be a significant step for the region's sustainability. In this article, the challenges, opportunities, best practices, and policy recommendations to deploy and utilize two innovative technologies; energy storage and hydrogen, for climate change mitigation, based on the available data and brief analysis.

Introduction

Throughout Earth's history, the climate has changed every day. Climate change is a change in the physical condition of the Earth's atmosphere that can be identified (e.g., by using statistical tests) through changes in the average and/or variability of its properties and does not occur just for a moment but over a long period (IPCC, 2018). The United Nations Framework Convention on Climate Change (UNFCCC) makes a distinction between climate change caused by human activities that alter the composition of the atmosphere and climate variability caused by natural causes. Today's causes of climate change are primarily human activities, such as burning fossil fuels (coal, oil, and gas) and cutting down forests (deforestation). Carbon dioxide produced from burning and cutting trees is released directly into the atmosphere, causing the Earth's average temperature to increase. The increase in the temperature of the planet is called global warming. Natural processes can also contribute to climate change, including internal variability (e.g., ocean cycle patterns like El Nino, La Niña, and the Pacific Decadal Oscillation) and external forcing (e.g., volcanic activity, changes in the Sun's energy output, variations in Earth's orbit) (NASA, 2021).

With the carbon dioxide elevating in the atmosphere each day, global sustainability is threatened. The polar ice shield is melting, and the sea level is rising. In some areas, extreme weather events and rainfall are becoming more common, while others are undergoing extreme heat waves and droughts (Climate change consequences, 2017). These effects are projected to escalate in the coming years. The Intergovernmental Panel on Climate Change (IPCC), which includes more than 1,300 scientists from the United States and other countries, foretells a warming of about 0.2°C per decade is projected for a range of Special Report on Emission Scenarios (SRES) over the next two decades. According to IPCC, the extent of climate change impacts on individual regions will differ (IPCC, 2013).

Therefore, the urgency to address future impacts is currently being encouraged under the Paris Agreement. Many initiatives are undertaken in order to limit global warming to below 1.5°C. Battery storage is considered one of many technological solutions in alleviating the intermittency issues of electricity generation from renewable energy. When the first oil crisis took place in the mid-1970s, the United States initiated a number of energy storage Research and Development (R&D) programs, particularly establishing the rechargeable battery focused. The first storage-related program in 1978 was titled "*Batteries for Specific Solar Applications.*" This renewable-based program incorporated development and testing of the state-of-the-art as well as advanced battery technologies, systems analysis, and research on the integration of batteries with photovoltaic (PV) and wind energy systems (ESS History | Energy Storage Systems, n.d.).

The use of hydrogen also has high prospects in technological innovation for the energy transition. But for hydrogen to make a significant contribution to clean energy transitions, it needs to be adopted in sectors where it is almost absent, such as transport, buildings, and power generation (IEA, 2019). Today, Hydrogen technologies are also being considered as an opportunity to develop national industrial sectors, in a recovery perspective after the COVID-19 pandemic.

Energy storage: The key for renewable energy penetration

Trend and opportunity

The role of power storage, especially the battery system, is progressively being highlighted. Storage, from batteries in solar powered systems to batteries in electric vehicles (EVs), is pivotal to accommodating renewable energy integration. As in ASEAN, the region has set targets of 23% of renewable energy in total primary energy supply (TPES) and 35% of renewable energy in ASEAN's installed capacity by 2025 (APAEC, 2020).

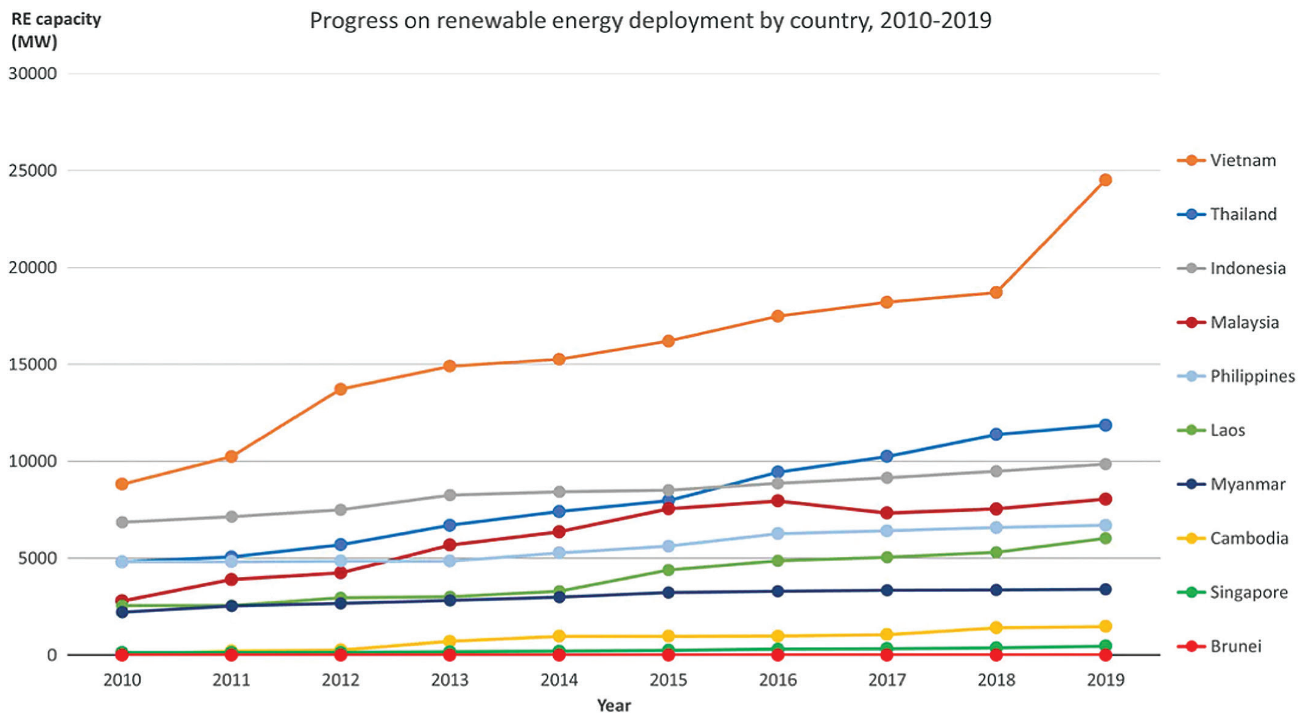

Figure 1: Renewable energy in ASEAN 2010–2019 (IRENA, 2020)

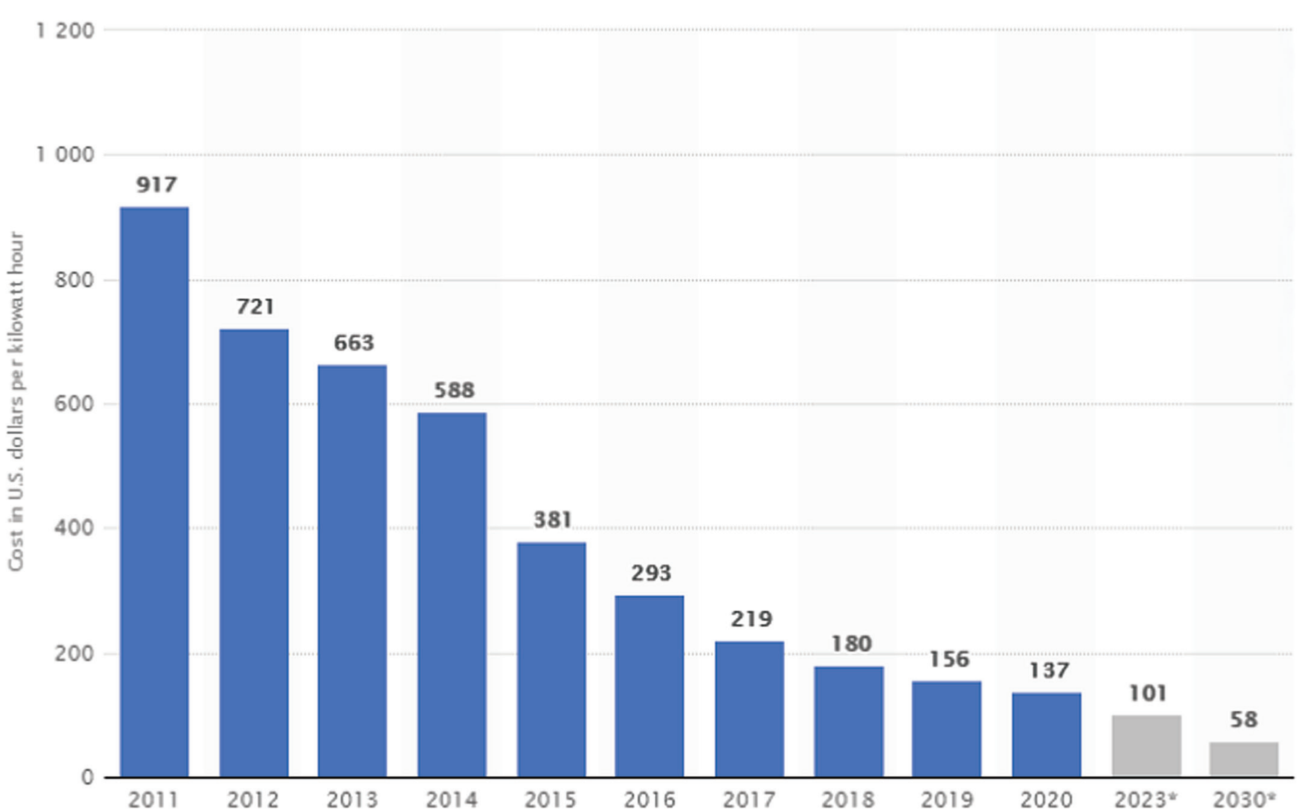

Figure 2: Global lithium-ion battery costs (in USD/kWh) between 2011–2030 (Statista, 2021)

Figure 3: Battery electricity storage energy capacity growth in stationary applications by sector, 2017–2030 (IRENA, 2017)

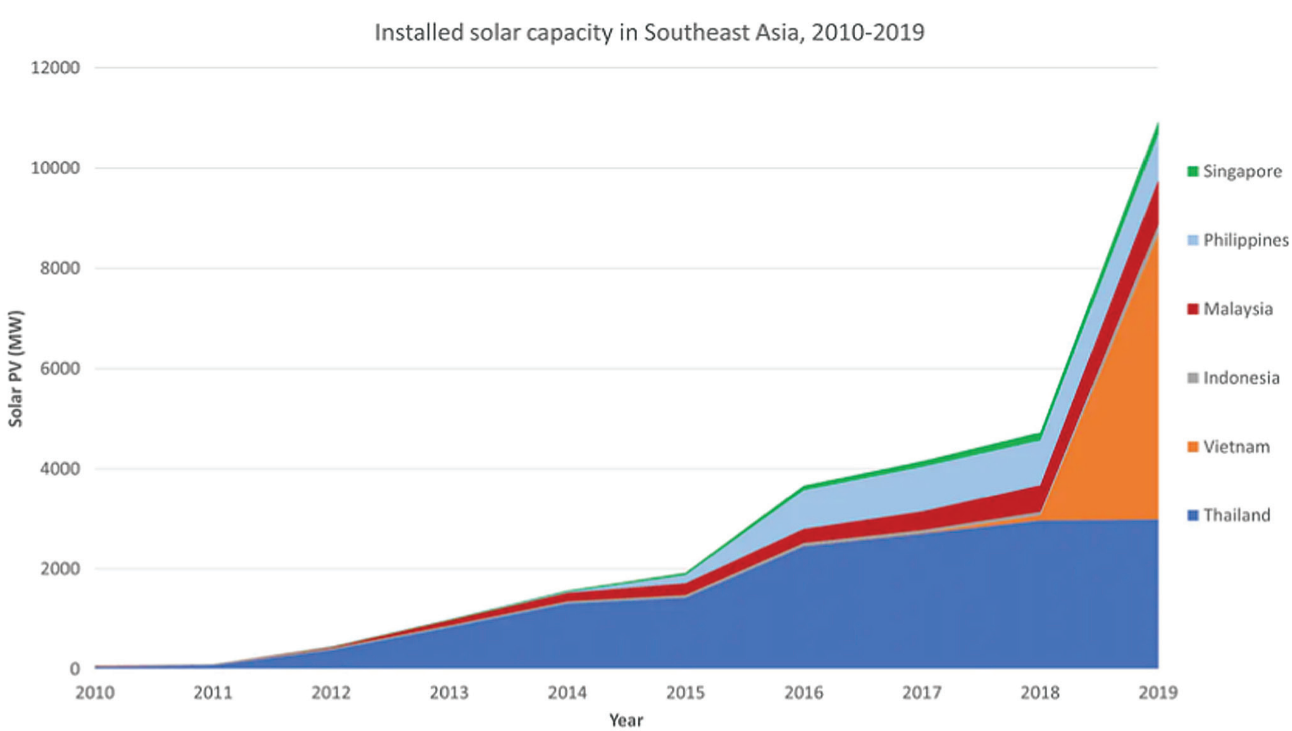

Figure 4: ASEAN solar capacity growth 2010–2019 (IRENA, 2020)

Figure 5: Akuo Energy Indonesia (AEI), Solar GEM® and Storage GEM® in Kalimantan (Akuo Energy, 2018)

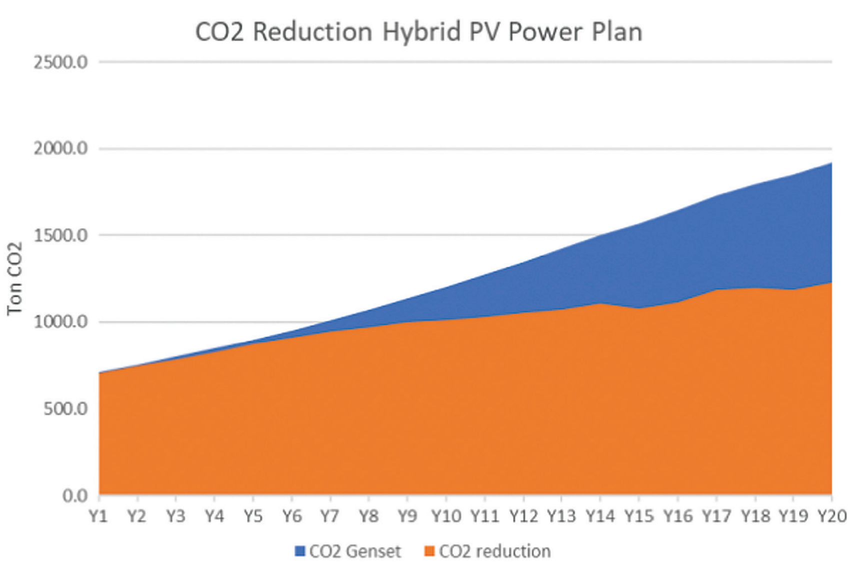

Figure 6: Carbon dioxide reduction Akuo hybrid PV power plant (AEDS, 2021)

This energy storage provides some of the flexibility that power systems need to alleviate the fluctuating availability of solar and wind energy. In the long run, the importance of energy storage will only grow as the ASEAN's decarbonization efforts strive to reduce carbon emissions from the fossil fuels power generation substantially.

Battery storage is considered one of the most essential tools for ASEAN in addressing climate change's global issue. As the electric vehicle market expands and the demand for uninterrupted renewable energy continues to thrive (Figure 1), the battery such as lithium-ion batteries may experience significant growth until 2025. This battery storage system is used to regulate voltage and frequency, reduce peak demand, as well as aforementioned integrate and store renewable energy.

Due to the fact that the lithium-ion batteries' prices are significantly declining (Figure 2), the battery market has witnessed a massive demand in the global storage market. In 2020, the average price for the lithium-ion battery was about USD 137/kWh and is estimated to fall approximately to USD 58/kWh by 2030 (Statista, 2021). With the decreasing cost and increasing demand of the battery market for renewable projects, lithium-ion batteries are likely to grow in the ASEAN energy storage market at a Compound Annual Growth Rate (CAGR) of around 9.5% from 2020 until 2025 (Mordor Intelligence, 2020). Furthermore, falling battery costs will also open up several new economic potentials for the storage technologies to provide a wide range of grid services and uplift the economic value of using distributed batteries to increase the self-consumption of rooftop solar PV.

According to the report developed by International Renewable Energy Agency (IRENA), total battery capacity in stationary applications could increase from a current estimate of 11 GWh to between 100–167 GWh by 2030 in the Reference case and to as much as 181–421 GWh in the REmap Doubling case (Figure 3). Since the extent of storage used in each application remains uncertain, hence this uncertainty is explored in the high and low cases. However, both low and high cases still imply that utility-scale batteries would be rapidly growing to increase the self-consumption share of the output from rooftop solar PV. As shown in Figure 4, the increasing number of installed solar capacity within the region thus far confirms that the largest market for battery storage in the period until 2030 (Figure 3) is foretold to be the pairing of battery storage systems with the installation of new small-scale solar PV.

Case study—Solar PV + Battery storage best practice

Local Community Minigrid, Hybrid PV Power Plant in Berau, East Kalimantan, Indonesia.

Looking at the great prospect and benefits in installing the pair of solar PV and battery storage, Akuo Energy Indonesia, a subsidiary of Akuo Energy, the leading French Independent Power Producer (IPP), has developed a renewable hybrid power plant facility incorporating the distribution network in three villages at Berau Regency, East Kalimantan, Indonesia.

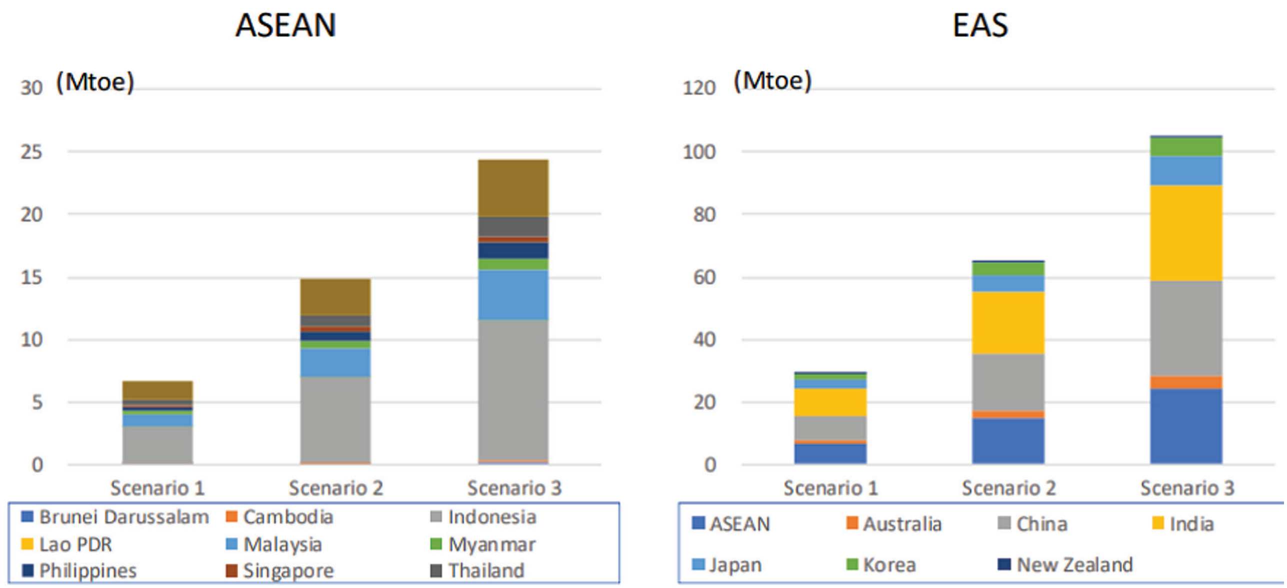

Figure 7: Hydrogen demand potential in 2040, by country (ERIA, 2019)

The power plant and distribution network are owned, managed, maintained, and operated by local communities for their self-energy consumption.

The three villages are Merabu, Long Beliu, and Teluk Sumbang. In total of 460 homes consisting mostly of farmers, beekeepers, laborers, and fishermen, the three villages usually had a few diesel generators which supplying pollutions and unstable energy. In addition, the cost of fuel was quite high because of these villages' remoteness, and fuel expenditure could represent up to 30% of these villagers' monthly income. Also, the generators only operated for 4 hours a day because of recurrent break-downs and their prohibitive cost.

Akuo Energy Indonesia has deployed its two innovative flagship products Solar GEM® and Storage GEM® in these villages to address the issues. With a combined solar capacity of 1.2 MWp and a storage capacity of 2.1 MWh entirely integrated, the three minigrids supply these rural communities with renewable electricity fully 24 hours a day. Solar GEM® provides the flexibility and portability of solar PV, whereas Storage GEM® allows the excess solar PV energy generated during the day to be stored. Fortunately, the villages now can continue to reap the benefits from uninterrupted green electricity throughout the night (Akuo Energy, 2018).

The system itself is fully operated in 24 hours in 365 days for a year. The PV module generates electricity throughout the day to supply the demand and charge the battery. When the battery is fully charged in the afternoon, the electricity from PV module will be curtailed equivalent to the electricity demand. Most of the electricity is used for household consumption and public facilities. After the sunset, the electricity is supplied by the battery. In the evening, electricity consumption is much bigger rather than during the afternoon. The peak load occurred around 6 pm to 8 pm about 35 kW. The battery will keep supply the electricity until the Sun rise at the next day.

As Figure 6 shown, the Akuo Solar hybrid PV power plants were built to cover 20-year growth energy demand which according to Electricity Supply Business Plan (RUTPL) by Indonesia's State Electricity Company (PLN) is 6% per year. Thus, it is calculated that after 20 years long of running, the solar hybrid PV could help contributing to the fight against climate change by reducing approximately 20,000-ton CO_2. Furthermore, with the electricity from PV systems, the villagers do not have to use diesel generators, hence, not only it helps reducing the carbon emissions yet also the noise pollution. Raising the awareness from rural community toward sustainability to preserve the planet as well as raising its social-economic potentials seem to be a prominent effort for the Southeast Asia region in regard to fighting the climate change (AEDS, 2021).

Challenges

However, the adaptations of these battery storage technologies are still not equally implemented in other ASEAN countries. There are several factors behind the lack of the region's development. Many battery storage developers still believe that tons of knowledge are needed because many industry players, including utilities, regulators, and financiers, are often not familiar with the battery storage, technology's advantages, and how it should be properly deployed. Also, in most regions, including Southeast Asia, storage systems have not been fully recognized in competitive markets for being able to offer both energy capacity and ancillary services. Many battery storage developers and vendors believe that this enabling technology should have their own set of rules and be considered as a pivotal technology in countries' regulatory frameworks for the sake of human's future.

In addition, although significant reductions in system costs that have been achieved over the years, utility-scale battery storage remains a high-priced technology. The initial cost for systems is one of the major obstacles for the market's growth. Furthermore, critical factors enabling this market are the programs supporting solar PV that compensate system owners for excess generation. Yet, many utilities are opposed to these programs, including the net metering and Feed-in Tariffs (FITs), which can be disruptive to the entire power industry and may not agreeably worth the price of maintaining enabling grid infrastructure owned by the utility. The removal of these programs would significantly restrain the energy storage market, due to the fact that how closely it is tied to the development of the solar PV market. The distributed storage industry knows it cannot expect to follow the same path as solar PV by relying on subsidies to prop up the industry. Thus, there must be a sustainable value proposition regardless of subsidies, and this may require changes in rate structures and regulations that effectively quantify the value created by distributed energy and battery storage while accurately accounting for the underlying grid system cost to support this new distributed system.

Lastly, the issuance of restrictive regulations and resistance from existing utilities. Utilities in some areas have eagerly worked to intercepted users from using the Behind-The-Meter (BTM) storage to consume more of the electricity they generate on-site. These efforts have included enactment of regulations prohibiting third-party system ownerships, which have driven market growth in leading markets, as well as ones imposing special fixed charges or tariffs for self-consumption of power generated on-site. Although the fact that these systems, when properly coordinated and incentivized, can increase the stability of the grid

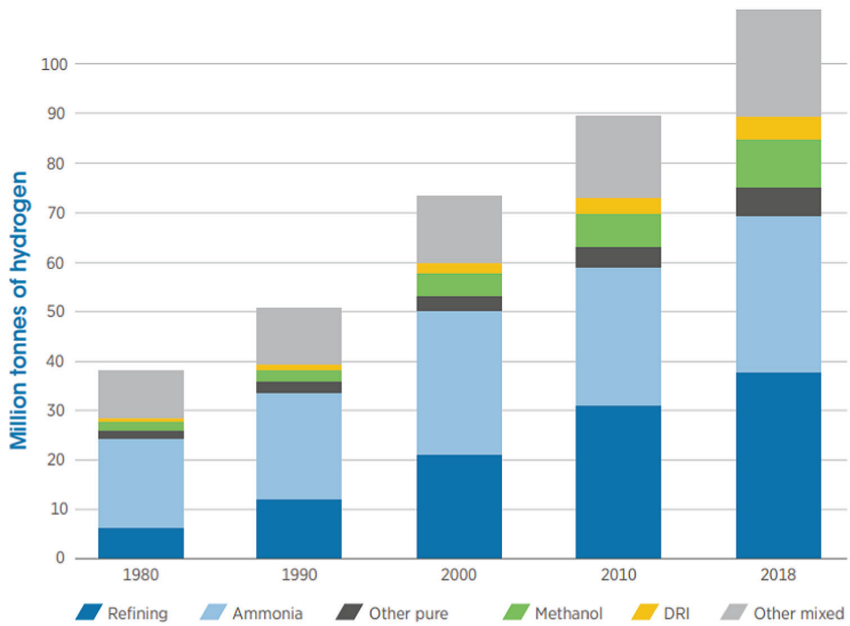

Figure 8: Global annual demand for hydrogen since 1980 (IEA, 2019)

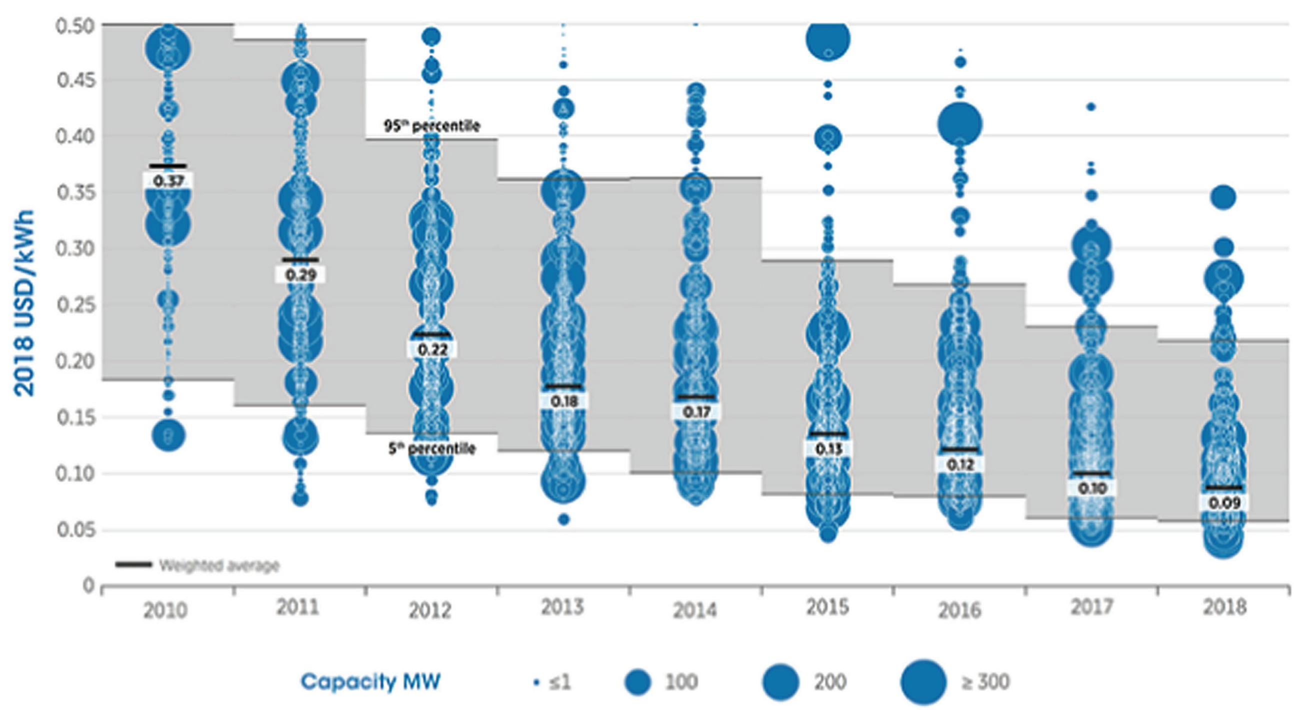

Figure 9: LCOE from utility-scale solar PV projects, global weighted average, and range, 2010–2018 (IRENA, 2019)

and allow for more renewables to be added effectively, they are viewed by some utilities as a direct threat to their business since it could allow some clients to defect from the grid or greatly reduce the amount of energy they purchase from the grid (ESMAP, 2017).

Recommendations

Therefore, several recommendations are made to help enhancing further deployment and adaptation of battery storage in Southeast Asia, such as:

- Establish a specific institution to conduct further Research, Development, & Demonstration (RD & D).
- This recommendation is hoped to be helpful, particularly in raising the little knowledge and awareness of how essential battery storage is. Also, since numerous advanced battery storage technologies within ASEAN are still in a pre-commercialized stage, the costs of battery storage devices are aforementioned expected to decrease in the future. RD & D reduces the high capital costs of battery storage, increases the potential revenue streams through increased applications in ancillary services markets, and also helps to show the battery's viability of advanced and next-generation. Additionally, demonstration projects are crucial in order to show the viability of newer technologies. Successful demonstrations will reduce the risk of investing in these technologies and help in securing private investor funding for large-scale battery storage systems.
- Create an Investment Tax Credits (ITCs) for the battery developers' incentives.

  It is believed to be an effective method of reducing capital costs and limiting exposure to technological and capital risk. ITCs also promote a more rapid increase in storage capacity for services such as frequency regulation. For instance, United States has been implementing this regulation. Research has shown that with a possible 20% federal ITCs for storage in the country over a10-year period, total capacity could triple compared to a scenario without the ITCs itself. An effective implementation of ITCs will promote battery storage expansion in the short run while

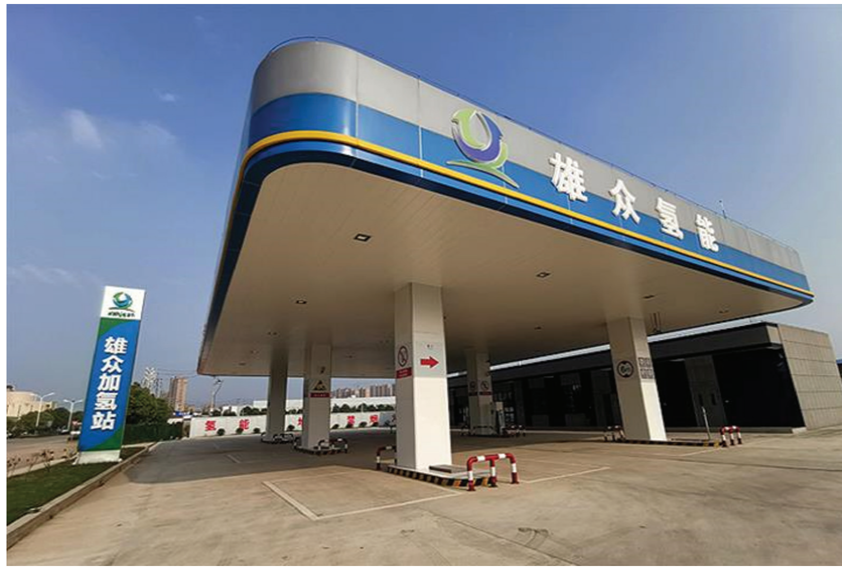

Figure 10: Refueling stations in Guangdong, China (Yicai Global, 2021)

  accelerating long-run capital cost reductions. A dynamic battery storage market characterized by stable supply and low costs is important to reach the full potential of further ASEAN's smart grids.

- Encourage market formation and support for battery storage.

  As the growth of deregulated markets, significant opportunities appear to expand the markets to exploit battery storage services more fully and significantly on the grid. Deregulated electricity markets provide the best opportunity for further developing battery services. The deregulation of utilities and energy markets and support for greater regulatory and market structure will accelerate participation by storage owners and allow third parties and independent access to energy markets. Energy markets will also become more diversified in terms of the services available for exchange and eligible participants. Therefore, by allowing storage to capture its full value in competitive markets may be among the most effective tools in supporting as well as promoting the deployment and adaptation of storage technologies in ASEAN (Zame et al., 2018).

Hydrogen: The key for decarbonization

Current trends and situations

The development and deployment of conventional green technologies have mostly been carried out in the context of national green growth strategies and energy transition. The increasing energy demand can be met by the supply of energy produced by renewable energy and other clean energy alternatives such as hydrogen and clean technologies. Hydrogen is the most abundant chemical element available in the atmosphere and can be a viable source to electrify homes, transport, and industry. Hydrogen is being pursued as a potential form of clean energy given its wide usage in areas such as ammonia production, petrochemical and oil refining industries, and many others. Adopting renewable hydrogen would bring more renewables into the energy mix and could be a game-changer in the transition from fossil dependence to a cleaner energy system in ASEAN. However, in the ASEAN region, hydrogen as an alternative fuel is not yet on the policy agenda. Nevertheless, policy measures are likely to be addressed on emerging and alternative technologies, as hydrogen and energy storage by ASEAN Plan of Action for Energy Cooperation (APAEC) Phase 2 is under preparation for endorsement at ASEAN Ministers on Energy Meeting (Phoumin et al., 2020).

The potential of hydrogen as an energy carrier and complementary development for large-scale expansion of renewable energy in ASEAN and East Asian countries should be studied. The ERIA report (2019)

Table 1: Central and local subsidies for fuel cell electric vehicles in China, as of 2019 (ERIA, 2020)

	Central Government	Guangdong Province
FC passenger vehicle	CNY6000/kW (up to CNY200,000 per vehicle)	CNY200,000 per vehicle
FC light truck or bus	CNY300,000 per vehicle	CNY300,000 per vehicle
FC heavy truck or bus	CNY500,000 per vehicle	CNY500,000 per vehicle
HRS		Up to CNY 8 million per station

CNY = yuan, FC = fuel cell, kW = kilowatt, HRS = hydrogen refueling station.

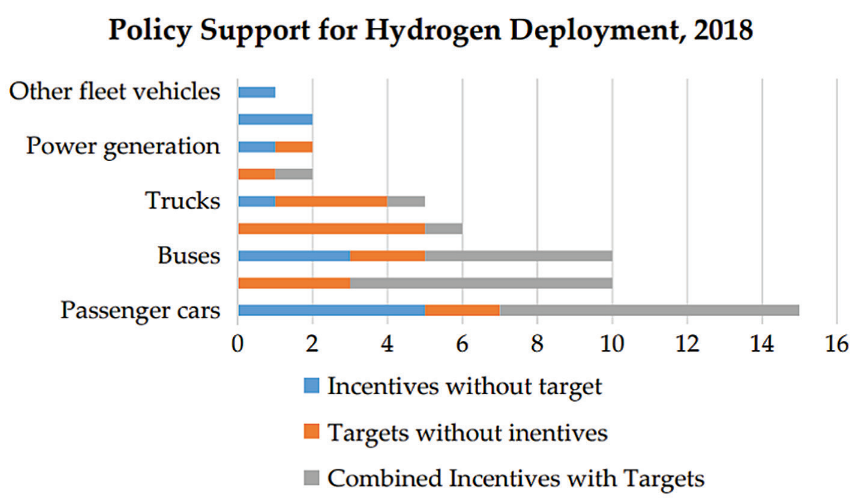

Figure 11: Support policies for hydrogen development (Muradov and Veziroĝlu 2005)

estimates the prospect of hydrogen demand by 2040 in ASEAN and East Asia Summit countries as shown in Figure 7.

ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.

Indonesia has the largest potential for hydrogen demand among ASEAN member countries, followed by Malaysia. Meanwhile, China has the largest potential for hydrogen demand in the EAS region, followed by India and ASEAN.

It is also supported by the hydrogen use trends in the IEA report (Figure 8) that global demand for hydrogen has increased from less than 30 Mt H_2 in 1975 to 115 Mt in 2018, including both hydrogens in pure form and mixed with other gases (with pure hydrogen summing up to more than 70 Mt in 2018).

Currently, around 95% of hydrogen is produced from coal and gas, also called "grey hydrogen," and a small portion is produced with carbon capture, sequestration, and storage (CCS), called "blue hydrogen." Less than 5% of total hydrogen production is produced from renewables, also known as "green hydrogen." Green hydrogen obtained through the electrolysis of water could be a non-polluting alternative for energy. Green hydrogen could be adopted in sectors such as transport, power generation, construction buildings, and energy storage as it can make a remarkable contribution to clean energy transitions. Hydrogen has the characteristics of being light, storable, and energy-dense, and no direct emissions of greenhouse gases make it an important part of a clean and secure energy future (Nepal et al., 2021).

The increasing scope and continued decline of renewables (such as solar and wind) in the costs demanded innovative green technology, could develop hydrogen storage facilities. As shown in Figure 9, shows the global weighted-average cost of energy (LCOE) of utility-scale solar PV declined by 77% between 2010 and 2018, from USD 0.371/kWh to USD 0.085/kWh.

With lower renewable energy costs, it is possible to create an economical and sustainable (low emission) process for "green" H_2 production; in particular, the market has shown a substantial reduction in the cost of electricity production from renewable energy, "green energy." In addition, the increase in electrolysis capacity is expected to have another additional impact in reducing the cost of producing green H_2.

Then, the cost of hydrogen is also considered competitive due in 2040 will fall by more than 50%. Indeed, the current cost of supplying renewable energy is about five times higher than gas, but the costs will come down with investments in the hydrogen supply chain. By 2023, many hydrogen projects in Organization for Economic Cooperation and Development (OECD) countries are expected to be launched, including electrolysers and pipelines for distribution to end-users. Island countries, especially in the ASEAN region, will benefit since hydrogen itself is a clean energy carrier that will provide the best prospects for accelerating its storage (ERIA, 2020).

Challenges

Despite its benefits and potential, hydrogen technology in developing economic regions such as Southeast Asia faces several challenges that impede its immediate broad-scale application. Clean hydrogen technologies are available, but costs remain challenging. Producing hydrogen from low-carbon energy is currently costly yet the cost of producing hydrogen from renewable electricity is falling rapidly. Combining wind power and hydrogen storage systems for power generation is also considered economically unfeasible, as mixed wind-hydrogen systems will increase investment costs in component infrastructure and significantly reduce profits.

Besides costs, the development of hydrogen infrastructure such as storage is a challenge and hinders the spread of hydrogen fuel technology adoption. Hydrogen is a light element that is several times less dense than conventional fuels. For example, in the gas phase, preventing leakage due to the permeability of pressurized gases requires premium materials used in the construction of storage vessels. Finding the right balance between the durability and weight of a hydrogen storage system is a challenge. Storage solutions that efficiently and economically require further development and deployment.

Last but not least, the other important challenge is the different government regulations, technological gaps, and the lack of progress in terms of regional cooperation in key areas such as physical infrastructure that challenge the country's energy security itself. Currently, the regulations of several countries limit the development of the clean hydrogen industry. Governments and industry must work together to ensure that the existing regulations do not become unnecessary barriers to investment (IRENA, 2019).

Lesson learned from China

Developing a cost-effective hydrogen supply chain such as the production of both hydrogen and hydrogen-based products requires the site-specific aspects of different technology options to be considered. Countries in the ASEAN region such as Singapore, Malaysia, Thailand, Indonesia, and the Philippines can take lessons from the OECD countries, to guide the economy such as investment and in terms of government policies on the development of hydrogen produced from both renewable and non-renewable.

China has abundant renewable energy resources are often located in sparsely populated vast areas far from the large industrial cluster. In some places, renewable energy has been used so rapidly that grid electricity has difficulty adapting in real-time. This provides an opportunity for producers of hydrogen and hydrogen-rich chemicals to utilize renewable resources and makes China one of the highest producers and consumers of hydrogen energy. The country has accelerated hydrogen investment support for local industry of which approximately US$ 2 billion was injected. In addition, as of 2019, the central government had issued more than 10 policy documents, and of 34 provincial administrative areas, had issued policies to develop hydrogen energy-related industries and infrastructure.

Hydrogen fuel has great potential to combat climate change by facilitating the transition to low-carbon energy sources. For the development of hydrogen fuel, infrastructure had a role of pivotal thing. Guangdong Province in Southeast China has devised a plan to accelerate the development of hydrogen fuel cell electric vehicles (FCEV) and also provides the most generous subsidies for FCEVs and hydrogen refueling stations (HRSs), in addition to central government subsidies. As shown in Table 1, a summary of central and local subsidy policies as of 2019.

Policy recommendations

Until now, ASEAN has not had a hydrogen road map. But in APAEC, mentions alternative technologies and clean fuels such as hydrogen and energy storage. APAEC will help AMS increase the share of hydrogen in its energy mix. The ASEAN hydrogen roadmap is needed to guide the national roadmap. Many developing countries have started to adopt strategies related to green growth into their economic development agenda. Effective policies can assist in accelerating hydrogen development and adoption, increasing economies of scale, cost competitiveness in hydrogen production, and attract investors.

The policy recommendations include:

- Hydrogen has been used as a feedstock in several key industrial segments for decades. The availability of hydrogen in the ongoing energy transition can help supply large amounts of renewable energy into sectors that otherwise is difficult to decarbonization. In this case, power-to-hydrogen can provide some of the additional flexibility needed to accommodate the large VRE stock expected to be online in the next decade (IRENA, 2018).
- The technologies are ready. A rapid scaling-up is now needed to reduce costs and ensure the economics of hydrogen's long-term viability. Initial efforts could focus on transitioning to a hydrogen carbon economy with minimal infrastructure requirements, and in sectors where hydrogen from renewable energy is prominent such as industries and transportation. The hydrogen economy is an economy that relies on hydrogen as a commercial fuel that can replace conventional fuels such as diesel and gasoline which can cause environmental pollution (The Edge Market, 2021).

  ASEAN countries can emphasize the efficient interaction between energy, environment, and the economy is moving towards a hydrogen carbon economy. As for the ASEAN region, Malaysia, Sarawak Local Government started to operate hydrogen buses immediately. Singapore is also working with companies from Japan to explore the development of hydrogen as new clean fuel to decarbonize emissions. Similarly, Brunei is also a leader in the hydrogen supply chain as it has been supplying liquid hydrogen to Japan since 2019. As shown in Figure 11, that investment support for hydrogen technology has increased recently in many countries with around 50 targets, mandates, and some policy incentives mainly focused on the transport sector.
- To achieve rapid improvement, a stable and supportive policy framework must be needed to encourage private investment. In terms of achievement of significant expansion, capital requirements may be beyond the ability of the operator, and additional funds from public and private sources of capital may be required.

Conclusion

With the carbon emissions increasing each day, the urgency to minimalize future climate impacts is significantly encouraged. Green technologies are one of the critical solutions in accelerating the world's path toward the greener future. The development of advanced technologies such as battery storage and hydrogen fuel cells was initiated when the first oil crisis struck in the 1970s. Battery storage has been utilized as the key to the renewable energy penetration. As the electricity generated from the renewables is intermittent depending on the external factors such as the weather, battery storage might be one of the tools for climate change mitigations that needs to be further adapted. In addition, hydrogen fuel cells can also be used as an alternative fuel which is the key to decarbonizing energy systems. Adopting hydrogen can reduce dependence on fossil fuels in this transition period. Therefore, this article has discussed the availability of such existing technologies, forecasts of demand potential including its competitiveness, projects of production potential including its costs of supply and infrastructure, economic feasibility analysis, as well as the potential applicable policies.

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Technology and Innovation Report 2021

Recent developments in frontier technologies, including artificial intelligence, robotics and biotechnology, have shown tremendous potential for sustainable development. Yet, they also risk increasing inequalities by exacerbating and creating new digital divides between the technology haves and have-nots. The COVID-19 pandemic has further exposed this dichotomy. Technology has been a critical tool for addressing the spread of the disease, but not everyone has equal access to the benefits.

The UNCTAD Technology and Innovation Report 2021 examines the likelihood of frontier technologies widening existing inequalities and creating new ones. It also addresses the national and international policies, instruments and institutional reforms that are needed to create a more equal world of opportunity for all, leaving no one behind.

The report shows that frontier technologies already represent a $350 billion market, which could grow to $3.2 trillion by 2025. This offers great opportunities for those ready to catch this technological wave. But many countries, especially the least developed and those in sub-Saharan Africa, are unprepared to equitably use, adopt and adapt to the ongoing technological revolution. This could have serious implications for achieving the Sustainable Development Goals.

The report urges all developing nations to prepare for a period of deep and rapid technological change that will profoundly affect markets and societies. All countries will need to pursue science, technology and innovation policies appropriate to their development stage and economic, social and environmental conditions. This requires strengthening and aligning Science, Technology and Innovation systems and industrial policies, building digital skills among students and the workforce, and closing digital divides. Governments should also enhance social protection and ease workforce transitions to deal with the potential negative consequences of frontier technologies on the job market.

The report also calls for strengthened international cooperation to build innovation capacities in developing countries, facilitate technology transfer, increase women's participation in digital sectors, conduct technological assessments and promote an inclusive debate on the impact of frontier technologies on sustainable development.

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