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Policy Perspective

Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications

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ABSTRACT

Being declared a global emergency, the COVID-19 pandemic has taken many lives, threatened livelihoods and businesses around the world. The energy industry, in particular, has experienced tremendous pressure resulting from the pandemic. In response to such a challenge, the development of sustainable resources and renewable energy infrastructure has demonstrated its potential as a promising and effective strategy. To sufficiently address the effect of COVID-19 on renewable energy development strategies, short-term policy priorities should be identified, while mid-term and long-term action plans should be formulated in achieving the well-defined renewable energy targets and progress towards a more sustainable energy future. In this review, opportunities, challenges, and significant impacts of the COVID-19 pandemic on current and future sustainable energy strategies were analyzed in detail; while drawing from experiences in identifying reasonable behaviors, orientating appropriate actions, and policy implications on the sustainable energy trajectory were also mentioned. Indeed, the question is that whether the COVID-19 pandemic will kill us or provide us with a precious lesson on future sustainable energy development.

1. Introduction

Since the first confirmed case of the coronavirus (COVID-19) was recorded in Wuhan, China in December 2019, the virus has wreaked havoc around the world necessitating drastic and critical responses from the World Health Organization as well as local and national governments around the world to combat the unprecedented global health crisis (Wang and Su, 2020; Nguyen et al., 2021). Despite the tremendous progress made in the research and development of new COVID-19 vaccines, the effort to distribute and inoculate the majority of the world population might last well into 2021 and possibly beyond (Organization, 2019; Leet al., 2020). To prevent the rapid spread of the virus, local, regional and national lockdowns at various scales have been placed into effect impacting up to 30% of the entire global population (Baiet al., 2020; Lai et al., 2020). In consequence, the limited movement and social personal interaction as a result of such lockdowns have led to temporary closure and/or permanent shutdown of 80% of businesses which foreshadows a 0.3% decline in GDP and an imminent economic recession

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(Gopinath, 2020; Hoang et al., 2021a). With the majority of daily activities indoors, major adjustments are needed to accommodate new habits, social behavior, family, and work priorities. (Kaplan et al., 2020; Nižetić, 2020). With hundreds of thousands losing their jobs or just being able to work remotely, the economy has taken a big hit from the precipitous fall in both production and consumption (Chen et al., 2020a). As a result, the slower pace of economic and production activities has led to a significant drop in global energy demand which in turn affected the deployment of clean, renewable energy resources. According to International Energy Agency (IEA) data, global energy demand fell by 3.8% during the first quarter of 2020 compared to the same period in 2019. As much as a 6% decline in global energy demand could be observed by the end of 2020 given the incremental phasing out of lockdown measures around the world (A and "Global Energy Revie, 2020). Such a decline in global energy demand resulted from responses to the pandemic would be as much as seven times greater than the impact of the 2008 financial crisis, reversing the increasing trend in energy demand over the past five years.

The renewable energy sector has been heavily impacted by the COVID-19 pandemic. Sharp downturns in economic activities have caused major delays in renewable energy supply chains, while the lack of available financing from the market and government incentives for renewable energy investment has raised serious concerns among developers (Karmaker et al., 2021). The reduction in global energy demand as a result of the pandemic-induced lockdowns has taken a big toll on renewable energy investments. Meanwhile, government incentives are being shifted toward pandemic relief efforts (Birol, 2020). From an economic perspective, the current decline in the global energy market is one of the steepest levels in the past 30 years, putting some renewable energy businesses at risk of financial loss. Particularly, the sudden halt in production has led to major disruptions in the global renewable energy supply chain (Ivanov and Dolgui, 2021). Furthermore, the absence of state and federal renewable energy incentives would be detrimental to current and future renewable energy development (Emma, 2020). The shutdown of several major wind turbine manufacturing plants is a prime example of the effect the pandemic has had on the renewable energy sector (David, 2020; Eroğlu, 2020; McPhee, 2020). Similar negative impacts can be observed in the solar industry with a 28% reduction in demand for 2020 ("D-19 indu, 2020), which has suffered from the pandemic-induced demand reduction. As a result, a large number of solar energy workers have been laid off or furloughed due to the pandemic. Several possible solutions have been proposed to alleviate these challenges facing renewable energy businesses ("D-19 Resources, 2021). In the United States, solar companies can take advantage of the Investment Tax Credit and the deadline extensions for project eligibility. On the other hand, regulations allowing local jurisdictions to grant solar permits and increase the number of renewable energy incentives (e.g., "Green Incentive") can help to re-energize new investments (Jin, 2020; Pradhan and GhoseShabbiruddin., 2020). As part of the pandemic recovery effort, national governments will introduce large fiscal stimulus to help with their battered economies. Besides, interest rates will either remain at the current low level (Fig. 1a) or be reduced further to stimulate economic growth (Global-rates, 2020). Furthermore, oil prices could remain depressed (Fig. 1b) in the near term due to the drop in global demand coupled with the supply-side uncertainty from the fall out between OPEC and Russia (Steffen et al., 2020). Hence, there are major implications for renewable energy development based on these aforementioned opportunities taking into account the technology readiness level and capital intensity.

In the light of the recent progress in international policy frameworks to promote clean energy and combat climate change, the COVID-19 pandemic has introduced a high degree of uncertainty as well as economic and political implications on the underlying structure on which these plans were constructed. Furthermore, it is critical to consider factors and ongoing conditions related to the pandemic situation when contemplating new energy and climate initiatives. In particular, certain long-standing energy policies may be questioned about their cost-effectiveness and suitability in today's highly risky and turbulent economic and political environment. Consequently, this review aims to reveal important insight that could help to inform legislators in making effective policy decisions in advancing the clean energy transition toward more resilient and sustainable energy systems that could withstand the impact of the ongoing pandemic and the potential risk of future global crisis.

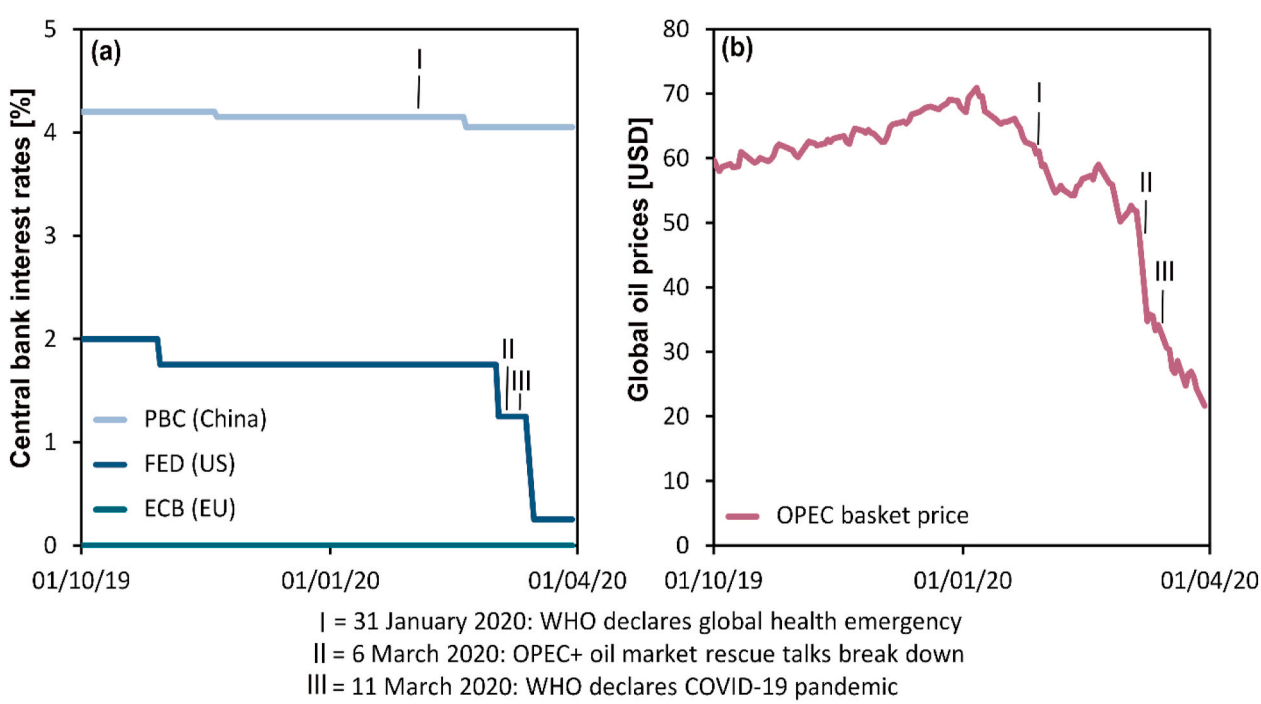

Fig. 1. The changing trend of bank interest and global oil prices over 6 months (from Oct 01, 2019 to Apr 01, 2020) with key events relating to COVID-19 pandemic; (a) - Base interest rate of various banks (Global-rates, 2020); (b) - Reference oil price declared by OPEC (Steffen et al., 2020).

2. Effects of COVID-19 pandemic on the global energy system

As a global health emergency, the COVID-19 pandemic has been a major setback to the global economy and the energy sector in particular (Chakraborty and Maity, 2020; Abu-Rayash and Dincer, 2020). Containment measures, including bans on all essential travel, closure of international border, transition to remote learning and working, etc., have drastically reduced the use of personal vehicles and other major forms of transportation (Elavarasanet al., 2020). Consequently, the level of energy production has been adjusted with a dramatic reduction in response to the lower overall demand as observed by the reduced output from nuclear plants in Europe and the US during the first quarter of 2020 (Fig. 2a). During the same period, demand for natural gas also dropped by as much as 2% with the largest reductions in China, Europe, and the U.S (Fig. 2b). Moreover, a significant reduction in demand for coal and oil in the world was observed in Fig. 2c&d. Despite the recent downturn in global energy demand, experts have pointed out the steady increase in renewable energy demand in the past several years (i.e., by as much as 1.5%) due to the addition of new wind and solar plants (Fig. 2e) (Mofijur, 2020). Indeed, a significant portion of renewable energy generation coming from the EU, US, China, Japan, Southeast Asia, and Africa has steadily expanded the percentage of renewable resources within the global electricity generation mix.

Over the past year, governments around the world have conducted massive lockdowns in response to the pandemic. Depending on the length and scale of such measures, the effect on regional energy demand might differ across several countries (Fig. 2f). For example, lower levels of restriction in South Korea and Japan have resulted in less than 10% reduction in energy demand. On the other hand, China highly controlled lockdowns across several hardest-hit provinces have led to a 15% drop in the nation's weekly energy demand. Despite the initial isolated measures restricting movements in Hubei and neighboring provinces, these containments quickly ramped up to include most regions in China. As Europe recorded major surges in the number of infections and deaths, the complete lockdowns in several countries resulted in an average of 17% drop in regional weekly energy demand during these social distancing periods. In another example, India experienced a nearly 30% reduction in energy demand as a result of the national lockdown. Specifically, its nation's annual energy demand would be expected to drop by as much as 0.6% per progressive quarantine week (A and "Global Energy Revie, 2020). According to IEA data, global oil production in 2020 was forecasted to decline up to 9% reaching the previous level in 2012. As electricity consumption has dropped by 5% in the past year, the major coal-fired power plant has experienced as much as a 10% decline in output, while coal production also reduced by 8%. Due to the temporary halt in major production and economic activities in China, coal production was heavily impacted by the sudden drop in energy demand. The daily coal consumption levels of 6 major energy companies in China

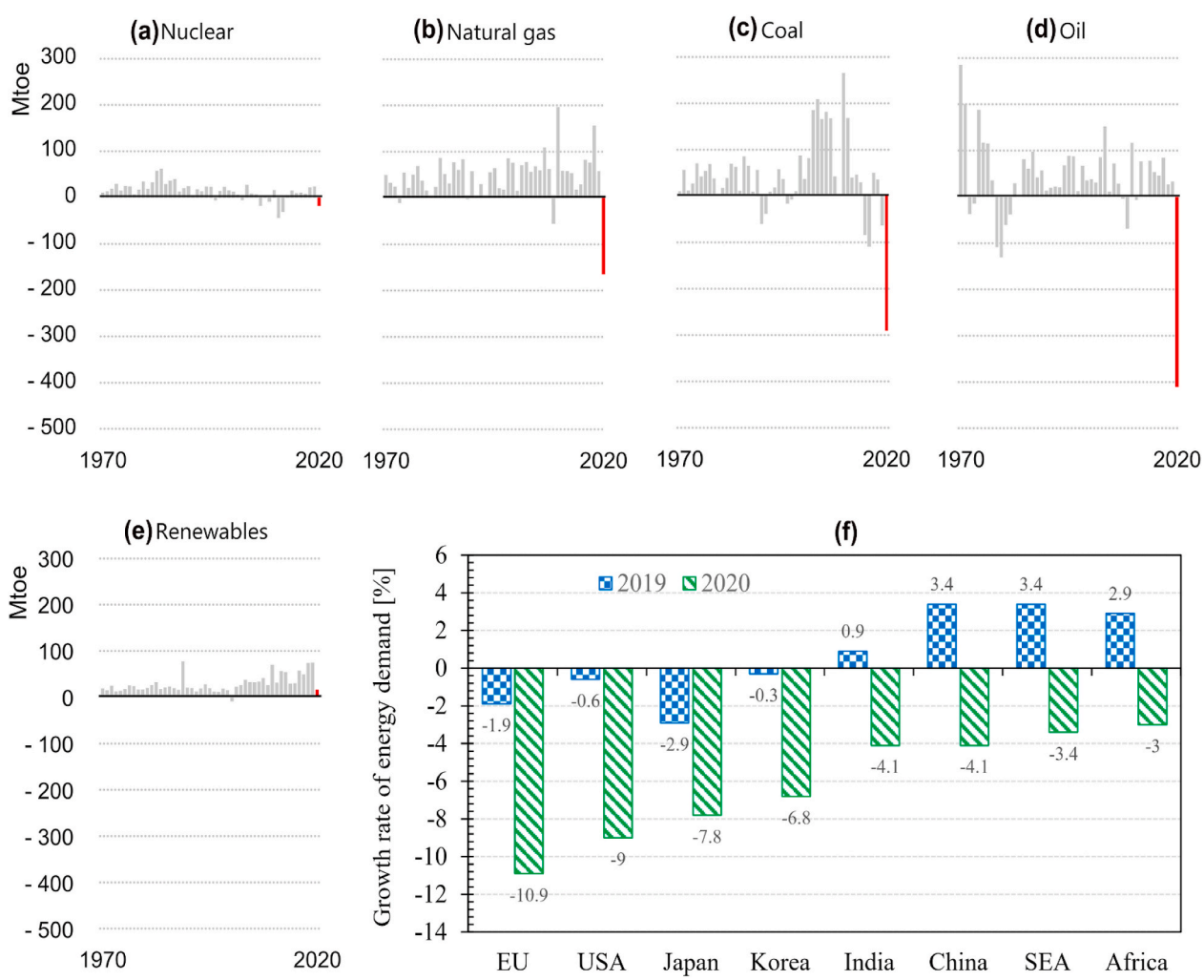

Fig. 2. (a–e)Change in global energy demand by fuel from 1970 to 2020 compared to that for World War II (horizontal baseline corresponding to zero), red vertical line presenting for global energy demand in 2020; (f) - Growth rates of the energy demand for some countries and areas in 2020 compared to 2019 (A and "Global Energy Revie, 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

can be seen in Fig. 3 (Myllyvirta, 2020). Besides the economic impact from the various lockdown measures, the heightened investment risks and concern over the blooming global economic downturn as a result of the fall in energy demand are challenges facing renewable energy developers and investors alike (Susskind and Vines, 2020). Power demand drops during pandemic times and tightening fiscal management could signal a smaller number of auction volumes available for new renewable energy projects. Taking into account the EU's nationally binding 2020 renewable energy targets, the reduced energy demand level could result in a lower incentive for member states to invest in new renewable energy projects and slow down the previously achieved progress (Bertramet al., 2021; Santiago et al., 2021). Looking back at 2019, some EU countries were on the brink of not being able to meet their targets due to the lack of aggressive policy to support the required volume of renewable energy projects (Stern et al., 2020). The unfolding event from the COVID-19 pandemic and its effect might have altered that scenario. The lower over energy demand has inadvertently increased the share of renewable energy in the electricity generation mix.

Power production is the main driver for natural gas and coal consumption which is indirectly affected by the scale and duration of the different lockdown episodes. Hence, the changing levels of industrial production have made it more difficult to accurately forecast future energy demand including coal, domestic gas, and electricity (Grandin and Sareen, 2020; Jiang et al., 2021). More importantly, the mid-term projection for many fossil fuel producers and critically depends on the likelihood of receiving government's aid to help with their struggling businesses. The particular dilemma currently facing the US oil shale industry can shed important insight into its existing plight. With the falling number of rig counts coupled with rising cases of bankruptcy, the industry is facing similar problems that it encountered during the 2014–2015 downturn. The industry is expected to come out of this turbulent time; however, experts believe that the production level will not likely return to the pre-pandemic levels (Landy, 2020). This setback will jeopardize the US goal in competing for the top spot among the world's energy producers and gaining an important geopolitical advantage. Furthermore, energy experts will continue to closely monitor the actions taken by major global energy companies, such as BP, Shell, and Total, as they assess potential divestment opportunities to account for the revenue loss from lower fossil fuel production. Overall, the speed and extent of economic recovery and energy demand will be important signals in determining the future outlook of the global energy sector.

Thus far, experts have observed the various impacts that the pandemic has on the renewable energy sector. On the one hand, decreasing production costs and greater availability of power systems have facilitated the growth in demand for renewable energy. As pointed out by Khan et al. (2020), international trade plays a positive role in promoting renewable energy deployment. Besides, investment in clean and sustainable forms of energy will not only benefit the environment but also improve the perception of foreign trade partners as a champion for environmentally-friendly practice and sustainability (Khan et al., 2021). On the other hand, despite the steady rise in renewable energy demand, disruptions to financing schemes and supply chains have reduced the rate of project installation in the long run. In particular, Germany is one of the leading renewable energy producers in the world with renewable energy sources enjoying the benefits of grid dispatching priority; therefore, coal generation is gradually discouraged and eliminated from the energy structure. However, the decreasing overall level of energy demand has negatively affected the pricing schemes for renewable energy production and carbon trading. Specifically, there has been a noticeably decreasing trend in per-unit prices of carbon observed in the US and European carbon cap and trade markets at the onset of the pandemic ("Allowance Price Ex, 2020). Furthermore, the lower energy demand generally hinders energy prices for systems with higher renewable energy mixes, resulting in significant revenue losses for both conventional and renewable energy producers (Waldholz, 2020). Renewable energy deployment has taken a big hit as a result of the pandemic-induced lockdown. Supply chain disruptions and halting of non-essential manufacturing activities have caused significant delays in the deployment of renewable energy projects. According to Bloomberg New Energy Finance, installations for solar and wind projects are

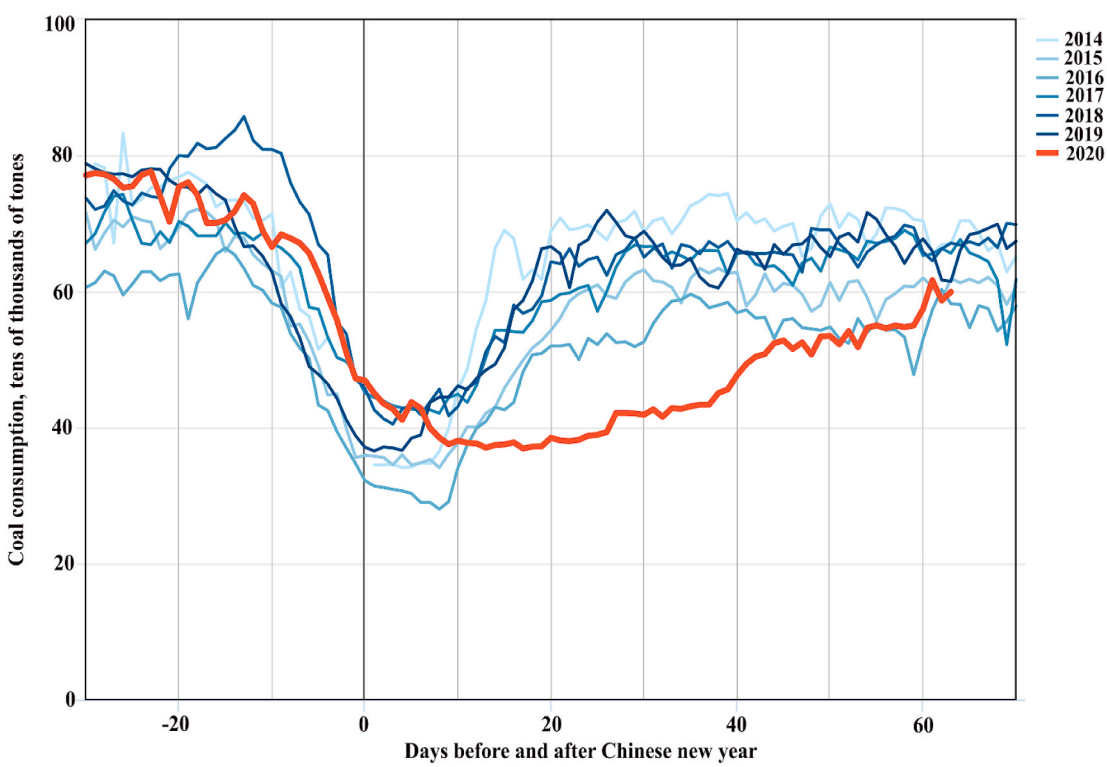

Fig. 3. Daily coal consumption at six major power firms of China (Myllyvirta, 2020) (Red curve presents the coal consumption of 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

expected to be reduced by 8% and 12% in 2020, respectively. Supply chain delays caused by disruptions to manufacturing activities during the pandemic have affected major industries, including renewable energy equipment. China, the leading supplier of solar PVs has experienced a widespread shutdown of its factories due to the COVID-19 outbreak. Besides supply chain delays, grid integration of new renewable energy projects has also been postponed due to the delay of non-critical operations by the Distribution System Operators (Energy Community and "Energy, 2020). For example, the pandemic could cause a shortage of electronic components due to the interrupted production and manufacturing. Major planned projects are temporarily put on hold as a result of the pandemic, including 3000 MW of combined solar and wind in India (Oxford Business Group and "C, 2021) and as much as 25 GW of wind power in the US (Wekoet al., 2020). According to a recent publication by Wood Mackenzie, it is forecasted as many as 150 GW of renewable energy projects in Asia are subjected to either delay or cancellation through 2024 if the recession persists (Frangoul, 2020). Several European countries have decided to either halt auction activity or reduce the volumes of renewable energy in upcoming auctions (Wigandet al., 2020). In response to the current crisis, major industry actors, such as the Global Wind Energy Council, have advocated for policy priorities, such as feed-in tariffs, tax credits, construction deadlines, and auction round extension (Global Wind Energy Counci, 2020). Stakeholders up and down the value chains are responding to the effect of the pandemic by downsizing (Majumdar et al., 2020) or cutting into their profits (D'Adamo et al., 2020). Despite the uncertainty caused by the pandemic on project financing, it can be certain that there are high financial risks and falling capital markets for renewable energy investment. Besides, these risks can be driven and accompanied by country and policy risks. Specifically, modifications to existing policies, cancellation of existing incentives, supporting frameworks, actions or auctions, as well as changes in public opinion can instill in the market a renewed sense of uncertainty and heightened risk during these troubled times (Monasterolo et al., 2020). Concerns have been raised among stakeholders out of the anticipation of possible retroactive changes by the government on existing policy frameworks. These potential changes in incentive structures and unfavorable capital market conditions can seriously affect renewable energy financing (Ji et al., 2020). As available capital is diverted toward state-backed loans to bail out struggling businesses during the pandemic, a significant portion of the capital that would be available for renewable energy project financing is now no longer accessible. Developers and owners in high-priced markets have been the most vulnerable and exposed to potentially higher losses. As part of a worldwide government loss relief effort, green investment measures that can be seen as part of an economic recovery plan may alleviate some of the obstacles the renewable energy financing schemes face. In hindsight, 2019 could have been the peak of global fossil-fuel demand (Uhlmannet al., 2019). Hence, the COVID-19 pandemic might have been the perfect storm for the fossil fuel industry setting the stage for its decline. Thus, the critical question remains on what kind of actions are required on the path towards a more sustainable energy future. Taking advantage of the stimulus money as part of the post-pandemic recovery plan to promote investment in clean energy infrastructure, production capacity, and innovative business model for renewable energy. Despite these opportunities, the outcomes of the COVID-19 pandemic still have reverberated across the clean energy sector stemming from its previous momentum (Edomah and Ndulue, 2020). Particularly, the outbreak has resulted in major production disruptions and supply chain delays while slowing the deployment of new renewable generation resources. Lack of access to financing schemes and government incentives have further compounded the challenges facing the industry over the past year (Capelle-Blancard and Desroziers, 2020; Armani et al., 2020). Consequently, the progress made in the past decade in advancing renewable energy resources is at imminent risk of being erased by the pandemic (Siddiqueet al., 2021). Policies favoring investment in renewable energy resources and infrastructure can not only act as an impetus to revitalize the industry's growth, but also have a positive impact on the environment and overall sustainability movement. Even though obstacles remain on the clean energy transition, one can be hopeful in a renewed momentum in renewable energy.

3. Opportunities and challenges for the renewable energy transition

Subjected to the negative impacts of the pandemic, comprehensive renewable energy policies also face the same uncertain future as their sustainability is put under scrutiny considering the highly volatile political and economic conditions in a post-pandemic world. As countries begin to recover from the pandemic, policies are geared toward revitalizing the economy and stimulating their battered industries. Certain fiscal measures could create barriers and delays in project development and deployment, as well as research advances in renewable energy technologies (Gebreslassie, 2020). Nevertheless, there might be a "silver" lining amidst the challenging situation rendered by the pandemic. The sharp decline in oil prices could signal a troubling future for the fossil fuel industry and yield potential opportunities for the renewable energy sector. On the one hand, the long-term outlook of crude oil and natural gas markets is shadowed by the price uncertainty. On the other hand, market volatility further increases the risk exposure for futures contracts. Based on basic economic principles, power demand would naturally increase with falling natural gas prices due to its significant share in the current electricity generation mix. The rise in energy demand and consumption can provide positive momentum to jumpstart economic growth (Fu and Shen, 2020). However, there are significant renewable energy impacts under these potential scenarios as a direct result of falling oil and natural gas prices. Hence, the path toward a clean energy transition continues to be subjected to new obstacles as progress can vary widely among geographical regions and types of resources available (Hosseini, 2020).

Investment in renewable energy can yield positive benefits to the overall economy and key industries by catalyzing renewable energy demand, rendering new project development, and increasing employment opportunities in the clean energy sector as part of the pandemic recovery phase ("Morecoal-fired pow, 2020). Once realized, these potentials can solidify the integral role of renewable energy as a key energy resource in the future. Dincer (2020) even suspected that the COVID-19 pandemic might provide the right conditions for the introduction of the hydrogen economy and such transitions can yield immense environmental, economic, and social benefits. As shown in Fig. 4a, renewable energy stands out as the least impact resource when comparing its project change rates of demand with other forms of energy including nuclear, natural gas, coal and oil.

As part of the clean energy transition, the deployment of distributed renewable energy systems would require the involvement of a wide range of community-based groups and other stakeholders in the decision-making process influencing the underlying energy, social and economic structure (A and "The Covid-19 crisis, 2020). Furthermore, certain advanced forms of distributed generation resources also offer remote control ability which ensures safe and reliable operations in emergencies (e.g., pandemic). It is anticipated that continued investment in technology, development of new technologies and infrastructure supporting the generation, and distribution of renewable energy has been proven to be an effective and integral part of the ongoing pandemic response (Graff and Carley, 2020). Despite major disruptions to the global renewable supply chains due to the temporary halt in production and manufacturing operations, Fig. 4b shows the varying growth rates in electricity generation from different renewable energy resources in 2020 with a remarkable decrease compared to 2019. Certainly, the experiences gained from the unfolding COVID-19 pandemic would likely contribute positively to the growing share of renewable energy resources among global generation capacity in the near future (Jiang et al., 2021). Among the expected benefits, as much as three times in the

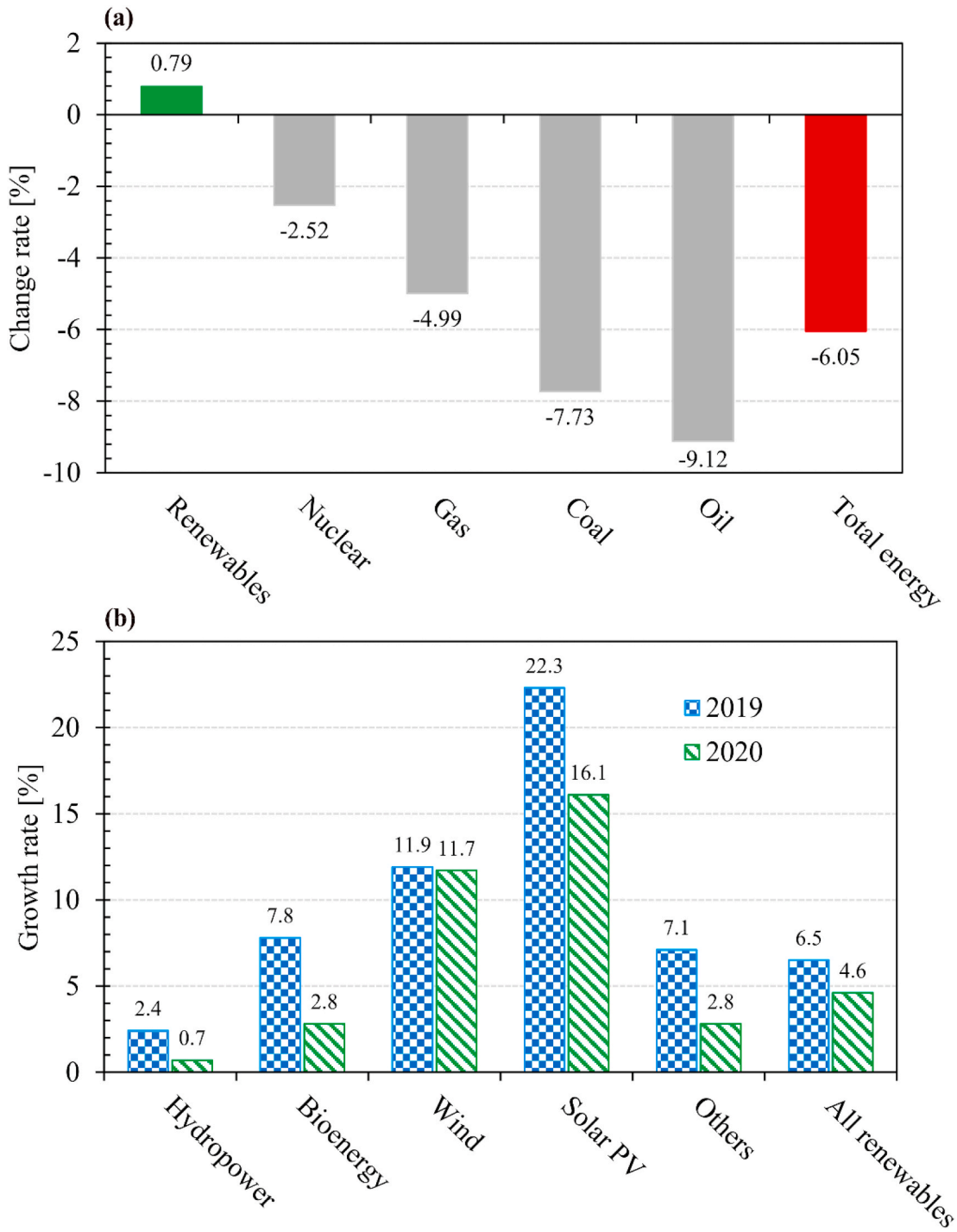

Fig. 4. (a) - Change rates of energy demand in 2020 compared to 2019 (horizontal baseline corresponding to zero); (b) - Growth rates of renewables-based electricity generation of 2020 (green) compared to 2019 (blue) [12][36]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

number of new jobs in the clean energy sector would be the result of continued investment in renewable energy as opposed to conventional fossil fuels (Dvořák et al., 2017). Such projection depends largely on the availability of core government incentives as demonstrated in the case of the Czech Republic ((United Nations Secr, 2020). For other countries like Germany, payment to wholesale customers by energy producers to avoid the scenario of temporarily shutting down plants has been applied. Facing the worst cases, the pandemic has highlighted the importance of incorporating a degree of flexibility in designing renewable energy systems that could handle variability introduced by unexpected circumstances (Amelang, 2020). Among the notable examples of clean energy technologies as hydrogen-based fuel cells offer the possibility in a multitude of applications, including delivery, ambulatory services, remote monitoring in urban areas, and enhancing agricultural production. Furthermore, the increased accessibility to smart grids and integrated energy storage systems would further create additional resilience to the renewable energy system and protect societies from potential shock from future crises. Taking another example, the shortage of electronic components in the post-COVID-19 pandemic could become an opportunity for the development of generators that are not based on

photovoltaic panels (Mehrotra et al., 2020).

Evidence has been shown to support the continued investment trend in long-term fossil fuel asset projects by multinational and international energy corporations. In countries like Japan and China, major investments and government subsidies in coal production have provided the underlying support to prop up the increased power production from coal-fired plants over the other more sustainable energy resources (A and "https://www.iea.org, 2020). Up till now, such common and long-standing investment practices have been a major obstacle in moving away from fossil fuel consumption (Newell and Lane, 2020). Nevertheless, there has been a steady divestment trend from fossil fuels in recent years by prominent private and quasi-state actors in several OECD countries. The observed phenomenon has grown out of the realization of heightened financial risks associated with fossil fuel investment. Besides, the increased probability of fossil fuel reserves that may become stranded assets proves to be an imminent threat to current investments. Experts believe that a strong price signal and the robustness of the renewable energy market would play a central role in promoting and enhancing the anticipated long-term transition toward a more sustainable energy future (Werth et al., 2021). Recently published results have further underscored the greater investment returns of renewable energy compared to fossil fuels over the past 5 years and since the start of the pandemic in particular (Donovan et al., 2020). According to IEA data, state and government-sponsored funds make up 70% of the total direct and indirect investment in energy (A and "Ministerial roundta, 2020b). Considering the stimulus packages, approximately USD 9 trillion is expected to be spent by national governments as part of their pandemic recovery efforts (Sustainable, 2020). Notably, clean energy investment strategies focusing on energy efficiency improvement of the current building stock, investing in renewable and clean energy infrastructure can have a positive multiplier effect on the economy and job market (Hepburn et al., 2020). Based on the supporting evidence and energy market outlook, there are reasons to believe in the better economic returns and positive yields of state spending on clean energy initiatives over traditional fossil fuel investments. Sustainable energy investment can further support countries in reaching their carbon emissions reduction targets while building up the resiliency for their respective national energy systems (Kuzemkoet al., 2020).

Assessing the impact of the COVID-19 outbreak on the global energy industry, experts have pointed out conflicting views on the measurable influence on the pace and integrity of system restructuring in response to the pandemic (Pareeket al., 2020). These changes are also subjected to the transition toward a low-carbon-based economy and gaining public interest in cleaner energy alternatives (Bertrand et al., 2020). Over the past year, the deployment of new renewable energy projects has been relatively more successful in markets where there are higher priorities and recognizable benefits from such clean energy investment. Among these, the majority of projects (e.g., an offshore wind farm) have been significantly impacted due to the pandemic which has caused a major delay in installations and interruption to major manufacturing activities of renewable energy parts and equipment. The pandemic-induced restriction measures have temporarily halted major construction activity and resulted in disruptions to global renewable energy supply chains (Eroğlu, 2020). As a result, power companies have turned to adapt their operations in response to the fallouts from the pandemic by putting aside new investment projects, tightening budgets, and cutting unnecessary spending, reassessing project implementation and investment priority that collectively resulted in major impacts on the global renewable energy production in the near term (Collaboration, 2015). Based on previous IEA projections, growth in renewable energy production in 2020 would be 13% less than what was recorded in 2019, while total annual investment would be expected to drop by 20% in 2020 (Kleinet al., 2018). However, experts anticipated a strong rebound in 2021 following the pre-pandemic growth and long-term trajectory (Cook et al., 2008). On the one hand, the falling demand for electricity over the course of the pandemic might dissuade potential investment in coal-based generation resources in certain growing economies. On the other hand, financing schemes and capital market conditions also play a crucial in divestment decisions from fossil fuels (Schultz et al., 2015). As the world becomes increasingly globalized, interdependence and reliance on highly interconnected global energy systems, supply chains, and external factors related to energy production systems are becoming more evident in the current sustainable energy transition. However, the effect of the pandemic has been indicated to support "re-shoring" as part of the strategies to shield the current operations from potential disruption (Klemeš et al., 2020). Nevertheless, little progress has been made in this respect due to the unavailability of coordinated efforts among the countries and comprehensive energy governance that includes all stakeholders across several energy sectors (Overland and Reischl, 2018).

In dealing with the ongoing pandemic, it has been come more evident in the exposure of global supply chains, such as medical products, equipment, and energy supplies, from potential shock or disruption. The temporary pause in state-funded projects shut down of ports, and closure of international borders have collectively contributed to the interference experienced by major international trading of manufactured goods and equipment (Shadish et al., 2008). As a result of the pandemic, the global energy system is positioned precariously in the current high volatile and uncertain market conditions following the initial sharp decline in demand and supply shock. In the short term, the temporary fall in energy demand would be followed by a less significant drop in demand and prices of electricity. Taking into account the fact that close to 80% of countries are net energy importers, the incentive to invest in more sustainable forms of energy could be stemmed from higher fossil fuel prices. Hence, to reduce their reliance on foreign supplies of fossil fuels, investments in more sustainable and reliable home-grown renewable energy resources could be politically and economically motivated. Overall, it would be a win-win scenario in which countries can benefit from a more robust clean energy economy while cutting down on spending over less reliable and more expensive imported sources of fossil-based energy.

4. Strategies for the renewable energy transition

The environment (i.e., lower carbon emissions and improved air quality) has been indirectly benefitted from the pandemic which prompted the ban of all non-essential travels, significantly reduced transport activities, and temporary shutdown of factories and industrial facilities. When considering the impact of the pandemic on the transition towards a low-carbon-based economy, a big emphasis has been placed on the time frame on which the analysis is based. Therefore, it should take into account for the temporary impact of the pandemic on the momentum of such transition. Firstly, the short-term is defined by the period during and immediately after the majority of the containment measures, such as quarantine, travel bans, temporary closure, etc., have been lifted. Secondly, the medium term is dominated by the easing of restrictions while social distancing has become a norm and recovery has begun to take shape. Last but not least, the long-term timeframe is considered to be the latter half of the decade between 2025 and 2030 by which the full impact of the various decisions is expected to fully manifest (Mastropietro et al., 2020). In the long run, the effect of the pandemic responses on future emission projection depends significantly on the structural modifications made to the existing energy system (Hoang et al., 2021b). Based on past economic cycles, the recent decline in global oil demand is expected to have a significant influence over the long-term economic outlook. During the 2008–2009 financial crisis, Italy experienced a record loss of 23 mt of refining products along with the permanent closure of five refineries. In the early months of the pandemic in 2020, a shattering record of 90% reduction in jet fuel demand was observed during March, while between 50 and 60% drop in gasoline and diesel demand was also recorded in the same period. These initial falls in fuel demand set an early warning for potentially unstable socio-economic conditions in the months and years to come.

Consequently, thousands of jobs and businesses could be significantly affected due to the low demand. An estimated loss of up to 50 million jobs is projected for the energy sector as a result of the pandemic (Chen et al., 2020b). Currently, the historically low prices of oil pose a major cost disadvantage to power generated from renewable energy resources. Among the developing economies, governments can be motivated by such low oil prices to begin providing subsidies to fossil fuel companies. Potential changes to these subsidy programs in light of future increases in oil prices should be taken into account along with supporting policies design to fast-track the transition toward a low-carbon-based economy (Matsuo and Schmidt, 2017). The future of renewable energy technologies could be dampened by the low oil prices if the current unfavorable condition persists. To minimize the possibility of laggards benefiting from such reform, policies should be designed to reflect a timely and effective strategy to reduce the potentially unintended risks to the clean energy transition within the transportation sector. To assess the potential effects of the emerging pandemic on society and the economy, one should be aware of the high degree of uncertainty and severity of the potential consequences associated with the long-lasting impacts directly resulted from the unprecedented health crisis. Hence, policymakers must address the short-term policy modifications while identifying and prioritizing strategic long-term policy actions towards a more sustainable and low-carbon energy future (Hale et al., 2020).

To assess the level of energy security of a particular region, firms can use renewable energy as a reliable and sole indication. In the case of the European Union, one can perceive the comparable alignment of the energy security initiatives with the core objectives of the European Green Deal. Despite the progressive goals and benefits of such a plan, the lack of communication plans to effectively promote these policies has unintentionally undermined its potential. Specifically, up to the publication of RED II (EUROSTAT, 2019), energy security and decarbonization in transportation topics have not been adequately addressed by the EU relative to countries in other parts of the world. Similarly, the effort put forth to decarbonize the EU's energy system as part of the European Green Deal has allowed for a wave of new domestic renewable energies being introduced to the market; yet the same priority has not been given to assess the security of energy supplies (Eroğlu, 2020). To further illustrate the above point, India can be viewed as another excellent example as the country's Ministry of Petroleum and Natural Gas has taken steps to promote sustainable growth of renewable energy resources and reduce reliance on imported energy while at the same time making significant progress in rural socio-economic development. India's success story was supported by the country's growing energy share of nuclear and hydropower sources from 22% to 27% while total coal consumption declined from 71% to 65% (Kumar Sing, 2020). Overall, there is strong evidence to support progressive domestic policy in advancing sustainable sources of low-carbon fuels, including both locally sourced renewable energy supplies and "recycled carbon" options that could act as a catalyst in promoting the economic, social, and environmental benefits associated with the current transition toward a cleaner and more sustainable energy system.

The production and consumption of energy form the backbone of modern society, which is essential for the normal functioning of our daily lives. The unfolding pandemic has caused major disruptions to social interactions and movement of people as well as the intricate socio-economic linkage between the different communities and the local/regional, national, global energy systems. Besides, the prioritization of the various such systems has also been identified through this experience. Notably, the bulk of recent research has examined the characteristics of low-carbon and sustainable energy system transition and the possible effects on these energy systems by the pandemic, including reduced daily electricity consumption (A and "Global Energy Revie, 2020) and shift in load patterns (Meinrenken et al., 2020). Nevertheless, it remains difficult to discern the effects of the different policy measures on these energy systems in scenarios with or without a pandemic. The ongoing pandemic has introduced an unexpected element to the current global discourse on the transition toward a low-carbon-based economy with the apparent and widespread effects of the pandemic on major aspects of our society including our perception and social ties to the existing energy systems. Such influences are difficult to separate from the other change drivers that also play an important role in influencing the societal view and support of the clean energy movement (Wang and Wang, 2020). As researchers based their investigations on the same aforementioned principles, they could now examine new research objectives spanning beyond minimizing potential threats in the validation of research design. New recommendations and best practices have been proposed as the outcomes of new research findings. The introduction of longitudinal, contextual, and behavioral elements in the current analysis has allowed researchers to glean valuable information on the effects of constant and fluctuating independent variables on the main outputs of such investigation. Furthermore, these findings also help to better formulate relevant follow-up research questions. The impact of the pandemic can be analyzed on an individual, societal and global scale. People and communities face direct consequences from the sudden loss of jobs and the closure of businesses. More broadly, one could potentially discern the varying effects that the pandemic has had on different communities and countries around the world. Hence, researchers are motivated by this observation to carry out investigations and experiments to explore the possible hidden causal links between the pandemic and various social-economic structures (Goldberget al., 2020). Moreover, there remains a large avenue for potentially innovative energy research projects. Concurrently, supporting policies and regulatory frameworks play an integral role as part of the post-pandemic strategic economic recovery plan. Considering the known benefits of collaborative research in supporting the replication and validation of research results, there has been a growing number of convergence research in solving complex issues at the nexus of energy and social dimension during the current crisis and post-pandemic recovery phase. Particularly, convergence research methodology utilizes an integrated and interdisciplinary approach in analyzing highly complex problems (Sui and Coleman, 2019). Due to the wide range and multi-level results of the COVID-19 outbreak, the integrated methodology employed by collaborative research is both relevant and beneficial in examining such a topic. Besides, as various types of research collaboration begin to take shape, it has the potential to reveal hidden relationships as well as new understanding and knowledge from comparing among referenced datasets. The need for greater transparency and research replicability has called for researchers to continue to address validity concerns related to research related to the effects of the ongoing pandemic. Because most types of energy research are inherently multidisciplinary, there is still a small number of resources that offer available methods concerning the reporting guidelines and submission of initial research proposal (Huebner et al., 2020). With the greater visibility and effectiveness of these research methods, it can be expected that higher recognition and adoption of such tools would be widespread. In the long run, a commonly used standard of practice should be developed and used by most researchers in the energy field that would further legitimize many of these current and future energy research topics.

5. Conclusion and policy implications

Over the past year, the unfolding consequences of the COVID-19 pandemic have significantly affected individuals, communities, and nations around the globe. The economic impact each country has experienced has largely influenced the progress made in the clean energy transition. Policies that could resilient and protect renewable energy investment from major disruptions and potential pitfalls are highly desirable. With the introduction of new renewable generation resources and production facilities, there would be a higher vision of supporting policies and legal frameworks intended for the low-carbon economy. Governments must identify appropriate strategies in their responses to the pandemic so that short-term policy goals can be established to

support both the recovery effort and sustainable energy development. Compared to traditional fiscal response in past crises, policies supporting investment in sustainable and renewable energy technologies yield a potentially higher return and more beneficial in improving the socio-economic conditions. Previous analyses of stimulus plans following the global financial crisis of 2008 have revealed higher long-term cost-saving and job creation as a result of investment in renewable energy infrastructure compared to traditional fiscal strategies (Allanet al., 2020). In the short-term, the high labor intensity of renewable energy-related jobs stimulated by the robust market results in positive multipliers promoting increased demand and consumption. Considering the current transition toward the low-carbon economy, policymakers should be ready to provide evidence in supporting the impending modifications to the existing policies and regulatory mechanisms as part of the newly proposed renewable energy plans. Particular attention should be paid to the structural implications in the evolving energy system and the potential spillover effect resulted from such policy changes (Pahleet al., 2018). Even though it can be very tempting to promote clean energy and sustainable development priorities as part of the post-pandemic economic recovery plan in the short term, experts advise the early rounds of stimulus money should be spent on minimizing the most severe economic outfalls from the pandemic and helping struggling businesses to avoid potential bankruptcy. Instead of focusing on small immediate benefits, policies should be designed to emphasize measurable changes as part of the long-term plan in supporting the low-carbon economy transition. In the post-pandemic, governments now face the subtle choice of reducing renewables or expanding investment and production tax credits to get back where they were and keep pace with the development of clean energy projects. Such potential changes are considered to be effective in allowing continued investment in renewable energy technologies by private corporations and the industry as a whole, while also moving closer to achieving the mid-term sustainability goals. Compared to electricity generated from conventional fossil-based resources, those that come from renewable energy resources can benefit greatly from lower interest rates as a beneficial mechanism in lowering the latter's levelized cost and improve its price competitiveness. Additionally, maintaining a low-interest rate condition can provide the momentum for clean energy investments as they are perceived to be favorable conditions by policymakers and project developers. Considering the purpose of calculating the levelized cost of electricity, one should take into account the low interest rate as an important variable influencing the relative price and cost advantage of renewable-based electricity over other conventional fossil-based sources (Schmidt et al., 2019). In certain countries, there are increased opportunities for the development of large-capacity renewable energy projects, (e.g., utility-scale solar, on-shore, and off-shore wind farms) as part of the post-pandemic economic recovery plan. Similar opportunities exist for a wide range of building energy efficiency improvement measures. The growth in the number of construction projects will provide the initial impetus to stir up the labor market with the addition of new employment opportunities and improve the overall visibility of these measures as part of the relief effort. Nevertheless, there are still sizeable obstacles in locating appropriate financing schemes for low-carbon energy projects that have been done away with during the pandemic as in the case of most developing economies as well as those holding large amounts of foreign debts (Jin, 2020). Considering the medium-term goals in the clean energy transition, there are potential obstacles facing policymakers as they continue to closely monitor the evolving macroeconomic and political conditions. Despite the high uncertainty in conjecture a highly reliable scenario in which these different drivers will unfold, one can rely on the macroeconomic conditions as a potential predator for future outcomes (Bowen et al., 2009). The blooming economic recession is fairly certain as countries scramble to find cost-effective responses that are appropriate in their respective economic and social-political conditions. Impacts from industry restructure, high unemployment rate, decreased demand for goods and services have collectively contributed to the sharp decline in the prices for carbon emission allowances. Following the initial relief funding, experts have called for additional stimulus packages to be approved as part of the long-term economic recovery plan (Akrofi and Antwi, 2020). Overall, as global oil prices are kept as low as possible, deteriorating market conditions are likely due to the pandemic-induced demand decline and the turmoil facing the supply and production agreement by OPEC+. These above conditions set up the perfect opportunities for the increased momentum in the clean energy and low-carbon economy transition. The progress, however, can vary based on the maturity and capital requirements of the different renewable energy technologies. As renewable infrastructure projects proceed in the later stages, the increase in the labor requirement will provide the impetus for increasing the number of jobs generated per dollar of investment as compared to traditional fossil fuel investments (Pollin et al., 2008). Additionally, there is a significantly smaller risk of off-shoring for investment in renewable energy construction (e.g., wind farm installation) and energy efficiency improvements (e.g., building insulation retrofits) relative to traditional fiscal stimulus methods (Blyth, 2014). As these technologies continue to improve in the future, such advancement would yield more cost-effectiveness in the deployment and maintenance of such renewable energy facilities. As a result, the reduced labor-intensive and requirements from these projects would result in greater long-run multipliers directly benefitted from realized energy cost savings (Jacobs, 2012) and the overall improvement of economic conditions. Hence, any potential postponement in energy policy reform could yield unfavorable to the long-term clean energy goals. On the other hand, short-term solutions such as temporary waivers or suspension could be viewed as alternative strategies in dealing with increasing demand from renewable energy industry stakeholders (Steffen et al., 2020).

Since the onset of the pandemic more than a year ago, the COVID-19 outbreak has significantly affected the global energy systems. The establishment of social distancing measures and various levels of restrictive measures in an attempt to prevent the spread of the highly contagious virus has resulted in major declines in commercial and industrial activities. Consequently, the subsequent fall in global energy demand has been the direct effect of these above measures. Furthermore, improvements in air quality and level of greenhouse gas emissions due to the reduced transport activities have been highly visible during the most restrictive periods. Besides, there are proportionately larger impacts that the pandemic has on the economy as a whole. In addition to a public health crisis, the pandemic has opened up a booming economic crisis that offers potential opportunities for the development of advanced technologies. As countries are taking appropriate measures in responding to the imminent recession, policy choices present a crucial and deciding factor in either advancing or slowing down the progress in the clean energy transition. Even though it might be a bit immature in making definite prediction and assessment of the full effect of the pandemic on the global renewable energy market, there are strong indications in the initiatives taken by selective countries in promoting sustainable and renewable energy development and investment in the clean energy sector as part of the "green recovery" effort. The pandemic has taught us an important lesson in dealing with the potentially major disruption caused by future crises. Heeding this warning, governments are taking a serious look at drafting effective policies and regulatory frameworks in protecting renewable energy investment and the risk of exposure from economic turmoil and instability. A win-win situation is possible as a result of the COVID-19 pandemic recovery effort in which governments can take advantage of the key renewable energy initiatives to support the clean energy transition while creating the appropriate conditions for the recovery of the economy and building a stronger and more responsive national health care systems that can withstand major health crises. In parallel, the economic responses to the pandemic and the mitigation measures from climate change risks are mutually beneficial and parts of a multi-prong sustainability strategy. Taking advantage of the framework offered by the Paris Climate Agreement and the

2030 Agenda, governments can prioritize policies supporting near-term economic recovery plans while focusing on supporting strategies for a stronger economy and more responsive health care systems in the long run. If all major world leaders adopt the "build back better" mindset with renewable energy investment at the crux of the recovery plan, potential co-benefits from such policy decisions could be soon realized (Helgenberger, 2020). Learning from the impact of the COVID-19 pandemic and subsequent response to the crisis, it has become clear that the significant effect of the initial economic shock on the clean energy transformation is evident. Considering the overall picture describing the relationship between the coronavirus pandemic and global energy security, these lessons have enlightened the better understanding of the similarities and differences between these two subjects. One pauses to ponder the question of whether there has been an increase in the recognition of the importance of energy security in individual livelihoods and socio-economic conditions during such extraordinary times. Hence, the potential role of renewable energy and low to non-carbon fuels during the various lockdown episodes has been highlighted in several countries around the world (Chen et al., 2020a). Therefore, the persisting misconception based on the assumption of a steady-state balance has been revealed by the current crisis. Indeed, two significant risk factors are omitted out of the consideration. First, if the economy is propelled by appropriate policy mechanisms, investment in clean energy technologies would be hampered by the fall in economic activities. Second, there is a high chance that newly adopted policies would fail to survive the economic shock during the recession and quickly replaced by the evolving political conditions if economic variables and aggressive goals are not included initially during the policy-planning phase. These two important risk factors are likely to play a major role in the transition toward clean energy and a low-carbon economy.

CRediT authorship contribution statement

Anh Tuan Hoang: Writing – review & editing, Conceptualization. **Sandro Nižetić:** Writing – review & editing. **Aykut I. Olcer:** Writing – review & editing. **Hwai Chyuan Ong:** Writing – review & editing. **Wei-Hsin Chen:** Writing – review & editing. **Cheng Tung Chong:** Writing – review & editing. **Sabu Thomas:** Writing – review & editing. **Suhaib A. Bandh:** Writing – review & editing. **Xuan Phuong Nguyen:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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