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Global low-carbon energy transition in the post-COVID-19 era

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HIGHLIGHTS

- We provide an overview of the dynamics between energy transition and COVID-19.
- We identify the challenges and opportunities for energy transition under COVID-19.
- We investigate the impact of global economic recovery stimulus on energy transition.
- We propose a practical roadmap for the post-pandemic energy transition.
- We enrich the framework on global low-carbon energy transition.

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ABSTRACT

The COVID-19 pandemic has created significant challenges for energy transition. Concerns about the overwhelming emphasis on economic recovery at the cost of energy transition progress have been raised worldwide. More voices are calling for "green" recovery scheme, which recovers the economy while not compromising on the environment. However, limited academic attention has been paid to comprehensively investigating the implications of COVID-19 for global energy transition. This study thus provides a comprehensive analysis of the dynamics between energy transition and COVID-19 around the world and proposes a low-carbon energy transition roadmap in the post-pandemic era. Using energy data from the International Energy Agency (IEA), we first summarized and reviewed the progress of energy transition prior to COVID-19. Building on prior progress, we identified the challenges for energy transition during the pandemic from the perspectives of government support, fossil fuel divestment, renewable energy production capacity, global supply chain, and energy poverty. However, the pandemic also generates opportunities for global energy transition. We hence also identified potential opportunities for energy transition presented by the pandemic from the perspectives of price competitiveness, policy implementation efficiency, and renewable energy strengths. We further provided an in-depth discussion on the impact of current worldwide economic recovery stimulus on energy transition. Based on the identified challenges and opportunities, we proposed the post-pandemic energy transition roadmap in terms of broadening green financing instruments, strengthening international cooperation, and enhancing green recovery plans. Our study sheds light on a global low-carbon energy transition framework and has practical implications for green recovery schemes in post-pandemic times.

1. Introduction

The accelerating climate change concerns highlight the importance of the global transition towards a "green economy" with lower fossil fuel consumption and greenhouse gas emissions [1]. Steady progress has already been made in energy transition globally. For example, global renewable energy installation capacity increased by more than 200 billion kilowatts in 2019 [2]. However, the COVID-19 pandemic has

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significantly hampered renewable energy development [3], leaving the future of the energy transition uncertain. Debates have erupted over how to promote the global energy transition in the post-pandemic era.

Currently, fossil fuels still dominate the global energy system, accounting for more than 80% of the total energy supply [4]. The vast consumption of fossil fuels has generated various challenges to human society, for instances, the growing supply–demand imbalance in the global energy market [5], the risk of oil reserve depletion [6], greenhouse gas emissions [7], etc. Moreover, due to the large volume of carbon dioxide emitted by using fossil fuels, the global temperature has risen by roughly 1.0 °C above the pre-industrial level [8,9]. If carbon emissions continue to increase at the current rate, the temperature is predicted to climb by 1.5 °C between 2030 and 2052 [10]. Meanwhile, the pernicious and spillover effects of global warming, such as rising sea levels, imperil the daily lives and economic activities of roughly one billion people [11].

Countries worldwide have implemented legislations and regulations in response to the growing concerns about traditional energy consumption [12,13]. More voices are calling for international cooperation and collaboration on dealing with fossil fuel divestment issues [14]. The Kyoto Protocol and the Paris Agreement are milestones for climate governance, providing the basis for global low-carbon energy transition [15]. Climate governance seeks to convert the usage of non-renewable energy into clean and renewable energy, thereby decarbonizing the economy [16]. The international climate agreements reflect a growing global demand for renewable energy development [17].

Although a large number of energy policies indicate a promising future for renewable energy development [18], the COVID-19 pandemic exerted an unprecedented shock across the entire energy sector, impeding the progress of energy transition [19]. Growing concerns have emerged regarding the post-pandemic energy transition [20,21]. Since the World Health Organization (WHO) declared the COVID-19 outbreak a global pandemic on March 11, 2020, many countries have entered a new state of pandemic prevention and control, restricting travel and economic activities to unprecedented levels [22]. A sudden disruption in the business activities results in a nearly 5% decline in global energy demand in 2020 [23] and a 7% decline in global emissions [24], and might have a longer-term impact on global energy consumption and carbon emissions in the coming decades [25]. Meanwhile, the pandemic has weakened the oil-producing countries' grip over the energy market [26], causing the oil price to continue to drop. The decreased oil price gives traditional energy a competitive edge over renewable energy. Moreover, although the pandemic lockdown measures effectively contained the virus and saved economic losses [27], the subsequent drastic reduction in international trade was a massive setback for the global renewable energy supply chain [3]. Numerous employees from renewable energy firms were on leave, corporate operation capacity plummeted, and a large amount of renewable energy equipment production, installation, and commissioning came to a halt [28].

The impact of COVID-19 on renewable energy development has been increasingly notable [29]. Since the pandemic, many countries have reshaped their investment structure by increasing medical and health expenditures while withdrawing funds from renewable energy projects and tax deductions [30]. In the absence of government support, high upfront costs and low immediate payoffs further demotivate renewable energy investments. Facing economic challenges, many countries are actively seeking effective strategies to recover the economy. Despite a growing call for green stimulus plans, the "green" element of announced stimulus plans was limited, and most nations' energy investment structure remains dominated by fossil fuels. In the long term, such irresponsible recovery mode will lead to negative consequences for climate change and energy transition, weakening the sustainability and resilience of the world economy.

Therefore, answers to the following questions are of vital importance to achieve an effective co-development of economic recovery and energy transition: What are the challenges and opportunities that the COVID-19 pandemic generates on energy transition? Are current economic recovery plans worldwide beneficial for renewable energy development? How can we achieve progress in energy transition post-pandemic?

We provide answers to these questions in the hope of contributing to the framework on global low-carbon energy transition and providing guidelines for post-pandemic green recovery policy formulation. To answer these pivotal questions, we first review and summarize the progress of global energy transition prior to COVID-19 (Section 2), followed by a comprehensive investigation of how the COVID-19 pandemic and economic recovery plans affect energy transition in Section 3. In Section 4, we present a detailed analysis and discussion of the roadmap for energy transition in the post-pandemic era, and Section 5 concludes this study.

2. Energy transition before COVID-19

2.1. Energy structure and climate change

The current energy structure is still dominated by fossil fuels such as coal, oil, and natural gas. According to the International Energy Agency (IEA) statistics, the global energy supply in 2018 reached 14,279,569 Ktoe, with coal, oil and natural gas accounting for 26.88%, 31.49% and 22.84%, respectively [23]. As illustrated in Fig. 1, the global energy supply demonstrates an overall increasing pattern. It is apparent that the increase was mostly driven by fossil fuels before 2015, however, after 2015, fossil fuel supply has flattened out while the supply of renewable energy sources such as biofuels, waste, wind, solar and hydro has begun to increase noticeably.

Although the share of fossil fuels in the global energy supply structure has declined, the overall supply still exceeds 80%. The high-carbon energy system has resulted in an increase in carbon emissions. The United Nations Environment Programme (UNEP) pointed out in its *Emissions Gap Report 2019* that total greenhouse gas (GHG) emissions from energy production and industrial activities reached 37.5 Gt in 2018, with total carbon dioxide emissions increased by as high as 2% [31]. And 65% of the total carbon emissions were from using fossil fuels [32]. Massive GHG emissions have exacerbated global warming, wreaking havoc on human society and the environment [33]. Furthermore, frequent natural calamities such as sea level rise and forest fires have already put people in danger in many regions [34].

In the face of climate change, it is crucial to synergize the economy, energy consumption, and climate change so as to achieve sustainable development and carbon neutrality [35,36]. In 2015, 196 participating parties jointly signed the "Pairs Agreement" to reach an agreement on decarbonization [25]. The agreement aims to keep global warming well below 2 °C, ideally 1.5 °C, above the pre-industrial temperature level [37,38]. To achieve this goal, many countries have made active efforts to restructure their energy system. For example, the European Union (EU) announced a 20–20–20 target, that is to improve energy efficiency by 20%, reduce carbon emissions by 20%, and increase the share of renewable energy to 20% by 2020. China set up a "30·60" plan, pledging to peak carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060. Energy transition has emerged as a new battlefield for global leadership on climate change.

2.2. Global energy transition

The growing concern about climate change has shifted people's attention towards renewable energy globally. A green energy transition is quietly kicking off amid the fourth industrial revolution. The green energy transition aims to replace high-carbon fossil fuels with low-carbon clean energy. Clean energy mainly consists of low-carbon renewable energy sources [39], such as solar, wind, hydro, bioenergy, geothermal, etc.

Fig. 2 illustrates the proportion of renewable energy consumption in total energy consumption around the world. As shows in the energy

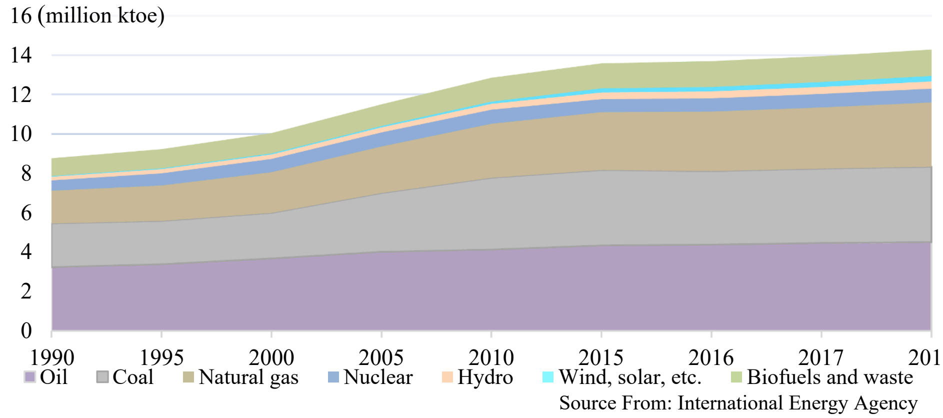


Fig. 1. Global energy supply from 1990 to 2018.

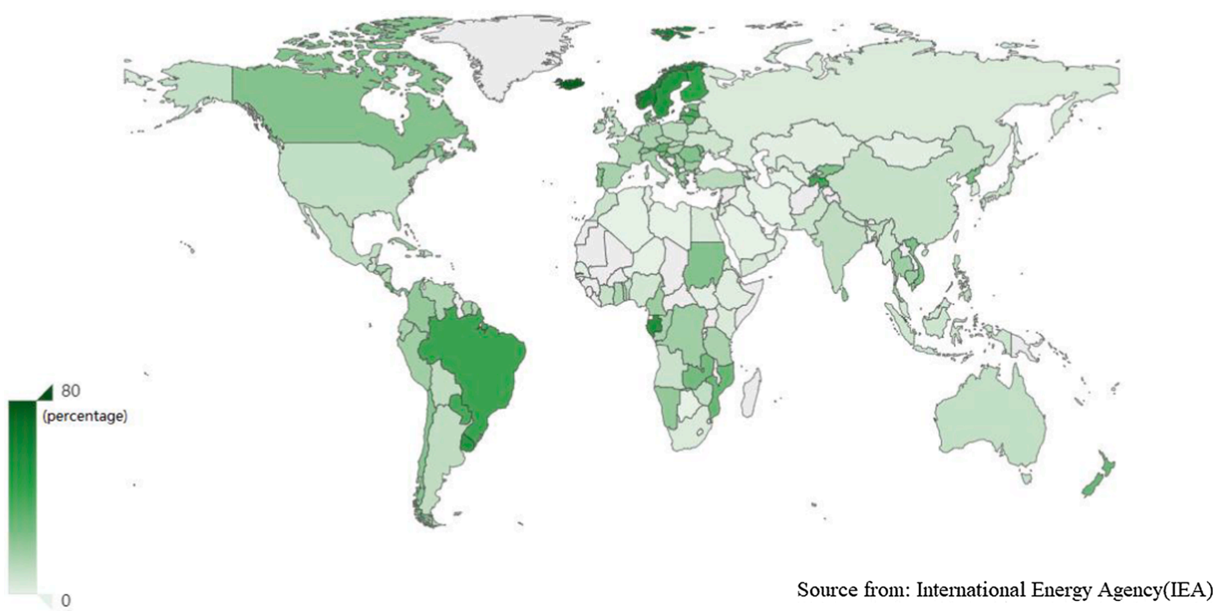


Fig. 2. Global renewable energy consumption in 2017.

consumption map, renewable energy consumption accounted for more than 25% of total energy consumption in Northern Europe and South America in 2017. Europe has the largest renewable energy consumption share globally, with most European countries exceeding 20%. For example, in 2017, renewable energy sources provided 76.7% and 61.2% of the power used in Iceland and Norway, respectively. Approximately 88% of Iceland's primary energy consumption came from renewable energy sources that year, with wind and solar together contributing up to 66%. Because of its geographical location, Iceland also has abundant hydropower and geothermal resources. Similarly, in 2017, Norway powered up 40% of its primary energy consumption with hydropower.

In South America, renewable energy consumption, primarily hydro and biofuels, ranked second in the total energy consumption in 2017, with many countries reaching 15% [40]. In Uruguay, for example, renewable energy provided 61% of its energy consumption that year, with biofuels and hydropower contributing 42% and 12%, respectively. Similarly, Brazil had 42.3% of its total energy consumption generated by renewable energy sources in the same year, with biofuels accounting for more than 30%.

In contrast, the proportion of renewable energy consumption is relatively small in the Asia-Pacific region. The majority of Asia-Pacific countries consumed renewable energy at less than 15% of total energy consumption, with the exception of New Zealand (30.4%), Vietnam (25.7%), North Korea (25.4%), Canada (23.2%) and Sri Lanka (22.8%). Specifically, New Zealand is located at the junction of the Indian Ocean and Pacific Ocean plates with active crustal movement, and so they have abundant geothermal and hydro energy sources, accounting for 29.1% and 12.8% of total energy consumption, respectively. In Sri Lanka, nearly 40% of the electricity mix is derived from hydropower. Although the share of renewable energy consumption in China and the United States is relatively small, both countries are world leaders in renewable power generation capacity. For example, in China, as power systems become more integrated, they are expected to account for 40% of global renewable power generation before 2024 [41]. In the United States, the power generation capacity of solar and wind energy is increasing year-on-year, and is expected to grow by 50% within a decade [42].

Globally, renewable energy is demonstrating a promising momentum. In 2019, worldwide investment in wind power generation totaled US$138.2 billion and investment in photovoltaic power generation reached US$131.1 billion. In South America, renewable energy investment surged by 54% over the previous year, with Chile and Brazil leading the way [43]. The European wind power market has also grown significantly. In 2020, wind power contributed approximately 57%, 32%, and 26.4% of the total energy supply in Denmark, Ireland, and

Portugal, respectively [23]. At the same time, in China, the use of fossil fuels such as oil and coal has been declining in recent years, while renewable energy consumption, especially hydropower, solar, and wind, continues to rise [44]. At the end of 2019, China's renewable energy installation capacity has reached 7.94 kW, a 9 % year on year rise.

Despite the sound progress of global renewable energy investment, there are still issues awaiting to be solved. First of all, renewable energy projects involve large upfront costs and technical requirements, making them especially challenging for many developing countries [45]. The high cost and technical requirements will largely hinder the energy transition progress [46]. In addition, although the green energy transition has diversified the energy mix, no renewable energy resource has yet possessed a monopolistic power like fossil fuels, leading to a limited proportion of renewable energy in global energy consumption. According to the IEA 2019 report, renewable energy accounted for barely 14% of the global energy demand [47]. Therefore, it is necessary to explore new opportunities in current changing global economic landscape.

3. Energy transition during COVID-19

The COVID-19 pandemic has posed serious consequences not only for public health but also for the energy transition. First, the economic downturn has exacerbated significant volatilities of renewable energy markets. Second, the declining fossil fuel prices have further weakened the price competitiveness of renewable energy. Third, international trade restrictions have impeded renewable energy supply chains, stranding numerous projects. Last but more importantly, the post-pandemic economic recovery plans continue to rely on fossil fuel investments, making the transition to renewable energy more challenging. Albeit the challenges facing the energy transition, the pandemic also opens the door to opportunities. In this section, challenges and opportunities for energy transition during the pandemic are discussed.

3.1. Challenges for energy transition during the pandemic

The primary hurdles for renewable energy transition under the influence of the pandemic are a lack of investment and poor market demand. First, as a result of the governments' significant reduction in subsidies, renewable energy projects are facing high start-up costs and technical investment. Second, the lower price of fossil fuels further increases the difficulty of fossil fuel divestment. Third, the restriction of industrial activities leads to a decline in the demand for renewable energy equipment and facilities, slowing the growth of renewable power generation capacity. Fourth, the global supply chain for renewable energy has been disrupted as a result of the mandated trade restrictions, making it difficult for new projects to more forwards. Last, energy poverty is more pressing than ever during the pandemic, making the renewable energy transition more struggling.

Specifically, the business lockdowns and extensive medical and health expenditures have caused enormous economic losses [48,49], resulting in the risk of government debt and so the fiscal deficit. According to International Monetary Fund (IMF), the global fiscal deficit as a share of GDP might rise from 3.7% in 2019 to 9.9% in 2020, while the percentage of public debt in developed economies would rise from 105% to 122% of GDP [50]. Governments in many countries had to withdraw funds from renewable energy investments in order to combat the pandemic and safeguard people's health. As per the IEA, the number of final investment decisions (FID) for public renewable energy projects decreased by 10% in 2020 compared to the same period in 2019, with February to March hitting a new lowest point since 2017 [51].

The pandemic has exposed the drawbacks of renewable energy development relying heavily on government funds, especially in countries with high government debt. Renewable energy projects often require government subsidies due to the high upfront costs, technical difficulties, and high operation and maintenance expenses [52]. However, the COVID-19 pandemic has significantly decreased government financial support for renewable energy initiatives. Thus, it became difficult for renewable energy companies to generate sufficient revenues to offset the high costs on their own. Moreover, capital flows have been tightening globally, and so more investors will shun high-risk investment options, further impacting commercial renewable energy investments [53]. The energy research company, Rystad Energy, commented that such a circumstance would result in insufficient incentives for renewable energy development, severely delaying green energy transition [21].

Even worse, the faulted fossil fuel divestment movement, along with the drop in oil and natural gas prices, has made commercial renewable energy investments more sluggish. The previous fossil fuel divestment campaign failed to differentiate fossil fuel companies, lumping together climate-conscious fossil fuel companies with heavily polluting ones. Failure to recognize the heterogeneity within the industry will send shockwaves across the entire energy sector, jeopardizing the stability of energy services and making the green energy transition more difficult. In addition, the divestment movement failed to engage individual investors, who hold a large share of energy stocks besides institutional investors [54]. Moreover, despite advocating fossil fuel divestment, the movement initiators failed to provide clear guidance on how to reinvest afterward, leaving investors to fend for themselves. It hence makes the campaign even less appealing to individual investors, who had already been overlooked [55]. Furthermore, the plunging prices of fossil fuels such as oil and natural gas caused by the pandemic have made renewable energy even less price-competitive [56]. Some cost-sensitive developing countries have already started to resume fossil fuel power generation [57]. As a result, fossil fuel divestment has become more challenging, resulting in a delayed energy transition.

In addition, according to IEA, the global industrial slowdown in the first quarter of 2020 has caused a decline in both production inputs and outputs, with China suffering the most, as shown in Table 1. China's renewable energy investment is the highest worldwide [58]. However, the pandemic lockdown in the first quarter of 2020 has hampered the procurement for numerous renewable energy projects in China. For example, the production of photovoltaic equipment such as solar panels, connectors, and battery components, was largely suspended, putting solar projects on hold [19,59]. From the corporate investment perspective, industrial profits are shrinking due to the pandemic, prompting cash to flow into lucrative ventures. For instance, in heavy industry, when production resumes, companies will prioritize raising production levels to stabilize the corporate structure while putting low-emission projects on the shelf due to high production costs. The shrinkage of low-emission projects will have a significant impact on energy transition.

Moreover, the COVID-19 pandemic has hastened the restructuring of global supply chain as global production capacity plunges. The lockdowns have hampered international trade, impacting both the supply and demand side of the renewable energy market [60]. According to Tradeshift, a global supply chain management platform, China's

Table 1
Industrial production in the first quarter of 2020.

	World	China	India	EU	United States
Industry	−5.4%	−9.4%	−3.3%	−5.8%	−2.1%
Steel	−1.4%	1.2%	−5.3%	−10.0%	−1.0%
Cement	−4.4%	−23.9%	−4.9%	−0.5%	7.7%
Petrochemicals	−2.7%	−5.0%	−11.7%	−4.4%	−0.2%
Manufacturing	−9.2%	−7.7%	0.5%	−5.6%	−4.3%

Notes:
1. Major data source: International Energy Agency.
2. Supplement data sources: Trading Economics (2020), OECD (2020), FRED (2020), World Steel Association (2020), CEMNET (2020), CEIC (2020), Platts (2020), Quandl (2020), Statista (2020), FXEMPIRE (2020a; 2020b), Investing.com (2020).

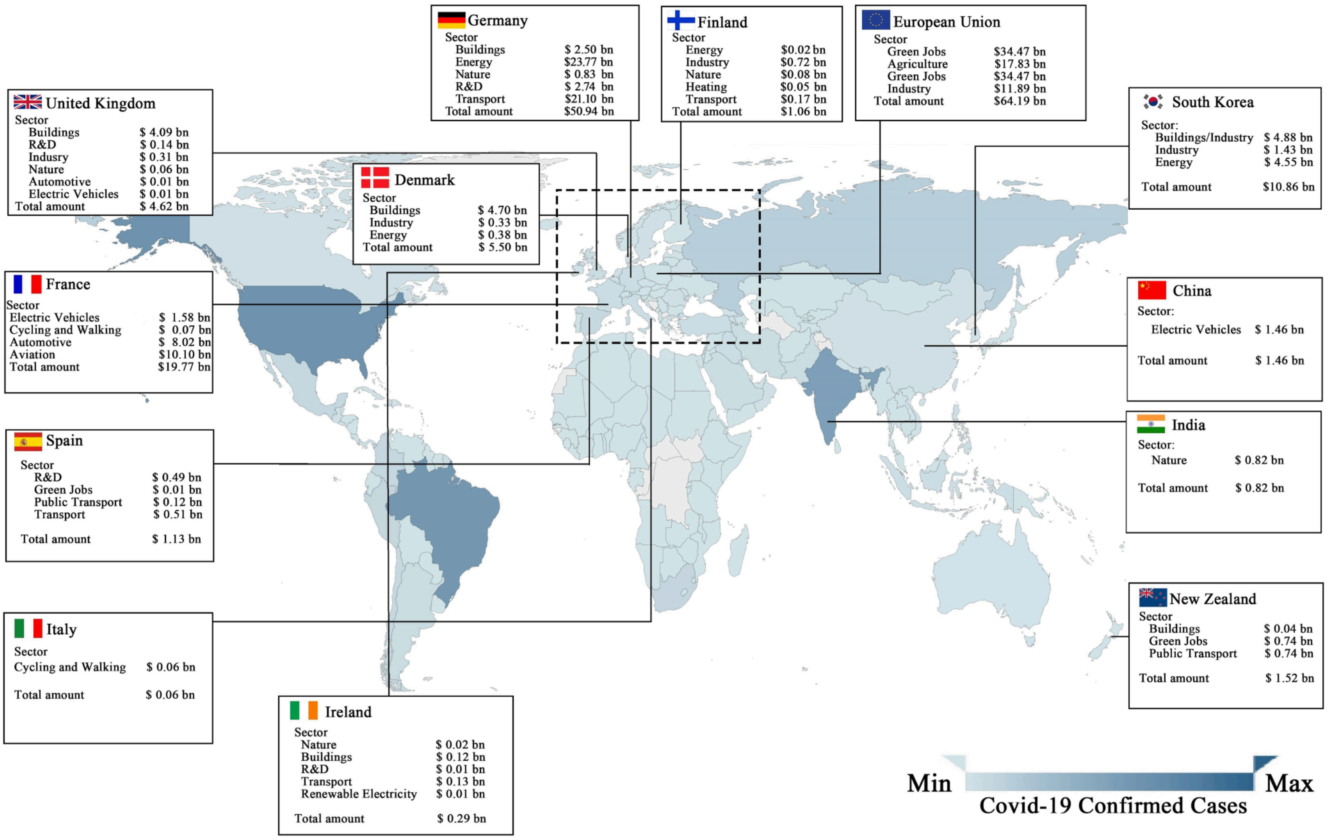


Fig. 3. Worldwide COVID-19 confirmed cases and green stimulus budgets.

domestic and foreign trade volume has dropped by 56% since mid-February 2020, with the United States, the United Kingdom, and the European Union trailing closely behind. Without a stable and resilient supply chain [61], renewable energy facilities can hardly be acquired, leaving many projects in jeopardy. For example, the wind energy manufacturer, General Electric, has disclosed several stranded projects [62]. Accordingly, the pandemic has slowed the energy transition substantially.

Energy poverty is another challenge to the green energy transition. The international community generally defines energy poverty as the inaccessibility to modern energy services [63], such as electricity. There are still many impoverished areas in the world that cannot access even basic energy services, especially in the historically colonized countries where people had long endured colonial exploitation, including loss of energy sovereignty [64]. During the COVID-19 pandemic, people in these regions were unable to use even the cheapest open-source ventilators due to electricity shortage [65]. In addition, the pandemic has disrupted local energy companies' capacity to ensure supply and services in times of volatility and tight liquidity. Moreover, due to the financial distress caused by the pandemic, governments are unable to afford subsidies for renewable energy projects. As a result, the pandemic will further aggravate global energy poverty and impede the energy transition.

3.2. Opportunities for energy transition during the pandemic

The COVID-19 pandemic has also created a unique opportunity for the renewable energy transition. First, the risks of investing in fossil fuels have increased dramatically as global demand for fossil fuels has plummeted. Second, governments have unprecedented implementation capacity to enact energy reform policies and legislation during economic recovery. Third, the unique advantages of renewable energy in allowing remote operation and digital intelligence provide a great opportunity to replace fossil fuels with renewable energy during the pandemic.

Specifically, while the drop in oil and natural gas prices has weakened renewable energy's price competitiveness, the volatile fossil fuel market during pandemic times has presented new opportunities. As of late April 2020, approximately 54% of the world's population were under pandemic lockdowns, with their daily activities heavily restricted [28]. Domestic economic and travel activities were reduced and international trade was restricted [66]. As a result, global oil demand has dropped to the lowest level since 1995. As most countries' economic activities were halted due to the lockdown, electricity demand fell precipitously [67]. According to the *Renewables 2020 Global Status Report*, global demand for oil, coal, and natural gas fell by 8%, 8% and 4% by the end of 2020, respectively, , while global energy demand declined by 6% compared to 2019 [2]. And it is doubtful that it would surpass the high in 2019 in the future [68]. On the one hand, the oil and gas markets are no longer stable due to the unprecedented impact of the pandemic on fossil fuel industries. The pandemic undermined fossil fuels' dominancy in the energy sector, threatening numerous long-term oil and gas contracts [57]. International oil companies drastically cut their investment plans, and capital began to flow out of the fossil fuel market. These capital flows will create new space for renewable energy investments. On the other hand, low oil prices have reduced the rate of return on fossil fuel investments. To hedge the losses of fossil fuel investments, investors may expand commercial investments in renewable energy, hastening the energy transition.

Moreover, the government has enormous reform capacity in terms of energy transition in the post-pandemic era. Although the COVID-19 pandemic largely halted productions and operations worldwide and resulted in widespread unemployment, it also provides chances to reshape the global economy and energy system [69]. During the pandemic, governments have unprecedented implementation power to impose reform. The post-pandemic period is a precious opportunity for governments to enact legislations and regulations to compel energyintensive companies to undertake structural adjustments so as to operate in an environment-friendly and low-carbon manner [68]. However, policymakers should be mindful not to repeat the mistake made after the 2008 global financial crisis (GFC) when economic stimulus plans resulted in large-scale funds flowing to fossil fuel industries.

Furthermore, renewable energy has demonstrated several advantages during the pandemic, offering new insights for policymakers. On the one hand, air quality improved considerably during the COVID-19 lockdown, prompting people to be more conscious of environmental governance and clean energy. Since renewable energy is clean and produces much less emissions than traditional energy, the renewable energy is recognized to be the key to improving air quality and public health [70]. On the other hand, as most renewable energy sources can be remotely controlled and digitally intelligent, renewable energy plays a key role in maintaining a stable energy supply during COVID-19. For example, the combination of the Internet of Things (IoT) and renewable energy generation allows technicians to use cloud-based controllers to deploy distributed generation based on different stages of electricity demand [71]. Besides, based on sensors' perception of ambient environment information such as light intensity and wind speed, power generation equipment can also be started and stopped automatically, greatly improving energy efficiency and equipment life [72]. In contrast, traditional power generation is both energy- and labor-intensive, and the lack of fossil fuel supply and labor scarcity during the pandemic makes it difficult to achieve an adequate supply of electricity. In addition, the use of renewable energy has also made significant contributions to the pandemic control, e.g., hydrogen/solar-powered unmanned ground vehicles and their airborne counterparts can be used for search & rescue, and remote monitoring of urban ecosystems and agriculture production during lockdowns. With tremendous reform capacity, governments can utilize these forward-thinking renewable energy technologies to open up a new path for the energy transition.

3.3. Energy transition under economic stimulus plans

The unexpected COVID-19 outbreak has caused the world's most significant economic downturn since the Great Depression. As the pandemic is progressively under control, countries worldwide are proposing and implementing various strategies to revitalize the economy. The announced economic stimulus investments have now totaled more than 11 trillion US dollars [28]. Once global restrictions are lifted, governments will commit to economic recovery and international trade will expand, resulting in a quick surge in energy consumption. Therefore, the post-pandemic period is a critical window for energy transition and sustainable development [73], especially as the public vigorously are calling for a "green stimulus" for a low-carbon economy post-pandemic [74,75]. Fig. 3 displays the number of confirmed coronavirus cases and the budget composition of various countries' economic stimulus packages. The stimulus plan data were sourced from Carbon Brief [1], a website that tracks energy policies and investments in the world's major economies.

In Fig. 3, the deeper the country's color on the map, the more confirmed coronavirus cases it has. Overall, there is a negative relationship between confirmed cases and "green" investment. As of August 31, 2020, more than 1 million people have died from the coronavirus, and the death toll is still rising. Moreover, it is estimated that 90 million people worldwide will be in extreme poverty as a result of the COVID-19 pandemic [29].

The figure shows that most countries promote domestic green transition by investing in environment-sensitive sectors such as construction, energy, industry, and electric vehicles. The European Union (EU) currently has the largest green stimulus budget. Its announced stimulus package is worth up to US$64.19 billion, covering green employment, the "Farm to Fork" initiative for food sustainability, energy-saving construction renovation, etc. The budget for green gobs is worth US $34.47 billion. For example, the "Just Transition Fund" will provide retraining opportunities for workers who are affected by the energy transition in order to maintain employment rates and ensure the sustainability of green programs. The stimulus package also allocated US $17.83 billion for agriculture to reduce pesticide and fertilizer usage. Moreover, it includes a new circular economy action plan (CEAP) worth US$11.89 billion, aimed at raw material waste reduction, recycling, and energy transition in high-emission industries such as steel and cement.

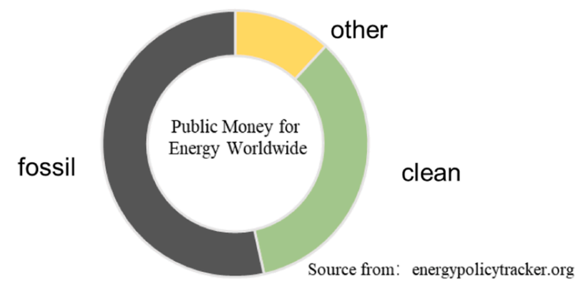


Fig. 4. Share of energy investment in G20 countries' economic recovery plan.

The EU member countries have also taken similar steps. Germany plans to invest US$50.94 billion in the stimulus scheme, trailing behind the EU. The budget covers industrial transition, clean transportation, building renovation, and energy research and development (R&D). It plans to invest US$23.77 billion, $2.74 billion, and $21.10 billion in energy transition, renewable energy R&D, and clean transportation, respectively. Italy, Spain, and France, despite their massive debts, continue to set aside funds for clean transportation and renewable energy R&D. Denmark, Ireland, Finland have also put forward investment plans in energy and environmental protection. For example, the Danish government has stated that the COVID-19 pandemic has strengthened its commitment to "green" investment and that they will develop offshore wind power and "Future Green Technology" such as carbon capture and storage (CCS), in order to improve energy efficiency. Ireland has announced to invest 113 million euros in the sustainable transformation of public transportation and infrastructure. Finland has made great efforts to develop biomass energy from its abundant forest resources and has set a target of halving its oil consumption and achieving a 30% renewable energy share in the transportation sector by 2030. Albeit some minor differences, EU members' investment plans overwhelmingly prioritize energy consumption sectors, such as transportation, heating, and electricity, as well as R&D and green jobs.

Similarly, nearly half of South Korea's stimulus plan (US$4.55 billion out of $10.86 billion) is for renewable energy investment, such as renovating buildings with renewable energy heating systems. China also devoted a significant portion of its stimulus budget (US$1.46 billion) to new energy vehicle development. India's stimulus plan is dedicated to environmental conservation. In New Zealand, despite fewer confirmed coronavirus cases compared with other countries, the government proposed a stimulus package (US$1.52 billion) for green construction improvement, green employment, and clean transportation.

As can be summarized from Fig. 3, several countries' stimulus plans have covered green projects; nevertheless, are these plans sufficient to ensure a green recovery? The answer is hardly to be "yes". The United Nations Environment Program (UNEP) uses the Global Recovery Observatory to track the world's 50 largest economies and reported that the global economic stimulus plans were worth 14.6 trillion US dollars in 2020, of which only 368 billion were used for green purpose, accounting for only 18% of the total value [76].

[1] https://www.carbonbrief.org/coronavirus-tracking-how-the-worlds-green-recovery-plans-aim-to-cut-emissions.

Moreover, most countries' energy investment structures remain dominated by fossil fuels. As illustrated in Fig. 4 [2], the G20 countries' fossil fuel investment in their economic stimulus plans accounted for 52% of total energy investment while renewable energy investment only accounted for 36%. Traditional energy is a shortcut when countries are under pressure to contain the pandemic, resume work and production, and revitalize the faltering economy, especially following the sharp drop in coal and oil prices [56]. However, extensive fossil fuel consumption will reduce demand for renewable energy, leading to carbon emission rebound and energy transition slowdown.

When we zoom into individual countries, we observe that the magnitude of economic devastation caused by the pandemic varies greatly, resulting in vast variations in each country's energy investment plan. Fig. 5 depicts a few G20 countries' investment plans for different energy resources. Some countries continue to rely heavily on fossil fuels in their stimulus programs, weighting economic recovery much more important than environmental protection. For example, the United States is the world's largest economy and one of the world's major fossil fuel producers. It thus has a significant influence on global energy transition. Since the COVID-19 outbreak, the US has made the biggest investment in its energy sector, totaling up to 100 billion US dollars, yet more than 70% of the funds are allocated for fossil fuels. Similarly, despite being a global leader in decarbonization and ranking third in global energy investment, the United Kingdom has a share of fossil fuel investment as high as 60%, but only 10% of its 30 billion pounds stimulus plan was dedicated for "green" purposes.

There are also countries investing heavily in clean energy in an effort to achieve green energy transition and green recovery. As the world's second-largest economy and largest coal producer, China invested certain amounts of public funds in the energy sector (US$40.51 billion), with the vast majority of them (at least US$27.41 billion) going to clean energy. In recent years, China's use of fossil fuels has been declining, while the share of clean energy in total energy consumption, particularly hydropower, solar energy, and nuclear energy, has continued to rise [44]. Likewise, Germany's announced public investment in the energy sector ranks second in the world, with renewable energy as its primary target. The nation dedicated 38% of its 130 billion Euro stimulus package towards energy transition and sustainable transportation [73]. Meanwhile, in France, as many nuclear reactors are to be decommissioned, the country is in urgent need of energy transition. Its Clean Unconditional initiative as part of the stimulus plan has the largest budget allocation among all countries to weed out the outdated nuclear power plants while maintaining a stable energy supply and a low-carbon economy, ultimately achieving the clean energy transition.

Figs. 4 and 5 reveal the fact that although some countries have invested in green projects as part of the stimulus plan, the amount was minimal, leaving the fossil fuel-dominated energy structure limitedly affected. If the world repeats the mistakes made during the economic recovery from the 2008 GFC, such as pouring a large sum of stimulus funds into heavy industries, it is very likely to make a comeback and erase efforts made in recent years. Moreover, economic development will be confined to high energy consumption and high emissions for a long time, further hindering the energy transition.

Overall, the macroeconomic turmoil caused by the COVID-19 pandemic has set off a chain reaction. Global shocks in manufacturing, financial markets, and trade have reached the renewable energy industry [74], leading to a renewable energy market slump, deglobalization, and disrupted global renewable energy supply chain. These effects might undermine the momentum of the energy transition in the short term. However, as the pandemic was gradually under control, the economy will rebound, international trade will resume, and the energy transition will proceed. The issue is that, despite the global demand for a post-pandemic green stimulus plan [75], most countries' stimulus plans continue to prioritize fossil fuel investments. As a result, rather than achieving the energy transition, the world may remain reliant on fossil fuels in the coming years or decades. The short-sighted economic recovery at the expense of the environment will stymie energy transition and sustainable development for a long time.

Therefore, the post-pandemic stimulus plan plays a critical role in the energy transition. It may bring new opportunities or obstacles depending on how it is implemented. To meet the global demand for "green stimulus" plans, it is essential for countries to include concrete "green" actions in the plan [76]. Given the government's unprecedented reform capacity during the ongoing pandemic, there are still chances to revise existing stimulus schemes or launch new ones to reinforce the energy transition and environmental protection. It is thus critical to seize the post-pandemic window to implement effective energy reforms while reviving the economy.

4. Post-pandemic energy transition

4.1. Broadening financing instruments

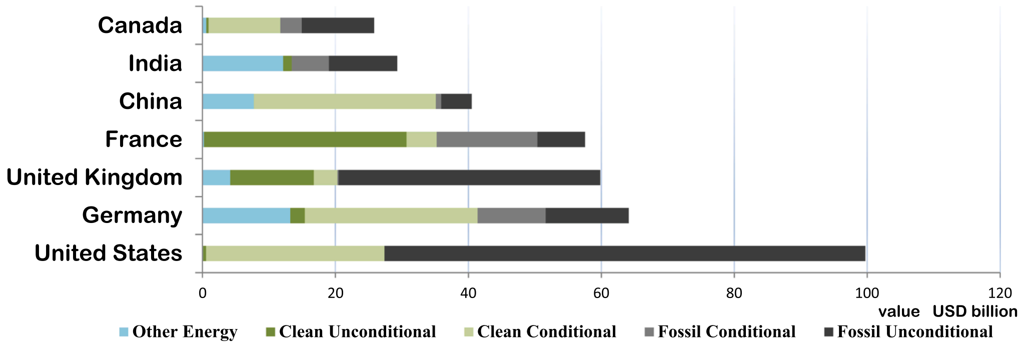
Since the pandemic, governments' fiscal deficits have grown. Numerous renewable energy projects have been stranded due to the decreased government solvency, highlighting the drawback of a predominantly government-funded renewable energy investment system. Therefore, in order to resume energy transition post-pandemic, it is critical to reform the current energy investment structure. Government investment, instead of being the primary source of financing, should play a supportive role in fostering a healthy environment for renewable energy projects to develop competitiveness and attract more private investments.

Global green energy development has sprouted up various financing instruments for environmental projects [14], such as Blockchain, climate crowdfunding. With the continuous development and data analytics and artificial intelligence (AI), blockchain-based web techniques are emerging; for example, blockchain-based financial technology (FinTech) can ensure transparency and accountability in the distribution of "green" funds due to its typical features of independency, openness and security [77]. At the same time, as a trusted third party, blockchain-based technique can significantly reduce the approval cycle for and improve the efficiency of green finance projects. Climate crowdfunding refers to the practice of raising modest sums of money from a large number of individuals in order to fund large-scale climate mitigation and adaptation projects. For example, *Oneplanetcrowd* [3], a Dutch climate crowdfunding platform, has had backers from the Netherlands and other countries participating in hundreds of climate campaigns, notably with an increasing number of participants in renewable energy projects such as photovoltaic and wind power generation [78].

Table 2 lists several successfully funded climate campaigns of the platform. Most of the Dutch renewable energy crowdfunding projects listed in Table 2 are related to renewable energy, such as solar and wind energy. They mainly contribute to the United Nations' Sustainable Development Goal of "Affordable and Clean Energy" (Goal 7). These crowdfunding campaigns raise funds from the public to expand solar panel coverage (e.g., Investeer In Groene Obligaties, Zonnepark Bomhofsplas Zwolle, and Energie Voor Apeldoorn), increase the installations of wind power (e.g., Samen Voor Opgewekte Windenergie), and improve renewable energy heating systems (e.g., InEnergieBreed Projecten BV, and Duurzame Warmte-Installaties), etc. Crowdfunding can be an efficient tool for renewable energy projects as it can raise a significant amount of initial capital from individuals worldwide in a very short period of time. Therefore, donation-based or reward-based

[2] The data was sourced from the Energy Policy Tracker database (https://www.energypolicytracker.org/).

[3] *Oneplanetcrowd* is a leading crowdfunding platform that is targeted to address the United Nations' Sustainable Development Goals (UN SDGs).



Source from: energypolicytracker.org

Fig. 5. Worldwide energy investment structure.

Table 2
Successful campaigns of *Oneplanetcrowd* crowdfunding platform.

Date	Project Name	Project Summary	Raised Fund
2020-11-01	Samen Voor Opgewekte Windenergie	The project is supported by the government and raises funds from local residents to jointly expand installed wind power capacity.	€450,000
2020-12-01	Investeer In Groene Obligaties	The project finances operation of solar power installations by issuing green bonds.	€2,000,000
2021-01-09	Zonnepark Bomhofsplas Zwolle	Funding for the project aims to make the most of the Park's sunlight and the cooling effect of the lake water to increase the efficiency of the solar panels in generating electricity.	€1,049,500
2021-02-17	InEnergieBreed Projecten BV	The project raises funds for solar power and sustainable heating systems for buildings.	€300,000
2021-03-05	Duurzame Warmte-Installaties	The project raises funds to equip new houses with sustainable heating units and accelerate the transition to natural gas alternatives.	€646,250
2021-10-01	Energie Voor Apeldoorn	The project raises funds from local residents to keep the solar park running, with residents having the opportunity to benefit from the Park's revenue.	€250,000

Notes: sourced from https://www.oneplanetcrowd.com/nl.

crowdfunding can be encouraged to help the initial funding of small and remote renewable energy projects. Once the fundraising campaign reaches a certain scale, it may attract angel investors and venture capitals [79]. This will significantly improve the financing efficiency of renewable energy projects.

In addition, the fossil fuel divestment movement has been posing pressure on fossil fuel investments while advocating for renewable energy investments. Several commercial banks have begun to defund fossil fuel projects to support cleaner and low-carbon businesses. For instance, Citibank and HSBC have pledged to no longer invest in coal power plants, while Mizuho Financial Group has loan cuts for the coal power industry. As the ultimate goal of the divestment movement is to eliminate the use of fossil fuels, the current classification criteria of fossil fuels should be improved to pinpoint high energy consumption and high pollution businesses more accurately [55]. Meanwhile, encourage enterprises to disclose their climate actions and "green" initiatives to provide investors with guidance on how to smoothly re-adjust their portfolios from fossil fuels to "green" investments. Besides, the large scale of retail investment highlights the importance of retail investors in the divestment movement.

4.2. *Strengthening international cooperation*

As aforementioned, the COVID-19 pandemic has hit the global economy and renewable energy market at unprecedented levels. With sweeping lockdowns and restricted international trade, multinational enterprises (MNEs) face both supply and demand difficulties, revealing the fragility of modern supply chains [80]. The takeaway from this pandemic is to build a more resilient global supply chain to ensure the progress of renewable energy projects.

Many developed countries have strengthened their strategies to enhance resilience in manufacturing supply chains in preparation for future global supply chain disruption [81]. For MNEs, they shall consider strategic outsourcing and adjusting their business structures to prevent future renewable energy supply bottlenecks and project disruption due to lockdown measures.

Moreover, the re-opening of international trade shall function under the green recovery consensus. For example, while China's Belt and Road (B&R) Initiative encountered certain setbacks during the pandemic, it proceeded with a stronger emphasis on green projects in post-pandemic times, with the bulk of investments being in renewable energy [82]. Countries under the B&R Initiative are paying more attention to sustainable development, e.g., Egypt has pledged to take this pandemic as an opportunity to promote green recovery and sustainable development [83]. China and other participating countries have also been working actively to improve the cooperation framework, aiming to transform the B&R Initiative into a "green" silk road that promotes green economic recovery and energy transition.

Furthermore, energy poverty is another global energy transition problem that awaits to be addressed. Energy poverty has grown even more prevalent in the aftermath of the pandemic. The international community is expected to strengthen exchanges and cooperation in alleviating energy poverty. A successful collaborative example is the "solar sheep farm" model that originated from a solar farm in Western China. Western China's terrain is primarily semi-desert, with plenty of sunlight exposure, making it ideal for large-scale photovoltaic power plants [84]. As the clean water utilized for photovoltaic panels causes the grass in and around the solar arrays to grow extremely fast, the solar farm uses sheep to maintain the grass, significantly lowering its weed control costs. This "solar sheep farm" integrates renewable energy power generation with livestock farming, forming a sustainable circle that serves as a model for reducing energy poverty. The model has been shared and replicated in many B&R Initiative countries. Such collaborative efforts help developing countries alleviate (green) energy poverty and accelerate energy transition without relying heavily on developed countries.

4.3. Enhancing green stimulus plan

The implementation of a green stimulus plan is the key to economic recovery and energy transition. Fig. 6 displays the timeline and key measures of several countries' green stimulus plans. As of August 2020, approximately 100 stimulus plans have been announced worldwide. These plans are in various phases, i.e., "proposed", "agreed", "approved", and "implemented". Countries that have implemented the stimulus plan include China, France, Ireland, Italy, New Zealand, Spain, and the United Kingdom. Among other countries, Nigeria has one policy implemented, which is to cancel the oil price ceiling on June 4, and has other policies in the "approved" stage, such as developing solar power and increasing renewable energy R&D, etc. Most countries' stimulus plans are still in the "proposed" or "agreed" phase. These stimulus plans, once implemented, will present new opportunities for global energy transition.

The majority of the announced stimulus plans prioritize three major energy consumption sectors: transportation, heating, and electricity. In April 2020, China proposed a charging network expansion plan and extended the subsidy and tax reduction for electric vehicles to 2022. China's stimulus plan focuses on "new infrastructure" construction, such as power grid installation, in an effort to improve the market competitiveness of new energy vehicles and promote low-carbon transportation. In addition, China's national carbon emissions trading scheme (ETS) was officially launched in July 2021, covering 12% of global CO_2 emissions, which aims to accelerate China's energy transition process and ultimately achieve its carbon neutrality goal [85,86]. Despite the dismal global renewable energy market caused by the pandemic, China has emerged as a leading player in the green energy transition, with its wind turbine and photovoltaic installations increased by 36% and 20%, respectively, in 2020 [87].

The French government has also put forward plans to reduce aviation emissions and develop zero-emission renewable energy technologies. Likewise, in May and June 2020, the Danish government proposed several green stimulus initiatives covering construction, green technology, and industrial structure upgrades. Specifically, the proposals include: upgrading the heating system of social housing, investing in wind power generation through public–private partnerships, financially supporting industries that are struggling with decarbonization in making the transition to green energy and circular economy business model, and funding carbon capture and storage research through a technology funding pool.

In terms of financing instruments, most countries fund their green stimulus plans through fiscal expenditures and public–private partnerships. Some countries have also increased taxes on fossil fuels. For instance, on March 15, 2020, India raised the consumption tax rate on gasoline and diesel to balance the tax shortfall caused by substantial pandemic control spending while simultaneously reducing carbon emissions and promoting renewable energy [88]. According to the Reserve Bank of India, stamp duty is the main source of tax revenue for all Indian states. However, the social isolation of workers and the decline in construction activities during the pandemic have further worsened the tax deficit. Increasing gasoline and diesel tax can effectively make up for the budget deficit incurred by the pandemic [89].

In addition to the energy and transportation sectors, the announced green recovery schemes also address the green transition in industry, agriculture, and construction. For example, the UK government has committed 171 million pounds from the Industrial Decarbonisation Challenge Fund to achieve the target of 20 TWh industrial low carbon electricity replacement for fossil fuels by 20,230 and to capture 3 million tonnes of carbon dioxide ($MtCO_2$). Besides, a net-zero hydrogen fund of 240 million pounds and a carbon capture and storage (CCS) infrastructure fund of 1 billion pounds are in the pipeline. In terms of agriculture, the UK government is calling for "low carbon agricultural practices" where one fifth of farmland is separated from conventional agriculture and used for long-term carbon storage and emissions reduction over the next 30 years. In terms of green transition in construction industry, the Canadian government has launched the Community Building Retrofit Program, which will leverage federal investment of 167 million dollars to retrofit community buildings to improve energy efficiency and reduce emissions.

These green policy supports have far-reaching implications for restarting the engine of renewable energy development and achieving a green recovery. First, green stimulus guarantees the solvency of public utilities. At the beginning of the pandemic, the energy market becomes extremely volatile. However, following the introduction of green stimulus plans, renewable energy companies started to outperform fossil fuel companies [14], making them an appealing alternative to investors [23].

Second, a few countries have promoted the green transition of emission-intensive enterprises through their green stimulus plans. With the unprecedented reform capacity, governments are making bold reforms in the following aspects. The first is to improve the utilization efficiency of raw materials to ultimately establish a circular economy. The second is to impose mandatory taxes on companies that do not meet carbon emissions standards while subsidizing clean energy projects and

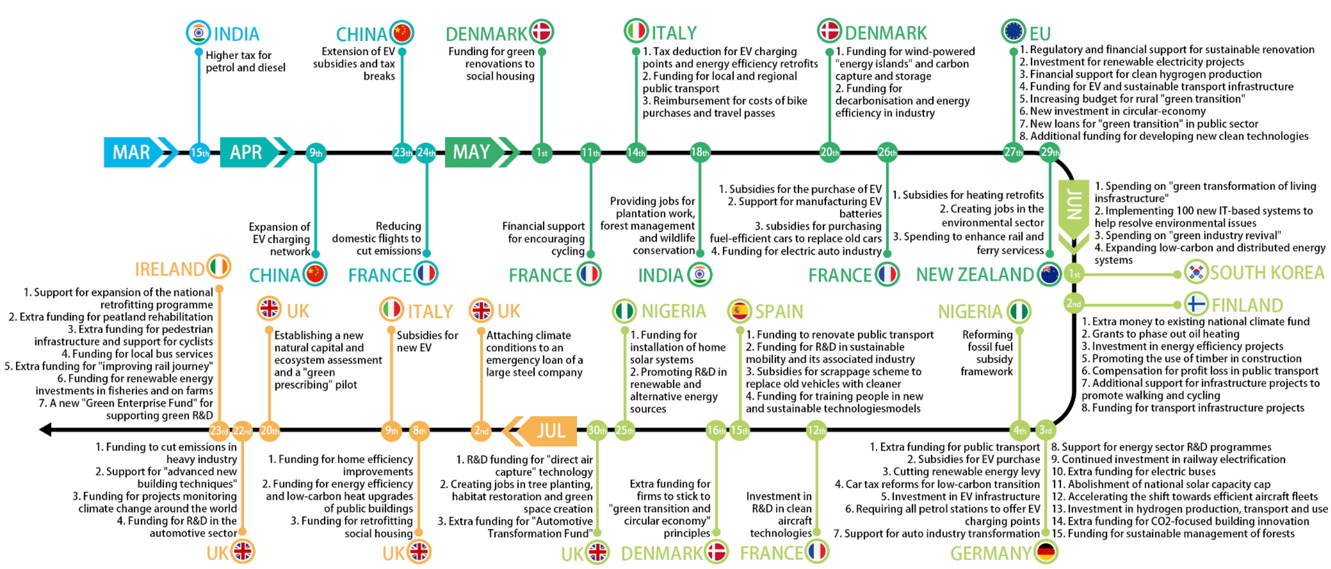


Fig. 6. Timeline of green stimulus plans worldwide.

encouraging industrial restructuring. At the same time, in light of the unpredictable economic climate, the stimulus package provides financial assistance to energy companies to assist with industrial upgrading and energy transition.

Third, the renewable energy industry is labor-intensive, making it an excellent investment choice for increasing jobs and revitalizing the economy. Many countries' stimulus programs include green job creation and assistance. Such initiatives increase employment while promoting green transition, establishing the groundwork for a socially inclusive production-consumption system and sustainable development [90]. For example, India also adopted a green employment stimulus plan to boost jobs in plantations, forest management, and wildlife protection. The plan is inherited from India's Green Skill Development Programme (GSDP), which emphasizes environmental restoration and ecosystem protection skill training above traditional mechanical and technical skill training.

Finally, the green stimulus plan provides financial support for renewable energy research and development (R&D). A few examples of the existing renewable energy technologies include "green hydrogen", carbon capture and storage technologies, energy-efficient technologies [73], etc. The energy transition has spawned a new round of technological innovations. R&D in clean energy plays a key role in global green revolution. Some countries have already increased or prolonged clean transportation subsidies as part of the stimulus plan to encourage green travel and clean transportation R&D.

5. Conclusions

The COVID-19 pandemic has had an unanticipated impact on energy transition. The impact is multi-dimensional, ranging from the continued downturn in the energy market to the disrupted global energy supply chain. The plunging fossil fuel prices have also weakened the price competitiveness of renewable energy. Although these negative effects have impeded the energy transition, more voices are calling for a quicker transition to a low-carbon world. The increased risk of fossil fuel investment and the unique advantages of renewable energy demonstrated during the pandemic will create new opportunities for the energy transition.

Many countries have been proposing and implementing a variety of strategies in order to achieve green recovery and energy transition post-pandemic. Nonetheless, despite the growing demand for green stimulus plans globally, half of the announced economic stimulus plans are still dominated by fossil fuel investments. If the recovery model of high energy consumption and high emissions continues in the post-pandemic era, it will delay the global energy transition and erase the sustainable development achievements made in recent years.

To explore the effective way to accelerate energy transition in post-COVID-19 stage, we first summarized and reviewed the energy transition progress prior to COVID-19. Building on the past progress, we looked into the current state of energy transition. Specifically, we identified the challenges that the pandemic has exerted on energy transition from the perspectives of government support, fossil fuel divestment, renewable energy production capacity, global supply chain, and energy poverty.

Something that appears broken may open the door to something better, so we also identified the opportunities for clean energy transition during the pandemic, from the perspectives of unpromising financial and social outlooks of fossil fuels, policy implementation efficiency, and competitive advantages of renewable energy. We further analyzed the impact of current economic recovery schemes worldwide on clean energy transition. Based on the identified challenges and opportunities, a roadmap for post-pandemic energy transition is proposed, including broadening green financing instruments, strengthening international cooperation, and enhancing green stimulus plan.

To sum up, this study provides a comprehensive review of the dynamics between global energy transition and the COVID-19 pandemic. We thus contribute to the framework on global low-carbon energy transition and provide practical guidance for post-pandemic green recovery policy formulation. The post-pandemic period is a critical time for energy transition around the world. An effective recovery plan shall promote economic recovery without compromising the efforts of global energy transition. Therefore, effective integration of "green" in the economic recovery scheme is highly recommended in the post-COVID-19 era.

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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