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Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities

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HIGHLIGHTS

- Impacts of COVID-19 on energy demand and consumption have been substantial.
- The changes in energy intensity (GDP/Mtoe) presented spatial-temporal differences.
- System thinking is recommended to analyse how to stabilise energy demand.
- The energy recovery presents heterogeneous characteristics in countries/regions.
- The rebound effects of digitalisation in energy consumption need to be assessed.

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ABSTRACT

COVID-19 has caused great challenges to the energy industry. Potential new practices and social forms being facilitated by the pandemics are having impacts on energy demand and consumption. Spatial and temporal heterogeneities of impacts appear gradually due to the dynamics of pandemics and mitigation measures. This paper overviews the impacts and challenges of COVID-19 pandemics on energy demand and consumption and highlights energy-related lessons and emerging opportunities. The discussion on energy-related issues is divided into four main sections: emergency situation and its impacts, environmental impacts and stabilising energy demand, recovering energy demand, and lessons and emerging opportunities. The changes in energy requirements are compared and analysed from multiple perspectives according to available data and information. In general, although the overall energy demand declines, the spatial and temporal variations are complicated. The energy intensity has presented apparent changes, the extra energy for COVID-19 fighting is non-negligible for stabilising energy demand, and the energy recovery in different regions presents significant differences. A crucial issue has been to allocate and find energy-related emerging opportunities for the post pandemics. This study could offer a direction in opening new avenues for increasing energy efficiency and promoting energy saving.

1. Introduction

The coronavirus disease 2019 (COVID-19) has been swiping the world. By the Mid-December 2020, approaching 75 M confirmed cases of COVID-19 and over 1.7 M deaths in 220 countries had been reported to the World Health Organization [1]. By comparing the early 2020 COVID-19 outbreak and the 1918 flu pandemic, Faust et al. [2] suggested that the COVID-19 pandemic might get more deadly than the most severe pandemic in the last century. Many measures such as quarantine, social distancing and lockdown have been set to mitigate the coronavirus infection [3]. The COVID-19 pandemic has caused profound influences for many industries, including agriculture, manufacturing, finance, education, healthcare, sports, tourism, and food [4]. The energy industry is naturally not immune in the influences [5]. According to statistic and projection data from the International Energy Agency (IEA) [6], the shock to energy demand in 2020 is set to be the largest in the last 70 y. Global energy demand in 2020 is estimated to decline by 6% compared to 2019, a fall seven times greater than the 2009 financial crisis. Compared to the mean value from 2015 to 2019, the total mean

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Nomenclature

CE	Circular Economy
COVID-19	Coronavirus disease 2019
GDP	Gross Domestic Product
ICT	Information and Communications Technology
IEA	International Energy Agency
IoT	Internet of Things
Mtoe	Mt of oil equivalent
PPE	Personal Protective Equipment
SEA	Southeast Asia
WHO	World Health Organisation

electricity generation from 16 European countries in April 2020 dropped by 9% (25 GW), where fossil energy generation decreased by 28% (24 GW), nuclear energy decreased by 14% (11 GW), whilst renewables increased by 15% (15 GW) [7]. Although the fact that overall energy demand declines, is simple and clear, the repercussions are very complicated in different energy types and consumption patterns of different regions. The energy industry is on the way to understand the complicated impacts and identify emerging opportunities.

Some existing literature overviewed the changes and challenges with various focuses. Brosemer et al. [8] provided a perspective overview of the energy crises related to the intersections of inequity, indigeneity and health. Zhong et al. [9] reviewed the implications and challenges of COVID-19 for the electricity sector. They stated that increased uncertainty of electricity demand posed greater pressure on system operators. Fell et al. [10] stressed the considerations, challenges, and responses for the energy social research during and after pandemics. Mastropietro et al. [5] overviewed urgent global measures on energy consumer protection during the pandemic. There are more studies focusing on problems in specific countries or regions, such as the analysis of the short-term impacts on the United States electricity sector [11], the review of government innervations in Africa [12], the review of solar energy pathway in Malaysia [13], the impact analysis for power sector operation in Indian [14], the impact overview analysis of impacts on energy grid dynamics in Europe [7], the overview of impacts on electricity and oil demand in China [15], and the impacts of containment measures on European electricity consumption [16]. The aforementioned studies contributed to the understanding of the impacts of COVID-19 pandemic from different views. In the chaotic and emergent environment under COVID-19 pandemic, more contributions are not enough, and it is beneficial for the whole energy industry and society by providing more perspectives. This paper aims to overview the global impacts and challenges of COVID-19 pandemic on energy demand and consumption and highlight energy-related lessons and emerging opportunities. Partial data used in this paper are based on currently available data from the relevant agencies, and due to fast development, cannot be precise. The value of this paper aims at presenting some new thoughts on energy challenges, lessons, and emerging opportunities by capturing main trends rather than details with precise data. The major contributions of this study are highlighted as follows:

(I) Structural changes in energy demand and consumption have been overviewed comprehensively. The overview covers the (a) pattern variations in time-, space-, sector-, and usage-dimensions, (b) extra energy demands, (c) energy stabilisation, and (d) energy recovery.

(II) Novel perspectives have been provided for how to consider and analyse extra energy demands, energy stabilisation, and energy recovery. The decision and planning of energy stabilisation need to consider extra energy demands. The energy recovery in different regions presents heterogeneous characteristics, which is determined by many factors, including measures, policies, and pandemic development.

(III) Energy-related lessons and emerging opportunities have been identified. Critical comments have been offered for potential opportunities and their possible defects in terms of the (a) enhancement of digitalisation and Internet of Things (IoT), (b) new lifestyles in cities with lower energy usage, (c) resilience enhancement with Circular Economy, (d) opportunities for renewables and energy storage, and (e) fighting infectious diseases and saving energy.

The remainder of this paper is organised as follows. Section 2 overviews the emergency situation and its impacts. Section 3 presents environmental impacts and stabilising energy demand. Section 4 introduces the recovery of energy demand. Section 5 highlights energy-related lessons and emerging opportunities. Section 6 concludes this paper and provides a future work agenda.

2. Pandemic occurring – emergency situation and its impacts

The global energy-related CO_2 emissions have implied the real emergency situation in the energy industry. The estimated year-on-year reduction of energy-related CO_2 emissions in 2020, 2.58 Gt [6], significantly exceeds the reductions of any emergency situations in history, including the Spanish flu, great depression, world wars, oil shocks and recent 2008 financial crisis. During the extensive lockdown, CO_2 emissions were decreased by 26% (at their peaks) on average in individual countries [17]. If the power consumption gap based on prediction in 2020 [18] is considered, rather than the year-on-year reduction, the emergency situation in the energy sector would be terrifying. This section overviews the variation in energy demand/consumption and extra energy demands.

2.1. Variation in energy demand and consumption

During the lockdown (i.e. limited restrictions, partial lockdown or full lockdown), curtailment in many activities, e.g. mobility, economic activity, construction and manufacturing, dropped the global energy demand. The decline in energy demand and consumption brings damage to the energy industry. For example, the COVID-19 pandemic caused bankrupts of at least 19 energy companies in the United States industry [19]. Government interventions have been implemented promptly for energy industry responses [12]. The latest data in July 2020 shows that, compared to the same period in 2019, the peak reduction rates of electricity consumption (weather corrected) in France, Germany, Italy, Spain, UK, China and India during the lockdown period were more than 10% [20]. The weekly energy demand was estimated to be cut by ~9% under limited restrictions, ~17% under partial lockdown and ~24% under full lockdown [6]. Fig. 1 shows the projections on the changes in energy demand in the whole year of 2020. According to Fig. 1a, a total of 626.6 Mtoe (Mt of oil equivalent) drops are calculated for the eight regions worldwide. The order of energy demand drops of the eight regions ranked from the USA, the EU, China, India, Japan, Africa, Southeast Asia (SEA) to South Korea. Based on the data in Fig. 1a and 1b, the year-on-year average growth rate in 2019 is calculated as 1.1%, and the year-on-year average growth rate in 2020 is calculated as −6.2%.

An accurate assessment of the energy demand variation based on continuously updated data is urgently needed to promote global responses and planning for energy production and supply, considering that the investments and global supply chains of energy resources have been hindered and disrupted [21]. From a macro-scale, although there would be an overall drop of energy demand in 2020, the elevation in residential energy consumption and medical energy consumption [22] should be considered comprehensively to make a better conclusion on the energy demand. From a micro-scale, the spatial and temporal distributions/patterns of energy consumption have changed significantly in

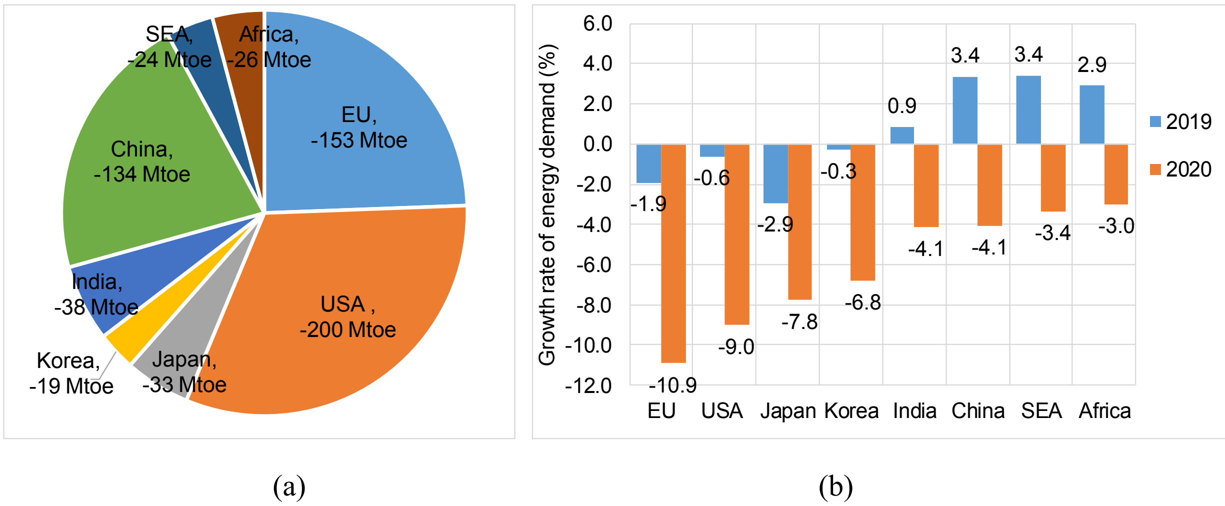

Fig. 1. Energy demand development. (a) The projected drops of energy demand by regions in the whole year of 2020, (b) The year-on-year growth rates of energy demand in 2019 and 2020 (projected). Note: Mtoe = Mt of oil equivalent; Korea = South Korea; SEA = Southeast Asia. Data retrieved from IEA [6].

the short term. The load curves, especially the peaks of electricity consumption, have also shifted. The reduced electricity demand had an acute impact on the generation and supply of fossil fuels like coal rather than those cheaper renewables [23]. The renewables seem to accelerate the trend of replacing fossils. Watts and Ambrose (2020) thought the coal industry might never recover post-pandemics [24]. To date, the demand/consumption changes from both macro and micro scales are highlighted as follows:

- The short-term demand declines when implementing lockdowns [14], but the demand is expected to recover gradually after relaxing lockdown measures [20]. The decline-recovery dynamics would go on as the second wave of pandemics has been on the way.
- Traditional fossil energy demand declines, but renewable energy demand increases [6]. The energy variations in different sectors, including renewable, nuclear, gas, coal, and oil, are significant [6], which is discussed in detail in Section 5.2.
- Commercial and industrial demands decline, but residential demand increases [25].
- In the district level, the thermal energy demand of buildings declines, but the electricity demand of buildings increases [26].
- The peak time for electricity demand also changes. For example, the peak time of pre-pandemic occurred in the latter week (Wednesday to Friday), whilst that of post-pandemic was observed in the earlier week (Monday to Tuesday) in Ontario, Canada [27].
- The demand in the regular morning peak time declines [28], but that in the potentially new peak time might increase [29].
- The consumption of private cars declines during the lockdown, but that increases sharply after lifting the lockdown [30]. What might be worse is that 56.3% of respondents would decrease the usage of buses post-COVID-19 [31].
- The energy demand for producing regular products (e.g. clothes and travel necessities) declines [32], but that for producing medical products and personal protective equipment (PPE) increases [22].
- The variations of projected energy intensities present geographical differences. The change rates of projected energy intensity are calculated in Table 1. Although the gross domestic product (GDP) decreases with the decreasing of energy demand, the projected energy intensities in China, the USA and Japan have varying degrees of elevation. Based on the two forecasted scenarios, the USA would have a high change rate of energy intensity (+29.3%), followed by Japan (+7.8%); whilst China shows no significant change (+2.8%). Similar with China, the energy intensity in the EU is projected to have a slight elevation at +1.03%, which is inferred by the 8.3% reduction in GDP [33] and the 11% reduction in the year-on-year energy demand [6].

2.2. *Extra energy demands*

As discussed in Section 2.1, there exist extra energy footprints due to the structural changes in energy demand and consumption during COVID-19 compared to the regular time before 2020. The extra energy demands come from multiple pathways. Firstly, the most direct pathway is the energy consumed by confinement measures (e.g. working from home [38] and telemedicine [39]), and fighting measures of disease prevention (e.g. antiseptic/disinfectants and PPE, including gloves, masks, face shields, protective suits and fast test kits). The residential electricity demand in Australia during the lockdown in March 2020 increased 14% compared to that in pre-lockdown [40]. Based on preliminary estimations on the extra energy needed to produce disinfectants and PPE [22], the annual extra energy consumption (including the ethanol production associating with disinfectants and the energy consumption of the production of gloves, masks, face shields and 390 M fast

Table 1
The projected change in energy intensity ($\times 10^9$ USD/Mtoe) under the impact of COVID-19.

	Energy intensity in 2019	Energy intensity in 2020[#1]	Change rate (2020[#1]/2019)	Energy intensity in 2020[#2]	Change rate (2020[#2]/2019)	Average change rate
China	4.18	4.37	+4.5%	4.22	+1.0%	+2.8%
USA	7.70	10.39	+35.0%	9.51	+23.5%	+29.3%
Japan	11.66	13.04	+11.8%	12.09	+3.7%	+7.8%

Note: The GDP in 2019 is based on [34]. GDP in 2020 is based on source #1 = Statista [35], which is based on a global pandemic scenario; whilst source #2 = OECD [36] where the impact of continuous pandemic (including the second wave) is taken into account. The energy demand for 2019 is based on Statista [37], and 2020 is based on [6].

test kits) is calculated as 236.5 PJ. Besides the above fighting measures, the energy consumption of sample collection, sample storage by refrigerators and freezers related to COVID-19 has been analysed by Schatz Energy Research Center [41]. The research, development and broad testing of vaccines could consume massive extra energy. In general, there were limited spare time and resources for managers, faced with the unexpected global disease pandemic, to propose a balanced scheme on both the disease mitigation and the energy footprints reduction. It is the right time now to diversify solutions for disease prevention during the new normal period. More solutions should be discussed on the use of reusable masks [42], the identification of ideal disinfection agents [43], and the transitions of renewables [9]. Secondly, another pathway with a considerable priority during the COVID-19 pandemic is emergency and establishing supply chains. In the beginning phase of the disease pandemic, the sudden demand spike and panic buying boosted massive production and transportation [44], which increased extra energy consumption rapidly. The potential risk lies in the ripple effects in supply chains due to huge fluctuation in the demand side. Without proper planning, more embodied energy and environmental emissions would be produced in the supply chain networks. In the new normal phase of the disease pandemic, those establishing medical supply chains and updated e-commerce supply chains would be challenging to manage, especially when the future scenarios are difficult to plan or estimate. Currently, the world has been looking forward to vaccines. The potential energy consumption of the distribution of vaccines is non-negligible. According to the DHL white paper [45], ~10 billion (10^9) doses of vaccines are estimated to be distributed globally, for which 15,000 flights and 200,000 movements by shippers and ~15 M cooling boxes may be needed. Thirdly, besides the consumption-related energy spike, the waste disposal-related energy involvement and possible energy recovery [46] from waste is a non-negligible pathway. Klemeš et al. [47] reviewed and estimated the environment and energy issues related to municipal solid waste, especially the plastic waste during and after the COVID-19 pandemic. More attentions are required to be paid on minimising environmental and energy footprints through suitable planning and diversified solutions.

3. Pandemic running – the environmental impacts and stabilising energy demand

During the lockdown or the new normal period, people are learning to live and function with the virus, social distancing, precautions and other new lifestyles. The declining trend of energy consumption is unavoidable in such a period. When running the pandemic, more attention needs be paid on assessing the environmental impacts (e.g. medical and municipal waste, energy-related air emissions and waterborne pollution) and stabilising energy demand (e.g. the regular energy demand for basic production and life and the extra demand for COVID-19 fighting, including the energy usage in materials, research and development, and supply chains).

3.1. Assessing the environmental impacts

The energy waste and environmental pollution are unavoidable and generally receive a lower priority in the crucial period of COVID-19 fighting; however, as the COVID-19 pandemic continues, the environment footprints/impacts should be assessed and possibly reduced [22]. At the early stage of pandemic and lockdown, based on limited available data and information, the preliminary conclusion of “the pandemic created a very positive impact on the world environment” [48] seems to be too absolute. In April 2020, Klemeš et al. [47] appealed to minimise the plastic waste, energy, and environmental footprints during and after the COVID-19 pandemic. Zambrano-Monserrate et al. [49] analysed negative and positive indirect impacts of COVID-19 on the environment. You et al. [50] appealed to unsustainable waste management during the COVID-19 pandemic, that is followed by the rethinking of plastic waste management and policy solutions [51], the challenges and opportunities for effective solid waste management [52], and the environmental pollutants, impacts, and recommendations for facing future threats [53]. Fan et al. [54] compared COVID-19 related waste management in Singapore and another two cities, including Shanghai in China and Brno, Czech Republic in the EU. The impacts of COVID-19 on waste generation behaviours were found to be diverse, which significantly depended on different sociological and geographical factors. The corresponding waste disposal strategies and energy recovery from waste should be personalised for different cities. Jiang et al. [55] analysed the impacts of lockdown on urban sustainability, including economic sustainability and environmental sustainability. Transportation-related air emissions were observed to be reduced by 44.3–55.4% in Singapore, and total electricity consumption was also reduced by about 7% although the home consumption was elevated. Compared to environmental sustainability, economic sustainability in a city was cautiously thought to be a more crucial issue to conserve urban sustainability. Stabilising energy demand contributes to maintain economic and energy sustainability and further improve urban sustainability, which is discussed in Section 3.2.

3.2. Stabilising energy demand

Before the COVID-19 pandemic, energy efficiency, energy-saving, and new energy solutions are regarded as critical elements to stabilise energy demand [56]. Stabilising energy demand is a key indicator to conserve economic/urban sustainability during and after the pandemic. As the pandemic continues, it is understandably challenging to stabilise and recover the energy demand absolutely. Fig. 2 shows the diagrams of stabilising energy demand under different thinking manners. Under a traditional thinking manner in Fig. 2a, the overall energy demand is more concentrated on, which may mix up and overlook the actual fluctuations of energy demands, especially the extra energy demand for COVID-19 fighting [22]. Under a system thinking manner, as we recommend in Fig. 2b, the two sides of the coin deserve attention. One is to rationalise the extra energy demand highlighted in Section 2.2. Another one is to conserve the regular energy consumption. As the two aspects have opposite trends, the potential decision making under traditional thinking may overlook the actual impacts of the convex energy curve of regular demand and the concave energy curve of extra energy consumption during the COVID-19 pandemic.

- Regarding rationalising the extra energy consumption by supply chains of PPE, disinfectants and food, it is better to move from emergency supplies when energy was not an issue to step by step optimised. Another important and ultimate fighting measure, vaccines, is a long-awaited product for disease prevention and control. It is understandable that the demand and supply of vaccines (if successful) will be exceedingly high [57], as well as the related energy consumption. The extra energy demand deserves substantial attention related to the development, production and distribution of massive vaccines.
- Regarding conserving the regular energy consumption, there are significant challenges, especially during the crisis period [58]. Several extreme events occurred due to dropped energy demands, such as the negative wholesale power prices in Germany [59] and the negative oil prices in the USA [60]. Global decision-makers were/are proposing emergency measures to conserve energy consumption and subsidise energy producers. Amongst many tricky problems, the issues of energy poverty [61] and energy bill increases [62] are more urgent than ever in the COVID-19 crisis. Mastropietro et al. [5] compared the global measures from disconnection bans to bills cancellation that were used to protect energy consumers. Brosemer et al. [8] discussed the intersections of indigeneity, inequity, and health. For a better solution, decision-makers should personalise the decisions on subsidies considering the different geographical and

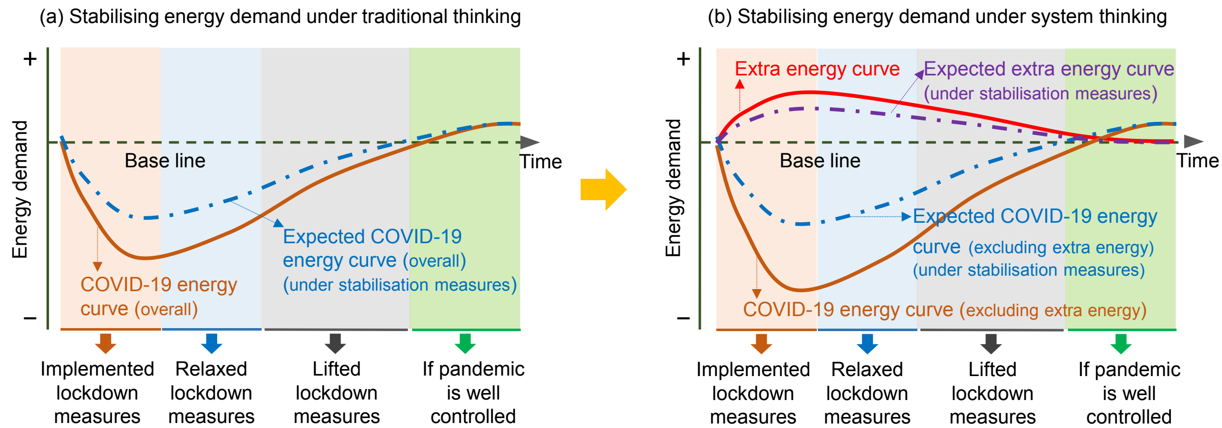

Fig. 2. Conceptual diagrams of stabilising energy demand under (a) a traditional thinking manner and (b) a system thinking manner (developed by the authors). Note: The curves are used to present general trends rather than show quantitative results. The conceptual curves reflect the overall energy demand approximately by considering commercial, industrial and residential demand comprehensively. The overall decline status and recovery trend are discussed in detail in Fig. 3 and Fig. 4. The diagram embeds an assumption of a single-wave COVID-19, which seems not to finally be the case. It can be extended by adding more energy curve periods if intermittent lockdowns are needed and implemented for multiple waves of COVID-19.

sociological factors. Big urban data analytics on household electricity consumption could be employed to offer targeted subsidies.

4. Pandemic mitigating – recovering energy demand

The politicians/policymakers always face a dilemma between the lockdown holding to keep people healthy and the lockdown exit to recover the energy and economy. Different governmental policy responses [63] may explain the different magnitudes of impacts. When relaxing or lifting lockdown, along with the re-start of economic activities, the energy demand/consumption in transport, production and services could recover gradually. Fig. 3 shows the reduction of electricity demand and the number of daily COVID-19 cases in selected countries. The number of days after the lockdown in Fig. 3 is detailed in Table 2. When the number of daily COVID-19 cases exceeded a certain threshold, policymakers implemented lockdown measures. The reduction rate steeped down sharply after strengthening lockdown measures. During the lockdown period, the number of cases reached a peak and decreased gradually. Policymakers made trade-offs on when to relax measures.

After relaxing lockdown measures, the recovery processes of energy consumption are reflected by the trend lines in Fig. 3. Compared to the five countries in the EU, China, and India presented unique situations. In China, the number of daily COVID-19 cases nearly approached to zero after the lockdown. There was more confidence in society to recover economic activity and energy consumption. In India, although energy consumption nearly returned to normal status as in China, it was at the expense of the increasing number of daily COVID-19 cases. The five countries in the EU presented similar characteristics in terms of the lockdown measures, the trend of daily cases and the relatively slow recovery of energy consumption. The bold line 'average'—namely, the average reduction rate of the five countries in the EU—changes from ~21% (the peak during the lockdown) to ~15% (about two months after relaxing lockdown). The ongoing disease epidemic and partial lockdown/restrictions result in a relatively slow recovery.

Different countries have implemented various mitigation and control measures for COVID-19. The policy responses from more than 180 countries have been tracked by a research team from the University of

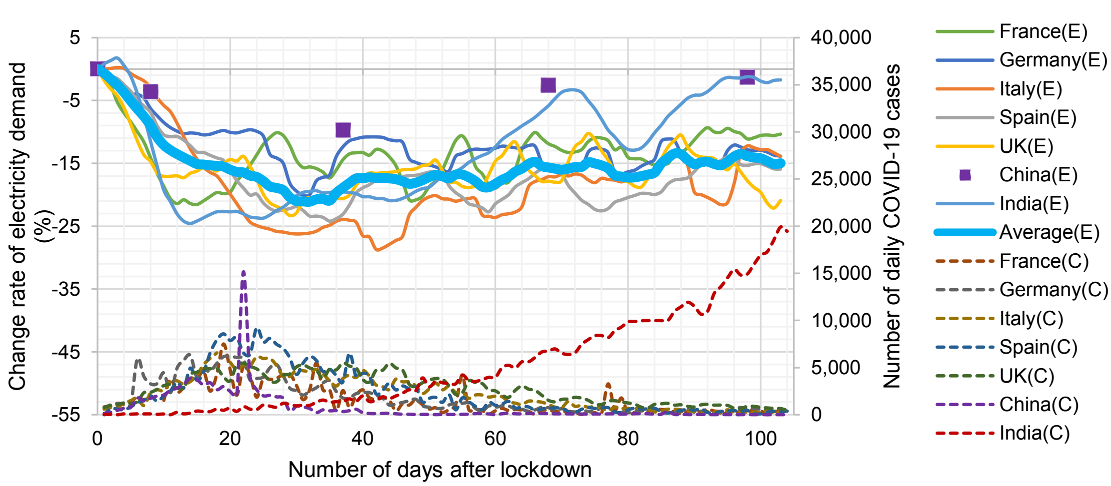

Fig. 3. The reduction of daily electricity demand (weather corrected) after implementing lockdown measures and the number of daily COVID-19 cases in selected countries. Note: 'E' denotes electricity. 'C' denotes the number of cases. Only data of monthly reduction rate are available for China, which are marked with discrete purple squares. The time of lockdown measures relaxed of each country is shown in Table 2. The data on the reduction of electricity demand are retrieved from IEA [20]. The reduction of electricity demand after the implementation of lockdown in 2020 is compared to the same period in 2019. The processed daily data are archived in Table S1 in Supporting Information for possible other applications. The related data on daily COVID-19 cases are from WHO [1]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Time points on implementing, strengthening and relaxing lockdown measures [20].

	Lockdown measures	Measures strengthened	Measures relaxed[b]
France	Day 0 (14/03/2020)	Day 3 (17/03/2020)	Day 55 (11/05/2020)
Germany	Day 0 (15/03/2020)	Day 7 (22/03/2020)	Day 36 (20/04/2020) & Day 50 (04/05/2020)
Italy	Day 0 (04/03/2020)	Day 9 (13/03/2020)	Day 41 (14/04/2020) & Day 61 (04/05/2020)
Spain	Day 0 (09/03/2020)	Day 6 (15/03/2020)	Day 55 (11/05/2020)
UK	Day 0 (19/03/2020)	Day 4 (23/03/2020)	Day 55 (11/05/2020)
China[a]	Day 0 (23/01/2020)	/	Day 76 (08/04/2020)
India	Day 0 (18/03/2020)	Day 7 (25/03/2020)	Day 47 (04/05/2020)
USA[c]	Day 0 (16/03/2020)	/	Day 45 (30/04/2020)
Japan[c]	Day 0 (07/04/2020)	/	Day 48 (25/05/2020)

[a] The lockdown time window is for Wuhan, Hubei, China. Not all provinces in China experienced the same restrictions.
[b] Relaxing lockdown by soft regulations.
[c] Soft lockdowns compared to the other countries.

Oxford [64]. As the electricity demand has been treated as a real-time indicator of the COVID-19 crisis [65], Fig. 3 has indirectly reflected the regional differences among the measures to control pandemic as well as the differences in energy consumption behaviours. To get a more global comparison, Fig. 4 shows two cases with soft lockdowns in the USA and Japan. Overall, after implementing soft lockdowns, the change rates of electricity demand are lower than those under strict lockdowns, as shown in Fig. 3, except for China, which has only locally severe pandemics. Compared to other countries, the USA implemented more complicated measures with great spatial heterogeneity. The change rate of electricity demand in the USA is relatively low but at the expense of blooms in the number of COVID-19 confirmed cases.

What might be more interesting is a possible estimation about when the trend lines can break through the baseline (i.e. 0%), considering that the potential energy shortage could be a great challenge in the post disease pandemic. However, this kind of estimation is challenging due to many factors, e.g. policies, weather conditions, pandemic controls and even supply chains. The situation in China, where the disease pandemic is temporarily over, can offer some inspiration. The year-on-year increase of energy demand in China exceeded the baseline in 2019 by 5.1% in June 2020 [20] after correcting the influence of hotter weather in 2020. At the end of June 2020, the demand was further enlarged along with that the purchasing managers' index for manufacturing increased to 50.9 (i.e. an expansion signal in economic activity) [67]. That indicates the energy consumption recovers to the regular level after about 3 months after relaxing strict lockdown measures if the pandemic is well controlled. As a comparison, the USA and Japan implemented soft lockdowns. Although the energy recovery durations are also about 3 months, i.e. 16 weeks (the USA) and 19 weeks (Japan) as shown in Fig. 4, the second-round decline/recovery of energy demand occurs due to improperly managed soft lockdowns. Although the worldwide recovery time duration should be different due to the policies, sociological factors and geographical factors, the quantitative three-month information based on the Chinese managerial experience offers a reference and even confidence for other countries.

National and local stimulus packages were effective accelerators to recover energy demand. However, the economic packages may increase the growth rate of environmental emissions in coming years, especially when short-term plans that were made before COVID-19 are kept on being satisfied [68]. In contrast, with recovering economy and energy consumption using green stimulus and suitable reductions in fossil energy investments, it could avoid global warming of 0.3 °C by 2050 [69]. Hit by this unprecedented crisis, more sustainable economic packages are required to promote energy/waste/climate management goals by reshaping some long-term sustainable and resilient plans.

It is understandably possible that global energy consumption would expand once the COVID-19 pandemic has been mitigated. At that time, hungry investment companies and the anxious/panic psychology of population would collectively stimulate more global energy demand. For example, sales in the automotive industry shrank extensively after implementing lockdown measures. However, a surge of car consumption was widely observed after lifting the lockdown [30]. Population prefers to use more frequently private cars to avoid public transportation [31], which cannot fully follow social distancing. What can be problematic is that it can develop into a longer-term habit without active intervention.

5. Energy-related lessons and emerging opportunities

5.1. Lessons

A series of environment and energy-related lessons under the COVID-19 challenges have been highlighted. Although the positive environmental benefits during the pandemic cannot be directly copied for non-pandemic times in the future, the gain inspiration and lessons have shown the possibility [70]. Similar lessons from the COVID-19 also trigger the thoughts and discussions on how to achieve such positive benefits, as part of a more resilient and desirable low-carbon future, in a more inclusive, planned and less disruptive way [71]. The main lesson stated by Carmon et al. [72] is that the low energy consumption caused by COVID-19 affects the control of electricity generation units and further leads to reduce the resiliency and reliability of electricity systems; whilst, the lesson was regarded as experience for the readiness of electric grids to fight future global health crises. COVID-19 could cause

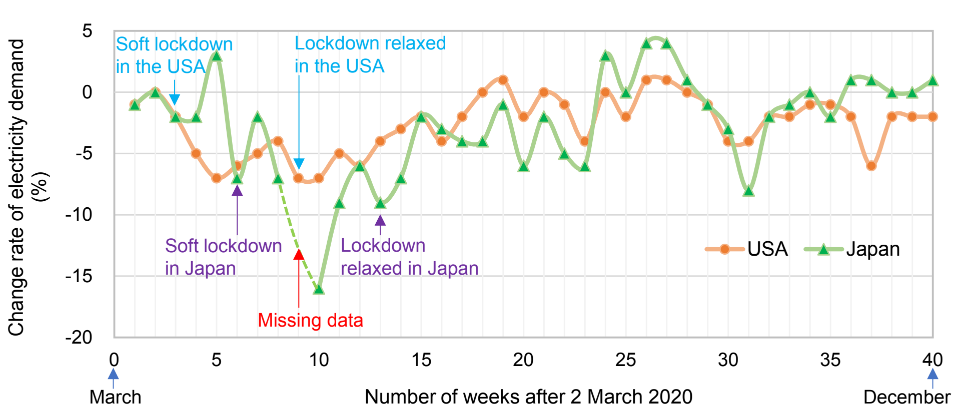

Fig. 4. The change rate of electricity demand in 2020 (temperature adjusted) relative to 2019 in the USA and Japan. Note: The electricity demand data are retrieved from Bruegel electricity tracker [66]. Only the peak-hours (08:00–18:00) in working days were recorded in the week data information. As the (i) data sources, (ii) year-on-year comparison method, and (iii) lockdown manners are different, Fig. 3 and Fig. 4 are presented separately. The time of soft lockdown and its relaxation is given in Table 2.

negative impacts in both short-term and long-term on the emission intensity, in particular of the EU power market since the clean technologies also suffer from the lower energy/electricity demand and consumption [73]. Due to the resilience and competitiveness of low carbon emissions technologies, the wind, solar and nuclear powers in many countries present higher shares, which supports the transition to the resilient, clean and low carbon energy systems [74]. However, under lockdown, limited production activity, less global energy investments [75], and fewer renewable energy installations due to the shortage of raw materials [14] and energy efficiency audits [76] would collectively destroy the economic and energy sustainable development.

The commonly implemented macro measure during the COVID-19 pandemic has been lockdown with social distancing and wearing PPE. The measure is a powerful action to reduce various infections. However, the overuse of such a measure can negatively influence urban and energy sustainability, although the original intention was usually to prevent disease infection and keep people healthy. It is a chance that the energy consumption and environmental emissions could be reduced by the social distancing and lockdown measure. However, this is not a sustainable way for the whole society in the long run. One of the main issues is how to implement social distancing and lockdown. A general lesson has been to reduce social distancing in a safe way and in a suitable time during the new normal period. After relaxing lockdown measures, different pathways of social distancing associate with different energy and economic recovery. There are several beneficial strategies under the COVID-19 situations which carefully consider disease mitigation without significant compromise on urban and energy sustainability:

- New lifestyles in cities with lower energy usage: For example, the "15 min city" [77], the "20-minute neighbourhoods" [78] and the self-sufficient buildings/lifestyles based on energy-efficient strategies [79]. These have been gradually popular concepts in the new normal circumstance. The arrival of the pandemic made those plans more supported and urgent. The very welcome side effects are that these strategies can significantly reduce energy demand and CO_2 emissions for the travel, ease the traffic jams, provide cleaner air and considerably reduce the pollution. Their adverse effects and possible solutions are further discussed in Section 5.2.
- The intelligent quarantine strategies: Many intelligent strategies have been proposed for different countries/regions. For example, (a) tracking contact history using smartphones of patients [80], for which the privacy needs be taken seriously [81], (b) permitting low-risk population to return to work and activities, and (c) gradually opening some sectors in the consequent time durations. These intelligent quarantine strategies are helpful for resuming production and life and further stabilising the energy demand, as discussed in Section 3.2.
- The flexible lockdown exit strategy: A long-term lockdown is not a wise option to recover energy demand and economic activity. Whilst a premature nationwide lockdown exit may cause another infection wave [82]. The smart traffic mobility monitoring and the spatial-temporal potential exposure risk analytics based on the IoT and big data technology could offer dedicated suggestions on the spatio-temporal crowd division and flexible local lockdown scheme [55]. A flexible lockdown strategy could provide greater benefits for urban and energy sustainability especially when the society has expectations on the "protracted-war" against the epidemic [83], and when the intermittent lockdowns are the new normal [84].

Although awareness is beyond the scope of this paper, it is still noteworthy that these new strategies make sense if most of the inhabitants would like to collaborate. Considering that other issues may be stemmed from these new strategies, more detailed extra energy benefits or demands should be assessed further. Beyond lessons, the potential opportunities and benefits are discussed as follows.

5.2. Emerging opportunities

The emerging opportunities during and after the COVID-19 pandemic are highlighted in terms of (i) enhancement of digitalisation and IoT, (ii) new lifestyles in cities with lower energy usage, (iii) resilience enhancement with Circular Economy, (iv) opportunities for renewables and energy storage, and (v) fighting infectious diseases and saving energy. The energy consumption, both potential reduction and increment, in these implementations are analysed.

(i) Enhancement of digitalisation and IoT (Internet of Things)

COVID-19 triggers lockdown, movement restriction and social distancing. The crisis occurs concurrently with opportunities. It reshapes the original system (e.g. education system, business system) and lifestyle, accelerating the growth of digitalisation [85]. Digitalisation could be an advanced development; however, the exact effectiveness and energy consumption have remained uncertain. The assessment is complex where the current datasets and methods are still underdeveloped to answer fully and defined the benefits. Fig. 5 illustrates the different energy consumption of centralised offices, schools/universities with commuting, compared to a home office. The consumption is interrelated, where the decrease in energy consumption in offices will lead to an increase in energy consumption at home. However, the degree of increment and decrement, which contribute to the net consumption is not equivalently shifting between the options. It highly depends on user behaviours as well as energy efficiency at a place. There is still a lack of studies, especially those who including social factors in the assessment to concretely prove that, e.g. teleworking and e-learning are better than centralised office and schools. The reduction of energy consumption in commuting is the main contributors to lower energy usage. However, there are still several studies suggest that the potential increase in non-work travel and home energy use may outweigh the gains from reduced commuting. Hook et al. [86] stated that despite the generally positive verdict, there are uncertainties and ambiguities about the actual benefits in energy saving. O'Brien and Aliabadi (2020) [87] suggested that the rebound effect of telework tends to offset and even exceed energy savings significantly. The factors which could affect the energy consumption of the comparative options could be summarised as:

(a) Commuting distance (e.g. if it is a "15 min city", the energy consumption is less significant) and route (e.g. together with grocery shop on the way home)
(b) The energy efficiency of buildings (e.g. the lighting, cooling, and heating system of home versus office)
(c) Occupancy (e.g. home office or e-learning – one person occupied a room)
(d) The duration of usage (e.g. computers)
(e) Information and communications technologies to support the digitalisation (e.g. data centre, the demand for equipment)
(f) Daily activities (e.g. travel as there is no need to attend the office physically)

The net saving in Fig. 5 or adverse effect needs to be further assessed considering the behaviour and lifestyle changes as it is highly dependent on contextual details. The assessment is not rocket science but does demand sufficient understanding. Other than the direct energy consumption, the energy consumption needed for information and communications technology (ICT) production, treatment and disposal of e-waste, the consumption of rare metals as well as the effectiveness of the approaches need a better quantification towards sustainability. With an escalation of the use of big data, the energy contempt is expected to grow substantially. In addition, one potential limitation of the IoT and virtual approaches lies in the stability of electricity and internet supply, especially in peak demand of internet use [88]. Along with the technological development, it has the potential to be well addressed by the energy-

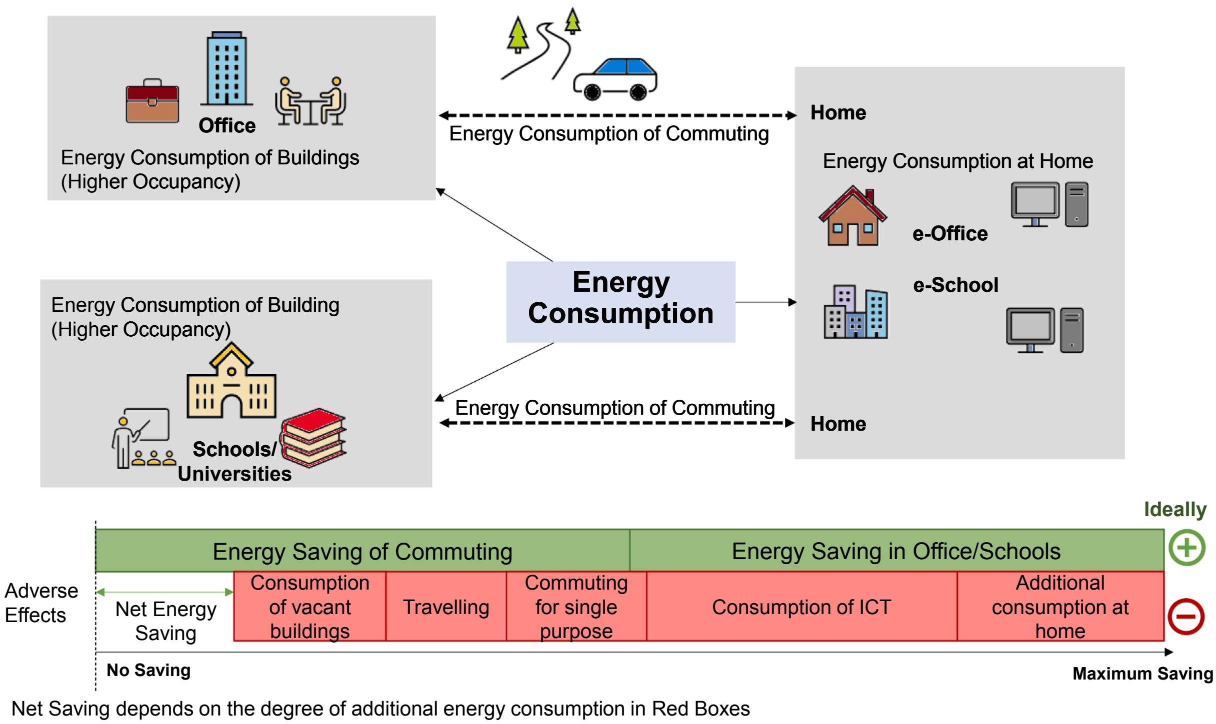

Fig. 5. The different sources of energy consumption of physical and virtual schools/offices. Note: Red boxes indicated with a negative (minus) sign shows the other effects which could be minimised or overrule the positive effects of e-office (teleworking) and e-schools (e-learning), in green. The lengths of boxes denote rough estimates of the magnitude of the effect. A longer length means a higher effect. It is used to present some new features under COVID-19, which should be assessed comprehensively when more data are available. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

efficient 5G networks [89] and the promising SpaceX Internet service, Starlink [90].

According to the energy consumption in the information technology sector [91], other than the use of devices (20%), data centres (19%), networks (16%) and computers (17%) are the main sources of energy consumption. The power consumption of ICT activities has been expected to reach close to 40 PWh in 2030 [92]. The energy use of global data centres is estimated as 205 TWh (6% increase compared with 2010) in 2018, constitutes 1% global electricity consumption [93]. The CO_2 emissions related to artificial intelligence computations are non-negligible nowadays [94]. The service demands of data centres and intelligent computations have risen significantly; however, there is a notable increase in energy efficiency (energy use per compute instance). Masanet et al. [93] also suggested that a significant decline in the energy consumption of data centres infrastructure including cooling and power provisioning is enough to offset more of the growth in the energy use of ICT devices. The increase in the energy efficiency of ICT services has also been suggested by Lange et al. [95]. However, they also stressed that, overall, digitalisation increases energy consumption. The ICT sector is especially prone to high rebound effects and inhibiting the sufficient absolute reduction in energy demand. Digitalisation is a relatively energy-intensive solution [95] unless the promoting effect on production, usage and disposal as well as the role of demand driver can be figured out.

In contrast to work from home and work from the office, the energy savings of virtual conference compared to the in-person meeting is more apparent and less likely to overturn by the rebound effects. The potential rebound effects include: (i) growth in the number of conferences due to the improved availability of video conferencing systems, (ii) high definition video streaming (iii) higher usage and demand of ICT devices and, (iv) steep rise of hours streamed and of data traffic associated with video streaming [96]. In general, the energy consumption per person of a virtual conference is significantly lower than the energy consumption needed for travelling. Based on an assessment by Ong et al. [97], video conferencing takes at most 7% of the energy/carbon of an in-person meeting, suggesting as an alternative with lower carbon emission footprint. However, the effectiveness of the meeting, including the interaction, deserves more evaluation. Effective e-waste management is also essential [98] in supporting the development of digitalisation. COVID-19 is viewed as an accelerator to the development of digitalisation. Fig. 6 shows the predicted emission and energy consumption by ICT. The emission contributed by ICT-related energy consumption was expected to be increased by about five times. The ICT-related energy consumption was suggested to consume 8% of the global electricity supply in 2030 and up to 51% in the worst-case scenario. These trends in Fig. 6 would be enlarged sharply due to COVID-19. Questions remain on how the invested energy in IoT could reduce the overall energy consumption in all sectors and how the COVID-19 will affect the forecast.

(ii) New ideas for safer and cleaner cities with lower energy usage

As correctly, the majority of the world population has been living in cities, and this trend has been continuing. The issue of safer cities is becoming very urgent. However, this is a longer-term issue as to develop the structure of a city further is not a matter for a few months, it is rather a strategy to follow in the horizon of several years when building new cities or making the substantial rebuilding of existing cities. The idea is not complicated, as shown in Fig. 7. The C40 city mayors [102] are leading actions for health and well-being – giving public space back to people and nature, reclaiming our streets and guaranteeing clean air to ensure liveable, local communities by:

(a) Creating a “15 min city” [77] where all residents of the city are able to meet most of their needs within a short walk or bicycle ride from their homes.

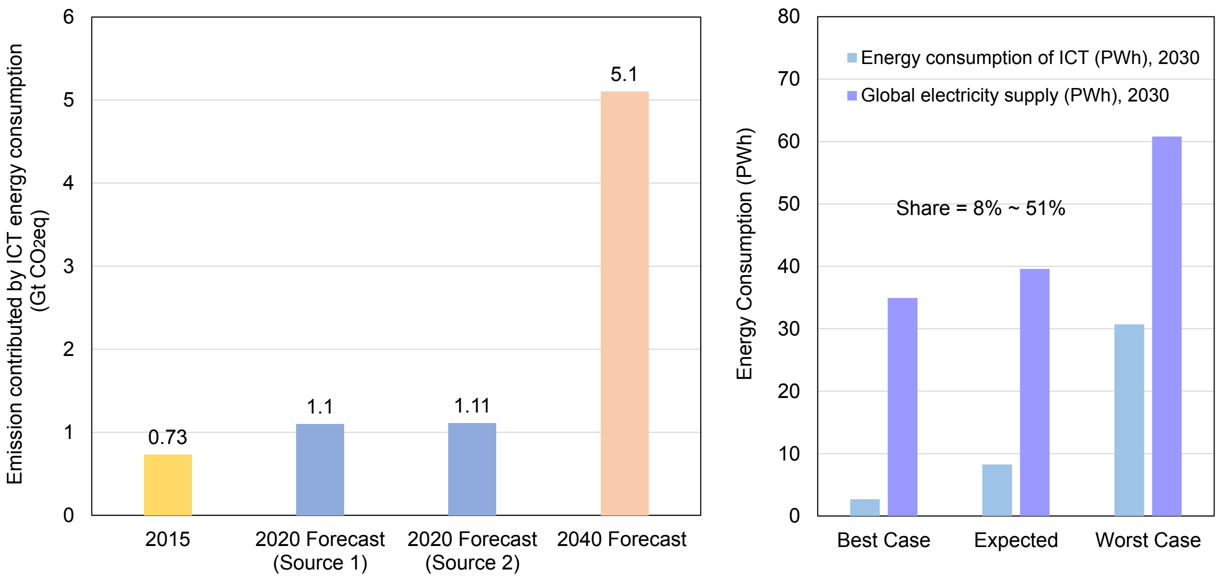

Fig. 6. The emission contributed by ICT energy consumption and forecasted energy consumption in 2030 [92]. Emission contributed by ICT energy consumption: 2015 based on Malmodin et al. [99]; 2020 forecast = Source 1 [100], Source 2 [101]; 2040 forecast = [100].

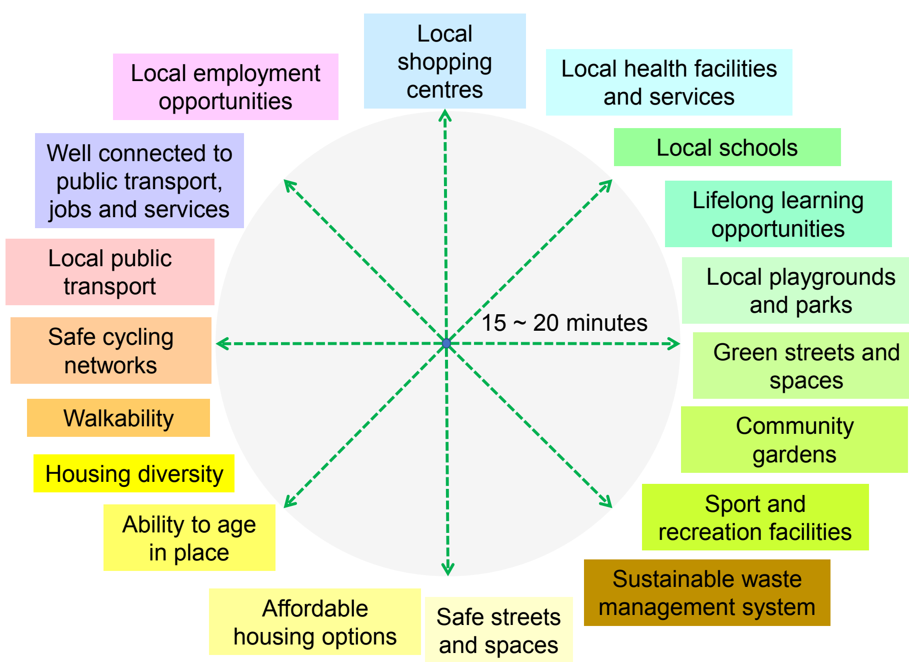

Fig. 7. The features of a 15- and 20- min city/neighbourhoods, where a sustainable waste management system is a newly added feature. Adapted from the “15 min city” [77] and the “20-minute neighbourhoods” [78].

(b) Giving streets back to people, by permanently reallocating more road space to walking and cycling [103], investing in city-wide walking and cycling networks and green infrastructure.
(c) Building with nature to prioritise ’nature-based solutions’ [104] such as parks, green roofs, green walls, blue infrastructure and permeable pavements, to help reduce the risks of extreme heat, drought, and flooding, and improve liveability and physical and mental health [102].

The pandemics made those plans even more striking, as they can significantly contribute to social distancing and reduce the danger of the infection spreading. However, deeper analysis is needed what this means from the point of energy demand and consumption. The general idea is to replace centralised supplies with distributed ones. What can be a considerable energy saving is the reduction of human flows and traffic jams related to that. However, the 15- or 20- min city/neighbourhoods/superblocks [105], as various terminology has been developed, should cover all the frequent inhabitant needs if it is supported with e-shopping and the other e-activities, e.g. home office, e-learning, remote medical monitoring and care, it can provide substantial reduction of energy consumption and related emissions. Very important for that neighbourhood is efficient waste management as when inhabitants would less commute and be concentrated in one “superblock”. They would likely generate more waste locally concentrated. For this reason, projects would need to consider superblock compositing nodes, perhaps even biomass units. As much as energy should be generated locally, implying the energy transition losses can be reduced as well if renewable sources of the energy could be well designed and mastered. An issue which requires more attention in the "15 min city" is the waste collection and management system. This feature has not been well-integrated and assessed in the elements of 15- or 20-min city/neighbourhoods (See Fig. 7). The task is widely multidisciplinary and demands close collaboration of architects and urbanists with the technology and especially information technology specialists. For example, the incorporation of IoT and digitalised waste management [106] has the potential to help managers understanding the new waste-dumping behaviours and facilitating democratic decision-making in the COVID-19 new normal period. In addition, more environmentally friendly information-sharing and publicity related to waste management can be implemented by social media platforms [107] under the scenario of new lifestyles with lower energy usage.

The density of "15 min city" makes it efficient and reduces the energy use and the carbon footprint in transporting activities [108]. The food access and food aid are quite crucial during COVID-19 [109]. The "15 min city" emphasised easy access to services and goods, particularly fresh food, which triggers to shorten cities' food-supply chains [110]. Such a 15-minute walking neighbourhood scale favourites diversified manufacturing and supply, rather than large manufacturing and large-scale shopping [111]. Although the "15 min city" could provide so many advantages in terms of safer and cleaner cities with lower energy usage, there are still some open questions on the waste collection and management system in a high population density area of the "15 min city". How should the waste collection be done? Whether it should be door to door, kerbside containers, or containers in a drop off points? Should the treatment locate in the city or outside the city? Is the transfer station needed? Is an automated collection system a sustainable solution? What about the cleaning sticky bio-waste and pests? What about preventing the spreads of infections? Pneumatic waste system [112], an automated collection system, is less labour intense, safer for collection workers and the garage lorry for waste collection is no longer interfere with general traffic. The energy use by transport for waste collection could be reduced. However, the efficiency, the other form of energy required to support the system needs a better evaluation. Pérez et al. [113] identified pneumatic systems to have a more significant impact on climate change, and other environmental issues due to the significant electricity consumption and the pipelines manufacture reported as 42.5 kWh/t of waste. The energy consumption of the truck system depends on the distance and type of transports (around 1.1 kWh/tkm [114]). Punkkinen et al. [115] stated that the pneumatic system (56 kg CO_2eq/t_{MSW}) has a carbon emission footprint of 2–3 times higher than the door-to-door system. However, the environmental impacts of both system, pneumatics, and truck system, could be reduced through the selection of renewable energy source [116].

(iii) Urgent needs to improve energy resilience and implement the Circular Economy

The disease outbreak prompted disruptions of some energy-transportation supply chains and the supply chains of PPE, disinfectants and even food. The importance of modelling and analysing disruptive situations, especially for the current COVID-19 crisis, is urgently needed [117]. For the purpose of emergency response, some of the recovered supply chains operate at the expense of massive energy consumption and environmental emissions. The energy consumption of emergency transportation could be elevated by more than 17 times by plane instead of by ship during the COVID-19 pandemic [22]. It is understandable for those life-saving resources in emergency situations. However, it is urgent to develop more resilient supply chains with the consideration of both emergency response and low energy consumption, especially for those resources that are not so urgent. Even for the essential supplies of life-saving resources, it is rational to prevent the exhaustion of supplies in the coming weeks and beyond [2] when the global disease pandemic and its impacts would exceed expectations. The new normal period provides such opportunities to rethink the issues and improve resilience in emergency supply chains. By identifying the significant factors, Sharma et al. [118] developed a conceptual framework to enhance the survivability of green and sustainable supply chains in and post-COVID-19 pandemic.

No limited to supply chain problems, the resilience of energy systems deserves attention [119]. Bagheri et al. [120] appealed to the city-integrated renewable energy mechanism for climate-resilient and low-carbon communities. The climate-resilient electricity system was suggested to assist in tackling climate change and COVID-19 [88]. Although facing great challenges, electric power grids and small energy markets are adjusting to getting more resilient to fight future crises [72]. In addition, resilience should be synergistically improved in energy management and waste management. COVID-19 has exposed some vulnerabilities in the power systems; however, it also offers an opportunity to safeguard sustainable and reliable energy and resilient power sector planning [121]. A promising comprehensive solution for resilience improvement is Circular Economy (CE) which functions with principles including circularity, low carbon, sustainability and system thinking. The usage of plastic and other PPE products has spiked during the COVID-19 pandemic, resulting in plastic pollution problems during and after the COVID-19 pandemic. For example, plastic waste in Thailand increased from 1,500 t/d to 6,300 t/d at the peak time because of food deliveries [122]. It was expected that ~40% elevation in plastics demand in Spain [123]. Hopefully, the problems can be dealt with by the CE strategy [124]. The CE strategy offers the possibility of sustainable and resilient development, which assists in coping with uncertainties not only in the current phase but also in the future. During the COVID-19 pandemic period, a series of observations in the use of reusable marks [22] and the reuse of N95 masks after disinfection [125] have been demonstrating energy and materials savings without compromise of effective disease prevention. Circularity, energy-saving, collaboration and IoT (digitalisation) are likely to be more popular topics in the post-pandemic phase.

(iv) Opportunities for renewables and energy storage (e.g. when the drop in demand)

Although it is still early to analyse the net effects of COVID-19 on global sustainable and renewable energy systems [126], the COVID-19 pandemic brings opportunities for renewable energy [75] and perhaps also for hydrogen as an energy carrier. Dincer [127] stated that the disease outbreak in 2020 might open the hydrogen age, and a large-scale shift to hydrogen energy could make benefits for the environment, ecosystem, energy efficiency, resources use, economic development, healthier societies, and renewable energy options. Fig. 8a shows the projected change rates of different types of energy demand. Oil and coal energy would have significant declines. Renewable energy would be the least affected type compared to nuclear, gas, coal, and oil energy demand. Although the renewable industry encountered serious disruptions of supply chains caused by the lockdown and quarantine measures, the variations of the growth rate of electricity generation using wind (a relative 1.7% decrease, i.e. from 11.9% to 11.7%) and solar photovoltaic (PV) (a relative 27.8% decrease) were not expected to be reduced significantly compared to hydropower (a relative 70.8% decrease), bioenergy (a relative 64.1% decrease) and other pathways (a relative 60.6% decrease) (see Fig. 8b). Compared to the growth rate of wind energy, the decrease in the growth rate of solar PV energy is also significant in absolute value. The renewable sector encountered supply chain disruption during COVID-19. The supply chain of wind energy is globally distributed. Whilst the supply chain of the solar PV module is relatively centralised, with over 70% module manufacturing in China [6]. In the future, the growth rate of the proportion of renewable energy amongst total energy is expected to be enlarged due to the lesson from the COVID-19 pandemic. It is expected that the investments in

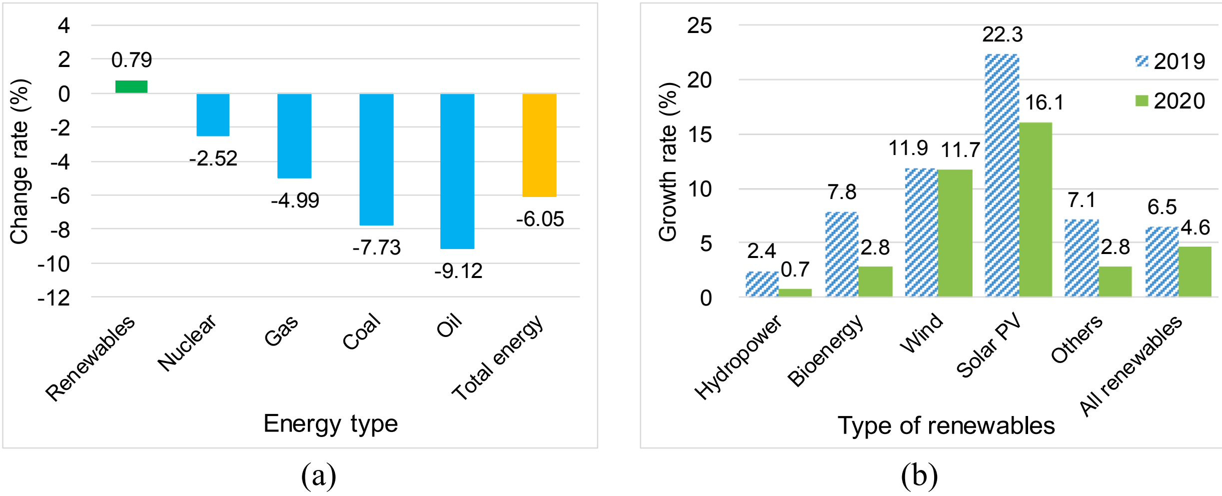

Fig. 8. The projected change rates of (a) primary energy demand in 2020 compared to 2019 and (b) growth rates of renewable electricity generation in 2020 and 2019. The dashed blue bar shows the annual growth rate in 2019 compared to 2018. The solid green bar shows the projected growth rate in 2020 compared to 2019. Data retrieved from IEA [6].

renewables create three times more jobs than those in fossil fuels [128], which is supported by Wei et al. [129]. However, the experience from the Czech Republic indicates that job creation depends heavily on the continuation of financial incentives [130]. Opportunities triggered by COVID-19 also exposed the worst-case problem. In Germany, the low energy demand during the pandemic and high renewable energy outputs in good-weather days set a record of negative wholesale power prices [59]. In such a situation, energy producers had to pay for wholesale customers to avoid turning off plants. The worst-case problem exposed during the pandemic offers motivation for energy producers to design more flexible systems for renewables.

Energy storage could mitigate demand variations, enhance the flexibility of energy systems, and enable the dispatching of renewables [131]. The COVID-19 pandemic influences energy storage. Before the COVID-19, due to the uncertainties of battery safety and the unstable policy support in markets, energy storage had been losing momentum as the annual total installations of the energy storage technologies year-on-year in 2019 fell by 20% [132]. In a short-term, COVID-19 changed the economic structure, reduced investment for the energy storage industry, and disrupted the supply chains from cells to installers. Some storage projects were hung on temporarily, which dragged the growth rate of energy storage development. In a long-term, COVID-19 offers opportunities for the energy storage industry. The crisis could trigger energy transitions [133], including the sustainability transitions [134], clean energy transitions [135], and sustainable energy transitions under different politics related to COVID-19 [136], which further offers potential development/opportunities of novel energy storage technologies. In addition, according to the experience of other crisis in history, including the Spain flu, great depression, world wars, oil shocks and 2008 financial crisis [6], energy demand would be recovered significantly after a crisis. These long-term opportunities would be further enhanced if policymakers could improve energy investment tax and focus more on the energy industry for a possible economic drive.

(v) Fighting infectious diseases and saving energy

The COVID-19 mitigation measures, including lockdowns, social distancing, wash hands properly, wearing masks, closing schools, working from home, and other strategies to minimise the virus spread lessened the transmission of other infectious diseases as well [137], e.g. global influenza, a regular infectious disease with seasonality. Similar observations were reported in the WHO European Region [138], Japan [139], Singapore near the equator [140], and some other places in the southern hemisphere [137]. This implies that the COVID-19 fighting could have the potential to help with fighting influenza, which was regarded as a more common and bigger killer. Klemeš et al. [22] highlighted the high energy consumption of the hospitalisation stay in terms of medical equipment usage, power supply, and requirements for air quality and disease control. Intuitively, the COVID-19 pandemic and its mitigation are cautiously thought to reduce the potential energy consumption that was used for controlling some other infectious diseases in previous years. To obtain comprehensively quantitative results, it requires more investigations on the epidemic/pandemic evolution of COVID-19 and the possible worst-case scenario where COVID-19 and other viral respiratory diseases may overwhelm the healthcare systems. For example, some researchers are focusing on the possible impacts of the dual epidemics of COVID-19 and influenza, including the preparation for the influenza-COVID-19 co-epidemics [141] and the vaccine acceptance and coverage [142]. The emergence of COVID-19 also brings hope and opportunities for fighting infectious diseases and saving potential energy. By this chance, the whole society has viewed the possibility of substantially decreased influenza activity due to the mitigation measures. After relaxing the lockdowns, population behaviours in wearing masks and handwashing change positively [84]. Even after the COVID-19 pandemic, the hygiene measures, such as wearing masks and handwashing, could be long-term habits in population. This could produce long-term impacts on future influenza partitivities or intermittent COVID-19 pandemics, which helps to reduce energy consumption in hospitalisation at the same time.

6. Conclusions

The COVID-19 pandemic has been developing into one of the most severe challenges that the humankind has been facing in the long history. It has been attacking modern society like the global economy based on global trade and movements. Besides medical, business and commercial issues, there are also issues of the impact on the environment based on "blood" of the modern society – energy. The challenges obviously are going to be further developed and get increasing influence on the energy industry. Based on the overview of the impacts and challenges of COVID-19 pandemics on energy demand and consumption, point-by-point observations are highlighted as follows:

(i) Structural changes in energy demand and consumption have been observed in the (a) short-term versus long-term expectations, (b) different sectors of the energy industry, (c) residential versus nonresidential consumptions, (d) peak demand patterns, (e) consumption philosophy during and after lockdowns, (f) consumed products, and (g) energy intensities in different regions.

(ii) Compared to 2019, the energy intensity in 2020 has presented apparent spatial–temporal differences, although both energy demand and GDP decreased. The projected energy intensities of the four comparison regions have varying degrees of elevation. The USA presents the highest change rate (+29.3%), followed by Japan (+7.8%); whilst China (+2.8%) and the EU (+1.03%) present no apparent variations.

(iii) This study offers thoughts on how to consider and analyse extra energy demands and energy stabilisation. It is crucial to outline the extra energy curve and the actual COVID-19 energy curve to guide the energy stabilisation clearly. The major pathways of extra energy consumption include (a) confinement measures, e.g. home office, and fighting measures, e.g. PPE, (b) emergency and establishing supply chains, and (c) waste disposal-related energy involvement.

(iv) The energy recovery presents heterogeneous characteristics in regions. The energy consumption recovers to the regular level about 3 months after relaxing lockdown measures in China when the pandemic was well controlled. Although similar ~3-month durations have been observed in the USA and Japan cases with soft lockdowns, pandemics have been repeating or continuing to worsen in these two countries. The energy consumption in India nearly returned to normal status but at the expense of the increasing number of daily COVID-19 cases. The energy demand recovery in the EU is on the way. The time period of energy recovery depends on policies, sociological factors and geographical factors.

Every challenge brings the mobilisation of resources as well as energy efforts/opportunities. Fig. 9 summarises the challenges and opportunities discussed in this paper. The four main energy challenges include (a) demand fluctuating and uncertainties, (b) structure and pattern changes, (c) associated environmental impacts, and (d) the challenge to recover energy demand. In the energy industry, there have been numerous negative and restrictive issues during the COVID-19 pandemic; however, it is very important to look in the future when the society relaying on energy is going to recover with the minimum impact on the environment. There are some potential new ways on how to organise daily life, production and logistics. This paper made an attempt to highlight some of them and offer some suggestions and critical comments on possible defects of them for better future development related to energy. The five energy opportunities cover the (i) enhancement of digitalisation, (ii) new lifestyles with lower energy usage, (iii) resilience enhancement with Circular Economy, (iv) opportunities for renewables and energy storage, and (v) fighting infectious diseases and saving energy.

The pandemic situation has been still developing, continuous observations and research are important to be conducted to provide as many benefits from this challenging development in the energy industry. Although COVID-19 caused many energy-related challenges, with learned lessons and proper actions, it offers opportunities and motivations to envisage and build a high energy-efficiency and low-carbon future [143]. Several future research directions deserve further investigation:

(I) Except for quantitative analyses, this paper also introduces some conceptual thoughts, including the diagrams of stabilising energy demand by considering extra energy demands and the 15- and 20-min city/neighbourhoods with an additional function of sustainable waste management. When more quantitative data are available in the future, quantitative assessment and analyses are important to move the conceptual parts forward.

(II) It is noted that the results on energy recovery, as shown in Fig. 3, are based on the first wave of COVID-19. As the global second wave has been hitting the world [144], some countries implemented lockdown/restrictions again. When more data belonging to the second wave are available, it deserves more investigation on whether the relationship between energy recovery and COVID-19 case number changes significantly.

(III) More spatial comparison is crucial for a better conclusion on energy recovery. However, two challenges hinder its implementation currently. First, although some references show time-serial electricity demand, the raw data are hard to obtain. Second, the weather corrected data are key to analyse the unique effects of lockdown on the variation of electricity demand. However, some data from other sources just present the actual electricity demands in 2019 and 2020, rather than temperature

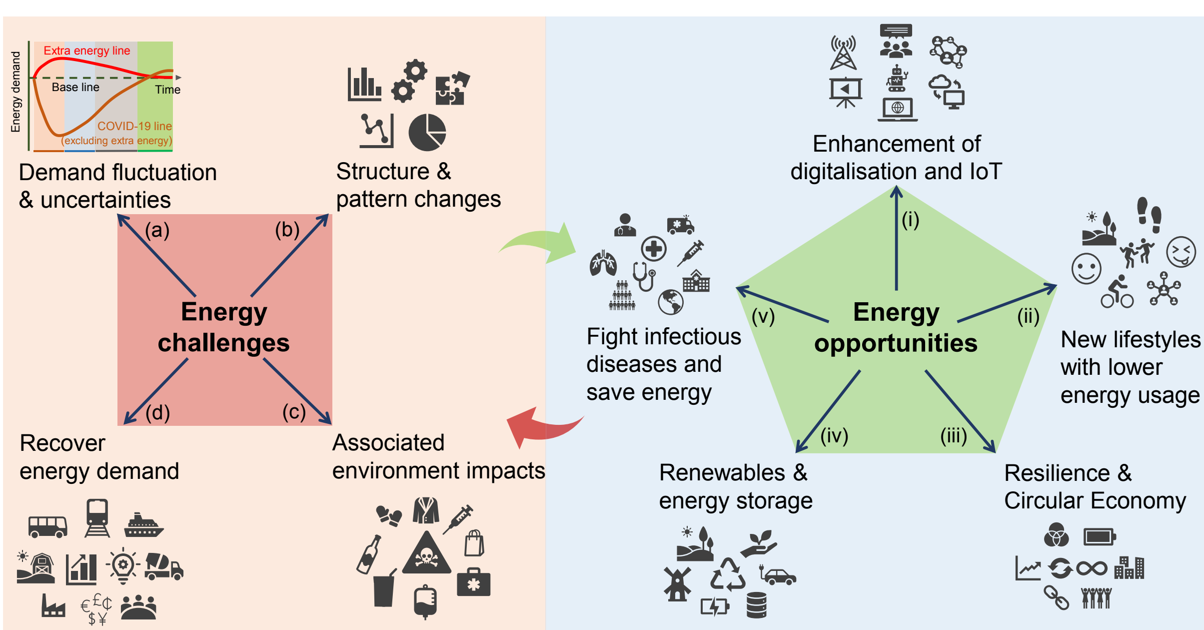

Fig. 9. Summarised challenges and opportunities in the energy industry related to COVID-19.

adjusted demands. Openness and practicality of raw data would contribute more to the energy industry.

(IV) As the world is more or less fighting COVID-19 together, coordination and collaborations [145] amongst countries/regions were, are and will be enduring topics in the energy industry. Coordination and collaborations are crucial for energy access [21], energy security [62], and energy justice [146], especially in less developed countries, e.g. African continent [147]. The strategic management framework [148] could be enhanced quantitatively to manage global energy resources and energy strategies post-pandemics.

(V) Long-term plans and their justifications deserve increasing attention in every country/region. Some open questions are worthy of exploring. For example, what are the resilient, robust and flexible plans/strategies for coping with the fast development of pandemics and mitigation measures? How will the national and local stimulus packages affect long-term energy recovery and air emissions? Will the energy-related sustainable development goals be reset [149] or be remained by incorporating new implementation strategies?

CRediT authorship contribution statement

Peng Jiang: Conceptualization, Writing - original draft, Data curation, Formal analysis, Visualization. **Yee Van Fan:** Conceptualization, Writing - review & editing, Formal analysis, Visualization. **Jiří Jaromír Klemeš:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.116441.

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