The interplay between energy technologies and human health: Implications for energy transition

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Review article

The interplay between energy technologies and human health: Implications for energy transition

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A B S T R A C T

This paper explores the relationship between human health and energy technologies, with a focus on how energy technology needs to adapt to new health challenges. The authors examine how a clean, affordable, and reliable energy infrastructure is critical for mitigating the impact of future pandemics. They also look at how increasing the proportion of solar and wind energy can create a near-zero emission energy system that is independent of fuel supply and its associated environmental problems. However, to ensure system resilience, significant investments in energy storage and smart control systems are necessary. For instance, the pandemic led to around 5% increase in US residential sector electricity consumption share in 2020 compared to 2019 due to stay-at-home orders, which could impact grid reliability and resiliency. This work also highlights the importance of designing energy-efficient and low-cost cooling and heating technologies for residential buildings to protect vulnerable populations from the health consequences of rising temperatures due to climate change. Additionally, the growing number of refugees worldwide and the need for efficient portable power sources in refugee camps are also addressed. The authors demonstrate how pandemics like COVID-19 can have far-reaching effects on energy technologies, from household energy use to large energy companies, and result in energy insecurity and decreased quality of life for many.

Contents

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1. Introduction

The appropriate utilization of energy is critical to our wellbeing. It helps families with sufficient income to remain healthy by providing the energy required for cooking and heating, cooling and air conditioning (HVAC). While industrial processes associated with power production support public and private transport systems, provide access to jobs and living arrangements, and also ensures the functioning of the communications networks needed to maintain electricity supplies (Wilkinson et al., 2007; Peng et al., 2021). In general, electricity consumption is an indicator of overall life quality. Thus the growth in electricity consumption in the US has been directly associated with the annual gross domestic product (GDP) since 1950 (Arora and Jozef, 2014). Therefore, it is unsurprising that the United Nations (UN) includes affordable clean energy and health among the key Sustainable Development Goals (SDGs) within its Agenda 2030 framework (UN, 2016). While both health and clean energy are defined by the UN as separate SDGs, recent wars, climate-related disasters and pandemics highlight the linkages between human health and energy use. The emergence of disasters such as pandemics or the Ukraine war create global crises, forcing large-scale changes not only for the healthcare sector, but also for many other social and economic sectors, necessitating behavioral changes (Van Bavel et al., 2020) and changes to industrial structures (Craven et al., 2020). In 2003, the Harvard Medical School predicted that man-made changes in ecologic systems and climate can lead to a plethora of emerging diseases (Epstein et al., 2003). Similarly, Danish researchers (Lorentzen et al., 2020) have argued that the global biodiversity crises and climate change are interconnected with pandemics and underline the importance of national and international investments in sustainable solutions that address climate change. Moreover, climate change appears to be increasing the rates of transmission of infectious diseases (Wu et al., 2016). The unprecedented heat waves and high temperatures resulting from climate change have serious health consequences, especially for cardiovascular diseases. Many researchers have noted that we are living in a period in which human activity profoundly affects the biosphere, using the term *Anthropocene* to describe the era in which human activity is the dominant influence on climate and the environment. Thus, both the direct and indirect consequences of human activity and modern technology affect us all, especially in terms of climate change and phenomena such as pandemics (Morand and Walther, 2020; Rieder, 2020; Bowman et al., 2020). Such global challenges require profound changes to the current system of energy technologies while maintaining clean and pollution free energy for all including vulnerable groups to secure health. In addition, the detection and control of future pandemics and other diseases require developing functioning health systems powered by energy systems as well as the application of new online health monitoring methods (implantable or placed directly on skin for instance) where data is collected by the internet of things (IoT). The IoT utilization leads to a smart energy system where the power generation and consumers are linked enabling more efficient regulation of loads and energy supply (Chong et al., 2022). Smart buildings have the potential to interact well with smart grids to enhance energy efficiency, demand flexibility, grid services, and indoor comfort and health (Krarti and Aldubyan, 2021).

The price of energy has been increased by the pandemic, moreover the Ukraine war and the associated inflation and market changes has produced energy scarcity and insecurity. In the US, for instance, rural low-income families spend up to 9% of their income on energy (Graff and Carley, 2020), and many have been forced to reduce their energy consumption due to a pandemic induced economic crisis. In Poland, Nagaj and Korpysa (2020) have shown that the level of energy poverty has increased from 7.7% to 21.4% as an economic consequence of the pandemic. Energy supply disruptions and increased electricity and gas prices, increased utilization of alternative energy conversion methods such as indoor fossil fuel combustion for cooking/heating in poorer countries leading to poor air quality, including increased particulate matter (PM) with major health consequences.

The aim of this paper is to provide a comprehensive analysis of the interrelation between energy technologies and human health. This paper is novel in its examination of (1) the major challenges in the energy sector that can lead to negative impacts on human health, particularly during pandemics, (2) the effects of pandemics on the energy sector, and (3) potential solutions for transitioning to a health-friendly energy system. Drawing on the latest research published, the paper evaluates the impact of energy sources on human health, including energy pollution, pandemic recovery budgets, and environmental spending. Additionally, the paper explores the role of urban planning, energy efficiency, energy security, centralized *vs* decentralized energy systems, energy-efficient transportation, and energy devices for health monitoring in shaping human health. Finally, the paper delves into the impact of pandemics on the energy sector, including the effect on energy industry staff, the energy generation mix, the distribution of energy use, the chemical/petrochemical markets, and air quality. The discussion about the chemical/petrochemical health related markets is given because these industries are crucial in producing medical and pharmaceutical items including personal protection equipment supplies while also experiencing negative impacts on their economics due to the pandemic-induced reduction in demand for chemical materials.

2. Impacts of energy technologies on human health

Energy technologies have a variety of impacts on human health, as discussed below.

2.1. The importance of reliable energy sources for human health

A reliable energy infrastructure is essential to maintain a public health system during pandemics, and energy grid failures are potentially catastrophic. For instance, the information necessary to provide provision of emergency responses is dependent upon data centers, which use large amounts of electricity (Smith, 2020). The energy shortage due to the 2022 Ukraine war threatens health services due to either energy shortage of or increased energy prices required to offer health services (Choudhary et al., 2022). Another example is Iran where the dedication of a large share of national power generation to electricity consumption in mining of highly energy intensive cryptocurrencies (Li et al., 2019) has led to severe periods of regional electricity blackouts (Shabestari et al., 2022). The electricity blackouts are expected to double from 2020 to 2040 in Iran mostly due to the increase in average temperatures in warm months and lack of renewable energy sources (Shabestari et al., 2022). As a consequence of large regional electricity black outs, many respiratory patients suffer medical treatment disruptions. Any disruption of the energy grid that affects data centers will disrupt the processes of data interpretation and decision-making in hospitals. Ventilator, which are key elements in the treatment of patients with respiratory diseases, are another example of health system dependence on a reliable electricity system. Any disruption in the supply of electricity to ventilators will pose serious risks to patients with respiratory diseases who are in intensive care units (ICUs).

Energy poverty and energy insecurity, and the negative health impacts of insufficient and inefficient energy usage and poorly insulated buildings are amplified for vulnerable and less-adaptable groups such as young children and the elderly, highlighting the need to provide vulnerable groups with better energy solutions (Brown et al., 2019). Many countries have allowed persons with low income to delay paying their energy bills during specific disasters and the associated recessions. As an example of the importance of energy security for human health, new findings correlate the severity of COVID-19 to home energy standards, and show that homes with high energy standards have lower risks of infection and complications related to respiratory illnesses and patients have enhanced immune protection against illness (Baker et al., 2020). In general, ensuring improved thermal comfort in homes leads to health improvements, particularly when the improvements are directed toward individuals who are living in residences with insufficient heating and who have chronic respiratory diseases (Thomson and Thomas, 2015). Historically, cold homes in winters have negative health effects, while warm homes in winters helps maintain health and increase the chance of an infected person having 'milder' disease symptoms (Baker et al., 2020). On the other hand, unprecedented high temperature also damages health. Suboptimal temperatures were recently added to the Global Burden of Disease parameters and are responsible for 1.96 million deaths globally with the major death share related to high temperatures (Peters and Schneider, 2021). The Global Burden of Diseases (GBD), Injuries, and Risk Factors Study is a summary of the available evidence on levels and trends in health outcomes, a diverse set of risk factors, and health system responses (Murray et al., 2020). Due to the recent unprecedented heat waves and increased average temperatures in many countries, it is vital to address the health consequences of high temperatures. At high temperatures, elderly people and individuals with underlying health conditions are at high risk of heat-related acute cardiovascular disease, including myocardial infarction (Peters and Schneider, 2021). The importance of health consequences of ambient high temperatures for energy conversion lies in the necessity to produce new cooling methods in for residential buildings which are typically energy-consuming. As extreme temperatures are expected to be a major health concern and social justice issue, short-term suggestions include developing cooling centers with emergency power generators to provide temporary temperature reliefs (Gronlund et al., 2018). In the long-term however, energy-efficient pollution-free air conditioning and cooling installations in residences are important. With heightened temperatures, residential electricity demand will grown 41%–87% between 2020 and 2060 (Reyna and Chester, 2017). Therefore, rapid development of energy-efficient heating and cooling systems are necessary to decrease rapidly growing cooling energy consumption.

Thus, while measures that temporarily help people with energy bills are valuable, the implementation of a high energy standard for all households is necessary to minimize the consequences of future respiratory syndromes, including the future waves of infection due to viral variants. High household energy standards can be pursued by improving energy efficiency measures, supporting new technologies for producing and consuming electricity, and ensuring a high level of energy equality.

Globally, about 840 million people (mainly in sub-Saharan Africa) are without electricity and many more depend on an unreliable supply of electricity (Ogunbiyi, 2020). Energy insecurity is also a public health threat among low-income populations in the United States and is associated with serious health consequences and can lead people to engage in risky coping strategies such as the use of unreliable heating sources and occasional deaths due to CO poisoning (Memmott et al., 2021). While more than a billion people suffer from unreliable electricity supply, half of the world inhabitants depend on traditional (unhealthy) coal and biomass combustion methods for cooking and heating (Casillas and Kammen, 2010). Such levels of energy poverty entail impaired global economic and educational opportunities, particularly among women, children, and minorities.

Another area of increasing concern is providing energy and power sources for refugees and refugee camps (Neves et al., 2021; Mukumbang, 2021). Here, the estimated 82.4 million people who have been forced to flee their homes, often experience power and energy shortages, and their lives have been also significantly worsened by pandemics (UN, 2021).

The lack of or limited access to reliable energy sources may adversely affect the battle against the pandemics in three major ways:

(1) Electricity disruptions in health clinics disrupt energy intensive medical equipment ICU operations, such as the use of ventilators and blood testing processes (Klemeš et al., 2020; Jiang et al., 2021).
(2) Unreliable supply of electricity makes it difficult to work from home, which can be crucial in reducing the risk of spreading infection, while maintaining core societal functions.
(3) Online and digital lifestyles including online shopping are hindered by the lack of reliable energy sources and limit self-isolation strategies (Birol, 2020).

2.2. Energy pollution impacts on human health

Energy conversion is responsible for 75% of the global greenhouse gas emissions, 66% of NO_x emissions and most of the PM emissions (Wang et al., 2019). A recent world health organization (WHO) report (WHO, 2019) shows that 90% of global population are breathing polluted air leading to seven million premature deaths annually. Moreover, air pollution (mainly from energy conversion) is responsible for more than 30% of strokes, lung cancer and heart diseases. While the threats posed by air pollution stemming from fossil fuel-based energy conversion has been increasingly noted by the public, the gradual lethal impacts of the air pollution have not been taken seriously by many countries in comparison to the effects of sudden disasters such as floods or earthquakes. The COVID-19 pandemic serves an example of how current air pollution weakens public health and has led to the death of millions of COVID-19 patients who might have survived if they had clean air to breathe. The World Bank has reported that COVID-19 infection risk double when air pollution concentrations increase by 20% (Andrée, 2020). In this context, fine inhalable particles, i.e., particulate matter with diameter $\leq$2.5 micrometers or $PM_{2.5}$, represent the most dangerous air pollutant for patients with COVID-19. $PM_{2.5}$ not only severely damages the respiratory and cardiovascular systems, thereby increasing mortality risk (Brook et al., 2010; Pope III et al., 2004; Pope III et al., 2020), but also worsens the severity of COVID-19 symptoms and worsens the prognosis for patients with COVID-19. Thus, even slight increases in chronic exposure to $PM_{2.5}$ lead to large increases in the COVID-19 death rate (Wu et al., 2020). A study of patients with COVID-19, researchers in California, US (Bashir et al., 2020) underlined the importance of stricter regulation of $PM_{2.5}$ and PM_{10} levels as a critical step in protecting human life from the lethal effects of particulate matter on human health.

It has been long known that air pollution worsens respiratory diseases (Tang et al., 2018; Daniel et al., 2019; Zhao et al., 2019; Kan et al., 2005)) but the extent was less clear, thus one study found that an increase of 1 $\mu g/m^3$ in long-term $PM_{2.5}$ exposure led to an 8% increase in the COVID-19 mortality (Wu et al., 2020). This implies that an increase of only 12 $\mu g/m^3$ in particulate emissions may lead to a doubling of the risk of death for patients with COVID-19. Similarly, research in the United Kingdom (Feng et al., 2020) has shown that an increase in the interquartile range (2.1 μg/m^3) in $PM_{2.5}$ is associated with a 10% increase in the risk of COVID-19 mortality. The direct relationship between $PM_{2.5}$ and mortality was also confirmed by (Borro et al., 2020), who found that the mortality rate of patients with COVID-19 doubled when the average $PM_{2.5}$ concentration increased from 10 to 25 μg/m^3. While most studies and statistics focus on ambient particulate matter pollution, indoor air pollution is also very important and at the same time often neglected. For instance, the number of premature deaths due to urban residential $PM_{2.5}$ sources in China was 202,000 in 2014 (Zhang et al., 2021). The deleterious influences of air pollution on human health are attributed to the penetration of fine particles into the lungs, leading to hypertension, heart disease, and breathing problems, and possibly increasing the chance of developing diabetes. All of these complications are likely to increase patient mortality rates. In addition, inhaled particulate matter causes the immune system to deteriorate and increases lung inflammation and respiratory tract damage, leading to higher overall mortality rates from respiratory syndromes (Gardiner, 2020). Particulate matter may also enable rapid spread of the virus. The Italian Society of Environmental Medicine (SIMA) has cited particulate matter as a key carrier of the virus (Setti et al., 2020). Italy itself has exceeded the regulatory limits for $PM_{2.5}$, PM_{10}, nitrogen dioxide, and ozone emissions during the recent years, especially in northern Italy, which is highly industrialized with the population exposed to chronically high level of air pollution. Italy's Po Valley, which suffered one of the highest rates of spread of COVID-19 in Europe, has one of the highest levels of air pollution in Europe, as well experiencing high concentrations of particulate matter due to geographic features that prevent the dispersion of air pollutants (Zoran et al., 2020).

For those people who suffer from cardiovascular or lung diseases, research in the United States (Wu et al., 2020) has also found that exposure to $PM_{2.5}$ increases the mortality rate. Studies on the health effects of particulate matter using data from individual patients in Mexico City (Lopez-Feldman et al., 2020) have shown that long-term exposure to $PM_{2.5}$ effects increases considerably with age, demonstrating the vulnerability of the elderly. It should be noted that the higher average age of the population in Europe, as compared for instance to the US and China, necessitates greater efforts in Europe to protect senior and vulnerable citizens from air pollution complications. Fig. 1 compares the average $PM_{2.5}$ concentrations and COVID-19 mortality rates in Pakistan, India, Italy, Mexico, the Netherlands, United Kingdom and the US. It should be noted that complete measurements of $PM_{2.5}$ are not available for many countries, which makes a full assessment challenging (Isphording and Pestel, 2020). Even before COVID-19, it was recognized that the fossil fuel share of $PM_{2.5}$ was responsible for a global total of 10.2 million premature deaths annually, with the greatest impact on mortality noted for regions with high fossil fuel-related $PM_{2.5}$ concentrations, most notably China (3.9 million premature deaths annually), India (2.5 million premature deaths annually) and parts of the eastern US, Europe and Southeast Asia (Vohra et al., 2021). While all of these studies underline the potential lethality of $PM_{2.5}$ in terms of affecting patients with COVID-19 (or in principle, any respiratory disease), the wide range of reported $PM_{2.5}$ concentrations in Fig. 1 shows that energy technologies and their associated emissions, especially $PM_{2.5}$, have not been considered properly by the international community. Furthermore, the difference between the mean levels of $PM_{2.5}$ (1000 μg/m^3 for Pakistan and 8.4 μg/m^3 for the US) shows a significant gap between poor and rich countries in terms of $PM_{2.5}$ levels. This implies increasingly adverse impacts on vulnerable groups from pandemics and respiratory and cardiovascular diseases in poorer countries. In the US, changes in environmental protection guidelines have led to increased generation of fine particulate matter, such as decisions made by the Trump administration to increase mining and fossil fuel exploration and lower National Ambient Air Quality standards for fine particulate matter (Furlow, 2017; Reilly, 2018; Gerrard and McTiernan, 2020). Such decisions will have adverse consequences, as it has been established that counties with higher levels of long-term air pollution have higher disease mortality rates than other counties (LaMotte, 2020). In total, the US suffered 9,700 additional premature deaths in 2018 due to $PM_{2.5}$, and also suffered financial losses of an additional 89 billion United States Dollar (USD), as estimated using common valuations from the literature (Clay and Muller, 2019).

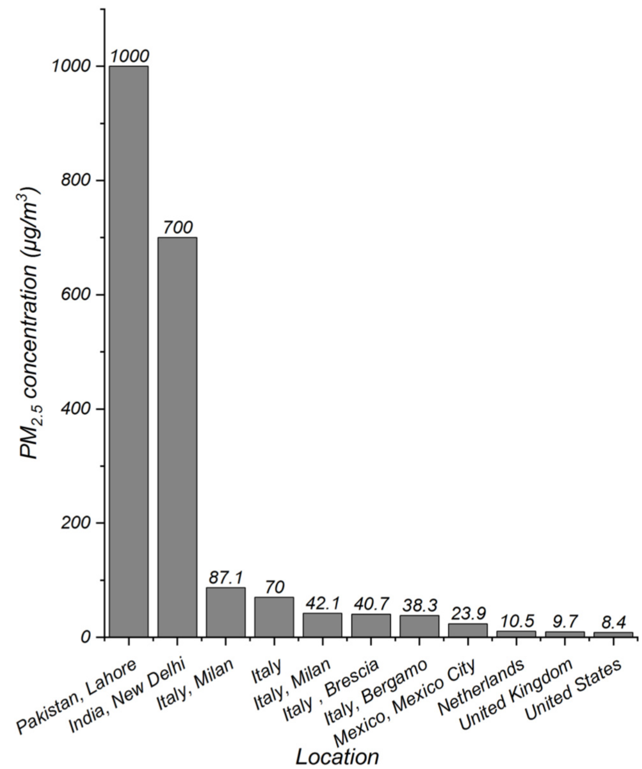


Fig. 1. Mean $PM_{2.5}$ concentrations in regions/countries with varying COVID-19 mortality rates: Pakistan (Sipra et al., 2020), India (Sipra et al., 2020), Italy (Zoran et al., 2020; Borro et al., 2020; Comunian et al., 2020), Mexico (Lopez-Feldman et al., 2020), Netherlands (Cole et al., 2020b), the United Kingdom (Feng et al., 2020) and the United States (Wu et al., 2020).

Fig. 2 shows the main sources of the global anthropogenic $PM_{2.5}$. It is clear that 75% of anthropogenic $PM_{2.5}$ originates from the following three sources: residential combustion, industrial processes, and large-scale combustion. To reduce the levels of particulate emissions from these three sources, several parallel strategies should be pursued, with utilization of renewable energy sources and clean combustion being the top priorities (assuming that new nuclear energy will contribute in only a minor way in the next few decades, given its long lead times, high cost and considerable public resistance (Baron and Herzog, 2020). As for transport sector, Fig. 2 shows particulate matter is mainly related to road transport. Emissions of particulate matters from vehicles should be reduced by improving both combustion exhaust and non-exhaust particulate matters where brake linings and tire tread wears contribute heavily to particulate matter as non-exhaust emission in the transportation sector (Cai et al., 2020; Jaafari et al., 2020; Kermani et al., 2021). Alternative energy vehicles (AEV) such as electric cars or hydrogen fuel cell vehicles can provide health benefits by reducing combustion-related

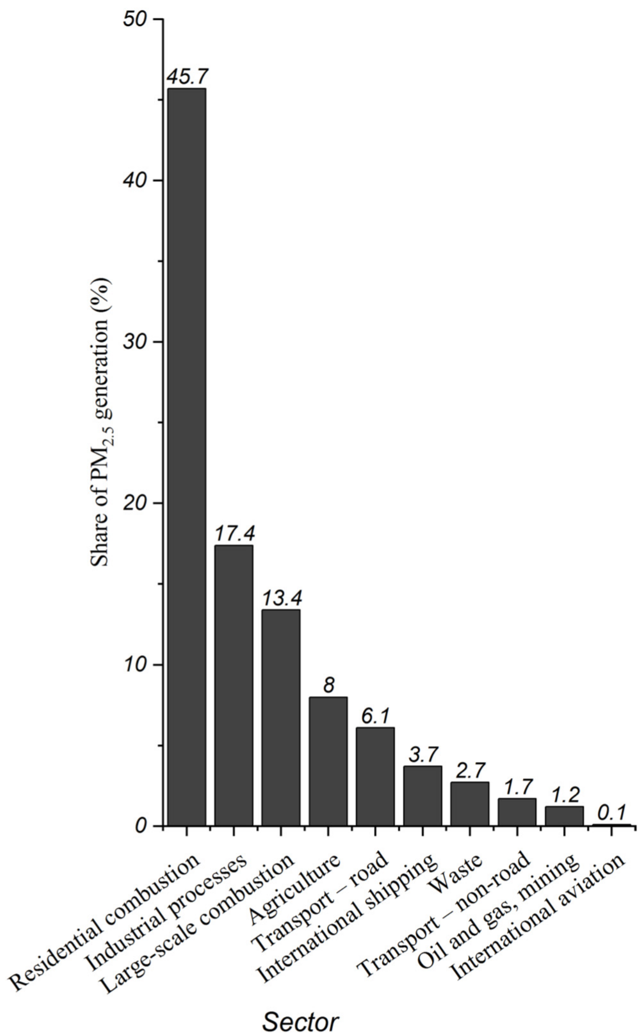


Fig. 2. Shares of generated global anthropogenic $PM_{2.5}$ with raw data taken from Klimont et al. (2017) for various sectors.

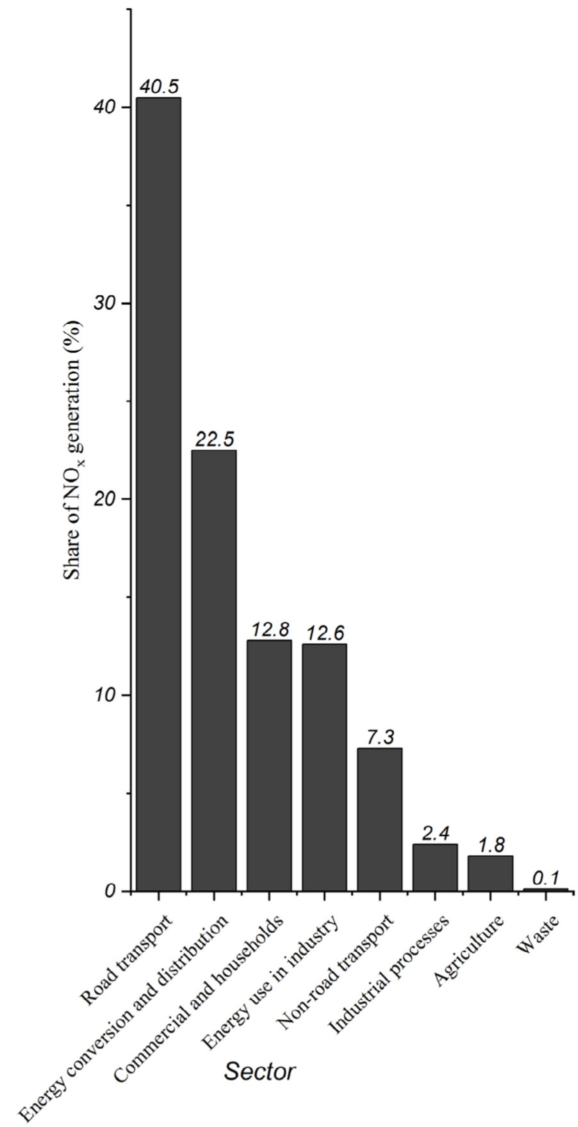


Fig. 3. Sector shares of nitrogen oxide emissions; data from the European Environment Agency (EEA) (EEA, 2017).

emissions (Peng et al., 2021). Regarding emissions in transport sector, the aviation industry also requires special attention when the goal is to reduce emissions (Klöwer et al., 2020). As an example of climate-adapted aviation, Sweden has introduced a new airport fee system based on the amounts of greenhouse gases emitted by different types of aircraft and fuels, with implementation via increased take-off and landing fees in Sweden (Johnson, 2021).

In Europe, where Italy, Spain and UK experienced COVID-19 outbreaks/infection waves with high mortality, studies have shown that in regions where there is chronic exposure to tropospheric nitrogen dioxide (NO_x), the COVID-19 fatality rates is higher (Ogen, 2020). Almost 80% of all COVID-19 fatalities occurred in regions with high NO_2 concentrations (Ogen, 2020). Fig. 3 shows the NO_x emission shares of the various sectors. In contrast to particulate emissions, which arise mainly from stationary sources, NO_x emissions are strongly linked to road transport. While major efforts have been made to reduce NO_x emissions from internal combustion engines, increased car usage is expected to further increase such emissions. Thus, electrification and internal combustion engine modifications are both needed for reduced NO_x emissions (Loughlin et al., 2015). In the case of industries, the control of thermal NO_x emissions and aftertreatment systems are the main routes to reduce the levels of NO_x emissions (Ajdari et al., 2016; Si et al., 2019).

While the above national studies have revealed a clear relationship between COVID-19 mortality and air pollution, an examination of Organization for Economic Co-operation and Development countries (OECD), which generally maintain higher emission standards compared to other countries and which have low pollution levels, does not show a clear relationship between the air pollution level and the associated COVID-19 mortality in a specific country (see Fig. 4). This is not altogether surprising given that various factors other than air pollution affect the mortality rate for COVID-19. An additional reason for the difference in the national and international relationships between COVID-19 and air pollution is that COVID-19 mortality rates in different countries reflect issues such as the country's health system, quality of life, laws and regulations related to the prevention of the disease, quarantine laws, and many other factors (Middelburg and Rosendaal, 2020). Moreover, different statistical analyses of the numbers of infections and deaths due to the COVID-19 pandemic are conducted in different countries, and the reported data reflect the measurement techniques, measurement accuracy levels, case

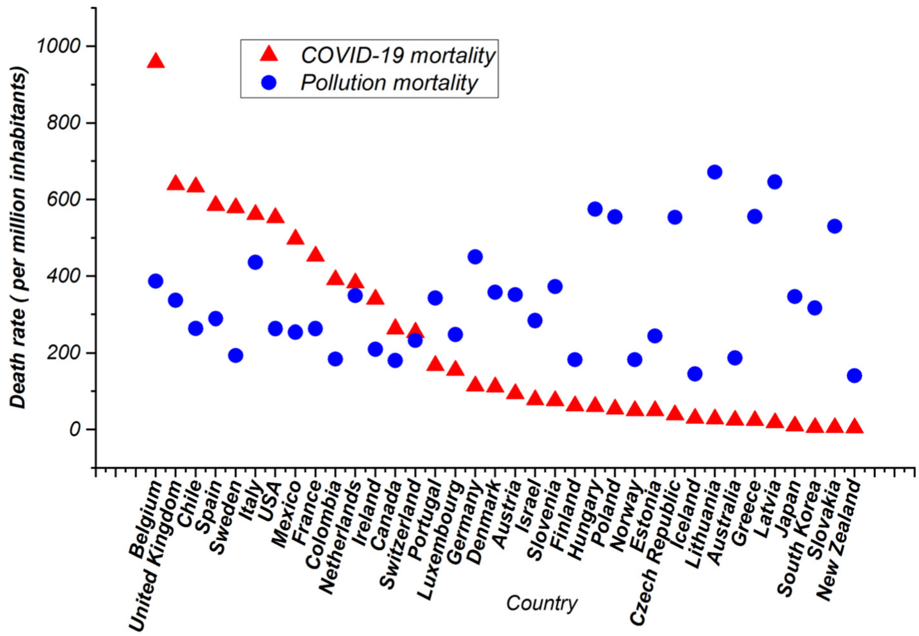


Fig. 4. Mortality rates related to COVID-19 and air pollution in OECD countries. Data for OECD pollution mortality is taken from 2017 OECD data (OECD, 2020a) and COVID-19 mortality is taken from world health (WHO) organization data up to September 2020.

monitoring, and active diagnostics, as well as the political will to measure them at all (Dyer, 2020; Ekong et al., 2020). The OECD countries were selected here, because they have a comprehensive data registry system (Du et al., 2018). Finding common ground for deriving and comparing such data between different countries is critical, since the relationship between air pollution and disease mortality has been proven for countries as diverse as the Netherlands (Cole et al., 2020a), China (Yongjian et al., 2020), and Italy (Fattorini and Regoli, 2020).

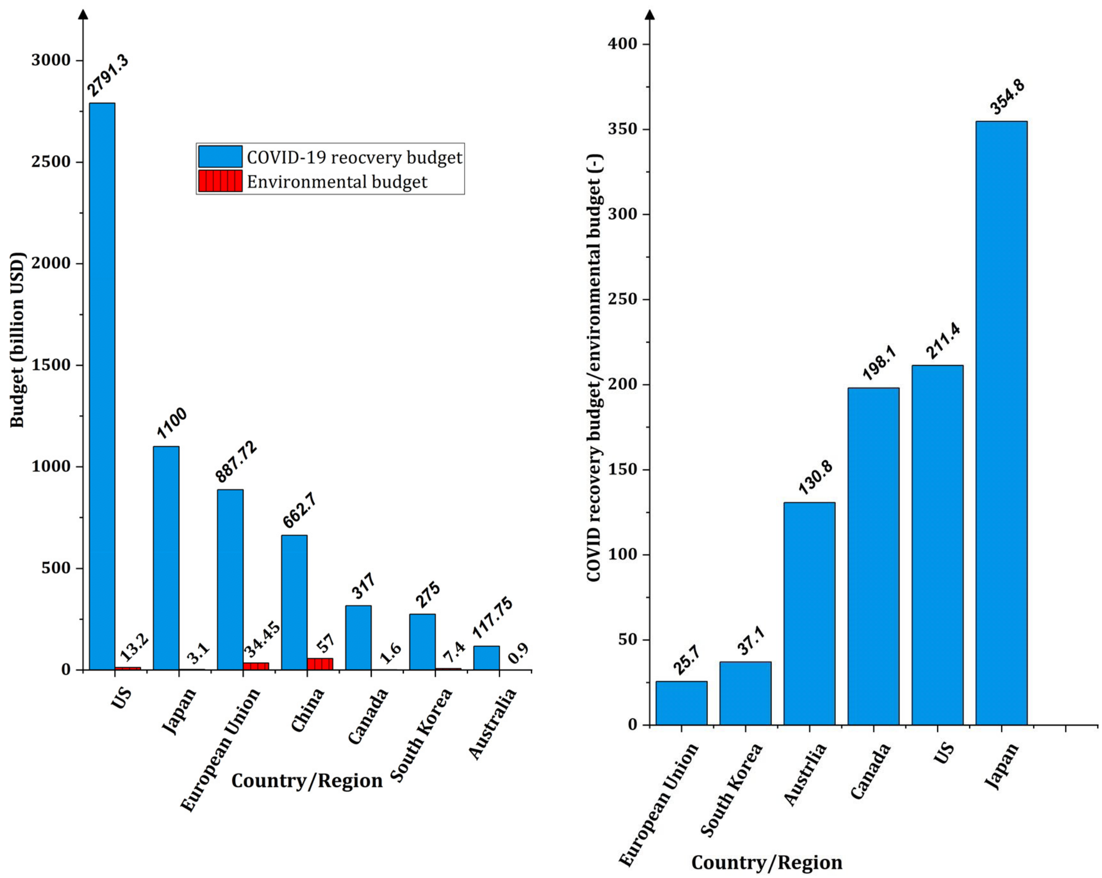
Air pollution has a strong negative impact on human health, damaging respiratory systems and increasing mortality (Cole et al., 2020b). While air pollution comprises various pollutants, the impacts of nitrogen oxides, sulfur oxides and particulate matter on respiratory illnesses and cardiovascular diseases are widely discussed. Fig. 4 shows that the lethality of air pollution is greater than that of COVID-19. The WHO has estimated that outdoor air pollution causes 4.2 million premature deaths worldwide each year (WHO, 2020a). Thus, while COVID-19 has killed approximately 230 persons per 1 million in OECD countries, air pollution takes the lives of 335 persons per 1 million inhabitants. Unfortunately, as noted above, this does not mean that the factors underlying air pollution and COVID-19 cannot act in a synergistic manner (Arvind et al., 2020).

2.3. Environmental spendings and pandemic recovery budgets

Fig. 5 compares the governmental budgets dedicated to pandemic responses and the environmental and climate change mitigation budgets of the US, Japan, European Union (EU), China, South Korea, Australia and Canada. The following conclusions can be drawn from this figure:

1- Even though climate change impacts, air pollution and environmental calamities have taken many more lives than COVID-19, Fig. 5 shows that the environmental budgets are dwarfed by the COVID-19 recovery budgets. Financial analysis at the state and corporate levels still do not fully acknowledge the serious risks linked to climate change and air pollution. The global costs of climate change for manageable assets in this century are estimated to range from \$4.2 trillion to \$43 trillion dollars, depending on the discount rates used (Goldstein et al., 2019). Until now, 1,600 of the world's largest companies have had plans to spend only tens of billions of dollars to address the major consequences of climate change and man-made pollution (Gray and Bakke, 2019). The results of a new study show that the levels of investments made to curb carbon emissions are low compared to the COVID-19 stimulus budget (Andrijevic et al., 2020). As the steps that will be taken by companies and governments to modify the energy system will shape infrastructures and industries for decades (2020a), a very careful examination of the required energy technology modifications is needed. The current low levels of investment in environmental remediation and climate change adaptations (Fig. 5) are key reasons for the high levels of air pollution. These in turn are a powerful driver of the high numbers of COVID-19 fatalities in various locations, ranging from northern Italy to New York City. Governments tend to cite fiscal constraints and competing priorities to justify underinvestment in climate change mitigation, although prolonged delays in making climate change investments will ultimately force the global community to accept vast and increasingly costly future interventions, and this will severely retard economic growth and destabilize fiscal balances (Catalano et al., 2020). However, if the US administration, as well as China and the EU follow their stated goals for carbon emissions reductions, the chances for the world to comply with the Paris Climate Agreement obviously increase (Le Quéré et al., 2021).

2- As shown in Fig. 5b, the EU has the smallest difference between its environmental budget and COVID-19 recovery budget. The leading role that EU has played in dedicating funding to environmental remediation and climate change is related to the relatively high level of awareness of its people and the relatively high level of trust that European populations have in their institutions. Thus, for instance Sweden, which shows the strongest national support for carbon taxation in Europe, needs to spend much less effort in convincing the general public to dedicate a reasonable share of the budget to tackling environmental problems



a b

Fig. 5. Comparisons of: (a) national spending dedicated to tackling the COVID-19 pandemic environmental spending; and (b) the ratios of COVID-19 recovery budgets to environmental spending. Data on recovery packages are taken from the International Monetary Fund (IMF) (2020). US environmental budget data related to federal funding for climate change, as obtained from the US Government Accountability Office (GAO) (GAO, 2018). Data for the Japanese environmental budget are taken from Japan environmental ministry budget (CEIC, 2020). The European environmental budget is taken from European Commission climate action budgets in (Dutheil et al., 2020). The Chinese environmental budget is assumed from the ecology and environment protection budget in (Xu et al., 2020). The data for the Canadian environmental budgets are taken from the Government of Canada Environment and Climate Change spending (Cicala et al., 2020). The data for the South Korean environmental budget are taken from the levels of environmental spending given in (Kwang-tae, 2020), and the data for the Australian environmental budget are from the Australian national environment organization in (ACF, 2020).

and climate change, as compared to a country with overall lower levels of trust in both their institutions and politicians and a lower level of environmental awareness (Fairbrother et al., 2019). In 2015, Australian and Canadian scientists (Ross et al., 2015) predicted the proximity of occurrence of a zoonotic pandemic and proposed that instead of allocating considerable amounts of resources to 'react' to pandemics, funds must to a larger extent also be allocated proactively to 'prevent' pandemics. In general, the lower a country's investment in system resilience and preparedness for disasters, such as environmental disasters and the COVID pandemic, the more funding must be allocated for the response and reconstruction. This problem is especially common in low- and middle-income countries. For example, in a previous study conducted by the authors for Iran (Seddighi and Seddighi, 2020), it was shown that the budget allocated for response to and recovery from sudden disasters was several times the budget allocated for mitigation and preparedness for natural disasters and climate change disasters. In contrast, in high-income countries, part of the cost of the disaster response and reconstruction is covered by insurance, which can help the government to allocate funds to preparedness and mitigation measures against natural and climate change disasters. In the event of sudden disasters, there is also an expectation that victims and those affected will be helped as soon as possible, given that the psychological pressure exerted by the populace on governments can be very high, sometimes leading to political unrest, e.g., the Tabas earthquake in Iran, a recent earthquake in Chile, etc. (Ibrion et al., 2015; Carlin et al., 2013; Drury and Olson, 1998). Therefore, governments try to allocate a large proportion of their budgets to these disasters rather than allocating spending to mitigate longer-term phenomena such as climate changes.

3- To compensate for the substantial differences between the recovery funds and the environmental budgets, the large funding for pandemic recovery being issued by many governments must be combined with strict requirements relate to environmental aspects, particularly given the need to change the current energy systems more in line with the key SDGs, such as climate change, environmental pollution and poverty. Most COVID-19 recovery packages simultaneously reduce carbon emissions while providing national and international employment (van de Ven and Dirk-Jan, 2022). There is obviously a risk that very few environmental requirements will be imposed on disaster recovery funds, such that once the disaster related crises are over, energy system designs will continue along the previous unsustainable path. Barbier (2020) proposes to transform the recovery packages so that in the near term they can be used to change the course of policies for green solutions, they should: (1) guarantee long-term commitments to public spending and pricing reforms (5–10 years); (2) support the private sector green innovation and infrastructure, the development of smart grids, transport systems, charging station networks, and sustainable cities; (3) enforce realistic carbon and pollution pricing and taxation and minimize emissions; and (4) pave the way for increased and sustainable financing of the public and private green investments and reduce the financial burdens of the green transition. Many countries are considering clean energy stimulus packages, while at the state level, policy actions such as state green banks and expedited permitting can bridge the gap, and pandemic recovery packages may lead to greater efforts in reducing emissions (Gillingham et al., 2020).

2.4. Urban planning, energy efficiency and health

A high level of preparedness in urban areas is critical for efficient responses to pandemics. Compactness, which has been an important feature of urban and city planning, results in increased energy efficiency and minimization of resource consumption (Amado et al., 2016; Kılkış et al., 2020). Urban densification, which has been pursued during the last several decades to optimize various parameters, such as land use, urban patterns, building typology and energy use, has led to compact residential buildings located close to each together, which enables lower energy consumption per capita compared to dispersed suburban designs, while facilitating economically feasible public transportation in densely populated zones (Lobaccaro and Frontini, 2014). Unfortunately, people living in crowded buildings and densely populated communities also have an increased likelihood of exposure to any airborne disease transmission (Deziel et al., 2020). While compact urban design may decrease pollution concentrations by shortening trip distances, densely populated areas also lead to the increased share of population breathing excessive air pollution concentrations (Yuan et al., 2021). Thus, reducing building density in high-density urban centers increasing polycentric urban structures would improve the air quality experienced by individuals.

People who are living or working in large and compact buildings, such as towers or hospitals, are at significantly higher risk of disease infection according to Global Construction Review (GCR) (GCR, 2020). According to the WHO, densely populated cities and travel hubs are associated with a high risk of virus spread and high numbers of deaths due to high population densities and extensive public transport networks (WHO, 2020c). The World Heart Federation has concluded that densely populated areas and townships that suffer from widespread poverty and high levels of migration are highly vulnerable to airborne pandemics (Thienemann et al., 2020). However, it has also been suggested that population density is not the main factor, with infection risk being instead dependent upon the number of people with whom an individual interacts and the average number of infected people within the region (Andrée, 2020). Social distancing is obviously effective when it limits the number of people to whom one infected person can transmit the virus, ensuring that the R number stays below one (Lytras and Tsiodras, 2020). Social distancing is of course more difficult to maintain in densely populated urban areas and, as should be clear from the above, it is also challenging to limit anthropogenic pollution in such areas, thereby increasing the risk of pandemic complications.

2.5. Centralized vs decentralized energy industry and health

Traditional decentralized energy sources, such as in-house combustion facilities, emit high levels of particulate matter that significantly increase the mortality rates of respiratory diseases. Annually, 4.3 million premature deaths are linked to pollution caused by traditional in-house heating and cooking by burning solid fuels (Egan, 2020). Most studies of particulate matter emissions have focused on developed countries using a narrow range of exposures, e.g., concentrations <200 $\mu g/m^3$, with relevance to outdoor air quality in industrialized countries. However, indoor air pollution in developing countries is of the magnitude of thousands of $\mu g/m^3$ and is not particularly well understood due to a lack of data and low prioritization by local governments. More than two billion people rely on the combustion of biofuels (wood, charcoal, agricultural residues, and animal manure) as their main source of energy, entailing exposures to particulate matter concentrations >2,000 $\mu g/m^3$ inside their homes. Even before COVID-19, acute respiratory infections (ARI) were responsible for 6% of global disease-related deaths, mostly in less-developed countries (Ezzati and Kammen, 2001). The existence of such high levels of indoor air pollution (mainly particulate matters) stemming from biofuel combustion is a deadly combination for many respiratory and heart patients in developing countries. The WHO gives household air pollution as the main cause of 3.8 million deaths per year, equivalent to 7.7% of global mortality (WHO, 2020b).

The United Nations (UN) defines sustainable access to energy as a precondition to achieve socioeconomic and sustainable development (Egan, 2020). Globally, 1.3 billion people do not have access to modern energy technologies, while 840 million people live without electricity, 570 million of them in sub-Saharan Africa where 25% of clinics have no electricity, and a further 28% of clinics have only occasional access to electricity (Alers, 2020; Egan, 2020). As noted previously, a reliable energy supply is essential for proper operation of health systems such that diagnosis and treatment can be performed.

The main motivation behind centralized, large-scale energy grids and power plants has been the desire to increase efficiency while reducing the electricity cost for the end-user. In addition, centralized plants (heat and/or electricity) can be equipped with efficient flue gas cleaning systems. The transition toward low-carbon energy systems that will provide large-scale, low-cost electricity involves a combination of various electricity generation technologies, such as biomass-fired combined heat and power (CHP) plants (which can be equipped with carbon capture and storage (Bui et al., 2018)), renewable electricity generation (e.g., wind and solar) (Hart and Jacobson, 2012; Amer et al., 2020), and nuclear power (Silva et al., 2010). These can possibly be complemented by natural gas-fired CHP systems (Hawkes et al., 2009; Slorach and Stamford, 2021) serving as bridging to a climate-neutral system. However, the high costs associated with large-scale power plants and their grids have led to billions of people being deprived of the outcomes of such centralized, electricity generation technologies. In this context, international organizations such as the World Bank can play a key role in reducing global inequality by ensuring funding to large-scale, sustainable energy projects in low-income regions (Schwerhoff and Sy, 2017). Thus, a wide range of decentralized, small-scale, low-cost energy technologies, from traditional biofuel combustion stoves to natural gas or liquefied petroleum gas technologies, are used in hundreds of millions of homes worldwide. In the case of a decentralized energy technology, the energy conversion occurs at or very close to the location of the demand (Farulla et al., 2020). Although decentralized solar photovoltaic (PV) systems appear promising, much of the current decentralized energy services are based on small-scale combustions systems, which are associated with considerable health and environmental costs. The potential of electricity from onsite solar panels and batteries may make decentralized energy systems more affordable than buying grid electricity from large scale utility companies (Schoolman et al., 2019).

In developed countries, such as Germany, electricity price liberalization and market competition have led to relatively low prices for electricity, leading to fewer private consumers installing decentralized energy systems (Praetorius and Schneider, 2006), although different subsidy schemes, such as feed-in tariffs for solar PV systems, have increased such decentralized electricity production. The goal of designing efficient, decentralized energy systems is being pursued by consumers who want to avoid potential grid interruptions and by those who want to secure their own renewable and independent electricity generation. Hospitals are another example of sites where decentralized backup power generators are necessary, since even short disruptions to the electricity supply can have serious consequences, especially for those patients who are on ventilators. It should be noted that ventilators, which were already insufficient in number, were in critically short supply worldwide during the pandemic (Neighmond, 2020; Pearce and Joshua, 2020). Moreover, for some regions of the world, when open-source, low-cost ventilators become available in low numbers, the lack of reliable electrical energy services make those ventilators comparatively ineffective at saving lives (Brosemer et al., 2020).

Here, CHP systems may have a contribution to make, as they are one of the most cost-effective methods for maintaining clean electricity, in addition to heat and power for other purposes. In addition, they can achieve efficiencies of 60%–80%, as compared to regular heat and power systems (power plants electricity using grids), which have efficiencies of 45%–55% (2020). CHP plants can be divided into: small-scale units (from 50 kW to 1 MW) for residential buildings; medium-scale units with capacities in the range of 1–10 MW, used in hospitals, college campuses, and big office buildings; and large-scale units with power outputs >10 MW, which are mainly used for industrial purposes or as production units in municipal district heating systems. The introduction of emissions trading (with respect to CO_2 emissions) or carbon emission taxes is expected to increase the cost of main grid electricity, leading to improved market penetration for micro-grids or decentralized systems. Fig. 6 shows the shares of CHP in EU electricity generation and the shares of renewables and natural gas in powering CHP plants within the EU. The sharp increase in the share of renewables in the EU during the last decades is a positive development. Natural gas, which is the main energy carrier for CHP plants in Europe, is relatively clean compared to oil and coal and is very flexible, facilitating the integration of wind and solar power. However, Fig. 6 shows that the share of natural gas-fired CHP in EU is essentially constant and not increasing. This is important because natural gas is still a fossil fuel and, moreover, natural gas transportation systems are a major source of methane emissions (Boothroyd et al., 2018). Thus, there is a need to phase out natural gas if complying with the Paris Agreement. Therefore, we must understand what fuel-shift options are available in district heating systems, including applying heat pumps on various waste heat streams.

While an increased CHP capacity would ensure the availability of electricity at high efficiencies and allow the possibility for advanced emissions control, the emissions produced at power plants normally occur far from densely populated areas (Khanna et al., 2017). Given the negative impacts on respiratory health of pollutants (especially particulate matter), future development plans for CHP should have a strong focus on reducing emissions. The cost of standby tariffs (i.e., the amount of money that a

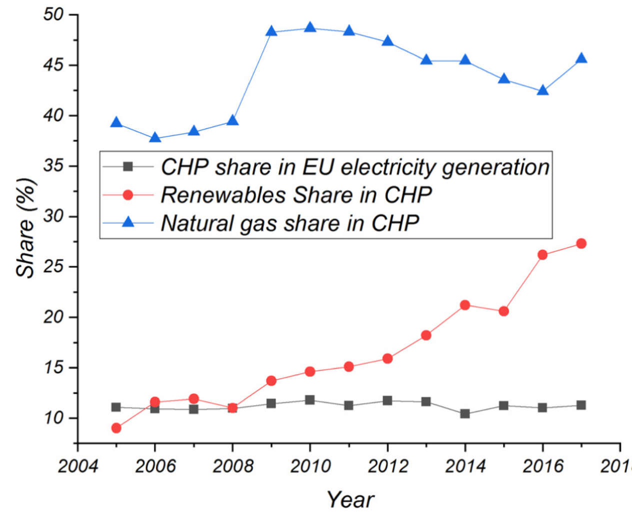


Fig. 6. Shares of CHP in EU electricity generation and the shares of renewables and natural gas in powering CHP plants in the EU, derived from official data published by Eurostat, European Union (Eurostat, 2019).

building must pay for standby power, even if it is not used), complicated processes for CHP permits, and inadequate financial mechanisms to meet upfront costs are among the main hurdles to be overcome to ensure faster market penetration of CHP systems (Saba et al., 2013).

Thus, while both centralized and decentralized energy systems have their merits, installing low-cost, clean, decentralized power generators for low-income families and key facilities, such as hospitals or remote aid workers, would reduce the effects of future pandemics. The type of decentralized system would of course have to be optimized for each case. For instance, solar PV systems in rural areas in developing countries are important for providing access to clean electricity. Remote aid workers can, for instance, utilize portable power sources such as micro-combustors or fuel cells (Shao et al., 2005). One should note that many decentralized systems such as solar and wind require energy storage systems (Teichmann et al., 2012). While large-scale CHP systems can be used for large complexes and districts, micro-combined heat and power (μ-CHP) plants can provide reliable electricity for households during grid shortfalls (Notter et al., 2015).

2.6. The paradox of energy-efficient transport and health

Public transportation has been a key contributor to public welfare in modern societies through reducing energy consumption per capita, reducing traffic congestion, and increasing social cohesion and social equality. The cultural acceptance of public transport in advanced economies is evident, for instance, in Gothenburg, Sweden, an opinion poll of citizens showed that the majority of respondents were positive in relation to shared urban mobility options, as well as the use of public transport as compared to using private cars (Serafimova, 2020).

Unfortunately for modern societies and for energy efficiency, public transport has been proven to play an important role in the spread of virus (Zheng et al., 2020b); the extent of spread depends on how many people work from home and how many have to travel. COVID-19 has led to an increase in the use of individual cars (Chang et al., 2020), replacing public transportation in many places and leading to increased local levels of air pollution. In the US, for instance, public transportation systems are confronting an extraordinary financial crisis (initiated in part by the pandemic), whereby transit agencies are struggling to adapt to significant declines in ridership and requesting help from the US Government, in order to cope with what has been termed an 'existential peril' for public transport (Wright and Will, 2020).

Air transportation has also dramatically increased the global spread of the virus (Hendrickson et al., 2020). In Wuhan, where the pandemic started, cases of infection connected to the use of public transportation proved to play a key role in the spread of COVID-19 (Zheng et al., 2020a). To prevent further COVID-19 spread, officials have urged people to avoid using public transport (Taylor, 2020), while at the same time enforcing strict hygiene protocols for those who have no other option than to take public transport (OECD, 2020c). In European cities, the use of public transportation systems has declined by 80% since the emergence of COVID-19 (Serafimova, 2020). Even after easing the lockdown, the fear of infection by the SARS-CoV-2 virus while using public transport has weakened the financial viability of the transportation industry. This means that the numbers of people walking and cycling to work have increased during the pandemic, and that using private cars to limit the spread of infection has become a new norm for many of those who previously only used public transport, while many still work from home. Thus, car travel is expected to rise dramatically after the easing of lockdowns, which will exert pressure on the urban mobility policies applied prior to COVID-19 (OECD, 2020b). If people choose private cars over public transport as the result of COVID-19, the urban transport systems in modern cities will become economically unviable and governments may need to reintroduce substantial financial subsidies for public transport (Tardivo et al., 2020). The usage of private cars as a way to avoid COVID-19 will also increase air pollution, thereby increasing the risk of complicated COVID-19 (Coccia, 2020), as well as creating more-severe congestion on roads. Thus, medium- to long-term solutions involve promoting electric cars, subsidizing public transport (Besley and Stern, 2020), and increasing the number of available buses and metro cars such that the number of people transported per bus allows social distancing. The extent to which cars are used depends of course on the percentage of employees working from home and whether schools and universities or closed or allow distance-education.

3. Impacts of the pandemics on energy technologies

For a well-functioning society, a high priority is maintaining the uninterrupted operation of critical infrastructures, including electricity distribution systems and power utilities (Mikellidou et al., 2018). Therefore, this section discusses how pandemics such as the COVID-19 pandemics have influenced the critical energy infrastructure and the use of different energy systems.

3.1. Economy downturn and energy industry

Major disasters such as wars and pandemics lead to global crises and with their lasting consequences on individual behavior, affect the economy and energy systems for quite a long time. Therefore pandemics such as Spanish flu, the medieval Black Death, severe Cholera pandemics of the nineteenth century, and recently the COVID-19 are trust-reducing catastrophes affecting various aspects of the societies including socioeconomic aspects (Aassve et al., 2021). The Ukraine war and COVID-19 outbreak are the latest examples which have slowed the economy, both at the national and global levels, leading to economic crises in many sectors. This has forced countries to take extraordinary measures to mitigate the deleterious impacts of the disaster.

In general, economic crises are associated with an abrupt shift from capital inflows to capital outflows and/or a sharp decline in economic activities (Blaszkiewicz, 2000). The Spanish flu pandemic (February 1918 to April 1920) had major economic impacts worldwide, including a strong negative impact on capital incomes, both immediately and in the medium term (Karlsson et al., 2014). It caused an 18% drop in the levels of manufactured products and a 23% drop in employment in manufacturing industries (Correia et al., 2022; Wheelock, 2020). Disasters affect the energy sector from the household level to the community, national and international levels. On the household level, the Ukraine war and COVID-19 pandemic has caused persistent and severe energy insecurity and uncertainty, particularly with regards to paying energy bills (Graff and Carley, 2020).

As noted above, energy represents a major cost for domestic users. For example, during a normal month, the average household in US spends 3.5% of its income on energy, whereas an American rural, low-income family spends up to 9% of its income on its energy bill, and in some US rural areas, 25% of the low-income households spend more than 15% of their income on energy (Ross et al., 2018). In Iran, 4.8 million workers lost their jobs as the result of the pandemic, which is equivalent to 20% of the total Iranian workforce according to the Ministry of Cooperatives, Labor, and Social Welfare (Khabaronline, 2020). The COVID-19 crisis has also led to a drop in income of at least 50% for 33% of Canadian and US workers, 25% of workers in the UK, and 45% of workers in China (Bell and Blanchflower, 2020). As a consequence, the household energy bill has risen to as much as 20% of the household income of a rural family in the US. These increases have led to severe energy insecurity for many families and involuntary reductions in energy consumption and life quality. This trend toward energy poverty brought on by the pandemic-related economy downturn could return parts of the world to historic situations, commonplace in the 19th Century and early 20th Century, whereby low-income households (especially those of the elderly) were incapable of paying for proper heating in wintertime, resulting in deteriorating health and increased mortality (Kuo, 2020). Energy poverty typically forces economically poor households into living at dangerously low temperatures during cold winters, so as to minimize their fuel consumption or utility bills, with concomitant impacts on health and social wellbeing (Adrian et al., 2020).

As for the impact of COVID-19 on energy companies, the pandemic led to an unprecedented collapse in global demand for energy carriers, resulting in the first instance of negative oil prices since 1983 (Egan, 2020). Fig. 7 shows the US sales of electricity for various sectors and the US fuel net generation using various energy sources between September 2019 to September 2020. As shown in Fig. 7a, consumption of electricity decreased in Year 2020 due to COVID-19-related downturns in the commercial, industrial and transportation sectors. The consumption of fossil fuels is shown in Fig. 7 to decrease considerably compared to other energy sources, which is attributed to the fact that the customers must pay for each unit of fossil fuel, while renewable sources such as solar are essentially free once the necessary infrastructure is built.

Although fossil fuel use declined, one of the major issues linked to the COVID-19-precipitated economic crisis is the loss of ability to support the transition toward clean energy in many regions. The COVID-19 pandemic also widens the gulf between the leaders and laggards in relation to the global energy transition, owing to the strong lock-ins of fossil fuel infrastructures and pandemic-related economic difficulties (Quitzow et al., 2021). As an example, Ukraine significantly reduced its green tariffs for renewable energy due to the recession caused by COVID-19 (Polityuk, 2020), which risks bankrupting several companies that are supplying green energy (Emil and Weichert, 2020). Given the uncertainties related to the causes and effects of the changing trends in energy systems, future energy and environmental policies should be drafted in the forms of short-term stabilizing

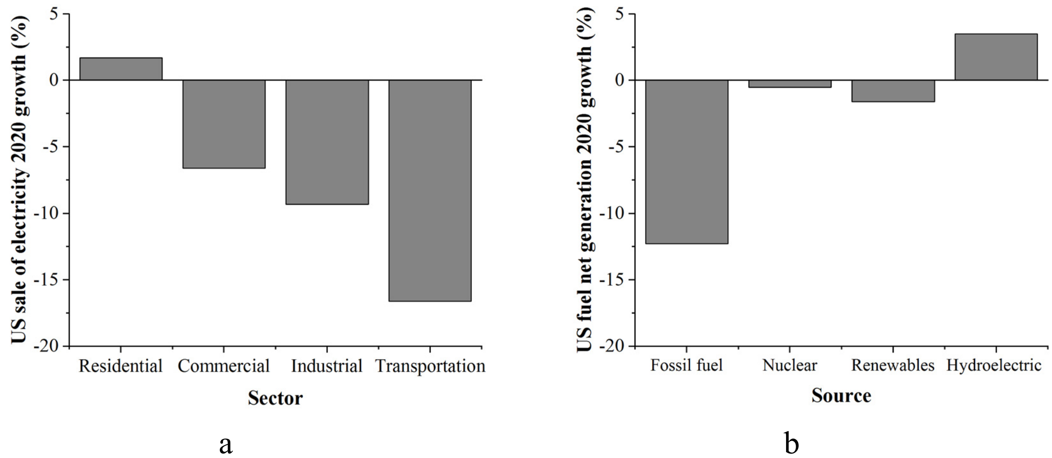


Fig. 7. Changes in US energy consumption from September 2019 to September 2020, using data from the US Energy Information Administration (EIA, 2020a) with the data for: (a) the growth of US sales of electricity for the residential, commercial, industrial, and transportation sectors; and (b) the growth of US fuel net generation using fossil fuels, nuclear energy, renewables and hydroelectric.

policies and long-term shock-proof policies (Steffen et al., 2020). The unprecedented reductions in carbon emissions experienced during the COVID-19 pandemic have already demonstrated that governmental and international policies have the power to reduce the carbon footprints, assuming that there is willingness to do so (Simpkins, 2020). One should, however, note that the reductions in carbon emission changes observed in Year 2020 are temporary in nature, being due to the pandemic alone, and it seems as though they will not produce any structural changes in energy systems (Le Quéré et al., 2020). Nevertheless, the lessons learned from the pandemic may offer possibilities to change course, toward developing more-resilient energy systems.

The dramatic drop in demand and the associated decrease in the price oil have forced the oil-and-gas industry to make unprecedented decisions to cut their costs. For instance, Chevron announced a 4 billion USD budget cut (Hiller and Khan, 2020), and British Petroleum (BP) cut its annual spending budget by almost one-quarter, to \$12bn, as a way to protect the company from the aftermath of the pandemic (Ambrose, 2020). The pandemic-related collapse in energy carrier prices led to the shutting off of less-profitable extraction wells worldwide, with negative effects on the workforces and financial health of energy companies and posing a threat to the supply chain for energy resources (DeCotis, 2020). The high frequency and long duration of lockdowns also damaged the resiliency and reliability of energy infrastructures, owing to the potential unavailability of unused parts of the system capacities once economic activity returns to pre-pandemic levels. To pave the way for a more resilient energy system, it is necessary to expand renewable electricity from sources such as wind and solar, which have nominal or no fuel costs and minimal emissions. Such a strategy is clearly in line with the Paris Agreement on climate change mitigation (McCollum et al., 2018).

The spread of COVID-19 worldwide acts as a major new external economic compass for changing market orientations. While declining industrial production has been a feature of the COVID-19 pandemic, the sector producing all grades of fuels, ranging from gasoline to diesel, has experienced a more drastic reduction than other industrial sectors (Kingsly and Henri, 2020). The COVID-19 pandemic has also led to the suspension of new investments in energy companies, which may ultimately increase the risk of future disruptions and weaken the capacities of companies to cope with new crisis situations (Eurelectric, 2020). For instance, in Year 2020, the effects of the pandemic on the oil and gas industries lowered capital spending in this sector by 100 billion USD (Takahashi, 2020). In the near-term, it seems unlikely that there will be a corresponding increase in spending on renewable energy, as indicated above. In addition, pandemic-related restrictions on travel between countries have limited access to the necessary equipment and expertise from abroad, and this has further weakened the energy companies. For example, the Norwegian energy consultancy DNV GL states that irreversible behavioral changes with respect to travel, commuting and working habits have occurred, and that these will lead to reduced fossil fuel demand for many decades to come, mainly due to shrinkage of the transport sector and reduced demands for iron and steel (Grigorievna et al., 2020). This reduction in demand for fossil fuels linked to the COVID-19-induced economic crisis may offer opportunities to decouple the global economy from fossil fuel use and its associated carbon emissions, and to move forward to a more sustainable, carbon-free energy structure in line with the Paris Agreement. In this context, it should be noted that the COVID-19 pandemic led to an 8.8% drop in global anthropogenic CO_2 emissions in the first half of 2020, as compared to the same period in 2019 (Liu et al., 2020a), although emissions are currently on the increase again (Zheng et al., 2020).

The International Energy Agency (IEA) estimates that 3.2 million jobs directly provided by the energy sector are at risk or have already been lost due to the COVID-19 pandemic (IEA, 2020a). Table 1 shows examples of the jobs lost in the energy sector due to the COVID-19 pandemic. It should be noted that while the numbers given in Table 1 are changing due to highly dynamic market conditions or to the cessation of state financial aid, they show the potent impact that the pandemic is having on the energy industry.

3.2. The impacts of health on energy industry staff and equipment

Accidents in the energy sector mainly resulted from failures to systematically help the epidemiological, health and working conditions of the staff in addition to the commonly known violations of safety requirements by personnel (Kondrateva et al., 2019). Various factors negatively affect those who work in energy industry or in energy-intensive industries. For instance, exposure to high concentration of dust in the cement manufacturing factories lead to more respiratory diseases and lung deteriorations in workers (Rav et al., 2020). Epidemiologic studies of lung disease have revealed significant correlation between disease and occupational exposures to for instance silica, silicates and metal dusts which are abundant in steel industries (Christine and Zarnke, 2021). In the oil and gas industry, exposure to CO, NH_3, C_2H_4 and

Table 1
Examples of COVID-19 job losses within the energy industry.

Company	Job losses (Thousands)	Reference
Oil and gas giants, including BP, Chevron, Halliburton, Schlumberger	45.6	Neate (2020), TheStraitsTimes (2020), IndustryWeek (2020), Eaton (2020)
Utility companies, including OVO Energy, Centrica, Vattenfall	9.1	Davies (2020), Karagiannopoulos and Pollard (2020)
Energy equipment manufacturers, including Rolls Royce, MTU Aero Engines, Bombardier	11.1	Thicknesse and Edward (2020), Davies (2020)
Clean energy sector in US	850	Kaufmann (2020)

H_2S are among health hazards having negative, and sometimes lethal, impact on the health of the workers (Kumar et al., 2017). In addition to occupational health hazards mentioned above, in the last 20 years several disease outbreaks such as SARS, MERS, Ebola and COVID-19 have had negative impacts on staff wellness, the moving plans of rotating staff, operation disruption, and the company's operational license (Nguyen et al., 2020).

Reduced staff numbers due to pandemics at key energy facilities, such as power plants and network facilities, also present a challenge to the energy industries (Eurelectric, 2020). There are various reasons for the reductions in onsite personnel in energy companies, e.g., large number of employees become infected during pandemics which was the case during COVID-19 or staff must quarantine themselves. Moreover, some personnel may be required to work from home, even if this is not ideal. The government regulator for gas and electricity markets in Great Britain (Ofgem) has expressed serious concerns regarding the challenges related to daily operations during the COVID-19 pandemic, including a shortage of essential staff and reduced work capacities (WattUtilities, 2020). Staff shortages due to self-isolating or sick staff or employees who are taking care of sick family members has forced Ofgem to reduce its work capacity and prioritize vulnerable customers. In India, where many people use liquefied petroleum gas (LPG) for cooking, staff shortages in utility companies have led to long queues and delays at LPG outlets for persons wishing to refill or replace LPG cylinders (EnergyNewsMonitor, 2020). In New York City, where COVID-19 has had particularly severe consequences, utility companies have tried to ameliorate staff shortages through the use of staggered shifts and cross-training of employees in critical areas, including customer service (SagaCommunications, 2020).

To tackle staff shortage problems during COVID-19, petrochemical plants and gas refineries in oil-rich Iran have, for instance, asked the employees who are on shift for the daytime lockdown, which is currently implemented, to remain onsite for two months instead of the usual 3-week shift. In the US, the Department of Homeland Security (DHS) has issued guidance for protecting key staff of "critical infrastructures" from the virus (DHS, 2020). Critical infrastructures include electric power plants, oil and gas infrastructures, and nuclear reactors. The US power sector had plans to keep essential staff on site at power plants and control centers, so as to maintain uninterrupted operation during the COVID-19 pandemic, while preparing a large stockpile of necessary living materials including beds, blankets, and food for onsite personnel (Volcovici and DiSavino, 2020). Offshore energy facilities also faced a major challenge in enforcing social distancing given the very limited physical space available for employees on such platforms. Regular medical check-ups, mobility permits to allow the transfer of employees to and from the platform, and the freezing of unnecessary new deployments, are among the measures taken in the offshore energy industry to maintain operations and ensure security of supply (Nathalie and Raval, 2020).

Moreover, air pollution negatively affects the mental health of individuals. The increased air pollution in combination with the COVID-19 pandemic, have exacerbated mental health disorders (Roberts et al., 2019; Zhang et al., 2017). As the decisions and actions of industrial staff are dependent upon mental cognitive processes (Gheorghe et al., 2018), the negative impacts of pandemics on the mental health of workers in power plants and energy industries may increase risks of human errors and, in extreme cases, industrial disasters and power outages.

The energy industry has developed creative and effective strategies and protocols as a plan to responses to any outbreak such as the epidemic management model by ExxonMobil. This is a scalable and standard approach to prevent and control the various communicable diseases in workplaces including essential procedures for communication and action plans needed in different phases of the disease outbreak developed during the MERS and avian influenza H7N9 outbreaks (Schneider et al., 2013; Diara et al., 2014). However, the failures in dealing with COVID-19 pandemic requires new solutions to address future health issues and pandemics. Firstly medical data gathering, transfer, interpretation, and processing require standardization in digitalization (Nguyen et al., 2020). Secondly the utilization of online health monitoring systems and wearable technology for health risk management of chronic disease such as cardiovascular diseases or infectious diseases such as respiratory pandemics such as SARS and COVID-19 could be of great benefit to be used by energy industries for ensuring a proper health management system and preventing and preparedness against negative impacts of next pandemics. It should be noted that artificial intelligence (AI) technology and machine learning can use the information obtained by wearable electronic devices to provide complex health monitoring functions (Xu et al., 2021).

3.3. Energy generation mix and distribution of energy use between sectors

In general, pandemics lead to reduced energy consumption which negatively impacts the management and control of generation units by voltage and frequency deviations and, more importantly, reduced grid reliability and resiliency (Carmon et al., 2020). High shares of renewable energy and reduced electricity consumption due to a pandemic lead to increased ramp-rates of conventional power and consequently reduced reliability, poor resiliency, non-optimal economic dispatch. In large power plants part-load operating during pandemic low consumptions, less spinning reserve and lower rotational inertia would make the power plant and the grids susceptible to small deviations in the power produced by renewable sources (Carmon et al., 2020). These grid problems arise from the increased share of renewable energies such as solar energy. The increasing share of renewables is possible if combined with energy storage devices and demand flexibility (Kroposki et al., 2017). In addition, enhanced control of variable renewable energy sources, and frequency regulation capabilities are to be used by utility companies or the Transmission System Operator (TSO) to avoid grid problems (Denholm and Hand, 2011).

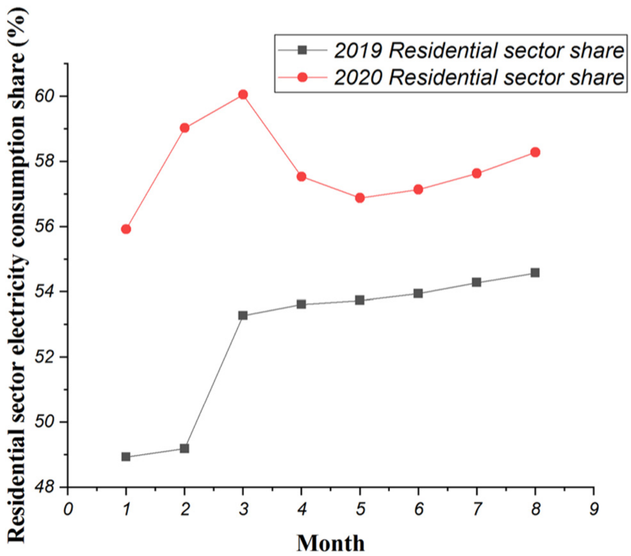


Fig. 8. The shares of US residential sector electricity consumption in first 8 months of 2020, as compared to the corresponding period in 2019; data from the US Energy Information Administration (EIA) (EIA, 2020b).

In the case of COVID-19, industrial energy consumption declined by up to 30% as a result of the lockdowns that were imposed to protect public health from the virus outbreak (Liu et al., 2020b). In addition, the fact that many people are working from home has increased the share of household energy consumption, leading to an increased share of household energy consumption in the total national energy consumption, which may have important implications for power grids and peak hours. For instance, one-third of Japanese consumers reported that their energy consumption increased because of the pandemic (Zhang, 2020). In New York City, while the pandemic reduced industrial and commercial energy consumption by 7%, household energy consumption increased by about 23% in March 2020 (Qarnain et al., 2020). During the pandemic, the electricity consumption share of the administrative buildings at the University of Almeria decreased by nearly one-third (Chihib et al., 2021). In Romanian Universities, computer use accounts for 11.28% to 60.5% of total consumption, which was reduced by 75% to 96.42% during the pandemic (Andrei et al., 2022).

Fig. 8 shows the share of US residential sector electricity consumption in the first eight months of 2020, as compared to 2019 with data obtained from the US Energy Information Administration (EIA). That the residential share of electricity consumption in the US has increased considerably during 2020 compared to the same period of 2019 can be attributed to the "Stay-at-home" orders after the emergence of COVID-19. In India, the virus outbreak has led to considerable increase in domestic energy consumption, whereas the share of industrial energy consumption has decreased, leading to profit losses for utility companies. This phenomenon arises because there are subsidies and regulations in place to protect domestic consumers and, consequently, control the cost of electricity for domestic users. An example of this regulatory regime is Indian power companies being forced to sell to domestic consumers rather than to industrial consumers (Elavarasan et al., 2020).

COVID-19 has also led to an increase in the shares of renewable energy sources in the electricity market, owing to their prioritized access to grids and low operating costs. For instance, solar PV and wind accounted for an increase in global renewable electricity generation of 5% in 2020 (Brosemer et al., 2020). In addition, almost 90% of the global power capacity expansion in 2020 is due to wind, hydropower and solar PV (IEA, 2020b). However, it is evident that public funding authorities are under extreme pressure to help various sectors recover from the COVID-19-induced recession, and this may have important and adverse implications for financing renewable energy systems (HIRST 2020). For instance, subsidies that have facilitated the development of wind and solar power generation may be cut in the future (Vlam, 2020). The COVID-19-linked economic meltdown has also led to job losses, with twice as many jobs lost in 2020 as were created during the previous 3 years in the US (Kaufmann, 2020). The pace of development of advanced energy technologies, such as renewable energies, electric cars, and carbon capture and storage, will depend on the current market penetration, support from the public and business interests, the costs faced by end-users, and the prioritizing of individual technologies such that they receive support from public funds and governments. As a potential solution, the United Nations Secretary-General has suggested investing COVID-19 stimulus funds in green growth and renewable energy (Guterres, 2020). In the wake of COVID-19-associated market instabilities, the main goals should be to promote the expansion of new industries within the renewables field and to ensure that the recovery funds and state budgets accelerate the development of sustainable renewable energy, particularly solar and wind power. The latest research also shows that spending a small fraction of the COVID-19 recovery packages on green recovery could address the dual crises of COVID-19 and climate change (Andrijevic et al., 2020; Sovacool et al., 2021). However, it may be difficult to achieve a balance between the inevitable demands for quick savings by businesses – even if unsustainable – and changing course to a more sustainable development.

3.4. Chemical/petrochemicals markets in health-related products

The petrochemical industry is essential for the production of medical and pharmaceutical items and personal protection equipment (PPE). For instance, manufacture of the critical N95 masks requires polyurethane, polypropylene (as the filter) and polyester (mask shell). Furthermore, polyester blends and non-woven polypropylene are used in the production of surgical and patient gowns (Cooper, 2020). It is noteworthy that the recession brought on by the COVID-19 pandemic has led to a drop in worldwide demand for chemical and petrochemical products, which according to the international Agency ICIS has resulted in a crisis for petrochemical companies (Grigorievna et al., 2020) (Fig. 9). While the pandemic reduced the reuse of plastic waste (Grigorievna et al., 2020) and many other petrochemical products, the demand for primary polymers has increased. Thus, one could propose that the post-pandemic economic recovery will be the main factor in returning the petrochemical companies to full-capacity production. It can be argued that the problem of the considerable amount of COVID-19-related medical waste, which typically has a high calorific content, and the urgent need to dispose of such waste can be solved using thermal methods such as incineration, gasification and pyrolysis, which can serve as sources of heat and power (Purnomo et al., 2021).

To help control the pandemic, many chemical/petrochemical plants have modified their production processes to produce materials for health, medical and pharmaceutical purposes. For example, Exxon Mobil announced that the production of isopropyl alcohol (IPA; used in sanitizers, rubbing alcohols and cleaning wipes) and polypropylene (used to make medical-grade masks, shields and gowns) has been prioritized and maximized to meet the significant rise in demand for COVID-19-related hospital supplies (ExxonMobil, 2020). In Iran, petrochemical companies have changed their production lines to deliver materials such as protective gear and gloves (Klimont et al., 2017). As another example, the petrochemical companies Karoun and Arvand have both

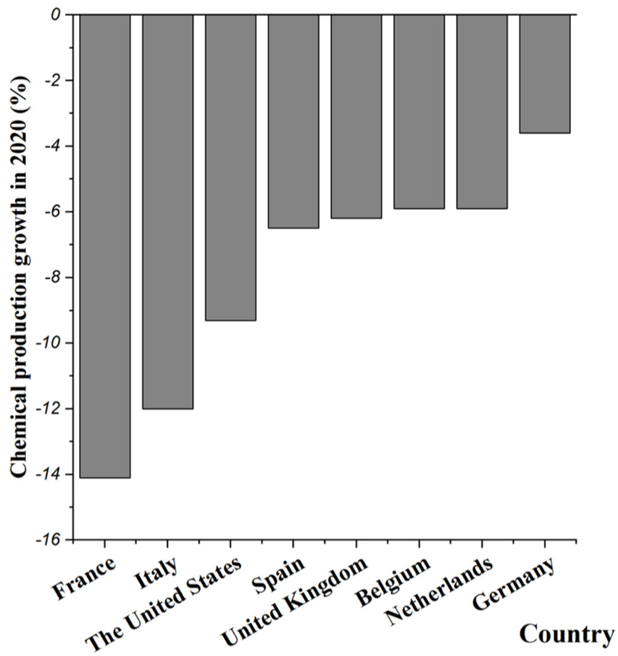


Fig. 9. Growth in chemical production in 2020 for France, Italy, US, Spain, UK, Belgium, The Netherlands and Germany: data from (Cefic, 2020) and (Tullo, 2020).

shifted their production lines toward producing bleach and caustics, which are used as raw materials in disinfectants and hygiene products, such as soaps (Ogen, 2020). It should be noted that the lockdown implemented during the COVID-19 pandemic reduced the demand for and consumption of many chemical materials, including fuels in some regions. Given that gasoline is mainly produced by refining crude oil through chemical processes and that this is accompanied by the creation of many other valuable chemical products, the sudden reductions in demand for gasoline have negative impacts on the economics of chemical production and on the Oil & Gas value chain. The US EIA has estimated that the global demand for petroleum and liquid fuels, which are main products of refineries, decreased by 8.1 million barrels/day (b/d) in 2020, as compared to 2019 reaching 92.6 million b/d in 2020 (EIA, 2020c).

As the global vaccine production is increasing to meet the demand, there is an increased need for energy and materials and feedstock to this industry. A life cycle assessment shows that each vaccine needs 0.69 kW_h of energy and emits around 329 gCO_{2eq} (Klemeš et al., 2021). Considering the global population, the vaccine production itself will require considerable amount of energy and material, and emit considerable amount of CO_2.

3.5. Pandemic impact on air quality

The WHO (Cohen et al., 2017) estimates that 4.6 million people die each year as a result of diseases linked to air pollution. (Dutheil et al., 2020) and (Torkmahalleh et al., 2021) claim that the lockdowns implemented by most of the developed and developing countries have led to a decrease in air pollution and, paradoxically, have reduced the total number of deaths during lockdown periods by drastically decreasing the number of fatalities due to air pollution. Le Quéré et al. (2020) estimated that there was an unprecedented (albeit temporary) 17% reduction in CO_2 emissions during the lockdowns. There are also studies, such as that conducted by Cicala et al. (2020), showing that the lockdowns implemented during the pandemic reduced emissions-related fatalities. For instance, the lockdowns in the US reduced pollution-related mortality by >360 deaths per month, mainly due to reductions in vehicle usage and the consequent reductions in particulate and NO_x emissions (Cicala et al., 2020). In Delhi, India, which that has one of the highest global pollution levels, the $PM_{2.5}$ and nitrogen oxide levels dropped by 70% during the lockdowns (Gardiner, 2020). This can be compared with decreases in emissions of up to 60% in the European cities of Vienna and Zaragoza, and 42% in Shanghai, China (Kumar et al., 2020). However, eastern India experienced higher air pollution levels than usual, mainly due to the presence of coal-fired power plants clusters and coal mining (Tyagi et al., 2021). The US EIA has also estimated a 7.5% drop in CO_2 emissions due to the slowing economy and the restrictions imposed on business and travel activities during the pandemic (EIA, 2020c). The US has also experienced a 5.5% reduction in NO_2 concentrations, as compared to the historical average (Berman and Ebisu, 2020).

However, it is over-simplistic to think that reduced travel and mandated business restrictions automatically lead to a reduced number of deaths. Thus, while atmospheric pollution in China was the main cause of 1.6 million preventable deaths in 2016 (Rohde and Muller, 2015), the strict lockdown imposed by China only reduced the primary pollution, and several periods of heavy haze pollution in eastern China, and showed the need for a coordinated and balanced strategy for controlling multiple pollutants, including NO_x and volatile organic compounds (Huang et al., 2020).

4. Conclusions

This paper examines the connections between the energy technology applications and human health and in particular, how technologies affect health and how disasters such as pandemic disease affects energy technologies. From this, we draw conclusions on what are preferable technology transitions which can deal with the new human and global health challenges. In addition, the way that pandemics has changed or has the potential to change the use of and development of different energy technologies and their associated effects on human health are examined with especial focus on COVID-19. The following conclusions can be drawn:

- Energy technologies must adapt to structural changes and become integrated into long-term plans for recovery from the pandemics, so as to: (1) increase energy technology resilience; (2) repair economic damage caused by the pandemic; and (3) minimize the environmental emissions of greenhouse gases associated with power generation.
- Mortality risks are highly correlated to local levels of air pollutants, such as particulate matter (especially $PM_{2.5}$) and NO_x. On the one hand, 75% of anthropogenic $PM_{2.5}$ originates from residential combustion, industrial processes, and large-scale combustion. On the other hand, NO_x emissions are mainly from internal combustion engines and combustion for energy conversion. Given that the sources of $PM_{2.5}$ and NO_x are linked to combustion, implementation of clean combustion remains critical to prevent the deadly outcomes of air pollution. The large differences in particulate matter emissions between poor and rich countries mean that it is incumbent upon the international community to develop and implement plans for affordable clean energy technologies for the billions of vulnerable poor people who still lack access to such energy sources and technologies.
- Increasing the decentralized energy capacity could secure access to electricity with high efficiencies. However, in such a situation, the emissions that are currently produced at

power plants and mainly released away from densely populated areas would then be released in more-residential locations, if based on combustion systems. Given the important negative impacts of pollutants (especially particulate matter) on human respiratory health, decentralized energy systems should be scrutinized to ensure very low levels of pollutants, with solar PV and battery storage systems being prioritized for clean electricity production.

- The increasing heat waves and rising average temperatures in many countries provide new global challenges with heat-related diseases and negative health consequences such as heat-related acute cardiovascular disease events and myocardial infarction. These effects imply that energy conversion technologies should develop toward energy-efficient and low-priced new cooling methods and HVAC technologies for residential buildings to save the vulnerable groups from dire health consequences of increasing temperatures.
- The energy poverty produced by pandemic-related downturns in economies could return us to historic eras in which deteriorating health and increased mortality adversely impacted low-income and vulnerable households due to energy shortages. Thus, both short-term and long-term measures are necessary to ensure continued access to energy for vulnerable groups, not least because pandemics can be expected to reoccur.
- The pandemic negatively affected the workforce and the financial health of energy companies and threatened the supply chain for energy resources. Long periods of lockdown can damage the resiliency and reliability of energy infrastructures, potentially leading to loss of parts of the system capacities once economic activities return to pre-pandemic levels.
- Energy companies must identify sustainable solutions for organizational challenges, such as how to deal with reduced staffing during pandemics in key energy facilities, such as power plants and network facilities. Using advanced solutions such as the *Internet of Things* and deep learning can support robust staff planning in the future.
- It is of the utmost importance that recovery funds provided by different governments around the world are – as far as possible – used to drive change toward more-sustainable and renewable energy systems and to motivate climate change mitigation plans.

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.

Data availability

No data was used for the research described in the article.

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