Environmental Science and Pollution Research (2022) 29:79443–79465
https://doi.org/10.1007/s11356-022-20997-2

RESEARCH ARTICLE

Machine learning analysis on the impacts of COVID-19 on India's renewable energy transitions and air quality

Thompson Stephan[1] · Fadi Al-Turjman[2] · Monica Ravishankar[1] · Punitha Stephan[3]

Received: 23 February 2022 / Accepted: 17 May 2022 / Published online: 17 June 2022

Abstract
India is severely affected by the COVID-19 pandemic and is facing an unprecedented public health emergency. While the country's immediate measures focus on combating the coronavirus spread, it is important to investigate the impacts of the current crisis on India's renewable energy transition and air quality. India's economic slowdown is mainly compounded by the collapse of global oil prices and the erosion of global energy demand. A clean energy transition is a key step in enabling the integration of energy and climate. Millions in India are affected owing to fossil fuel pollution and the increasing climate heating that has led to inconceivable health impacts. This paper attempts to study the impact of COVID-19 on India's climate and renewable energy transitions through machine learning algorithms. India is observing a massive collapse in energy demand during the lockdown as its coal generation is suffering the worst part of the ongoing pandemic. During this current COVID-19 crisis, the renewable energy sector benefits from its competitive cost and the Indian government's must-run status to run generators based on renewable energy sources. In contrast to fossil fuel-based power plants, renewable energy sources are not exposed to the same supply chain disruptions in this current pandemic situation. India has the definite potential to surprise the global community and contribute to cost-effective decarbonization. Moreover, the country has a good chance of building more flexibility into the renewable energy sector to avoid an unstable future.

Keywords COVID-19 · Machine learning · Energy transition · Renewable energy · Air quality · Climate change

Introduction

The world's yearly oil consumption is approximately 35 billion barrels, and the earth is polluted owing to the massive dependence on fossil fuels, which are not everlasting (Mishra 2022). Scientists have estimated that the energy sector has consumed about 40% of the world's oil and, based on this estimate, it has been identified that oil and gas reserves may be exhausted in 50 years, while this timeframe for coal is around a century (Singh 2015). On the contrary, there is abundant sunlight, water, and wind which are considered as renewable energy sources and these would not expire over time. Hence, the dependencies in the electricity generation on fossil fuel can be shifted towards the power generation systems with renewable energy sources and this has been a recent trend in many countries around the world. However, renewable energy sources still count as a small percentage of our energy demands on earth as the shift towards 100% renewable energy-based generation facilities will only be possible when these become less expensive and more accessible. This represents a huge challenge, even in the

Communicated by Philippe Garrigues.

✉ Thompson Stephan
thompsoncse@gmail.com

Fadi Al-Turjman
fadi.alturjman@neu.edu.tr

Monica Ravishankar
monica.ravishankar@gmail.com

Punitha Stephan
punitharesearch@gmail.com

1 Department of Computer Science and Engineering, Faculty of Engineering and Technology, M. S. Ramaiah University of Applied Sciences, Bangalore, Karnataka, India 560054

2 Artificial Intelligence Engineering Dept., AI and Robotics Institute, Near East University, Mersin 10, Turkey

3 Department of Computer Science and Engineering, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu, India 641114

case of ignoring the politics involved while mainly focusing on science and engineering. The problems can better be understood by understanding the methods of using energy. The energy system is considered as one of the most complex systems and the energy usage around the world is another complicated part within this complex system. Therefore, it is important to have solutions for different parts of these complex systems in terms of transitions towards renewable energy sources and climate changes. The two most important factors in our everyday life are electricity and liquid fuels which means that these two forms of energy sources play a crucial role in our everyday activities. India is considered as the world's third-largest electricity producer and consumer in the world and this sector is currently being dominated by fossil fuels. At the same time, liquid fuels play a primary role in the transportation as well as in the energy production and these are considered as an important factor for the economic development. Considering the electricity proportion of the energy demand on earth, the motivating factor is that the technology has already advanced enough to capture all these electricity demands from renewable energy sources which can be evidenced by looking into individual sources of renewable energy. For example, the continuous irradiation from the sun has the ability to generate around 173 quadrillion watts in the form of the solar energy on earth and this figure is around 10,000 times greater than our everyday electricity demands (Gupta 2019). From common sense, it can be said that a huge surface (spanning several hundred thousand square kilometers) would be required to supply power and meet the electricity demands for human beings and other facilities on earth. Another major roadblock for the effective utilization of solar energy is the energy efficiency though it can be improved by appropriately placing solar panels in such locations that will enable them to receive direct light throughout the day. However, such facilities cannot be afforded by many people in these suitable areas. Similarly, the location and availability have very high impacts on implementing different forms of renewable energy sources such as geothermal, biomasses, wind, and hydroelectric. Theoretically, an electrical energy network connecting the different parts of the globe may empower the efficient electricity transportation to the locations with high energy demands. However, the cost of implementing such a system will be quite high, impractical, and may incur energy loss when transferred through power lines. Thus, it is important to construct cost-effective solutions to enable energy transmission and distribution. Superconductors could be an alternate solution; however, their maintenance in turn requires more energy and does not serve the purpose. Thus, it is important to employ renewable energy storage systems in an easily portable form. Enabling energy transition is highly complex as it involves politics, economics, and technology. There are many governments and businesses around the world who are continuously investing in technologies for harnessing energy from renewable energy sources. Since renewable energy resources (including the associated technologies) are getting cheaper day by day, the relevant industries want to utilize the maximum benefits from these sources. It is important to analyze the usage of renewables and impose practical expectations in the future. Before the COVID-19 crisis and bolstered by the rapid fall in costs, the renewable energy sector was politically supported. As recorded in January 2020, India's renewable energy generation has grown to 9.46% (Koundal 2020). Most of these come from wind and solar while mostly used as electricity. It can be expected to grow fast since many Indian states have set their renewable energy goals which are aimed to meet by 2050. The society requires major changes, like mandates for 100% carbon free energy through measures such as doubling offshore wind and ending any subsidies for coal or any other fossil fuels. However, the implementation issues are owing to the cost since 100% renewable would be a huge undertaking. It is important to completely connect our separated electrical grids and figure out the ways to store wind and solar when it is not windy or sunny. Furthermore, it is important to find ways to maximize the usage of electricity on vehicles and manufacturing. The bottom line is that the usage of renewable energy has increased more than ever before, but the states and cities are working out the kinks on their own. Thus, it means there is a long way from any kind of widespread deployments.

COVID-19: opportunities for saving environment

The coronavirus has taken over as the biggest worry for many as air pollution (Burns et al. 2022) has dissipated the virus which has emptied the streets of the world's megacities and slowed down the manufacturing. Drastic quarantine measures implemented by the government authorities have resulted in significantly cleaner air and emitting lesser greenhouse gas which is now considered as a small victory against global warming. Many recent studies in the literature have discussed the relationship between environmental pollution and the COVID-19 outbreak (Bashir et al. 2020a). Scientists have long been sounding the alarm on climate changes. The year 2019 was the second hottest year on record with the past decades and the greenhouse gas concentration was at the highest level in 3 million years (WMO 2019). While countries have been slowing to act in the face of global warming, many of them now implemented drastic measures to slow down the spread of the coronavirus. The climate crisis (Shuai et al. 2021) is somehow much more abstract than the virus and it is unpredictable that the number of people dying because of climate changes. The entire world is currently focused on mitigating the ill effects of COVID-19. On the other hand, there seems an improvement in the air quality (Ravindra et al. 2022) with nature making a comeback. However, the current scenario does not guarantee to permanently eliminate global warming. It is difficult to make a one-one comparison of two different crises, but the governments' reactions to tackle a global emergency like the coronavirus pandemic, versus decades of global inaction to solve an equally life-threatening climate crisis, actually represents the current situation. The effects of the pandemic are tangible, the people hear or see someone being infected, getting sick and, in some cases, even losing their life. And yet climate change is already affecting our lives, too. Perhaps, if more media covered the climate crisis like a dangerous disease, governments would take it just as seriously as this pandemic needed to be taken. For example, the air pollution caused by excess greenhouse gases emitted by cars and other human activities. The WHO has estimated that 4.6 million people prematurely die every year from respiratory difficulties directly linked to air pollution.[1] Patients with respiratory difficulties are now at greater risk of COVID-19 complications and for those currently contracting the new disease, unclean air is very bad news, too. Scientists at Stanford have recently estimated that a country's pandemic lockdown (Bontempi et al. 2022) alone might have saved as many as 77,000 lives by curbing carbon-di-oxide (CO2) emissions from factories and vehicles (Jeff 2020). In other words, the coronavirus outbreak has proven once and for all that there is a strong link between the economy and health of our planet (Bashir et al. 2021). To date, climate change is mostly taking its toll on people who live in the developing world, or on the lowest income groups of our rich economies. The fact that many governments reacted so drastically to COVID-19 outbreak proves that strong economies do have the structural, financial, and political ability to quickly react to a life-threatening crisis and that our societies are capable and empathetic enough to make sacrifices for the common good. COVID-19 pandemic gives us a unique and historical window of opportunities to make structural changes needed to transition towards a fair and ecologically sustainable economic system. Different governments around the world are currently at the stage of finding out ways to invest their emergency funds on critical businesses which were forced to temporarily close due to COVID-19. Recently, some highly fossil fuel-based industries, such as oil and coal companies, aviation, or car manufacturers, are on track to secure funding from their governments. The government needs to focus on carbon-taxing to achieve its climate goals and reduce future emissions. Furthermore, the long-term economic funds and incentives must be arranged for less polluting industries to accelerate the energy transition. It is highly important to have a long-term investment plan and defined policy for the energy transition based on renewable energy sources and this is the best time for transforming the energy infrastructure goods so that the air quality can be managed at a reasonable level. If any of these above sounds familiar, that is because the world has never been in a similar situation before. During the world's most severe economic collapse in 2008 after the Second World War, no alternatives were identified to a neoliberal system and no one has proposed to utilize existing solutions for preparing a comprehensive plan for setting out policies that can readily be implemented in future crisis conditions such as COVID-19 pandemic . Though there have been some proposals, e.g., US or European Green Deals which are considered as roadmaps for developing a resilient and more sustainable economic system, these do not consider the planetary boundaries. However, the economy may go down the same path as it was in 2008 if these changes related to the planetary boundaries are not imposed by different governments around the world. From the recent news in different newspapers around the world, it can be evidenced that the economic system is not sustainable yet from the perspectives of both people and climate. After COVID-19, our societies will never be the same as we will be moving to a new normal. The impacts of human activities on the environment were well known before COVID-19. Carbon and sulfur di-oxides (two most dangerous gases) are produced from burning fossil fuels that are used to generate electricity and these gases significantly contribute to climate changes at the global level as well as to the air quality at the local level and India could be a great example for demonstrating the impacts of air pollution (Pal et al. 2022) at the local level because of burning fossil fuels. In 2018, the Inter-Governmental Panel of the United Nation (UN) on Climate Change reported that the prolific emitters need to transition away from fossil fuels and cut carbon emissions to net zero by 2050 in order to avoid the level of global warming that could be seriously harmful for the environment and human health. As different countries around the world are now passing stimulus bills to alleviate the financial strain on their economies caused by COVID-19 pandemic, people are calling on governments, which drive up to 70% of global energy investments, to also invest in clean energy transitions (Darius Snieckus 2020). The decision we make now will impact our environment for around 30 to 40 years and will change the way the industries are currently functioning. There is an opportunity to accelerate some of these transitions that can be done, e.g., the fossil fuel subsidy reform. If fossil fuel energy prices are low, it is important to reform those subsidies and redirect them to the green industry.

[1] Air pollution. https://www.sciencedaily.com/terms/air_pollution.htm.

Table 1 Factors related to the energy transition [11]

Percentage of the global average energy transition index (ETI) score in 2020	55.10%
Number of countries improving their ETI score since 2015	94
Number of countries making steady progress each year since 2015	11
Percentage increase in the average ETI score of countries in the top quartile since 2015	<1%
Percentage of global population using as much energy as the remaining 80%	20%
Expected percentage of decline in the coal power generation globally in 2019	3%
Percentage of young people considering the energy transition speed to be either stagnant or too slow	70%

Impacts of COVID-19 in India

The 30th January 2020 was the first date when India reported the confirmed case of COVD-19 in the state of Kerala which was identified as a link with travel history from Wuhan, China (considered as the source of COVID-19). India has reported more than 0.2 million cases of COVID-19 (as of 4 June 2020 08:00 IST (GMT+5:30)), replacing China as Asia's hotspot (Government of India 2020c). As India enters into Lockdown 5.0 for reducing the transmission rate of COVI-19, Indian citizens have been advised to continue actively exercising social distancing. Based on the prevalence of COVID-19 infections, more than 700 districts in the country are currently classified into Red, White, and Green zones (Nair 2020). The tracking speed and direction of the energy transition has been enabled owing to the annual benchmarking of energy systems across the country and further allowing opportunities to be identified for improvements. The hard-earned momentum for transforming the energy system to combat climate changes has been lost due to the economic and social damages caused by the ongoing COVID-19 pandemic. In recent times, COVID-19 pandemic has redefined the economic, political, and social aspects relevant to the energy transition and it is unprecedented in its scale and speed. To address this global outbreak, societies are forced to change and relinquish valuable commodities and freedoms, and such an effect is required for successfully achieving the energy transition which could alleviate the storm caused in the energy markets. COVID-19 has caused severe disruptions of almost a third of the global energy demand and uncertainties over the employment prospects of millions of workers in the energy sector.

Energy transition and energy transition index

The transition of fossil fuel-based energy production and consumption, especially from coal, natural gas, and oil, into renewable energy sources that include solar energy, hydropower, and wind energy in the energy sector is termed the energy transition. The major drivers for the energy transition include the spread of electricity, enhanced energy storage capacity, and rising access to renewable energy in the energy mix. According to the Geneva-based World Economic Forum (WEF), different factors associated with the energy transition are provided in Table 1 (World Economic Forum 2020). It is worth mentioning that the ETI is a ranking system based on facts and intends to allow policymakers and business people to strategize a blooming energy transition. Across different countries, the energy systems are benchmarked annually. The ETI tracks the energy system's performance of a country and is used as a global index tool for decision-making with regard to energy. For an effective energy transition, ETI integrates social, institutional, geopolitical, and macroeconomic deliberation.

Energy transition: facts related to India

As the global energy system has been destabilized, COVID-19 crisis has put a spotlight on vulnerabilities. The ETI from this year shows the progress at a slower rate (but surely there is progress) with more than 80% of countries increasing their score on the index since 2015. Around 75% of countries have enhanced their environmental statuses in 2020 (World Economic Forum 2020). Since 2015, India is considered one of the very few countries to have steady improvement on a Global Energy Architecture Performance Index (EAPI) which was released as a part of the report from the WEF. The WEF collaborated with Accenture Strategy (a company having its headquarter in Ireland) to develop a composite index, named as the EAPI. The EAPI tracks 18 indicators for measuring the performance of energy systems. The WEF has developed the ETI 2020 framework by considering the system performance imperatives in conjunction with transition readiness enabling dimensions as shown in Fig. 1 (World Economic Forum 2020).

From Fig. 1, it can be seen that system performance imperatives are presented in terms of the energy security and access; environmental sustainability; and economic growth and development within an energy triangle by placing these factors on three sides. At the same time, transition readiness enabling dimensions are presented in the form of a hexagon having six factors that include capital and investment; regulation and political commitment; institutions and governances; infrastructure and innovative business environment;

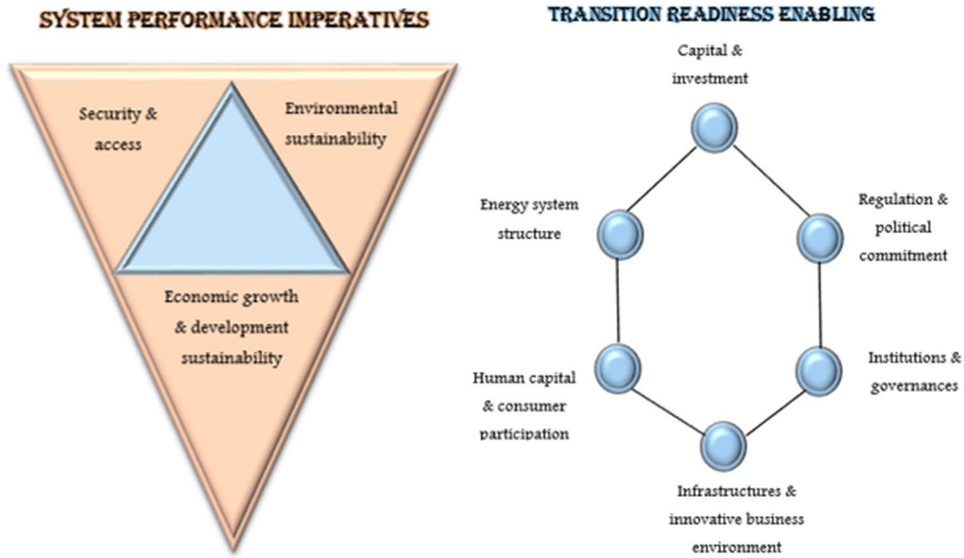


Fig. 1 ETI 2020 framework World Economic Forum (2020)

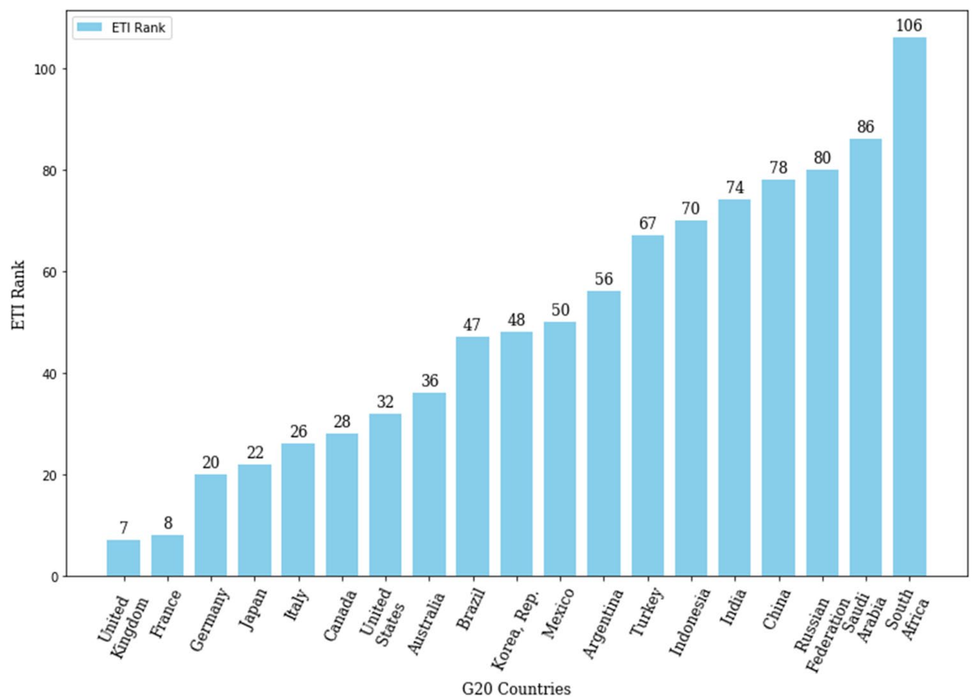


Fig. 2 The ETI ranking in 2020 for G20 countries

human capital and consumer participation; and energy system structure. The ETI is built on its EAPI, which is considered as its predecessor and it is important to note that the ETI does not perform benchmarking of countries according to its current energy system performance but measures its preparedness for the energy transition.

India is currently facing a big challenge to maximize the energy access and security indicators though it is showing gradual improvement in the performance index. India's chances of leading the renewable energy capacity chart are high as it has committed to maximize the solar power generation capacity to 100 gigawatts (GW) by 2022 (NewIndianXpress 2019). India along with China, Italy, and Argentina is one of the major countries with steady improvements annually. According to WEF, India is ranked as 74th in the ETI ranking and 15th among G20 countries as shown in Fig. 2 (World Economic Forum 2020).

Furthermore, India is recognized as one of the emerging centers of demand while making steady attempts to bolster the energy environment. Major gains for India have come from the government-mandated renewable energy expansion program, now extended to 275 GW by 2027 (Gupta 2019). Moreover, the mass procurement of smart meters, LED bulbs, and programs for appliance labeling have driven important strides in enhancing energy efficiency and driven unprecedented oil price volatility and subsequent geopolitical implications.

Thus, the major objective of this research is to:

- analyze the impact of COVID-19 on the country's renewable energy transitions.
- forecast the growth of renewable energy generation.
- analyze the impact of COVID-19 lockdowns on the climate.
- analyze the impact of partial lockdowns on a country's air quality.

The remainder of this paper is structured as follows. The works related to the impacts of COVID-19 on energy and air quality are discussed in Section 2. Section 3 presents the major threats in the energy sector due to COVID-19. Section 4 discusses India's renewable energy ambitions during COVID-19. Section 5 presents the impacts of COVID-19 on India's energy transition goals. Section 6 presents COVID-19 and its impact on air quality in India, while India's strategy towards enhancing the renewable energy transition and air quality is presented in Section 7. Finally, Section 8 presents the conclusion along with future directions.

Related works

Recently, it has been identified that renewable energy sources may experience the first annual decline in two decades as the global renewable power capacity additions in 2020 are likely to fall by 13% year-on-year to 167 GW (Shumkov 2020). COVID-19 pandemic is directly delaying and posing challenges for the construction and financing in the renewable energy sector which has been indicated in a report released by the International Energy Agency (IEA) (Iea 2020). The recent Indian Government notifications and initiatives concerning the impact of COVID-19 on the energy sector are summarized in Arora (2020). Three different policy horizons are differentiated in Steffen et al. (2020) to assist the energy policymakers with policy frameworks during COVID-19. The influences of lockdown on the air quality and water pollution in several cities in the world are investigated in Saadat et al. (2020). The necessity for new rules and regulations while considering the socio-economic and unpredictable environmental aspects of COVID-19 is also discussed (Saadat et al. 2020). Furthermore, the authors in Saadat et al. (2020) have discussed the risk of being affected by COVID-19 and the importance of social distancing for eliminating the spread of COVID-19. A comprehensive study for the estimation of the environmental effects owing to COVID-19 epidemic lockdown strategies in Italy is presented in Rugani and Caro (2020) using the globally accepted carbon footprint (CF) indicator. Though the estimated CF includes uncertainties, the authors in Rugani and Caro (2020) have provided a quantitative analysis of the degree to which the climate is affected by the lockdown measures in Italy and the investigation gives an insight into the relation between COVID-19 spread and air pollution. The analysis in Manka Behl / TNN / Apr 18 (2022) by the Centre for Research on Energy and Clean Air (CREA) has revealed that a drastic fall in Nitrogen Dioxide (NO2) pollution is witnessed in the major Indian cities and other important COVID-19 hotspot areas. This study has revealed that NO2 levels are mainly down due to a decline in the consumption of diesel and petrol in the transportation sector; decline in the consumption of petroleum products and coal by industries; and drop in the overall power demand and coal consumption for the power generation. This study also recommends shifting from a fossil fuel dependent economy to a clean energy-based system by investing heavily on green energy solutions, transforming existing transportation systems towards intensive public transportation systems, and strengthening emissions standards for polluting industries. The Central Pollution Control Board (CPCB) has recently assessed the effects of the lockdown due to COVID-19 over the water in the Yamuna, the longest tributary in India.[2] From this analysis, it has been revealed that important parameters such as the Biochemical Oxygen Demand (BOD) which indicates the amount of oxygen needed by the river to maintain its flow and Dissolved Oxygen (DO) which indicates the oxygen level presented in the river for the survival of aquatic life, have decreased during COVID-19 lockdown. However, it was not within the acceptable limits set for the bathing standards. In all monitored areas by the CPCB, there was a significant decrease in the level of Chemical Oxygen Demand (COD) which indicates the existence of industrial effluents in a water body. However, the domestic sewage contributes to 80–90% of the pollution load. Thus, the major positive was the decreased discharge of industrial sewage and the decline in human activities such as bathing, washing clothes down by the local river, disposal of solid waste, etc. The impacts of COVID-19 spread is discussed in[3] as a momentary change or long-lasting effect on the pollution and greenhouse gas emissions across the continents while the links between high levels of air pollution and the rising COVID-19 death risks are studied (Khadka 2020). The hilarious trends in twitter owing to the impact of COVID-19 lockdown are shown in Kohli (2020). The impacts of

[2] Central pollution control board. https://www.cpcb.nic.in/.

[3] Will COVID-19 have a lasting impact on the environment? https://www.bbc.com/future/article/20200326-covid-19-the-impact-of-coronavirus-on-the-environment.

COVID-19 pandemic shutdowns are discussed in Levy (2020) in terms of aiding to decline the pollution and influence of aerosols over the climate while the same has been done in Eric (2020) to highlight the impacts on the environment. Some satellite photos are portrayed in Ghosh (2020) showing the impact of COVID-19 lockdowns on global emissions. COVID-19 lockdown is discussed as an unprecedented natural experimentation in Welle (2020) for noise pollution along with the trends in falling down the transportation during COVID-19 lockdowns that have led to a drop in pollution levels which has benefitted animals. The impacts of COVID-19 in terms of ruining weather forecasts and climate records are presented in Viglione (2020). The opportunities for capitalizing the moment created with COVID-19 are analyzed in Watts (2020) with respect to delivering remarkable environmental benefits such as lower carbon emissions and cleaner air. The dramatic impact of the world's largest COVID-19 lockdown on pollution in India is studied in Watts (2020) which demonstrates the remarkable fall of NO2 levels in India's major cities like Delhi, Mumbai, Bengaluru, Chennai, and Kolkata. Furthermore, the reduction of air pollution due to the decreased fossil fuel emissions occurring as a result of a slowdown in the transport sector and emission-related activities is rigorously discussed in Watts (2020) including the necessity of renewable energy transitions and India's investment for a cleaner future. The relationship of climate indicators with the COVID-19 epidemic in New York City is examined in Bashir et al. (2020c) which clearly indicates that there is a considerable correlation with COVID-19 pandemic and air quality. Another study in Muhammad et al. (2020) has revealed that there is a 30% decrease in the pollution levels in COVID-19 hotspots such as China, the USA, Italy, and Spain. Correlation tests are performed in Bashir et al. (2020b) to examine the impact of most significant pollutants on COVID-19 pandemic in California. All these studies are useful to motivate the regulatory bodies to endorse changes for minimizing the adverse effects of environmental pollutants. COVID-19 measures have improved the overall air quality which has been reviewed in Wang et al. (2020). The decreased emissions from the industry and transportation sector are one of the major reasons for the overall improvement and the necessity to control emissions from the residential sector is also discussed in Wang et al. (2020). The significant relationship between COVID-19 spread and air pollution is examined in Zhu et al. (2020) in which the authors have discussed the positive impact of national lockdown on air pollution. However, the authors have also examined that the number of daily confirmed COVID-19 cases is negatively associated with Sulphur dioxide (SO2). The changes in air quality during COVID-19 pandemic are analyzed in Li et al. (2020) in the Yangtze River Delta Region in China. In Li et al. (2020), lowered human activities are identified as the key factor that positively affects the changes in the air quality. The study in Li et al. (2020) has also revealed factors related to residual pollution in order to control the future air quality. The impacts of travel constraints on the air pollution are estimated in Bao and Zhang (2020) from where it is found that the human mobility is one of the main reasons underlying the significant reductions in the concentrations of particulate matter (PM)2.5, PM10, SO2, carbon monoxide (CO), and NO2 by 5.93%, 13.66%, 6.76%, 4.58%, and 24.67%, respectively. The authors in Bao and Zhang (2020) have also investigated that the government imposed travel bans have impacted human mobility to drop by 69.85%. A similar study has been presented in Kerimray et al. (2020) to examine COVID-19 lockdown effects on the concentration levels of PM2.5, NO2, and CO which has evidenced that these levels are reduced by 21%, 35%, and 49%, respectively in Almaty, Kazakhstan. The study in Kerimray et al. (2020) has also shown a rise in ozone (O3) levels by 15% while comparing the previous 17 days prior to COVID-19 lockdown. Similarly, the toluene and benzene concentrations are found as 2–3 times higher as compared with the same seasons of 2015–2019 Kerimray et al. (2020). The analysis as presented in Lal et al. (2020) has demonstrated a considerable drop in NO2, a slight decrease in CO, and a slight to moderate reduction in Aerosol Optical Depth (AOD) during COVID-19 pandemic. Another study as presented in Nakada and Urban (2020) is carried out to examine the impacts of the partial lockdown due to COVID-19 on the air quality in the regions of São Paulo state, Brazil which is among the world's most populous cities. From the study in Nakada and Urban (2020), it is observed that there is a 64.8% decrease in the concentration of CO in the city center while the decreases in the nitric oxide (NO), and NO2 concentrations are observed as 77.3%, and 54.3%, respectively for urban roads. The effects of partial lockdown due to COVID-19 on the air quality are also studied in Dantas et al. (2020) for another Brazilian region, of Rio de Janeiro, the second-most populous municipality in Brazil). In this study, the effects are analyzed in terms of vehicular as well as industrial emissions and it is found that there have been significant reductions in such emissions, i.e., the reduction in the CO levels. At the same time, it is found in Dantas et al. (2020) that the decline in industrial emissions has also decreased the NO2 levels and during the first week of the partial lockdown, the region has observed a drop in the PM10 levels. The study in Xu et al. (2020) has focussed on examining the relationship between confirmed COVID-19 cases and the air quality index (AQI) while another analysis in Sharma et al. (2020) has estimated the impact of human mobility owing to COVID-19 on the air quality in 22 Indian cities. The authors in Sharma et al. (2020) have examined that most of the regions experienced maximum reduction in PM2.5 levels. While comparing with previous years, this analysis revealed a correlation among different Indian cities, particularly in eastern and northern regions. The impacts on the air quality in Milan (a metropolis in Italy's northern Lombardy region) are assessed in Collivignarelli et al. (2020) due to COVID-19 lockdown on air quality in Milan, a metropolis in Italy's northern Lombardy region where the trends of 9 pollutants are meteorologically analyzed for a specific time period along with relevant comparable time frames. The analysis in Collivignarelli et al. (2020) has revealed that there are significant reductions in key pollutants such as PM10, PM2.5, BC, benzene, CO, and NO owing to COVID-19 lockdown. In the more peripheral areas, the SO2 concentration has been observed to be unaffected while the decreases in NO levels due to COVID-19 lockdown increase O3 levels. A study in Otmani et al. (2020) has examined the impact of Covid-19 lockdown and analyzed that the concentration levels for PM10, NO2, and SO2 have decreased by nearly 50% during the lockdown period in Salé city (North-Western Morocco). The air quality of 4 European cities and 1 Chinese city is assessed in Sicard et al. (2020) during the COVID-19 lockdown which has revealed that oxides of nitrogen (NOx) levels in these are substantially reduced by 56%. A different study in Chauhan and Singh (2020) had analyzed the impact of lockdown on the concentration levels of PM2.5 for major cities of the world and this study indicates a noticeable decline in the levels of PM2.5 in major Indian cities such as Delhi and Mumbai. In Mahato et al. (2020), COVID-19 lockdown effects in the regions of Delhi, a highly polluted Indian city, are analyzed in terms of the concentration levels for PM10 and PM2.5 are reduced by 50% while comparing with the pre-COVID-19 period. Furthermore, the levels of CO and NO2 are also assessed in Mahato et al. (2020) which have considerably declined during COVID-19 lockdown. The analysis in Mahato et al. (2020) has shown the significant improvements in the air quality for the eastern and central Delhi and it is worth noting that around 40–50% improvements in the air quality was observed in the 2nd and 4th day of COVID-19 lockdown.

COVID-19: major threats for renewable energy transitions and air quality

COVID-19 is having a huge impact across the whole energy sector in both demand and supply sides. On the demand side, due to the sharp reduction in the energy consumption, e.g., 10–25% reduction in the oil demand on a global scale while focusing on individual countries such as Italy (which is mostly affected by COVID-19 pandemic), it is to be noticed that the electricity demand was dropped by 13% in the first week of the first lockdown and gas demand was likewise dropped by 10% (GECF 2022). There is widespread concern that the fight against pollution and climate change will have a negative impact on global renewable energy transitions, both short- and long-term. In the short term, hydrocarbon prices are much lower, so consumers may be inclined to increase their consumption and delay their transition towards cleaner technologies such as electric vehicles. Moreover, the production of some clean technologies (e.g., solar panels, wind turbines, batteries, etc.) will further face delays due to the problems related to the supply chain disruptions. Thus, governments should consider these opportunities to step up their climate ambitions and launch sustainable stimulus packages focusing mostly on clean energy technologies. In real-time, COVID-19 has unleashed cascading effects throughout the economy, including the energy sector and uncertainty over its long-term consequences. COVID-19 has eroded almost a third of global energy demand and is affecting every industry in some way or other. The current COVID-19 pandemic had caused unusual unpredictability in oil and gas prices. Pre-planned energy projects are being delayed and the investments are getting stalled, which is affecting the lives of millions of workers working in the energy sector. Though short-term benefits are expected due to this alignment, considerable benefits are expected in the long-term. The prosperity of the economy is still highly dependent on oil and gas. In the case of electricity, the security and reliability of the energy sector are also required to maintain its balance. The vulnerabilities in the system are highly exposed owing to the increased risk of cyberattacks, extreme weather incidents, and disturbances to supply and demand balance from sudden pandemics such as COVID-19, which are harmful to society on a large-scale. Stability in the energy markets can be promoted by achieving a balance between security, reliability, and economic growt. The following are the two main reasons to act in order to achieve and maintain sustainability in this current COVID-19 pandemic situation. There is a need to reboot the pre-COVID-19 energy system by investing in a revival that could accelerate the energy transitions. This necessitates the coordination of various solutions such as the circular economy, improving the efficiency of the current energy system, reducing fossil fuel emissions, maximizing financial assistance for future energy systems, and, most importantly, shifting the focus to renewable energy systems. The prospects are promising, as energy-based companies plan their long-term investments with these solutions in mind. The collapse in oil prices has greatly reduced the cost of energy for large-scale energy consumers such as India. The significance of steadiness in the energy markets is greatly emphasized by the aggravated COVID-19 disturbance. This can be mainly achieved by focusing on improving the overall architecture of the energy system instead of acting based on immediate requirements. Stability may also be achieved by taking necessary measures to stabilize the electricity system along with gas and oil. The frequent priority conflicts can be harmonized through efficient energy regulatory bodies. Such measures ensure the market remains competitive and open and further help in preparing to tackle the difficulties caused by any future catastrophic events or a pandemic similar to COVID-19. Usually, the shifts are gradually driven by global geopolitics or a country's political economy. However, the world is currently facing a sudden fright and it is important to carefully reboot the energy system for a cleaner environment.

COVID-19 and India's renewable energy ambitions

India has set one of the most belligerent renewable energy ambitions in the world. For several energy policies, India is considered as a social welfare center. However, India's energy model is at risk due to the ongoing COVID-19 pandemic. The existing state of affairs may not remain the same though it is a too early prediction regarding the deep structural change in India. Due to this severe lockdown in recent days, India is heavily hit by the recession, tourism, spending patterns, and variations in discretionary purchases. India's current energy transition may likely be impacted due to COVID-19 pandemic and there are high levels of uncertainties over the trajectory being shifted or paused or prompting radical changes. Considering the 2020 ETI as shown in Fig. 2, India is ranked almost in the middle among G20 countries and masked some important details (World Economic Forum 2020). Globally, the renewable energy ambitions of India are the most aggressive. India has set the short-term target to have 175 GW capacity from renewable energy sources by 2022 that would not require heavy storage or grid upgrades and this may be upgraded to 450 GW by 2030 (www.ETEnergyworld.com 2020). At the same time, many policy interventions are being planned to push energy storage, electric vehicles, smart grids, and other upcoming renewable energy technologies and practices. However, the economic contraction induced by the current COVID-19 pandemic toppling the priorities of India's renewable energy transition is still a big question that needs to be answered. In recent years, India has received a lot of international attention owing to its ambitious renewable energy goals. Currently, India is producing almost half of its commercial primary energy from coal, which is the dominant fuel for the power generation. At least for the most new electricity generation systems, coal is now being replaced by renewable energy sources. Importantly, India is focusing on implementing electric vehicles (EVs). Moreover, the financial status in India is unsteady though the supply and demand can be balanced by the electrical grid. One of the main aspects of the energy policy is the social welfare redistribution, through which homes and agriculture sectors are cross-subsidized. However, this model is facing high risk as the overall demand has come down to 25% as many well-established companies such as the Tata Consultancy Services (TCS), one of the largest Indian companies, have planned to establish work from home policies by the end of 2025 (Online 2020). Renewables are the recent investment of energy generation in India, however, owing to the challenge of managing the financial liquidity as the capital is of more concern than the labor. Before COVID-19 lockdown, India had excess capacity, and the addition of non-renewable capacity was in the proposal. However, COVID-19 pandemic has delayed it further from the implementation. The strategic capabilities and supply chains are highly difficult for many countries owing to COVID-19. India's manufacturing capacity is modest as it stands at 3 GW and 80% of our solar cells and modules rely on the Chinese manufacturers, however, it is now a concern after COVID-19 pandemic (Times 2022). On the other side, India's Make in India movement which is a local movement that covers 25 sectors of the Indian economy and it was launched at the end of third quarter in 2014 for encouraging Indian companies to manufacture their products in India, which has boosted domestic manufacturing and job creations. Coal might be a good suggestion as it is highly domestic. Though India might strategize their investments on renewable energy sources as well as batteries which could highly support the implementation of electric vehicles in the country. The bold reforms are highlighted in the proposed amendments to the Electricity Act 2003 (Pardasani 2018). The full cost to the electricity has to be paid in the case of direct distribution of subsidies to the consumers. Such initiatives would increase the use of separate funds for implementing renewable energy technologies. However, 50% of the electricity in India would still come from coal by 2030 (Ali and Tongia 2019). Nevertheless, India should find ways to clean up coal emissions and prevent health impacts of air pollution from India's coal power expansions (Guttikunda and Jawahar 2014). Therefore, it is important to combat climate change through clean energy and move towards efficient energy transition. The main challenge of implementing energy transition is the lack of willingness among the largest emitters in the world which include India.

COVID-19 and energy transition goals of India

According to the Indian Energy Exchange (IEX),[4] it is important to address the fluctuating domestic demands during COVID-19 in India and ensure sufficiency of power through energy exchanges (Tomar and Gupta 2020). The power demand across India is experiencing increased variation due to the current lockdown. Major disruptions in the

[4] Overview. https://www.iexindia.com/Aboutus.aspx?id=Gy9kTd80D98%3D&mid=Gy9kTd80D98%3D.

availability of energy to the critical sector such as healthcare, communication, etc. might occur in the case of mismatch in the demand and supply. Considering the ongoing COVID-19 pandemic, the energy transition goals set by the Indian Government are highly influenced by four major factors that are discussed in the remaining part of this section.: The ongoing crisis has put the energy transition at high risk and induced fear that the transition may be completely abandoned. However, the Ministry of New and Renewable Energy (MNRE) under the Central Government of India is working for the quick restoration and continuously making efforts to ease the movement of materials by issuing enough extension during the lockdown period. The ministry is also looking for different locations to fit enough for manufacturing renewable energy technologies. The popularity and advantages of renewable energy sources, which have gained in recent years, are diminished because of the downtrend in the electricity demand and fossil fuel prices. The prices of crude oil have drastically declined along with coal prices. For example, the kerosene subsidy in India is reduced to zero in March 2020 and the cost of LPG subsidy came down to nearly zero in May 2020. To maintain demand and reduce the prices of coal, the coal ministry has eliminated the surcharges, restrictions in the quantity, and requirements of an advance payment. For production maintenance, substituting coal imports, and promoting sales; the Indian Government is still continuing its protection on coal as many workers, deprived states, and dependency of major Indian sectors such as railways on the economy of the coal. For boosting the revenues from the tax, the government has increased the excise duty on petrol and diesel. However, achieving the cost-competitive renewable energy technologies and benefiting fossils through the Central Government's use of tax and subsidy are highly unpredictable. The COVID-19 pandemic opens different investment opportunities, though there is increasing enthusiasm in the energy transition from the global capital. The current renewable energy expansion in India is financially highly supported by the private and foreign capital and this current support is going from bad to worse due to this current COVID-19 pandemic. The inactive energy assets are also limited to financial support from the domestic public capital which could affect the transition towards renewable energy. The space for fresh renewable energy technologies may probably diminish as the demand for the electricity declines. The maintenance of extra power purchase contracts is high for various distribution utilities. During the initial stages of COVID-19 lockdown, some states attempted to temporarily reprieve from the renewable energy plants though the Indian Government is mandating and providing financial support to ensure proper functioning. During COVID-19 lockdown, India is continuously providing support for renewable energy through the completion of tenders for solar power (2 GW). Moreover, the central may retire older and highly polluting coal-fired power stations to make space for implementing renewable energy. It is important to note that the support for the energy transition is signaled by the government's attempts to protect renewable energy. Moreover, the amendment of the Electricity Act notified in the middle of COVID-19 lockdown clearly indicates extra protections such as necessitating the national renewable energy policy. The three most important steps that may strategize India's approach towards sustaining the energy transition are: (a) engaging the politically economic opportunities, (b) considering state-level constraints, and (c) allowing the transition pathways to be charted by the states. The states should support the Central Government as they take necessary measures for generating financial aids and other incentives. The energy transition could offer an opportunity and major support in providing an infrastructure with clean energy. During recovery strategies for post-COVID-19, the energy transition should be used as the major force for rebooting the economy. For example, the decentralization of clean energy may help health emergencies to be managed through several health infrastructures. The energy transition in India is experiencing unpredictability as the electricity system of India is worsened due to the current COVID-19 pandemic forcing the country into lockdown. Though the requirement of power generation has dropped out, it is important to analyze the performance of other resources associated with the power generation. A decade back, the world's power systems witnessed a dramatic fall. However, the emergence of renewables has made a significant difference with solar, wind, and other renewable energy sources were counted as 5% of the total power generation capability of the world in 2009 and in the USA, the net domestic electrical generation has become 18% in 2019 clearly demonstrating the higher share of renewable energy sources in the market (Bossong 2020). The year-on-year changes in the power generation during COVID-19 lockdown by considering the timeframe in 2019 and 2020 are shown in Fig. 3 for India, US-PJM, South Korea, and Italy based on the available data in Zhou (2021).

Preventive measures must be taken to restrain the impact of the renewable energy system and fossil fuel. Such measures could be a combination of various technologies working towards the structural restoration of pre-COVID-19 which may balance and help to build a flexible electricity system in the future. Thus, incremental and multifaceted approaches which include restructuring electricity markets, pricing carbon, forcing coal plants to retire before schedule, and the integration of renewable energy sources may help India to sustain the energy transition. Figure 4a-d shows the comparison of energy requirement, energy availability, peak power demand, and peak power demand met, respectively, between 2019 and 2020.

As compared to Feb. 2019, the energy requirement, energy availability, peak power demand, and peak power demand for Feb. 2020 increased by 10.9%, 10.85%, 9.19%, and 9.27%, respectively. However, as shown in Table 2, there

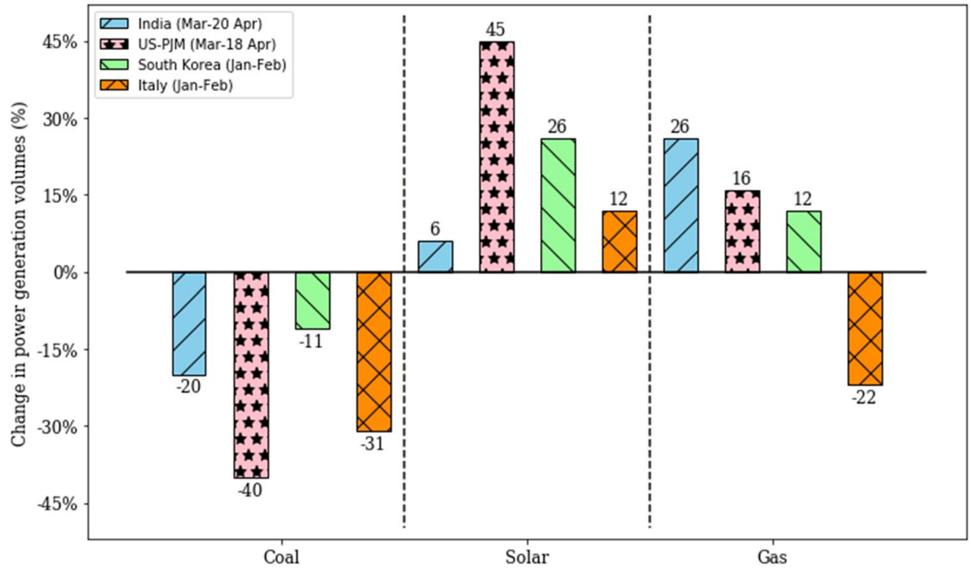


Fig. 3 Year-on-year changes in the power generation during COVID-19 lockdown by considering the timeframe in 2019 and 2020

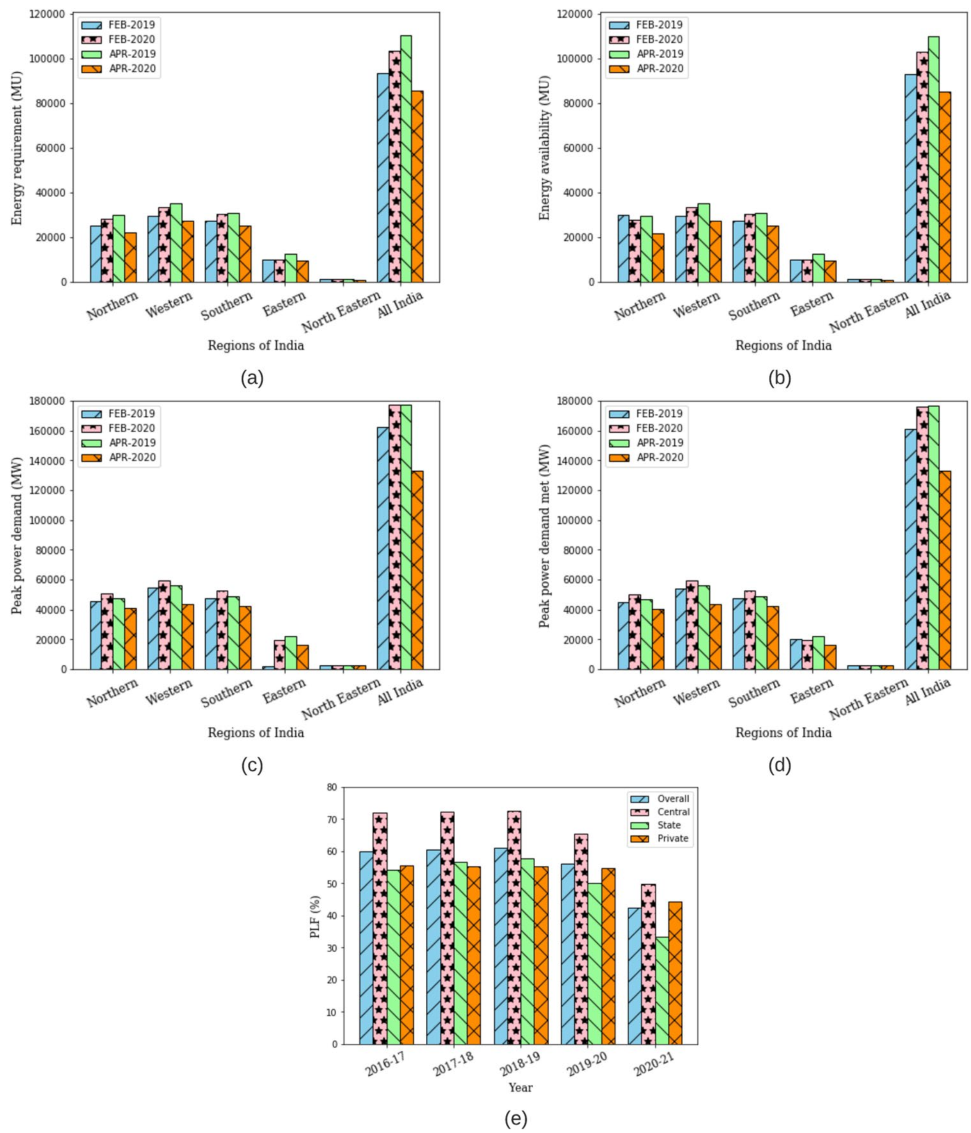


Fig. 4 (**a**). Comparison of energy requirement between 2019 and 2020 (**b**). Comparison of energy availability between 2019 and 2020 (**c**). Comparison of peak power demand between 2019 and 2020 (**d**). Comparison of peak power demand met between 2019 and 2020 (**e**). PLF in the country (Coal & Lignite based) from 2009–2010 to 2020–2021

Table 2 Comparison of energy and power between April 2019 and April 2020 in India

Region	Drop (%) in April 2020 as compared with April 2019			
	Energy (MU)		Power (MW)	
	Requirement	Availability	Peak demand	Peak met
Northern India	26.16	26.56	13.71	13.83
Western India	22.02	22.02	22.26	22.24
Southern India	19.4	19.4	13.11	12.9
Eastern India	23.9	23.67	25.97	25.85
North Eastern India	17.48	18.28	13.1	12.48
All India	22.57	22.66	24.86	24.9

is a high percentage drop in energy requirement, energy availability, peak power demand, and peak power demand for April 2020 as compared with April 2019.

COVID-19 and its impact on the air quality in India

According to the 2019 World Air Quality Report, India has 21 cities with the worst air pollution out of 30 cities in the world.[5] COVID-19 lockdowns are clearing the air in the polluted countries like China and India. With so few people driving and flying, the oil consumption has fallen off a cliff. Global greenhouse gas emissions are 5% lower this year than last year (Ambrose 2020) which would be the biggest drop in history. However, the current situation is temporary. In China, the air pollution is almost back to normal while CO2 is still being added to the atmosphere, just a little more slowly. The world needs to lower its emissions by about 2.7% each year over this decade to keep the planet under 2 degrees of global warming. That means big investments may be driven towards renewable energy and efficiency. Experts expect that trillions of dollars of government-supported COVID-19 stimulus could help to speed the shift towards a greener economy. To contain the spread of COVID-19 outbreak in India, the government has imposed lockdown measures through five different phases in the year 2020. Phase 1 lockdown was put in place for 21 days (from the 25th March 2020 to the 14th April 2020) with an almost complete shutdown of all services and factories. Phase 2 was implemented for 19 days (from the 15th April 2020 to the 3rd May 2020) with a conditional relaxation only for COVID-19 contained regions. Phase 3 (from the 4th May 2020 to the 17th May), Phase 4 (from the 18th May 2020 to the 31st May 2020), and Phase 5 (started from the 1st June 2020 and scheduled to end on the 30th June 2020) were more relaxed as compared to the first two phases. It is important to note that the first two major lockdown phases were implemented in between March and April 2020. Some of the major air pollutants (especially, SO2, NOx, and PM10 has been routinely monitored by India's CPCB and from such monitoring, it has been revealed that the concentration

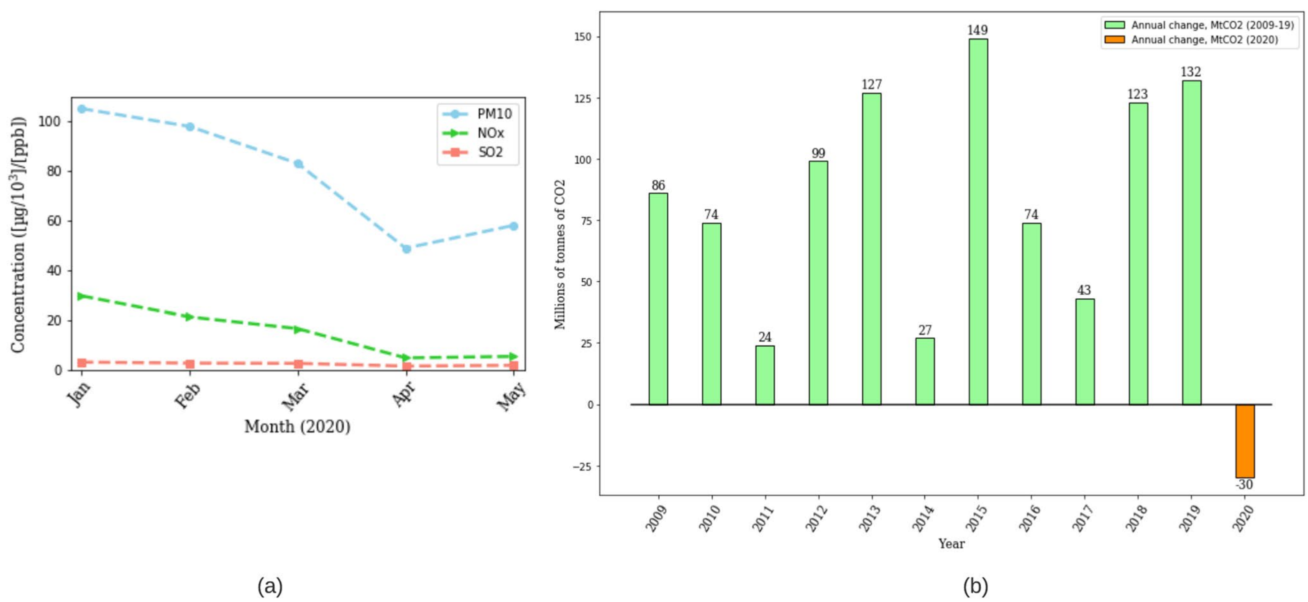


Fig. 5 (**a**). Concentration levels of the major air pollutants in 2020 (**b**). India's annual fossil fuel emissions

[5] World's most polluted countries in 2020 - pm2.5 ranking: Airvisual. https://www.iqair.com/world-most-polluted-countries.

levels of SO2, NOx, and PM10 have dropped by 41.16%, 71.08%, and 42.31%, respectively in April 2020 as compared to March 2020 as shown in Fig. 5a. Figure 5a also shows that the concentration levels of SO2, NOx, and PM10 have slightly increased by 18.81%, 12.5%, and 20%, respectively in May 2020 as compared to April 2020.

In four decades, CO2 emissions in India have significantly reduced due to the impact of COVID-19 which has slowed down the current economy, and negatively affected the growth in renewable energy (Myllyvirta 2021). In the fiscal year ending March 2020, the fall in the coal consumption and flattening of the oil consumption have resulted in the fall of emissions by around 1% (Myllyvirta 2021). Since 2019, the headwinds already affecting the Indian economy have been reflected due to the increased generation of renewable energy and the decline in emissions. Owing to the measures for combating COVID-19 pandemic, the Indian data analysis in the entire 2019–2020 financial year has seen a sudden fall in March 2020. The CO2 emission in India is expected to fall by 30% in the month of April 2020 as it has already seen an estimated fall of 15% during March 2020. As the Indian Government responds to the crisis, there is a significant chance for shaping India's longer-term outlook for emissions owing to the global CO2 impact of COVID-19 pandemic and key long-term implications for India's air quality trajectory and CO2 emissions. The coal is seen bearing the brunt of demand crunch. For the first time in three decades, the drop-off in March 2020 has pushed the generation growth below zero in the financial year which ended March 2020. Throughout the past 12 months, the demand for thermal power generation was weakened due to lower power demand growth and high competition from renewables. The thermal power generation growth has reached an average of 7.5% per year considering the preceding decade (Myllyvirta 2021). The coal sector has amplified the impact on emissions and resulted in a drastic fall in the total energy demand. According to the daily data from the Power System Operation Corporation, the power generation via coal fell by 31% in the first three weeks of April 2020 which was a follow-up to 15% fall in March 2020.[6] On the other hand, the renewable energy generation observed a minor reduction of 1.4% in the first three weeks of April 2020 which was a follow-up to the 6.4% increase in March 2020. Mostly at the expense of coal, the electricity demand in India has been observed owing to COVID-19. The data on coal supply provides evidence that the fall in total coal demand extends beyond the power sector. In the financial year 2019–2020, Coal India Ltd (which is the main coal producer in India) has seen a fall of 4.3% in the coal sales whereas the coal imports rose by 3.2% (Myllyvirta 2021). Thus, 2% fall in the total coal deliveries is signaled the first year-on-year fall in the consumption over two decades. There has been a sudden 10% fall in coal sales and a 27.5% fall in coal imports in March 2020 (Pti 2020). Thus, total coal deliveries fell by 15% which has been in line with the reduction in the power generation. The coal output shrinks to 6.5% in March 2020, though a heavy fall in coal sales has been observed (Chakraborty 2020). This trend has mainly been due to the lack of demand which in turn forced a drastic drop in the sale of coal though the mining of coal has been maintained at a high level. Figure 4e shows the plant load factor (PLF) in India (Coal & Lignite based) from 2009–2010 to 2020–2021.

Since 2019, the oil consumption in India has slowed down similarly to the electricity demand. The oil consumption has now increased further owing to the national level COVID-19 lockdown which has highly affected the transport sector. In March 2020, with COVID-19 lockdown, the oil consumption had fallen to 18% (Myllyvirta 2021). With a slower demand growth at the start of the year and an additional lower oil demand owing to the ongoing COVID-19 pandemic, the oil consumption has had a very slight increase of up to 2% which is considered the slowest in the last 22 years (Myllyvirta 2020a). Considering the natural gas sector, the consumption is predicted to fall by 15–20% during COVID-19 lockdown though it has been maximized up to 5.5% in the first 11 months of the financial year.[7] Compared to the last financial year, the natural gas and crude oil productions in India have decreased by 5.2% and 5.9% respectively (Government of India 2020). Over the last financial year, the refinery production with regard to crude oil processed fell by 1.1% (Government of India 2020). Compared to February 2020, the crude steel production in India fell by 22.7% in March 2020 (PTI 2020). According to the Ministry of Steel, in comparison to the last year, a fall of 2.2% was experienced in the financial year 2019–2020 (PTI 2020). For the first time in four decades, CO2 emissions in India have experienced a steep fall. For the financial year ending March 2020, the CO2 emissions were estimated based on the above indicators for oil, coal, and gas consumption and it is observed that the CO2 emissions are dropped by 30m tons of CO2 (MtCO2, 1.4%). It is observed that in four decades, the emission level of CO2 has seen the first annual decline. Moreover, CO2 emissions dropped by 30% in April 2020 which is a follow-up to 15% fall year-on-year in March. According to Fig. 5b, the values for 2009 onwards correspond with financial years ending that March, with the 2020 number showing the fiscal year 2019–20.

[6] Home. https://posoco.in/reports/daily-reports/.

[7] Petroleum planing & analysis cell. https://www.ppac.gov.in/content/152_1_Consumption.aspx.

Data analysis

The current COVID-19 pandemic is a historic opportunity for India to recover the economy and accelerate the energy transition by strategizing their investments. The ongoing COVID-19 pandemic may control the long-term strategy of India's energy usage and emissions along with the current impact which it is having over CO2 emissions in India. India's renewable energy program could be energized by directing the post-COVID-19 economic stimulus towards it.It is important to impose structural changes in the power sector by providing necessary financial assistance as existing financial problems in the power sector got worsened owing to the plunge in the current electricity demand. The standards and targets could be strengthened by adding momentum from the currently observed exceptional air quality to the attempts and measures taken against controlling air pollution. The country's policymakers could be further catalyzed, reinforced, or accelerated by the current COVID-19 pandemic. For instance, as stated by the European members to initiate the recovery through renewable energy programs, India has also taken measures for supporting such programs. One of the main motivations of taking such measures is the affordability of solar offers in comparison with coal and electricity. With an average of 2.55–2.56 rupees per kilowatt-hour, a 2,000 megawatts (MW) of solar capacity was secured in a recent auction which happened in the middle of a phase of high uncertainty over the current financial situation and the performance of the futures market, and moreover, the auction being conducted during COVID-19 lockdown period (Myllyvirta 2020b). On the contrary, India's prime coal generator, the National Thermal Power Corporation (NTPC) charged an average of 3.38 Rs/kWh to a unit of electricity.[8] Owing to the implementation of stringent emission standards, inflation, and increased cost of operation; this is likely to go in an upward trend each year. Furthermore, the distribution companies were called by the Indian Government to make appropriate payments to power generators and impose strict rules to ensure the operation of current solar and wind projects and this shows another example of the country supporting the renewable energy industry during COVID-19 lockdown. For COVID-19 lockdown period, the deadlines for renewable energy project completion were extended by the MNRE which could prevent the renewable energy developers from any kind of penalty for missing their timelines. India is also working towards maximizing the capacity of manufacturing domestic renewable energy technologies through notifications to different states. Enhancing the industries' political weights and supply chains could assist in strengthening the renewable energy program by maximizing the domestic supply.

Forecasting renewable energy transition: a case study with off-grid solar applications

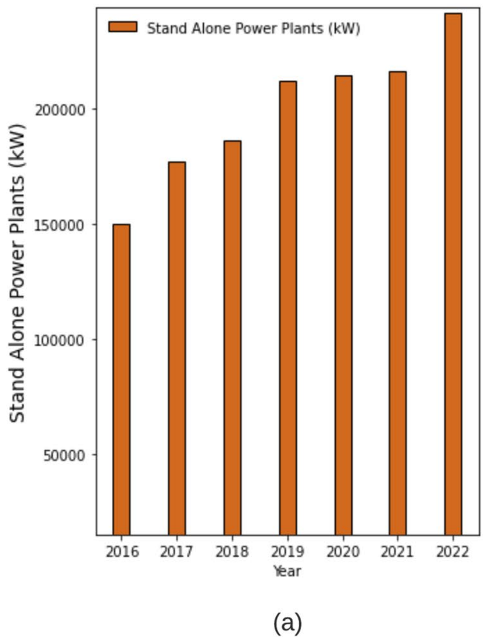
Since ancient times, the Sun has been revered as a life-giver to our world. The Industrial Revolution taught us how to use sunlight as a source of energy. India has a tremendous amount of solar energy potential. India's geographical area receives over 5,000 trillion kWh of energy each year, with most regions receiving 4–7 kWh per sq. m every day.

Solar photovoltaic electricity can be successfully harnessed in India, allowing for massive scalability. Solar also allows for dispersed power generation and allows for quick capacity expansion with short lead periods. One of the Indian ministry's oldest programs, the Off-Grid Solar PV Applications Program,[9] aims to provide solar PV-based applications in locations where grid electricity is either unavailable or unreliable. The program covers solar house lights, solar street lighting, solar power plants, solar pumps, solar lanterns, and solar study lamps, among other applications. Solar pumps are an important part of the Indian solar off-grid program because they provide dependable irrigation in rural and isolated regions. Solar photovoltaic water pumping systems may readily satisfy the irrigation needs of small and marginal farmers' landholdings. As a result, solar pumps are being employed to replace the existing diesel irrigation pump. Farmers will have a reliable supply of irrigation, which will enhance their revenue as well as their general economic standing and well-being. Rural electrification and fulfilling other energy demands for electricity, heating, and cooling in both rural and urban regions would benefit from off-grid decentralized and low-temperature applications. Solar is the most secure of all energy sources in terms of energy security since it is readily accessible. A small percentage of total incident solar energy (if caught efficiently) might theoretically fulfill the entire country's electricity needs.

Forecasting tools (Kariniotakis 2017) for renewable energy give useful information about the projected changes in energy generation in the near future. Renewable energy is becoming a larger part of the energy mix as fossil fuel supplies are depleted, and worries about climate change grow. Because solar, wind, wave, and hydro energy are all heavily reliant on weather, their growing penetration will result in significant variations in the power pumped into the electricity system, which must be regulated. For the easy

[8] Ntpc. https://www.ntpc.co.in/presentations/8262/presentation-15th-analysts-investors-meet-held-mumbai-19082019.

[9] Solar off-grid. https://mnre.gov.in/solar/solar-offgrid.



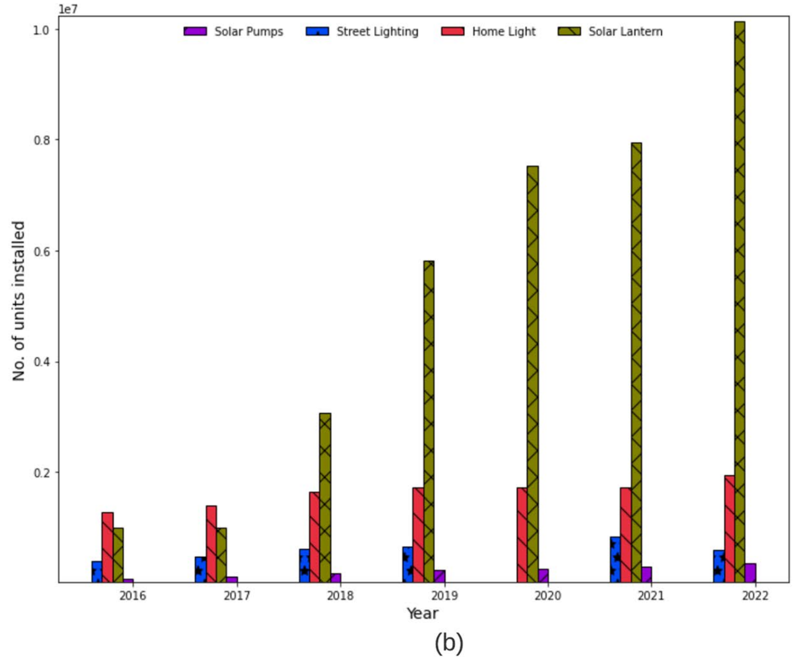


Fig. 6 (**a**). Predicted number of off-grid solar applications (**b**). Predicted Stand Alone Power Plants (kW)

Table 3 Forecasting off-grid applications

Year	Street Lighting	Home Light	Solar Lantern	Solar Pumps	Stand Alone Power Plants (kW)
2016	387632	1285877	996931	61834	150001.44
2017	464103	1407209	996931	114878	176847.36
2018	605249	1647821	3074002	171228	185900.07
2019	659218	1715214	5823800	237120	212054.17
2020	15029	1721343	7529365	256156	214565
2021	830373	1723479	7948219	286830	216407.67
2022	587247	1938529	10132680	353791	241842.77

integration of significant volumes of solar, wind, wave, and hydropower into the grid, as well as the profitability and efficacy of such renewable energy projects, reliable, high-quality predictions of renewable power output are required. Table 3 shows the forecasting of Off-grid applications for the year 2022 using Prophet (Mitchell 2021; Satrio et al. 2021), a procedure for forecasting time series data. Time series forecasting may be difficult due to the numerous techniques available and the numerous hyperparameters associated with each approach. The Prophet algorithm is built to discover a solid combination of hyperparameters to generate accurate forecasts for data with trends and seasonal structure. The prophet[10] is utilized in a variety of Facebook apps to generate accurate forecasts for planning and goal-setting. In the vast majority of situations, it is found to outperform any other strategy (Satrio et al. 2021). Outliers, missing data, and abrupt changes in the time series are handled efficiently using Prophet. For the year 2022, Fig. 6a shows the predicted number of off-grid solar applications, and Fig. 6b shows the predicted Stand Alone Power Plants (kW) using the Prophet algorithm.

It is observed that Street Lightings, Home Lights, Solar Lanterns, and Solar Pumps are expected to increase up to 18.97%, 22.42%, 130.56%, and 88.18%, and as compared to the average number of units installed during 2016–2021. Also, the Stand Alone Power Plants (kW) are expected to increase up to 25.55% compared to the average Stand Alone Power Plants (kW) recorded during 2016–2021.

[10] Forecasting at scale https://facebook.github.io/prophet/.

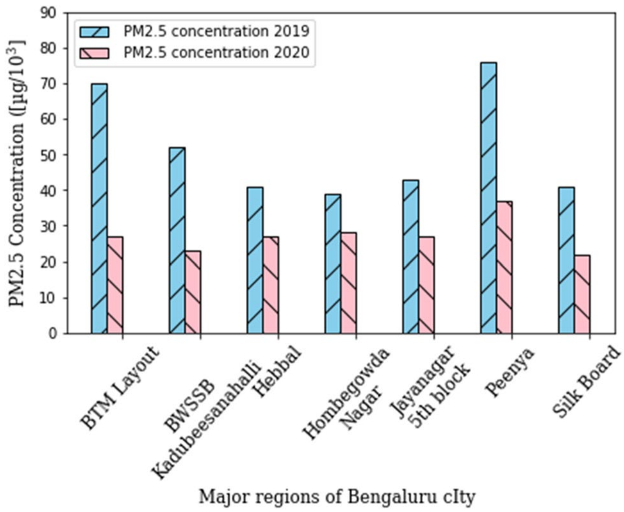


Fig. 7 PM2.5 concentration analysis in different parts of Bengaluru City during Phase 1 lockdown due to COVID-19

Air quality analysis: a case study with Bengaluru's partial lockdown

COVID-19 has influenced nationwide lockdowns that in turn allowed the air to be cleaner than before and led to a drop in the air pollution in major cities. For example, the World Air Quality Report issued by the World Health Organization (WHO) in 2019 has assessed PM2.5 of top cities across the globe from where it is found that Bengaluru, known as the Garden City of India and home to Information Technology Hubs, has had an annual average of 32.6 micrograms per meter cube while its standard value is 10 micrograms per meter cube (NewIndianXpress 2020). The main reasons behind such a high value of PM2.5 are emissions from vehicles, construction activities, poor traffic monitoring and management of traffic, etc. During Phase 1 lockdown due to COVID-19, the PM2.5 levels in major regions of Bengaluru have largely been under the acceptable limits in 2020 as compared to the same period in 2019[11] as shown in Fig. 7.

The lockdown in several Indian states resulted in the shutdown of power plants, transportation, and other businesses, resulting in a significant reduction in pollution concentration levels. Beginning in June 2020, services were restored in phases in India. "Unlock" was the name given to it. The government confirmed that the country's complete lockdown had ended and that the 'unlock' process had already begun. The lockdown was lifted in various zones with multiple relaxations. For most days from June 2020 to August 2021, the government imposed a partial lockdown on weekdays with severe travel restrictions and a partial/complete lockdown on the weekends in many states such as Bengaluru, India. Many non-essential business operations were be shut down in a desperate attempt to stop the spread of Covid-19 infections. Markets all around the city were compelled to close their doors. On weekdays, stores and institutions selling non-essential items, multiplexes, shops, malls, theaters, water parks, and clubs have been closed as part of the "partial restrictions." During partial lockdown in Bengaluru, buses, taxis, and other forms of public transportation were permitted to run at 50% of their capacity. Many private automobiles were only allowed for necessary purposes. Restaurants were allowed to provide takeout on weekdays and home delivery on weekends. Only takeout was allowed in stand-alone liquor vends and only on weekdays. Private offices in critical areas such as banking, insurance, medicine, water, and electricity supply were permitted to function from their offices, while government offices dealing with the pandemic were fully operational. Malls, movie theaters, gyms, and swimming pools were all closed. Marriage, funerals, and public gatherings were prohibited with tight restrictions. Metro rail and bus services were permitted, but with strict social distancing. Curfews were set at night to prevent needless movement. All facilities in the necessary commodities supply chain were allowed to operate, including wholesale and retail of such items through local shops and e-commerce firms. Restrictions like officials requiring ID cards for office work and students taking exams were required to present entrance tickets as a transit permit. The operation of all industrial operations, industrial enterprises, and production units was permitted. The employees were allowed to walk about by displaying ID cards supplied by the respective industries. All types of building and civil repair work were allowed. Outside the confinement zones, all agricultural-related operations, including stores and godowns, were allowed to operate. Most government agencies were urged to work from home. All health-related services remained operational, including AYUSH and veterinary facilities.

This section aims to study the impact of partial lockdowns on Bengaluru's air quality levels. We are primarily interested in the impact on specific air pollutants, such as PM2.5, PM10, and NO2.

Bengaluru has greater air pollution than some of the most polluted cities in the United States. Construction and automobile traffic are the villains in this metropolis (Anien 2021), unlike Delhi, another heavily polluted Indian city where stubble burning, in addition to vehicular and industrial pollutants, contributes to air pollution. Air pollution is a major problem in India. In India, one out of every eight fatalities is caused by this disease. Because of air pollution, life expectancy has been reduced by an average of 5.25 years. Bengaluru witnessed an 80% increase in respiratory diseases between 2015 and 2020. The most polluted people are those who ride two-wheelers, street sellers, and construction

[11] National air quality index. https://app.cpcbccr.com/AQI_India/.

Table 4 Climate factors affecting air pollutant concentrations

Climate Features	PM2.5	PM10	NO2
T: Average Temperature (°C)	0.03664602	0.03316525	0.04767059
TM:Maximum temperature (°C)	0.01763994	0.03148776	0.01931601
Tm: Minimum temperature (°C)	0.09971398	0.0960497	0.21996907
H: Average relative humidity (%)	0.0800367	0.08955058	0.09324564
VM: Maximum sustained wind speed (Km/h)	0.12050093	0.10674678	0.09099328
VV: Average visibility (Km)	0.21300068	0.22666861	0.28990238
V: Average wind speed (Km/h)	0.43246175	0.41633132	0.23890303

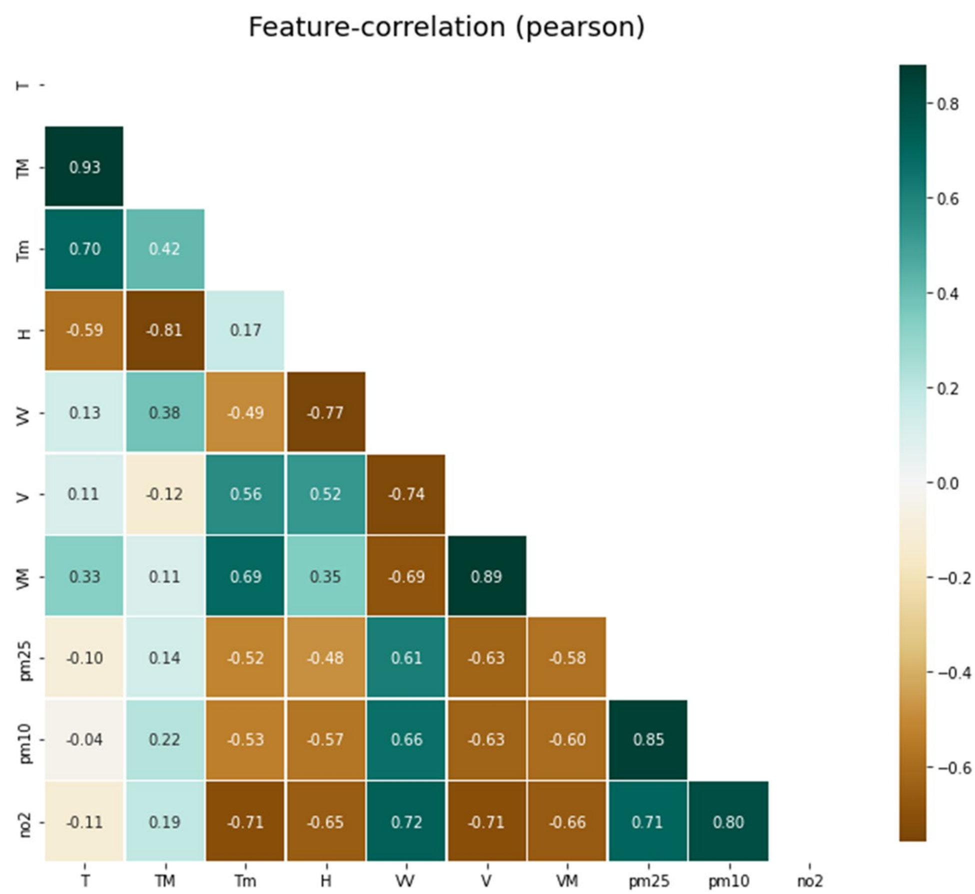


Fig. 8 Correlation values among different features

workers. Bengaluru's major pollutants are PM10 and PM2.5. Unlike Delhi, Bengaluru contributes more to air pollution through transportation. According to research by The Energy and Resources Institute,[12] PM10 is mostly caused by transportation (42%) and road dust (20%). Because vehicular activity stirs up road dust, a considerable portion of the 20% should be allocated to transportation, bringing transportation's contribution to over 50%. While particle matter (PM) continues to be the focus of attention due to its role in rising air pollution levels, nitrogen dioxide (NO2) is often ignored. Smog's reddish-brown color is caused by NO2, a toxic gas that reacts with other pollutants in the air to form ozone, which causes respiratory illnesses such as asthma. Experts (Contributor 2020) have expressed concern about the rising levels of NO2 in Bengaluru, citing vehicular traffic and garbage mishandling as the major causes. Vehicles, garbage burning, agricultural soil management, and industrial waste all contribute to the production of NO2 in Bengaluru. The burning of fuel by vehicles is mainly causing a rise in NO2. Short and long-term exposure to ambient air pollution can decrease lung function, respiratory infections, and asthma exacerbation in both children and adults. This section aims to study the impact of the stringent measures taken during the partial lockdown on the air quality. The dataset is downloaded and imported from Tutiempo Network (2015). It provides data from Jun. 2020 - Aug. 2021 (partial lockdown period) on average hourly measurement of key air pollutants

[12] Creating innovative solutions in energy, environment and sustainable development to accelerate india's transition to a cleaner future. https://www.teriin.org/.

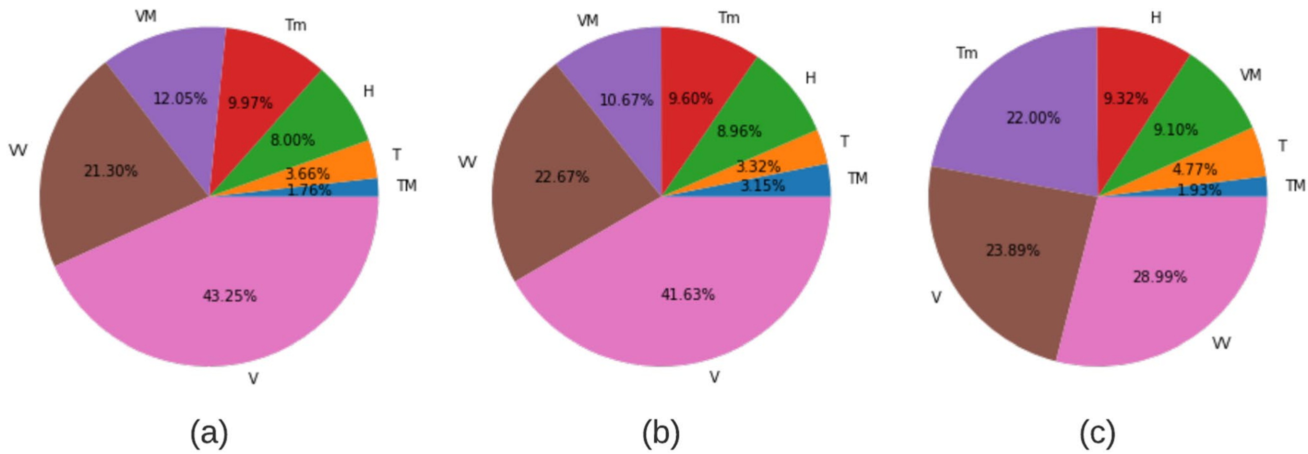


Fig. 9 Prediction of most important features

in Bengaluru city. Using regression analysis, this dataset is utilized to estimate the level of pollutants, namely PM2.5, PN10, and NO2, depending on key parameters. As shown in Table 4, the dataset includes seven key features, namely T, TM, Tm, H, VM, VV, V that aid in air quality prediction. The contribution of different features in assisting the prediction of the pollutant levels are shown in Fig. 8 as well as recorded in Table 4. The dataset is first preprocessed with appropriate approaches to eliminate inconsistent and missing valued data, and the required features from the dataset are then picked for better results. The dataset is then divided into train and test datasets in order to assess the model's performance. For reliable findings, the generated data sets are examined using 37 regression analysis techniques. Regression analysis is a predictive modeling approach that explores the relationship between independent (T, TM, Tm, H, VM, VV, V) Table 4 and dependent (PM2.5, PM10, NO2) variables. Pearson Correlation [100] is used to determine the correlation among the different features as shown in Fig. 8. Figure 9 shows the important features extracted using ExtraTreesRegressor (Reza and Haque 2020).

The prediction results and the key performance metrics, namely Adjusted R-squared (R^2_{adj}), R-squared (R^2), Root Mean Square Error (RMSE), algorithm running time (t_r), and prediction results (μ_{pr}) of all the 37 regression models are shown in Table 5. Considering the key performance metrics, KNeighborsRegressor (Tunkiel et al. 2022; Yasir et al. 2022) has given the best prediction results of 79.94 μg/m^3, 46.36 μg/m^3, and 8.86 ppb for PM2.5, PM10, and NO2, respectively. The average pollutant levels recorded during the pre-lockdown period (measured from Feb. 2019 to Feb 2020) for PM2.5, PM10, and NO2 are 99.96 μg/m^3, 58.65 μg/m^3, and 18.17 ppb. Thus, the pollutant levels of PM2.5, PM10, and NO2 are less than 20.04%, 20.95%, and 51.25% compared to the corresponding levels recorded during Feb. 2019 to Feb. 2020. As seen, the significant drop in NO2 levels is attributed to the reduction in vehicular movements due to stringent measures taken by the government during the period of partial lockdown. This study raises public awareness about the impact of poor air quality on people's health and supports environmentalists and the government in developing air quality standards and regulations based on hazardous and pathogenic air exposure and health-related risks to human welfare. As a result of less human activity, the amount of air pollution in Bengaluru decreased considerably throughout the partial lockdown periods. According to this study, air quality can be improved if rigorous procedures are applied, as seen during the partial lockdown. Other vehicles, such as jeeps and taxis, play a larger role in the vehicle fleet than other vehicles. In Bengaluru Urban, they account for roughly 21.5% of all cars. Over 35% of them run on diesel, which is a more harmful fuel.

The air pollution level and CO2 emissions have been observed to decline over the past year. There is a sense of belief among policymakers and the public that, with appropriate strategic measures, there is a definite chance of achieving cleaner air in India with the lockdown enforcing no taxis, no passenger trains, no flights, and only a few industries under-functioning, which are the major causes of India's CO2 emissions. Additionally, if the government considers taking measures to improve air quality standards, emission levels could further be reduced. With an aim to minimize air pollution levels by 20–30% across 102 cities by 2024 due to public demand, the National Clean Air Programme was introduced by the Indian Government.[13] The 2009 Air Quality Standards imposed by the Indian Government for the maximum permissible limits for pollutants require reassessment to improve its standards as there are reports regarding

[13] India National Clean Air Programme. https://urbanemissions.info/blog-pieces/india-ncap-review/.

Table 5 Pollutants prediction test results with regression algorithms

Models	PM2.5					PM10					NO2				
	R^2_{adj}	R^2	RMSE	t_r	μ_{pr}	R^2_{adj}	R^2	RMSE	t_r	μ_{pr}	R^2_{adj}	R^2	RMSE	t_r	μ_{pr}
AdaBoostRegressor (Al-Ash et al. 2019)	0.42	0.48	24.27	0.03	74.47	0.49	0.54	13.75	0.03	45.02	0.73	0.76	3.24	0.03	8.2
BaggingRegressor (Kadiyala and Kumar 2018)	0.46	0.51	23.49	0.03	74.06	0.47	0.52	14.12	0.03	44.8	0.78	0.8	2.95	0.04	8.42
BayesianRidge (Yang and Yang 2020)	0.49	0.54	22.83	0.01	74.07	0.47	0.52	14.09	0.01	45.04	0.77	0.79	3.03	0.01	8.27
DecisionTreeRegressor (Gupta et al. 2021)	0.46	0.51	23.4	0.01	74.2	0.49	0.54	13.82	0.01	45.15	0.8	0.82	2.8	0.01	8.29
DummyRegressor (Kwan-to 2001)	−0.11	−0.01	33.75	0.01	73.69	−0.1	0	20.3	0.01	44.12	−0.11	−0.01	6.61	0.01	7.95
ElasticNet (Hans 2011)	0.45	0.51	23.62	0.01	74.89	0.45	0.5	14.4	0.01	45.12	0.62	0.66	3.84	0.01	8.34
ElasticNetCV (Qaraad et al. 2021)	0.49	0.54	22.81	0.07	74.53	0.48	0.53	13.98	0.07	45.04	0.77	0.79	3.04	0.08	8.29
ExtraTreesRegressor (Reza and Haque 2020)	0.46	0.51	23.4	0.11	74.20	0.49	0.54	13.82	0.11	45.14	0.8	0.82	2.8	0.11	8.28
GammaRegressor (Tao et al. 2021)	0.45	0.5	23.72	0.01	74.86	0.44	0.49	14.48	0.01	45.17	0.59	0.63	4.03	0.01	8.25
GaussianProcessRegressor															
(Stamenkovic et al. 2017)	0.46	0.51	23.4	0.03	74.20	0.49	0.54	13.82	0.03	45.14	0.8	0.82	2.8	0.02	8.28
GradientBoostingRegressor (Li et al. 2018)	0.46	0.51	23.4	0.1	74.20	0.49	0.54	13.82	0.08	45.14	0.8	0.82	2.8	0.11	8.28
HistGradientBoostingRegressor															
(Hirasen et al. 2021)	0.46	0.51	23.39	0.15	74.20	0.49	0.54	13.77	0.19	45.17	0.8	0.82	2.8	0.14	8.29
HuberRegressor (Malki et al. 2020a)	0.58	0.62	20.67	0.03	73.01	0.58	0.62	12.56	0.03	44.46	0.78	0.8	2.94	0.03	8.21
KernelRidge (Vovk 2013)	−4.31	−3.81	73.67	0.04	73.41	−4.45	−3.94	45.13	0.02	44.56	−0.94	−0.76	8.74	0.02	8.18
KNeighborsRegressor (Patel et al. 2020)	0.58	0.62	20.63	0.01	79.94	0.59	0.62	12.43	0.02	46.36	0.84	0.85	2.54	0.01	8.86
Lars (Miche et al. 2011)	0.48	0.53	23.06	0.03	73.14	−4.05	−3.58	43.45	0.02	45.79	0.8	0.82	2.81	0.02	8.29
LarsCV (Manjunathan et al. 2021)	0.47	0.52	23.32	0.08	74.35	0.46	0.51	14.26	0.08	44.88	0.76	0.78	3.1	0.03	8.30
Lasso (Park and Casella 2008)	0.46	0.51	23.41	0.02	74.28	0.46	0.51	14.26	0.02	45.10	0.69	0.72	3.5	0.03	8.35
LassoCV (Muir and Zhan 2019)	0.54	0.58	21.75	0.15	73.86	0.55	0.59	12.95	0.15	44.90	0.78	0.8	2.97	0.11	8.28
LassoLars (Usai et al. 2012)	0.06	0.15	30.99	0.01	73.58	−0.1	0	20.3	0.01	44.11	−0.11	−0.01	6.61	0.01	7.95
LassoLarsCV (Leyva et al. 2019)	0.54	0.59	21.62	0.04	73.64	0.57	0.61	12.73	0.04	44.80	0.78	0.8	2.96	0.03	8.26
LassoLarsIC (Rao et al. 2020)	0.54	0.58	21.7	0.02	73.64	0.56	0.61	12.76	0.02	44.80	0.75	0.78	3.12	0.02	8.31
LinearRegression (Montgomery et al. 2021)	0.54	0.59	21.62	0.01	73.64	0.57	0.61	12.73	0.01	44.80	0.78	0.8	2.91	0.01	8.26
LinearSVR (Ho and Lin 2012)	0.46	0.51	23.56	0.01	73.84	0.45	0.5	14.35	0.01	50.69	0.77	0.79	3.02	0.02	11.98
MLPRegressor (Gabralla and Abraham 2014)	−0.17	−0.06	34.6	0.71	72.96	0.23	0.3	16.98	0.71	44.23	0.73	0.75	3.26	0.71	7.96
NuSVR (Faraone 2019)	0.35	0.41	25.73	0.03	71.57	0.44	0.49	14.47	0.05	44.49	0.8	0.82	2.83	0.05	7.72
OrthogonalMatchingPursuit (Wang et al. 2012)	0.33	0.39	26.25	0.04	73.12	0.35	0.42	15.52	0.04	44.79	0.43	0.49	4.73	0.02	8.17
OrthogonalMatchingPursuitCV															
(Kallummil and Kalyani 2018)	0.47	0.52	23.3	0.05	73.96	0.45	0.5	14.31	0.03	44.74	0.76	0.78	3.09	0.02	8.35
PassiveAggressiveRegressor (Malki et al. 2020b)	0.5	0.54	22.7	0.02	101.01	0.2	0.27	17.3	0.01	35.17	0.69	0.72	3.48	0.02	4.21
PoissonRegressor (Ranzato and Szummer 2008)	0.5	0.55	22.64	0.02	73.94	0.47	0.51	14.14	0.02	45.12	0.71	0.74	3.38	0.02	8.32
RandomForestRegressor (Graw et al. 2021)	0.47	0.52	23.36	0.19	74.12	0.49	0.53	13.86	0.18	45.12	0.8	0.82	2.82	0.18	8.28
RANSACRegressor (Aziz et al. 2020)	0.46	0.51	23.51	0.08	71.43	0.41	0.47	14.8	0.08	40.97	0.75	0.78	3.11	0.07	6.85

health issues emerging from low concentrations of pollutants (Vodonos et al. 2018) and needs to be benchmarked with the guidelines provided by WHO (2019). In spite of the flattering conditions for boosting the renewable energy sector, the government may not restrict coal generators from operation and is still expected to meet the basic demands even after the COVID-19 lockdown period.

Conclusion

Over the past six years, only few countries have steadily progressed on the annual ETI which proves the challenges and complexities involved for a successful energy transition. India's energy transition can be unlocked through efficiently strategizing technology development, investment, capital, political commitment, and regulating energy policies along with redeveloping standards. Machine learning techniques were used in this work for pre-COVID and post-COVID data analysis and forecasting. Through the analysis, it is observed that renewable energy sources are expected to increase in the post-COVID era as the pandemic has triggered a transition for the better. Partial lockdowns were imposed, leading to partial interventions in public transportation and office operations while the economy was not adversely affected. Analysis of air quality during the partial lockdown suggests a massive improvement in pollutant levels. Thus, governments should be encouraged to develop a system that can balance the economy as well as the environment's stability. There is a growing concern about India's efforts to strengthen their climate plans in this decade, considering their ability to withstand the impact of the economic slowdown. The COVID-19 pandemic has led to less road traffic and the closure of factories that have shrunk the demand for coal and other fossil fuels. It may be the case that emissions may decline and the air quality may improve in 2020. On the other hand, the reduction in emission levels is not a reason to rejoice as it must be highly influenced via efficient energy policies. Though the decade has begun in the worst possible manner due to the COVID-19 pandemic, the current situation also offers an opportunity to consider different strategies for stabilizing the energy markets and encouraging the use of renewable energy for a cleaner India. The government should ensure that the post-COVID-19 renewable energy systems sustain the expansion of a more prosperous environment and build communities more resilient to future pandemics and climate shocks.

Author Contributions Thompson Stephan: conceptualization of this study, methodology, software, writing — original draft. Fadi Al-Turjman: supervision, project administration. Monica Ravishankar: resources, data curation, writing — review and editing. Punitha Stephan: supervision, project administration.

Table 5 (continued)

Models	PM2.5					PM10					NO2				
	R^2_{adj}	R^2	RMSE	t_r	μ_{pr}	R^2_{adj}	R^2	RMSE	t_r	μ_{pr}	R^2_{adj}	R^2	RMSE	t_r	μ_{pr}
Ridge (McDonald 2009)	0.52	0.56	22.25	0.01	73.68	0.51	0.55	13.59	0.02	44.81	0.77	0.79	3.02	0.01	8.26
RidgeCV (Padhi and Padhy 2021)	0.54	0.58	21.73	0.01	73.64	0.55	0.59	12.92	0.01	44.81	0.78	0.8	2.94	0.01	8.26
SVR (Abo-Khalil and Lee 2008)	0.37	0.43	25.37	0.02	65.29	0.47	0.52	14.1	0.02	39.79	0.79	0.81	2.86	0.02	6.45
TransformedTargetRegressor (Brownlee 2020)	0.54	0.59	21.62	0.02	73.64	0.57	0.61	12.73	0.01	44.8	0.78	0.8	2.91	0.01	8.26
TweedieRegressor (Russo et al. 2020)	0.44	0.49	24.01	0.01	75.1	0.44	0.49	14.52	0.02	45.12	0.61	0.65	3.9	0.02	8.34

Data availability The authors do not have the authorization to share the data publicly.

Declarations

Ethics approval and consent to participate This section is not applicable to us as our manuscript does not report on or involve the use of any animal or human data or tissue.

Consent for publication This section is not applicable to us as our manuscript does not contain data from any individual person.

Competing interests The authors declare no competing interests.

References

Abo-Khalil AG, Lee DC (2008) Mppt control of wind generation systems based on estimated wind speed using SVR. IEEE Transactions on Industrial Electronics 55:1489–1490

Al-Ash HS, Putri MF, Arymurthy AM, Bustamam A (2019) An ensemble learning approach on Indonesian wind speed regression. In: 2019 12th international conference on information & communication technology and system (ICTS). IEEE. pp 76–80

Ali S, Tongia R (2019) The future of Indian electricity supply: Scenarios of coal use by 2030. https://brook.gs/3FslC0Z

Ambrose J (2020) Carbon emissions from fossil fuels could fall by 2.5bn tonnes in 2020. https://www.theguardian.com/environment/2020/apr/12/global-carbon-emissions-could-fall-by-record-25bn-tonnes-in-2020

Anien TS (2021) How bad is bengaluru air? https://www.deccanherald.com/metrolife/metrolife-your-bond-with-bengaluru/how-bad-is-bengaluru-air-909370.html

Arora P (2020) Impact of COVID-19 on energy sector - recent government notifications and initiatives - energy and natural resources - India. https://bit.ly/3mwOZqo

Aziz S, Ullah S, Mughal B, Mushtaq F, Zahra S (2020) Roman urdu sentiment analysis using machine learning with best parameters and comparative study of machine learning algorithms. Pakistan Journal of Engineering and Technology 3:172–177

Bao R, Zhang A (2020) Does lockdown reduce air pollution? evidence from 44 cities in northern China. Science of the Total Environment 731:139052

Bashir MF, Jiang B, Komal B, Bashir MA, Farooq TH, Iqbal N, Bashir M et al (2020) Correlation between environmental pollution indicators and covid-19 pandemic: a brief study in californian context. Environmental Research 187:109652

Bashir MF, Ma B, Komal B, Bashir MA, Tan D, Bashir M et al (2020) Correlation between climate indicators and COVID-19 pandemic in New York, USA. Science of The Total Environment 728:138835

Bashir MF, Benghoul M, Numan U, Shakoor A, Komal B, Bashir MA, Bashir M, Tan D et al (2020) Environmental pollution and COVID-19 outbreak: insights from Germany. Air Quality, Atmosphere & Health 13:1385–1394

Bashir MF, Shahzad K, Komal B, Bashir MA, Bashir M, Tan D, Fatima T, Numan U et al (2021) Environmental quality, climate indicators, and COVID-19 pandemic: insights from top 10 most affected states of the USA. Environmental Science and Pollution Research 28:32856–32865

Bontempi E, Carnevale C, Cornelio A, Volta M, Zanoletti A (2022) Analysis of the lockdown effects due to the COVID-19 on air pollution in brescia (lombardy). Environ Res, p 113193

Bossong K (2020) Solar and wind energy provide almost 10 percent of total generation in the us in 2019. https://bit.ly/3FqBukD

Brownlee J (2020) Data preparation for machine learning: data cleaning, feature selection, and data transforms in Python. Mach Learn Mastery

Burns CJ, LaKind JS, Naiman J, Boon D, Clougherty JE, Rule AM, Zidek A (2022) Research on COVID-19 and air pollution: A path towards advancing exposure science. Environ Res, 113240

Chakraborty S, (2020) Core sector output shrinks by 6.5% in march amid coronavirus lockdown. https://bit.ly/3oJh4NS

Chauhan A, Singh RP (2020) Decline in pm2. 5 concentrations over major cities around the world associated with COVID-19. Environmental Research 187:109634

Collivignarelli MC, Abbà A, Bertanza G, Pedrazzani R, Ricciardi P, Miino MC (2020) Lockdown for COVID-2019 in Milan: What are the effects on air quality? Science of the total Environment 732:139280

Contributor D (2020) Nitrogen dioxide: A major pollutant in Bengaluru. https://www.deccanherald.com/city/focus-bengaluru/nitrogen-dioxide-a-major-pollutant-in-bengaluru-807419.html

Dantas G, Siciliano B, França BB, da Silva CM, Arbilla G (2020) The impact of COVID-19 partial lockdown on the air quality of the city of Rio De Janeiro, Brazil. Science of the Total Environment 729:139085

Darius Snieckus DS (2020) Coronavirus crisis an 'excellent opportunity' to speed global energy transition: Birol. https://bit.ly/3loRsn6

Eric M (2020) On earth day 2020, coronavirus shutdowns are a gift to the environment. https://cnet.co/3AlEN8T

Faraone SV (2019) Nu support vector machine in prediction of fluid intelligence using mri data. Adolescent Brain Cognitive Development Neurocognitive Prediction: First Challenge, ABCD-NP 2019, Held in Conjunction with MICCAI 2019, Shenzhen, China, October 13, 2019, Proceedings 11791, 92

Gabralla LA, Abraham A (2014) Prediction of oil prices using bagging and random subspace. In: Proceedings of the fifth international conference on innovations in bio-inspired computing and applications IBICA 2014. Springer, pp 343–354

GECF (2022) Expert commentary - COVID-19 and its implications on the italian natural gas market. https://bit.ly/3mDWkEF

Ghosh I (2020) These satellite photos show how COVID-19 lockdowns have impacted global emissions. https://www.weforum.org/agenda/2020/03/emissions-impact-coronavirus-lockdowns-satellites/

Government of India (2020) Monthly production report. https://mopng.gov.in/files/petroleumStatistics/monthlyProduction/mproct20.pdf

Government of India (2020c) #indiafightscorona COVID-19. https://www.mygov.in/covid-19/

Graw J, Wood W, Phrampus B (2021) Predicting global marine sediment density using the random forest regressor machine learning algorithm. Journal of Geophysical Research: Solid Earth 126:e2020JB020135

Gupta U (2019) India will add 144 gw renewables by 2022, exceed 275 gw by 2027: Ieefa. https://bit.ly/3uRopMn

Gupta A, Bansal A, Roy K et al (2021) Solar energy prediction using decision tree regressor. In: 2021 5th international conference on intelligent computing and control systems (ICICCS), IEEE, pp 489–495

Guttikunda SK, Jawahar P (2014) Atmospheric emissions and pollution from the coal-fired thermal power plants in India. Atmospheric Environment 92:449–460

Hans C (2011) Elastic net regression modeling with the orthant normal prior. Journal of the American Statistical Association 106:1383–1393

Hirasen D, Pillay V, Viriri S, Gwetu M (2021) Skeletal age estimation from hand radiographs using ensemble deep learning.

In: Mexican conference on pattern recognition. Springer, pp 173–183

Ho CH, Lin CJ (2012) Large-scale linear support vector regression. The Journal of Machine Learning Research 13:3323–3348

Iea (2020) Renewables - global energy review 2020 - analysis. https://www.iea.org/reports/global-energy-review-2020/renewables

Jeff M (2020) Study: Coronavirus lockdown likely saved 77,000 lives in China just by reducing pollution. https://bit.ly/3Ao7eDl

Kadiyala A, Kumar A (2018) Applications of python to evaluate the performance of bagging methods. Environmental Progress & Sustainable Energy 37:1555–1559

Kallummil S, Kalyani S (2018) Signal and noise statistics oblivious orthogonal matching pursuit. In: International conference on machine learning. PMLR. pp. 2429–2438

Kariniotakis G (2017) Renewable energy forecasting: from models to applications. Woodhead Publishing

Kerimray A, Baimatova N, Ibragimova OP, Bukenov B, Kenessov B, Plotitsyn P, Karaca F (2020) Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in almaty. Kazakhstan. Science of the Total Environment 730:139179

Khadka N (2020) Air pollution linked to raised COVID-19 death risk. Environment correspondent. BBC World Service https://www.bbc.com/news/health-52351290. Retrieved on 23 Apr 2020

Kohli A (2020) Because of no pollution i can see...' hilarious trend takes over twitter. https://www.hindustantimes.com/it-s-viral/because-of-no-pollution-i-can-see-hilarious-trend-takes-over-twitter/story-CykQiSGlY7stGJ1AeU2ksL.html

Koundal A (2020) India's renewable energy generation grows 9.46 per cent in jan 2020 - et energyworld. https://energy.economictimes.indiatimes.com/news/renewable/indias-renewable-energy-generation-grows-9-46-per-cent-in-jan-2020/74442008

Kwan-to W (2001) Identification of structural-change models when the dummy regressor is misclassified. Ph.D. thesis. The Chinese University of Hong Kong

Lal P, Kumar A, Kumar S, Kumari S, Saikia P, Dayanandan A, Adhikari D, Khan M (2020) The dark cloud with a silver lining: Assessing the impact of the sars covid-19 pandemic on the global environment. Science of the Total Environment 732:139297

Levy A (2020) Covid-19 could help solve climate riddles. https://www.scientificamerican.com/article/covid-19-could-help-solve-climate-riddles1/

Leyva R, Doctor F, Seco de Herrera A, Sahab S, (2019) Multimodal deep features fusion for video memorability prediction

Li X, Li W, Xu Y (2018) Human age prediction based on DNA methylation using a gradient boosting regressor. Genes 9:424

Li L, Li Q, Huang L, Wang Q, Zhu A, Xu J, Liu Z, Li H, Shi L, Li R et al (2020) Air quality changes during the COVID-19 lockdown over the yangtze river delta region: An insight into the impact of human activity pattern changes on air pollution variation. Science of the Total Environment 732:139282

Mahato S, Pal S, Ghosh KG (2020) Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi. India. Science of the Total Environment 730:139086

Malki Z, Atlam ES, Hassanien AE, Dagnew G, Elhosseini MA, Gad I (2020) Association between weather data and COVID-19 pandemic predicting mortality rate: Machine learning approaches. Chaos, Solitons & Fractals 138:110137

Malki Z, Atlam ES, Hassanien AE, Dagnew G, Elhosseini MA, Gad I (2020) Association between weather data and COVID-19 pandemic predicting mortality rate: Machine learning approaches. Chaos, Solitons & Fractals 138:110137

Manjunathan N et al (2021) Feature selection intent machine learning based conjecturing workout burnt calories. Turkish Journal of Computer and Mathematics Education (TURCOMAT) 12:1729–1742

Manka Behl / TNN / Apr 18 (2022) No2 levels drop steeply as lockdown stops fossil fuel burning: Nagpur news - times of India. https://timesofindia.indiatimes.com/city/nagpur/no2-levels-drop-steeply-as-lockdown-stops-fossil-fuel-burning/articleshow/75210422.cms

McDonald GC (2009) Ridge regression. Wiley Interdisciplinary Reviews: Computational Statistics 1:93–100

Miche Y, Van Heeswijk M, Bas P, Simula O, Lendasse A (2011) Trop-elm: a double-regularized elm using lars and tikhonov regularization. Neurocomputing 74:2413–2421

Mishra R (2022) India's dependence on fossil fuels. https://www.thehindubusinessline.com/economy/indias-dependence-on-fossil-fuels-will-continue-to-be-high/article30809388.ece

Mitchell K (2021) Time series analysis with facebook prophet: How it works and how to use it. https://bit.ly/2YwltZb

Montgomery DC, Peck EA, Vining GG (2021) Introduction to linear regression analysis. John Wiley & Sons, New York

Muhammad S, Long X, Salman M (2020) COVID-19 pandemic and environmental pollution: A blessing in disguise? Science of the Total Environment 728:138820

Muir JB, Zhan Z (2019) Wavefield reconstruction and surface wave tomography from lassocv. In: AGU fall meeting abstracts. pp S54A–02

Myllyvirta L (2020a) Analysis: India's co2 emissions growth poised to slow sharply in 2019. https://www.carbonbrief.org/analysis-indias-co2-emissions-growth-poised-to-slow-sharply-in-2019

Myllyvirta L (2021) Analysis: India's co2 emissions fall for first time in four decades amid coronavirus. https://bit.ly/3iHRs00

Myllyvirta L, SGC (2020b) India's co2 emissions fall for first time in four decades amid coronavirus. https://www.weforum.org/agenda/2020/05/india-emissions-enviroment-air-pollution-coronavirus-covid19

Nair A (2020) Coronavirus: Full list of red, orange, green districts in India. https://bit.ly/2WTYwPt

Nakada LYK, Urban RC (2020) COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo State. Brazil. Science of the Total Environment 730:139087

NewIndianXpress (2019) 'India to meet solar power target of 100 gw by 2022'. https://www.newindianexpress.com/nation/2019/dec/29/india-to-meet-solar-power-target-of-100-gw-by-2022-2082352.html

NewIndianXpress (2020) Bengaluru's air quality inching towards danger levels. https://www.newindianexpress.com/cities/bengaluru/2020/feb/26/bengalurus-air-quality-inching-towards-danger-levels-2108652.html

Online F (2020) Tcs 'work from home' policy: Only one-fourth of workers to come to office; ceo explains vision 25×25. https://bit.ly/3oO5eCd

Otmani A, Benchrif A, Tahri M, Bounakhla M, El Bouch M, Krombi M et al (2020) Impact of COVID-19 lockdown on pm10, so2 and no2 concentrations in Salé city (Morocco). Science of the Total Environment 735:139541

Padhi DK, Padhy N (2021) Prognosticate of the financial market utilizing ensemble-based conglomerate model with technical indicators. Evolutionary Intelligence 14:1035–1051

Pal SC, Chowdhuri I, Saha A, Ghosh M, Roy P, Das B, Chakrabortty R, Shit M, (2022) COVID-19 strict lockdown impact on urban air quality and atmospheric temperature in four megacities of India. Geosci Front, 101368

Pardasani D (2018) Amendments to electricity act, 2003 - energy and natural resources - India. https://www.mondaq.com/india/renewables/764430/amendments-to-electricity-act-2003

Park T, Casella G (2008) The Bayesian lasso. Journal of the American Statistical Association 103:681–686

Patel N, Patel D, Patel S, Patel V, (2020) Crop yield estimation using machine learning. In: International conference on soft computing and its engineering applications. Springer, pp 328–342

Pti (2020) COVID-19 impact: India's coal import drops over 27 percent in march. https://bit.ly/3uUj1I4

PTI (2020) Crude steel output in march slumps to 7.38 mt due to COVID-19. https://bit.ly/3v60x7X

Qaraad M, Amjad S, Manhrawy II, Fathi H, Hassan BA, El Kafrawy P (2021) A hybrid feature selection optimization model for high dimension data classification. IEEE Access 9:42884–42895

Ranzato M, Szummer M, (2008) Semi-supervised learning of compact document representations with deep networks. In: Proceedings of the 25th international conference on Machine learning. pp 792–799

Rao AR, Garai S, Dey S, Peng H (2020) Building predictive models of healthcare costs with open healthcare data. In: 2020 IEEE international conference on healthcare informatics (ICHI). IEEE. pp 1–3

Ravindra K, Singh T, Vardhan S, Shrivastava A, Singh S, Kumar P, Mor S (2022) COVID-19 pandemic: What can we learn for better air quality and human health? Journal of Infection and Public Health 15:187–198

Reza M, Haque MA (2020) Photometric redshift estimation using extratreesregressor: Galaxies and quasars from low to very high redshifts. Astrophysics and Space Science 365:1–9

Rugani B, Caro D (2020) Impact of COVID-19 outbreak measures of lockdown on the italian carbon footprint. Science of the Total Environment 737:139806

Russo C, Liu S, Di Ieva A, (2020) Impact of spherical coordinates transformation pre-processing in deep convolution neural networks for brain tumor segmentation and survival prediction. arXiv:2010.13967

Saadat S, Rawtani D, Hussain CM (2020) Environmental perspective of COVID-19. Science of the Total Environment 728:138870

Satrio CBA, Darmawan W, Nadia BU, Hanafiah N (2021) Time series analysis and forecasting of coronavirus disease in Indonesia using arima model and prophet. Procedia Computer Science 179:524–532

Sharma S, Zhang M, Gao J, Zhang H, Kota SH et al (2020) Effect of restricted emissions during COVID-19 on air quality in India. Science of the Total Environment 728:138878

Shuai Z, Iqbal N, Hussain RI, Shahzad F, Yan Y, Fareed Z, et al (2021) Climate indicators and COVID-19 recovery: A case of wuhan during the lockdown. Environ Dev Sustain, 1–21

Shumkov I (2020) World seen to add 13% less renewables in 2020 as virus intensifies current challenges. https://bit.ly/3Bnx4s9

Sicard P, De Marco A, Agathokleous E, Feng Z, Xu X, Paoletti E, Rodriguez JJD, Calatayud V (2020) Amplified ozone pollution in cities during the COVID-19 lockdown. Science of the Total Environment 735:139542

Singh S (2015) How long will fossil fuels last? https://www.business-standard.com/article/punditry/how-long-will-fossil-fuels-last-115092201397_1.html

Stamenkovic J, Guerriero L, Ferrazzoli P, Notarnicola C, Greifeneder F, Thiran JP (2017) Soil moisture estimation by sar in alpine fields using gaussian process regressor trained by model simulations. IEEE Transactions on Geoscience and Remote Sensing 55:4899–4912

Steffen B, Egli F, Pahle M, Schmidt TS (2020) Navigating the clean energy transition in the COVID-19 crisis. Joule 4:1137–1141

Tao X, Shaik T, Higgins N, Gururajan R, Zhou X (2021) Remote patient monitoring using rfid technology and ml for early detection of suicidal behaviour in mental health facilities. Sensors 21:21030776

Times TE (2022) Covid-19: Need to focus on improving domestic solar manufacturing, says official. https://bit.ly/3afYYKZ

Tomar A, Gupta N (2020) Prediction for the spread of COVID-19 in India and effectiveness of preventive measures. Science of The Total Environment 728:138762

Tunkiel AT, Sui D, Wiktorski T (2022) Impact of data pre-processing techniques on recurrent neural network performance in context of real-time drilling logs in an automated prediction framework. Journal of Petroleum Science and Engineering 208:109760

Tutiempo Network S (2015) World weather: local weather forecast. https://en.tutiempo.net/

Usai MG, Carta A, Casu S (2012) Alternative strategies for selecting subsets of predicting snps by lasso-lars procedure. In: BMC proceedings, BioMed Central. pp 1–5

Viglione G (2020) How COVID-19 could ruin weather forecasts and climate records. Nature 580:440–442

Vodonos A, Awad YA, Schwartz J (2018) The concentration-response between long-term pm2. 5 exposure and mortality; a meta-regression approach. Environmental Research 166:677–689

Vovk V (2013) Kernel ridge regression. In: Empirical inference. Springer, pp 105–116

Wang J, Kwon S, Shim B (2012) Generalized orthogonal matching pursuit. IEEE Transactions on Signal Processing 60:6202–6216

Wang Y, Yuan Y, Wang Q, Liu C, Zhi Q, Cao J (2020) Changes in air quality related to the control of coronavirus in China: Implications for traffic and industrial emissions. Science of the Total Environment 731:139133

Watts J (2020) Climate crisis: in coronavirus lockdown, nature bounces back–but for how long. The Guardian 9

Welle D (2020) Coronavirus lockdown gives animals rare break from noise pollution: Dw: 16.04.2020. https://bit.ly/2Yzzrda

WHO (2019) Air quality guidelines - global update 2005. https://www.who.int/airpollution/publications/aqg2005/en/

WMO (2019) Greenhouse gas concentrations in atmosphere reach yet another high. https://public.wmo.int/en/media/press-release/greenhouse-gas-concentrations-atmosphere-reach-yet-another-high

World Economic Forum (2020) Energy transition index 2020: From crisis to rebound. https://www.weforum.org/reports/fostering-effective-energy-transition-2020

www.ETEnergyworld.com (2020) India to have 450 gw renewable energy by 2030: President - et energyworld. https://energy.economictimes.indiatimes.com/news/renewable/india-to-have-450-gw-renewable-energy-by-2030-president/73802626

Xu H, Yan C, Fu Q, Xiao K, Yu Y, Han D, Wang W, Cheng J (2020) Possible environmental effects on the spread of COVID-19 in China. Science of the Total Environment 731:139211

Yang Y, Yang Y (2020) Hybrid prediction method for wind speed combining ensemble empirical mode decomposition and Bayesian ridge regression. IEEE Access 8:71206–71218

Yasir M, Karim AM, Malik SK, Bajaffer AA, Azhar EI (2022) Prediction of antimicrobial minimal inhibitory concentrations for neisseria gonorrhoeae using machine learning models. Saudi Journal of Biological Sciences 29:3687–3693

Zhou X (2021) Coal, gas, or renewables: Electricity supply responding to lower demand during COVID-19. https://ihsmarkit.com/research-analysis/coal-gas-or-renewables-electricity-supply.html

Zhu Y, Xie J, Huang F, Cao L (2020) Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. Sci Environ 727:138704