An evaluation of the causal effect between air pollution and renewable electricity production in Sweden: Accounting for the effects of COVID-19

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Summary
The COVID-19 pandemic has made a significant disruption in the renewable industry, and the effects will last longer. In this context, understanding how and which specific renewable power got affected due to this crisis is of crucial importance. This study examines the nexus between COVID-19 and Sweden’s renewable electricity production from three sources of energy such as nuclear, solar, and wind, where the data ranges from January 1, 2019, to February 17, 2021. Since this study compares the period before and during the pandemic event, the study uses Air Quality Index as a measure of COVID-19 induced event and thus study the linkage between air quality and electricity production from three types of renewable energy. To analyse the above issue, several advanced techniques such as Wavelet Power Spectrum, Wavelet Coherence, Partial and Multiple Wavelet Coherence have been applied. The findings from the Wavelet Coherence approach demonstrate that COVID-19 has disrupted the linkage between wind energy generation and air quality, while the disruption in the case of solar and nuclear electricity generation has been minimal. Moreover, solar energy generation and air pollution both negatively affect each other, implying the need to generate solar power as well as reduce the level of air pollution in Sweden. In light of the above findings, the study discusses possible policy actions the country can take to fulfil its renewable development goals.

KEYWORDS
AQI, Causality, COVID-19, Renewable, Sweden, Wavelet

1 INTRODUCTION

According to World Health Organization, COVID-19 is an infectious disease from a large family of coronaviruses that may cause illness in animals or humans. In humans, several coronaviruses are known to cause respiratory infections ranging from the common cold to more severe diseases such as Middle East Respiratory Syndrome (MERS) and Severe Acute Respiratory Syndrome (SARS). On December 31, 2019, the first case of COVID-19 was discovered by the Wuhan Municipal Health Commission Chinese in Wuhan City, Hubei province, China. The commission reported a group of pneumonia cases with unspecified aetiology that had a history of exposure to Wuhan’s Huanan Seafood Wholesale Market. On January 9, 2020, the China Centre for Disease and Control reported that a novel coronavirus (2019-nCoV) was detected as the causative agent. The genome sequence
was made known to the public. Since then, most countries have ensured they followed preventive measures and early diagnosis in the host.

The early symptoms of COVID-19 involve fever, dry cough, fatigue, and myalgia. Other less common symptoms that may affect some patients include aches and pains, nasal congestion, headache, conjunctivitis, sore throat, diarrhoea, loss of taste or smell or a rash on skin or discolouration of fingers or toes. Most people (about 80%) recover from the disease without needing hospital treatment. Around 1 out of every 5 people who get COVID-19 becomes seriously ill and develops difficulty breathing. However, anyone can catch COVID-19 and become seriously ill, older people, and those with underlying medical problems like high blood pressure, heart and lung problems, diabetes, or cancer, are at higher risk of developing serious illness. Recent studies attuned that the pandemic can also be detected without human intervention, but with the help of suitable technology, precisely drones. The drones will be prepared with the help of a thermal vision camera to recognize body temperature, disinfect the environments, and detect infected persons, therefore, using the drones to screen the workplaces, shopping centre and training establishment of a thermal vision camera to recognize body temperature, disinfect the environments, and detect infected persons, therefore, using the drones to screen the workplaces, shopping centre and training establishment to distinguish to identify the mask through AI are viable without human intervention in less time.

Corona Virus Disease (COVID-19) is spreading worldwide, and Sweden, like other countries, has similarly been affected. Sweden, a northern European country situated on the Scandinavian Peninsula, has a unique situation with a much lower population density and one of the world’s highest percentage of single-person households. The first COVID-19 case was detected at the beginning of February 2020 in this country, but unlike other economies that have implemented strict lockdown and quarantine measures to control the spread of the coronavirus, the Swedish population health authority, Folkhälsomyntisgheten, implemented less stringent measures within its borders. As of 2021, the country is still doing voluntary social distancing based only on the scientists’ recommendations, particularly the health agency of that country. However, like the rest of the world, the Swedish economy, which is an export-dependent economy, is also likely to experience a significant disruption due to the pandemic. According to the National Institute of Economic Research, Swedish GDP is predicted to reduce by 7% while unemployment increases by 10.2%. This was evident in the first 3 months of 2020 when the economy contracted by 0.3% compared to other Eurozone economies. This slowdown in economic activity is accompanied by a reduction in energy demand and an increase in energy costs. According to the International Energy Agency, Sweden has the second-lowest CO₂ emissions per capita among its member countries and also has the lowest fossil fuel share in primary energy supply. This happens due to its greater share of renewable energy since almost 80% of electricity production in Sweden comes from renewable sources. Although the country did not enforce strict lockdown measures like its neighbouring countries, its economy will get affected by the pandemic, as has been predicted by the National Institute of Economic Research. Therefore, a spill-over effect of this contraction in the economy is also likely to be felt by the renewable sector.

Yet, Sweden demonstrates a bold commitment to achieving its renewable target through investment in a large share of R&D on renewable energy compared to other European countries. The country’s Framework Agreement on Energy Policy has the target to achieve a 100% share of renewable electricity by 2040 and a net-zero carbon economy by 2045. Moreover, a report about the electricity market in Sweden has revealed that renewable electricity capacity is estimated be doubled within the decade increasing from 14.8 GW in 2019 to 30.4 GW in 2030. In addition, the report further revealed that the general compound annual growth rate (CAGR) will increase by 6.8%, Solar PV by 16% and wind energy by 8.3% in 2030. Furthermore, Swedish solar PV capacity is expected to increase from 477 MW in 2018 to 3.1 GW in 2030. This demonstrates that the Swedish government is currently prioritizing solar and wind power generation and a move from the traditional sources of energy such as hydropower. However, given the recent pandemic event, whether Sweden can meet these targets is therefore of utmost concern to the stakeholders associated with the energy industry.

Against this backdrop, this study examines the causal relationship between renewable energy production and the air quality of Sweden in the context of COVID-19. The study has several major contributions to the empirical literature. First, the restrictions enforced due to the COVID-19 pandemic improved the air quality since there were fewer energy or fuel activities during the lockdown. Manavalan et al., for example, explored artificial intelligence to predict the air quality changes and accumulation of rainfall during the COVID-19 pandemic and revealed that there is a reduction in the concentration of pollutants released from various sources such as CO₂, ozone, particulate matters, and others. Le et al. also noted that the lockdown placed during the COVID-19 pandemic had a significant reduction in CO₂, NO₂, and particulate matters. The objective of this research is, therefore, to demonstrate whether Sweden’s more investment in renewable energy could reduce air pollution and increase air quality and whether air pollution is a threat to renewable power generation. The specific reason to
examine the causality between air pollution and renewable is that Sweden’s air pollution mainly comes from energy production.\textsuperscript{13} This paper makes an attempt to demonstrate that Sweden can reduce the harmful air pollutant gases by investing more in renewables. This is important since air pollution causes a lot of premature deaths in this country. Comparing Sweden with the neighbouring countries reveals that over the last several decades, more people have died in Sweden due to air pollution compared to Finland and Sweden (Figure 1).

However, renewable investment can be a solution for both the environment and human health as they can reduce the dependency on fossil fuel-based energy systems and lessen the burden on human health. In this context, the COVID-19 pandemic offers an opportunity further to explore this issue in a more comprehensive framework. Sweden’s renewable generation mainly comes from hydropower generation but it wishes to increase its share of renewable energy from wind, solar and nuclear power. As such, the study considers these three sources of renewable energy and explores their causal nexus with the air pollution of this Nordic nation.

Second, this study compares the pre-COVID-19 data and COVID-19 period data while examining the link between air quality index and renewable energy. The objective is to investigate whether the air pollution’s effect on Swedish renewable generation was affected due to COVID-19 restrictions, lockdown policies, and the nature of that effect. This is also one of the reasons why this study did not use COVID-19 death or confirmed cases or the lockdown and other policy measures because that will not allow us to explore the nexus between renewable and air quality during the pre-COVID-19 period.

The third contribution of this study is methodological. To investigate the causal nexus between renewable and air quality, this study applies several Wavelet techniques which can help see the variations as well as a causal effect between the aforementioned variables simultaneously during three periods’, short-term, medium-term, and the long term. In particular, Wavelet power spectrum. Wavelet coherence approach, Partial as well as multiple Wavelet coherence analyses have been considered for this study. The primary reason to choose the wavelet approaches over other methods is that these tools are useful to handle the daily data. They can very well capture the fluctuations or volatility associated with any high-frequency series.

The rest of this study is organized as follows: the second section describes the literature review, the third section presents data and methodology, Section 4 describes the empirical findings and the final section presents concluding arguments and recommendations.

2 | LITERATURE REVIEW

Based on the main objective of the study, the literature is divided into two subsections, one dealing with the AQI and renewable during the pre-COVID-19 period and another one dealing with the aforementioned variables in the COVID-19 period.

2.1 | AQI and renewable nexus in Pre-COVID-19 period

In the middle of the 21st century, solar energy development is predicted to experience a substantial growth than any other forms of energy, but this may be severely affected due to man-made particulate pollutants and dust. In this context, different scholars have reported different findings, for instance, Bergin et al.\textsuperscript{15} using China and India as a case study, investigate whether air pollution could affect solar energy. The study found that solar energy production decreases by about 7400 MW in China and about 780 MW in India due to atmospheric particulate matter (PM). For the 24 regions examined, an approximate 17% to 25% reduction in solar electricity was deposited to photovoltaic due to both ambient PM and PM. In the most similar context, Katzenstein and Apt\textsuperscript{16} were concerned with how renewable energy, such as wind, could affect air quality. It was reported from the study that wind energy does not itself emit any emissions but its effect on the system of electricity operation could cause a rise in traditional plants’ emissions level. Thus, the findings suggested that wind energy is not sufficient to reduce SO\textsubscript{2} and NO\textsubscript{x} Rather, a carbon tax should be implemented simultaneously. Yang et al.\textsuperscript{17} examined how

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Number of deaths attributable to AQI in selected countries}
\label{fig:aqi_deaths}
\end{figure}

Source: Vos et al.\textsuperscript{14} Global burden of Disease Study [Colour figure can be viewed at wileyonlinelibrary.com]
various solar photovoltaic (PV) pathways can affect China’s air quality and people’s health in particular. Different results based on the deployment of distributed PV were found. The results demonstrated that deploying in the east with inter-provincial transmission has the largest air quality-related health benefits. In particular, they demonstrated that deploying these decreases by 1.2% premature deaths due to air pollution compared to the base case.

In another study, Li et al.\textsuperscript{18} study how aerosol pollution can decrease the level of solar photovoltaic (PV) electricity generation in China. The result demonstrated interesting findings where an annual average of over 20% reduction in surface solar radiation, which is suitable for PV electricity production, can be attributed to the aerosol pollution in the atmosphere. The findings suggested that China should improve its air quality to facilitate solar PV generation. This will amount to efficiency that would in turn reduce air pollution. Sweerts et al.\textsuperscript{19} use 100 stations and observational data of radiation for a period of 1960 and 2015 and examined if solar PV generation could be affected by controlling air pollution. The result showed that anthropogenic aerosol emissions and changes in the cloud were responsible for an 11% to 15% reduction in PV potential. It also found that if reverted to 1960's surface radiation level, a potential 12% to 13% electricity production increase and US$4.6 to 6.7 billion of economic benefits in 2030 could be expected. In addition, the recent study by Li et al.\textsuperscript{20} investigated the atmospheric concentration of high-level particulate matter (PM) and its significant impact in hampering the development of solar PV capacity. In the paper, total PM impact into were segmented into panel soiling and atmospheric aerosol attenuation. The findings from the result averred that the electricity production efficiency of solar PV in abundant solar regions was negatively affected by PM through panel soiling and atmospheric aerosol attenuation. However, in the desert and hugely polluted regions, it was found that reducing this type of air pollution can double the electricity generation efficiency of PV because PM can decrease PV efficiency by over 50%. They recommended that it is extremely necessary to mitigate air pollution in the long run to increase the PV generation capacity for both of these regions.

Furthermore, the benefits of wind energy on air quality are well documented in the empirical literature. The development of this energy does not pollute the air or environment, which is why it is recognized as one of the clean energy technology. Traditional energy sources such as fossil fuels are responsible for air pollution. But wind energy development can curb the rate of nitrogen oxide and sulphur dioxide.\textsuperscript{21} However, Nordman et al.\textsuperscript{22} holds a very different opinion and has said that the benefits of wind energy development on air quality depend on what kind of energy source it is displacing. If a wind farm completely closes or makes a coal electricity plant slow down, air quality benefits will be huge. If the plant was emitting pollution at a higher amount, the environmental benefits will also be substantial. However, it should also be noted that any electricity plants (including wind farms) in their construction, maintenance, and demolition stages use electricity and therefore can emit pollution. Therefore, whether air quality can be improved due to wind energy is not truly a straightforward result. The benefits depend on what kind of energy mixed they have.

2.2 AQI and renewable nexus during COVID-19 period

Naderipour et al.\textsuperscript{23} using Malaysia as a case study, examined the impact of COVID-19 on the environmental consequences and renewable energy generation. As the result, it was observed the restriction on movement enforced in the country contributes to the reduction in air pollution. This, in turn, closed several recreational and industrial centres, resulting in a reduction of carbon footprint, CO\textsubscript{2} emissions, and air pollution. As a result, the maximum sunlight was able to reach the earth, and energy production was also observed to be increased. On the other hand, Jain and Dhadke\textsuperscript{24} assessed the impact of the lockdown on the Indian energy sector and found that electricity demand and consumption reduced as a result of confinement associated with curbing the spread of the virus. As a result, India’s energy demand reduced drastically, putting an economic strain on the energy sector. Although the cost of energy production remained the same, low energy consumption leads to low billing rates, which in turn resulted in a reduction in the profit margin, thus incurring more losses. However, there is a need to move from the consumption of fossil fuel energy to renewable energy production to ensure the sustainable energy goal and secure future energy demands even amidst uncertainties like the COVID-19 pandemic.

Bera et al.\textsuperscript{25} investigated the extent to which the COVID-19 outbreak affects the renewable energy sector. The result revealed some noticeable effects, such as delays in the supply chain, government tax, and inadequate spending from the government. Hence, the government and policymakers were advised to adjust its renewable energy contract and warranty mechanisms to minimize financial risks. This will help discourage investors from avoiding clean energy investments due to uncertainties like a covid-19 pandemic. The study further stressed the use of land surface temperature maps to demonstrate that lockdown and restrictions on industrial
and transport activities, with regards to COVID-19, have substantially reduced CO, NO₂, and SO₂ but increased O₃.

Hosseini²⁶ also considered an outlook on the global development of renewable and sustainable energy during the COVID-19 period. He discovered that adopting renewable energy can bring substantial solutions after the pandemic, that is, industries can be revived by ramping up renewable energy technologies while creating new jobs at the same time. In addition, a good number of renewable energies provide an approach for controlling energy issues associated with the pandemic situation. To return to normal condition and keep sustainable energy projects on track in the post-COVID-19 world, the government needs to support renewable investments. This is because the COVID-19 pandemic has shown that economic uncertainties are capable of harming the transition to a renewable energy regime.

Furthermore, Zhu et al.²⁷ explored the fluctuating characteristics of Air quality index in China. He discovered that environmental monitoring and management system would not reflect environmental quality without abiding by inherent laws of AQI fluctuations. Thus, adequate control of the weather, GDP, income levels, and AQI, PM₂.₅, and SO₂ would extremely decrease. The study further buttresses that the implementation of energy transition could amount to the synergy between emission reduction and air quality improvement. Further, the COVID-19 pandemic and the resultant lockdown measures led to the reduction in transportation activities, thereby leading to less energy use and oil demand. These changes in transport activities and oil & energy demand exert a significant impact on environmental quality. Razzaq et al.²⁸ used quantile on quantile methodology to examine covid-19 pollution nexus in 10 US counties. Their findings made a confirmation of the overall dependence that exists between COVID-19 and air pollution. Specifically, the study confirmed that air pollution is the main cause of chronic diseases like covid-19, and it has become imperative for the government to consider asymmetric channels and introduce appropriate policies to control atmospheric pollutions. Sandro,²⁹ using the EU as a target study, estimates the association between air transport mobility and Covid-19 while considering carbon footprint in pre and post-pandemic periods. The findings showed that air transport mobility was greatly affected by COVID-19 with a reduction in the number of flights that directly reduce the CO₂ emission. On the other hand, Qarnain et al.³⁰ investigated the energy consumption rates of residential society during the pandemic. The result noted that the mandatory lockdown forced target residents to consume more energy for their daily activities. This alludes that the surrounding air quality is not moderate, thus affecting their health status in this regard.

2.3 | Research gap

The overview of the literature outlined above revealed the harmful environmental effects exerted by air quality and environmental pollution in the context of the pandemic. However, the renewable energy and air quality index relationship during the COVID-19 pandemic is also of great importance, and this is what this study sought to evaluate in Sweden. Renewable electricity generation has significant benefits in terms of reducing air pollution. Clean energy sources are all considered to be the key technologies to reduce air pollution in Sweden since much of the pollutant gases are emitted by energy production. Therefore, if clean and sustainable energy can be generated, premature deaths from AQI can also be easily avoided. Moreover, following Bergin et al.¹⁵ and Li et al.,²⁰ this study attempts to see how renewable generation can be affected by air pollution. However, this study is different from Bergin et al.¹⁵ and Li et al.²⁰ in the sense that they only evaluated the one-way relationship from air pollution to solar energy. Our study considers three renewable energies sources and their relationship with AQI in a causal framework. Moreover, this causal relationship is evaluated for both the pre-COVID-19 period and COVID-19 period to see whether COVID-19 played any significant role in mediating this relationship.

3 | DATA AND METHODOLOGY

3.1 | Data description

To see the causal effect between air quality and renewable electricity production, the data have been collected from two different sources. The daily hourly data of renewable electricity generation has been collected from Svenska kraftnät, the Swedish transmission network for electricity’s statistics database.³¹ Since the data is hourly, the average value of 24 hours has been taken. Air quality data have been collected from the World air quality index (WAQI).³² The data range from January 1, 2019, to February 17, 2021. The data are split between the COVID-19 period and pre-COVID-19 period. For example, pre-COVID-19 data ranges from January 2019 to January 2020 and the COVID-19 period involves data from February 2020 to February 2021. The month of February has been chosen as the starting date for COVID-19 because Sweden encountered its first confirmed case at the very beginning of this month.
Descriptive statistics for all the variables are presented in Table 1. All the variables have been expressed in their logarithms and the data used for the empirical analysis are also expressed in their logarithms.

3.2 Methodology

In this current investigation, several wavelet techniques such as wavelet power spectrum, wavelet coherence, partial and multiple wavelet coherence which is quite suitable for handling the daily data, are used. The wavelet analysis takes both the frequency and time dimension into account simultaneously, which is a helpful device in the econometric examination since contempates are broadly led by either time arrangement investigation or dependent on recurrence area. In addition, utilizing time-sensitive customary causality tests and fixed boundaries causes mistaken outcomes when there are auxiliary breaks in time arrangement. At this juncture, determining where structural breaks occur in the modelling technique is quite remarkable. In this unique situation, the Fourier change is created by utilizing an alternate recurrence area approach. In this methodology, disregarding the data in the time area and zeroing in on the recurrence space represents a basic issue.

In addition, the wavelet analysis combines the two widely used separated techniques under a unified frame of time and frequency dimension. At the end of the day, the persistent wavelet coherence approach permits the current investigation to look at how the renewable energy production and air pollution got affected in the presence of COVID-19 in Sweden is connected at various frequencies and how their relationship fluctuates after some time since the wavelet examination has taken both the recurrence and time measurement into account all the while. In any case, it merits referencing that the quantity of studies in the monetary and condition writing utilizing the persistent wavelet coherence is significantly low contrasted with different fields, for example,

| Table 1 Descriptive statistics |
|--------------------------------|
| **Pre-COVID-19**              |
| AQI  | NP      | SP      | WP      |
| Mean | 1.476813| 8.246428| 5.365166| 7.685253|
| Median | 1.460397| 8.258864| 5.680123| 7.712315|
| Maximum | 1.879383| 8.304644| 6.349881| 8.223337|
| Minimum | 1.127105| 8.132072| 3.670408| 6.869537|
| Std. Dev. | 0.147556| 0.046829| 0.803674| 0.289861|
| Skewness | 0.435773| −0.716202| −0.557571| −0.458357|
| Kurtosis | 3.053104| 2.277886| 1.840923| 2.748872|
| Jarque-Bera | 12.54804| 42.35106| 42.57775| 14.86893|
| Probability | 0.001885| 0.000000| 0.000000| 0.000591|
| Sum | 583.3413| 3257.339| 2119.241| 3035.675|
| Sum Sq. Dev. | 8.578417| 0.864036| 254.4814| 33.10369|
| **During-COVID-19**            |
| AQI  | NP      | SP      | WP      |
| Mean | 1.423737| 8.098490| 5.653221| 7.770444|
| Median | 1.407956| 8.104124| 5.986857| 7.791880|
| Maximum | 1.870696| 8.271211| 6.600218| 8.263402|
| Minimum | 1.103804| 7.764609| 3.658013| 6.866371|
| Std. Dev. | 0.135706| 0.105030| 0.802522| 0.281800|
| Skewness | 0.685895| −0.432469| −0.760344| −0.549339|
| Kurtosis | 3.648463| 3.018729| 2.337964| 2.863632|
| Jarque-Bera | 36.45329| 11.85072| 43.55405| 19.40673|
| Probability | 0.000000| 0.002671| 0.000000| 0.000061|
| Sum | 541.0200| 3077.426| 2148.241| 2952.769|
| Sum Sq. Dev. | 6.978417| 0.864036| 254.4814| 33.10369|
engineering fields. All things considered, the ceaseless wavelet electricity range and coherence approaches have gotten more common as of late as the methodology takes into account acquiring profoundly important data about the connection of the monetary, money related, and condition time arrangement factors which cannot be seen by different strategies applied.

The study uses the wavelet equation developed by Goupillaud, Grossmann, and Morlet as follows:

\[ \psi(t) = \pi^{-\frac{1}{4}}e^{-\frac{1}{2}t^2}, \quad p(t), t = 1, 2, 3, \ldots, T, \]  

(1)

where \( \psi \) is applied on limited observations by Kirikkaleli et al. The simple equation of the continuous wavelet is shown below in equation two. The continuous wavelet is constructed from \( \psi \) as a function of k and f have given time series data \( p(t) \) as follows:

\[ W_p(k,f) = \int_{-\infty}^{\infty} p(t) \frac{1}{\sqrt{f}} \psi\left(\frac{t-k}{f}\right) dt, \]  

(2)

whereas \( k \) and \( f \) show time and frequency, respectively. “The main role of the \( k \) is to define a wavelet’s particular location in time by exchanging the wavelet while \( f \) controls the distended wavelet for localizing various frequencies.” Equation (2) presents the modified \( p(t) \) with the \( \psi \) coefficient.

\[ p(t) = \frac{1}{C_{\psi}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |W_p(a,b)|^2 da \frac{db}{b^2}. \]  

(3)

The current study employed the wavelet electricity spectrum (WPS) to gather data about the vulnerability of air pollution on renewable energy production. Therefore, WPS allows us to capture the vulnerable periods and frequencies of the time series variables.

\[ WPS_p(k,f) = |W_p(k,f)|^2. \]  

(4)

As referenced, the upside of the wavelet coherence approach against the customary relationship and causality tests is that the methodology draws out any connection or causality effect between air pollution and renewable production in consolidated time-recurrence-based causalities. As Kirikkaleli stated, the squared wavelet coherence equation is constructed, as shown below:

\[ R^2(k,f) = \frac{|C(f^{-1}W_{pq}(k,f))|^2}{C\left(f^{-1}|W_p(k,f)|^2\right) C\left(f^{-1}|W_q(k,f)|^2\right)}. \]  

(5)

Meanwhile, \( C \) shows time and the smoothing process over time, with \( 0 \leq R^2(k,f) \leq 1 \). Whenever \( R^2(k,f) \) approaches, the value of one indicates a correlation among the time series variables. In the figures, correlated areas are surrounded by a black line and depicted in red colour. However, whenever the value gets close to zero, this indicates no correlation between the time series variables and is pictured by blue colour. Obtaining \( R^2(k,f) \) does not give us a chance to discuss the relationship’s sign. To deal with this, Torrence and Compo postulated a means by which we can detect “the wavelet coherence differences through indications of deferrals in the wavering of two-time series.” The equation of the wavelet coherence difference phase is constructed as follows:

\[ \phi_{pq}(k,f) = \tan^{-1}\left\{ \frac{L\left[C\left(f^{-1}W_{pq}(k,f)\right)\right]}{O\left[C\left(f^{-1}W_{pq}(k,f)\right)\right]} \right\}, \]  

(6)

where, \( L \) and \( O \) denote an imaginary operator and a real part operator, respectively.

After analysing the relationship between air quality and renewable through wavelet coherence, the study undertakes both the partial and multiple wavelet coherence tools to understand the correlation further. The core objective of partial wavelet coherence is to characterise the association between two-time series variables such as \( z_1 \) and \( z_2 \) after the power of second-time series such as \( y \) is cancelled or removed. Following Aloui et al. and Mishra et al., the wavelet coherence between \( z_1 \) and \( z_2 \) and \( y \) can be written as follows:

\[ R(z_1,z_2) = \frac{S[W(z_1,z_2)]}{\sqrt{S[W(z_1)]S[W(z_2)]}}, \]  

(7)

\[ R^2(z_1,z_2) = R(z_1,z_2).R(z_1,z_2)^*, \]  

(8)

\[ R(z_1,y) = \frac{S[W(z_1,y)]}{\sqrt{S[W(z_1)]S[W(y)]}}, \]  

(9)

\[ R^2(z_1,y) = R(z_1,y).R(z_1,y)^*, \]  

(10)

\[ R(z_2,y) = \frac{S[W(z_2,y)]}{\sqrt{S[W(z_2)]S[W(y)]}}, \]  

(11)

\[ R^2(z_2,y) = R(z_2,y).R(z_2,y)^*. \]  

(12)

Ng and Chan notes that multiple wavelet coherence is more appropriate to investigate coherence among the
number of parameters while controlling other parameters. The following equation describes the multiple wavelet coherence:

\[ R(z_1, z_2, z_3) = R^2(z_1, z_3) + R^3(z_1, z_3) \]

\[ -2Re \left( \frac{R(z_1, z_2)R(z_1, z_3)R(z_3, z_2)}{1 - R^2(z_3, z_2)} \right). \]  \hspace{1cm} (13)

The above equation is the result of wavelet coherence squared which, at a specific frequency domain, derives wavelet power proportion of \( z_1 \), which in this case is the dependent variable, understood by the two control variables such as \( z_2 \) and \( z_3 \). The significance level of MWC is determined by the Monte Carlo simulations.40

4 | EMPIRICAL FINDINGS

The present study aims to capture the effect of Air pollution on renewable production and vice versa in Sweden while taking into account the effects of COVID-19. Here, we consider the short run to be 0 to 4 days, medium run to be 4 to 8 days, long run to be 8 to 32, and 32 onwards to be the very long run.

Based on the aim of capturing the co-movement between air pollution and renewable production, we employ the wavelet coherence approach, which allows capturing both the short-term and long-term causalities among the time series variables, but as an initial step, the wavelet power spectrum approach is used in the present study to identify the behaviour of the air quality index, nuclear electricity generation, solar energy production and wind electricity production variables in the present study.

Figures 2 and 6 present the Wavelet power spectrum for AQI, WP, SP, and NP during the pre-COVID and COVID period, respectively. Figure 2 represents the pre-COVID-19 period. Before the COVID-19 period, while (a) AQI exhibits high power (high variation) between July 9, 2019 and December 16, 2019, a high variation occurs for (b) Wind electricity production during the selected pre-COVID-19 period in the short-run; (c) Solar energy production from February 01, 2019 to April 10, 2019 and September 20, 2019 to December 25, 2019 in the short-term, (d) Nuclear electricity generation from February 20, 2019 to December 15, 2019 at the different frequencies. The outcome of the wavelet power spectrum for the times series variables during the COVID-19 period is reported in Figure 6, where (a) AQI exhibits high variation between February 20, 2020 and March 20, 2020 in the short-term and between August 15, 2020 and January 15, 2021 at the different frequencies, a high variation occurs for (b) wind electricity production in the short term at different periods. (c) Solar energy production from February 25, 2020 to March 21, 2020 and from July 10, 2020 to January 15, 2021; (d) nuclear electricity generation in the short-term and medium-term at different periods.

As a main empirical approach, the present study employs a continuous wavelet coherence to capture both long-term and short-term dependency between air pollution and renewable electricity production before and during COVID-19 periods. Figures 3 and 7 report wavelet coherence between renewable electricity generation and AQI for the periods before COVID-19 and during COVID-19, respectively. Figure 3A demonstrates the wavelet coherence between AQI and WP. Here, we find a mixed result depending on the time frequency. In the short run, there is no significant association between AQI and Wind power production. However, in the medium run, we have mixed results. From the end of May 2019 to the middle of October 2019, the arrows are left down, meaning that they have negative co-movement with AQI is leading. Since arrows are left down, it indicates that AQI has a negative causal effect on wind production in the medium run. However, at the end of 2019, in the long run, arrows are right up, meaning that AQI has a positive causal effect on wind electricity generation. This result is particularly consistent with the findings from Bekun et al42 for European Union countries, Dong et al43 for a global panel of 128 countries and Danish et al44 for BRICS countries who found that higher level of greenhouse gas emissions can trigger these countries to produce renewables.

While looking at the very long run, it can be observed that AQI has a negative causal impact on the wind industry during June-September and the initial sub-period of November 2019. Now, during the COVID-19 period in Figure 7A, a significant correlation can be found only in the long run periods between wind electricity generation and AQI. We find the arrows to be left downward, meaning that they have an anti-phase relationship and AQI is leading. Therefore, an increase in AQI negatively affected Sweden’s electricity production from wind. Therefore, it is possible to conclude that COVID has disrupted AQI and WP’s linkage during the long run. For the frequency bands of 32 and onwards cycles, the association between AQI and WP during both the pre-COVID and COVID periods remains the same. The outcome is consistent with the fact that due to less stringent measures taken by the government of Sweden in response to COVID-19, the country did not experience any decline in its AQI like others, and hence, the AQI could have negatively affected the Swedish wind generation. The IEA has also predicted that COVID-19 has slowed down the
development of onshore wind across the European countries, including Sweden, because of the stoppage of construction and disruption of the supply chain). Specifically, the IEA has predicted that the expansion of wind capacity additions will decline by 12% compared to 2019\textsuperscript{45}. In 2019, Sweden’s wind installation capacity more than doubled compared to 2018, and it was expected to increase during 2020 also. But as the COVID hit the country, 15% fewer new wind projects were installed in the first half of 2020 compared to the same period in 2019.\textsuperscript{46}

Now let us look into the causal association between AQI and solar energy in Figures 3B and 7B. During the pre-COVID time, Solar and AQI do not have any significant correlation in the short run except at the end of 2019, where arrows are left downward, indicating an anti-phase relationship. In the medium run, which also stretches in the long run, we have arrows left upward during July and October 2019. This indicates that these variables have negative co-movement where solar is leading. During the frequency bands of 8 to 32 days cycles, arrows are right upward with AQI leading during April.
and May 2019. Stretching between the long run and very long run, arrows being left down depicts an anti-phase relationship where AQI is leading solar electricity production during December 2019. This implies that when COVID was first detected in China in December 2019, AQI led to a decline in solar energy generation in Sweden. This is consistent with Bergin et al.15 who found that solar energy generation gets disrupted due to particulate matter in China and India.

In the case of AQI and solar energy during COVID, we see that arrows are left down in the long run during January 2021. This demonstrates that AQI and SP have a negative correlation with each other, with AQI leading. Furthermore, in the long run, a strong association between solar and AQI is observed from August 2020 to January 2021, where arrows are left upward, indicating that solar energy production leads to a reduction in AQI. Therefore, disruption due to COVID-19 was minimal in the case of solar energy generation for Sweden as only the short-run relationship between solar energy and AQI was disrupted. Solar energy production is reasonable because as solar energy generation increases, the fossil fuel dependency continues to decrease, which positively affects the environment as well as air quality. In particular, solar generation helps in reducing dependency on fossil fuel-dependent vehicles, and this indirectly helps in reducing PM emissions.47 Moreover, according to Yang et al.17 Solar photovoltaic (PV), electricity generation can help not just in reducing CO₂ emissions but also regional air pollution in China and therefore reduce the premature deaths caused by air pollution every year.

Let us now turn our attention to the relationship between AQI and NP during pre COVID period and COVID period. In Figure 3C, no significant association can be found between these two variables in either the short run or medium run. However, we have mixed results in the frequency bands of 8 to 32 days cycles. For example, we have arrows left down indicating that AQI reduces nuclear production during April and May 2019, and in July 2019, variables seem to have a positive relationship with each other since arrows are right upward. Some arrows are also stretched between the long run and very long run, and there is evidence of negative co-movement between the variables in the periods from the end of October to the sub-period of December 2019. In the frequency bands of 32 to onwards days cycles, that is, in the very long run, arrows are right upward from the initial days of May to July 2019, depicting that they have positive co-movement where AQI has a positive causal effect on nuclear power production. This is an indication that higher pollution leads the country to produce more nuclear power in order to counteract the effect of AQI.

**FIGURE 3** Pre-COVID-19 period. A, Wavelet coherence between AQI and WP. B, Wavelet coherence between AQI and SP. C, Wavelet coherence between AQI and NP [Colour figure can be viewed at wileyonlinelibrary.com]
This result resonates the finding of Dong et al.\textsuperscript{48} who demonstrated that carbon emission can cause nuclear energy consumption in China, implying that higher carbon emissions might lead a country to produce and invest more in nuclear energy development.

Figure 7C shows no significant co-movement between AQI and nuclear power production during the COVID period except in the frequency bands of 8 to 32 days cycles where it is evident that AQI reduces nuclear production. It is therefore evident that causal relationship that existed beyond 32 days cycles in the pre-COVID-19 period was disrupted in the COVID period. The World Nuclear Association\textsuperscript{49} reported that although the restart of Ringhals, the nuclear power plant in Sweden, got delayed due to suppressed market prices during the COVID period, in June 2020, an agreement was reached between Svenska Kraftnät and Ringhals to restart the unit so that operating situation can be handled. Moreover, according to IEA\textsuperscript{50}, nuclear power plants performed well even during the lockdown period.

The partial and multiple wavelet coherence results that explain our study variables' coherence plots are presented for Pre-COVID period in Figures 4 and 5 and the COVID period in Figures 8 and 9, respectively. Let us first focus on the results of partial wavelet coherence for both during Pre-COVID and COVID periods. Figure 4A demonstrates the PWC of AQI and WP after cancelling out the SP. We see only a few small numbers of red colour significant islands across the short and medium run. In the long run, between the initial period of September and October, we can observe one significant island. In both the long run and very long run, another significant red colour island is observed. During the COVID period, Figure 8A demonstrates the PWC of AQI and WP after cancelling out solar energy production. There are no significant red spots in both the short run, medium run, and very long run. However, in the frequency bands of 8 to 32 days cycles, a large red island is detected stretching from the sub-periods of May to July 2020. In addition, a very small red island is detected in the month of October in the long run.

While looking into the PWC between AQI and WP after cancelling out NP during pre-COVID, we find that there are only a few significant red spots in the long run and very long run during September, October, and December. While looking into the relationship between AQI and WP after cancelling out NP during COVID, we find two small red islands during the medium run and long run in the frequency bands of the sub-periods of March and August 2020. In the frequency bands of 8 to 16 days cycles, a large red island ranging from the middle of May to the middle of August can be observed.
Now let us turn to the analysis of AQI and SP after cancelling out NP. During the pre-COVID period, no significant red spot can be detected in the short run. In the medium run, during September and December months, only two small red islands are observed that also stretches in the long run. Three red spots can be observed in the long run during the sub-periods of April, July, and August 2019. In the long run and very long run, another red spot ranging from the sub-periods of February has been detected as well. In the COVID period, the relationship between AQI and SP after cancelling the effect of nuclear production (NP) is demonstrated in Figure 8C. Here, a few red islands are detected in the sub-periods of May, June, July, and November of 2020 in the medium run. In the long run, there is a large red island stretching from the sub-periods of October 2020 to January 2021.

Let us now turn to Figure 5A where we observe SP in the relationship between AQI and WP during the pre-COVID period for MWC. We can observe weak co-movement between the variables in the short run and medium run during April-May and during the end of October, and the initial sub-periods of November. However, in the long run, and very long run, a strong correlation can be observed as quite a few red islands are detected. First, in the long run, there is a strong correlation from the last half of February to the first half of April, from the middle of April to July 19, from September to October 27, and finally during November and December.

The MWC of AQI and WP after considering SP during the COVID period is provided in Figure 9A. We observe quite a significant red islands in this case. For example, we observe a red island stretching from the short run to the middle run during May and between the sub-periods of July and August. There are also two small red islands during the last sub-period of August and October. We can observe small red islands in the frequency bands of 4 to 8 days cycle in the February, March-April, May, October, November of 2020, and January of 2021. In the long run and very long run, we have quite a strong correlation ranging from 0.8 to 0.9 during the sub-periods of May-August and a correlation of 0.9 to 1 starting from the last of August of 2020 to January 2021.

Now let us consider the relationship between AQI and WP considering the nuclear power production in the pre-COVID period. A weak correlation can be observed between these two variables in the short run and medium run since only a few small red islands can be detected during the sub-periods of March, April, May, July, and November 2019. In the long run, we can detect weak association before September, but a strong correlation is
observed during September and December 2019. While looking into the relationship of AQI and WP considering nuclear power production during the COVID period, we find that there are only a few significant red islands in the frequency bands of 0 to 4 days cycle during January 2021 with correlation ranging from 0.8 to 0.9. In the medium run, there is a significant correlation during February, April, June and November of 2020. In the long run, there is a strong association between the respective variables in the months of May to the first of August with a correlation of 0.9 to 1 and during the last sub-period of August with a correlation of 0.7 to 0.8. In the long run, a correlation of 0.8 to 0.9 is detected during August of 2020.

Let us now consider the nuclear production in the relationship between AQI and SP, as in Figure 5C. We can see that, again, we have a weak correlation among the variables in the short run and medium run. In the long during May and June, a strong correlation ranging from 0.8 to 0.9 is detected, whereas, during July, that correlation becomes stronger, taking values between 0.9 and 1. In the very long run, we have a strong correlation in the sub-periods of April-July and September-October,
FIGURE 7  COVID-19 period. A, Wavelet coherence between AQI and WP. B, Wavelet coherence between AQI and SP. C, Wavelet coherence between AQI and NP [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8  COVID-19 period. A, Partial wavelet coherence (AQI-WP-SP). B, Partial wavelet coherence (AQI-WP-NP). C, Partial wavelet coherence (AQI-SP-NP) [Colour figure can be viewed at wileyonlinelibrary.com]
where the correlation value ranges from 0.7 to 0.8. However, during December, the correlation between the variables fall in the range of 0.9 to 1. Let us now turn to the analysis of AQI and SP considering NP during the COVID period, which is demonstrated in Figure 9C. We can observe several red islands stretching between the frequency bands of 0 to 4 and 4 to 8 days cycles during May, July, and September, where a correlation of 0.8 to 0.9 is formed. In addition, we also find a red island in the frequency band of 0 to 4 days cycle during November 2020. Several red islands can also be detected with a correlation of 0.7 to 0.8 between April and May and during June 2020. Two red islands are also stretched in the medium-run and long run frequency bands during June and October 2020. In the long run, a correlation of 0.7 to 0.8 is formed in the frequency bands of 8 to 32 days cycles during May 2020, whereas another correlation is observed during August 2020. In the frequency bands of the 8 to 32 days cycle, there is a strong correlation of 0.9 to 1, ranging from October 2020 to January 2021. Furthermore, a small red island is detected in the frequency bands of 8 to 32 days cycles between June and July 2020.

5 | CONCLUSION AND POLICY RECOMMENDATIONS

This study sheds light on the issue of renewable energy development in Sweden in the COVID-19 context. There is currently ample evidence on how renewable energy generation has been hampered due to COVID-19 induced lockdown and restrictions, but not enough evidence on how COVID-19 induced reduction in air pollution has contributed towards the development of renewable energy. Although COVID-19 does seem to present a hopeless scenario for renewables as the national respective budgets are currently diverted from developing clean energy towards handling the COVID-19 situation, the study attempted to see whether COVID-19 has a silver lining in terms of the effect of AQI on renewable energy and vice versa.

The study adopted the Wavelet techniques for investigating the aforementioned link. In particular, Wavelet power spectrum, Wavelet coherence approach, Partial, and multiple Wavelet coherence are used. Our findings can be summarized as follows: (a) The wind generation in Sweden got disrupted due to COVID-19, as proxied by the level of air quality, which confirms the prediction made by IEA (2020), (b) Disruption in Solar energy generation due to COVID-19 was minimal but AQI and Solar

**FIGURE 9** COVID-19 Period. A, Multiple wavelet coherence (AQI-WP-SP). B, Multiple wavelet coherence (AQI-WP-NP). C, Multiple wavelet coherence (AQI-SP-NP) [Colour figure can be viewed at wileyonlinelibrary.com]
energy both had negative causal effects on each other, (c) The nuclear electricity generation also got disrupted due to the COVID-19 induced air quality but only in the long run. From Partial Wavelet analysis, (d) the association between AQI and Wind energy after cancelling out solar energy got disrupted due to COVID-19 in the short run, medium, and very long run, (e) Correlation that existed before COVID period between AQI and Wind energy after cancelling out nuclear production got faded away during COVID-19 period, and the same is true for the relationship between AQI and SP after cancelling out the nuclear production. Finally, from Multiple Wavelet coherence, it is evident that (f) the relationship between AQI and Wind energy considering the solar generation has largely remained the same as strong correlation across both COVID and pre-COVID period was detected, (g) Strong correlation can be detected between the AQI and Wind energy after considering nuclear production at the end of 2019 (Pre-COVID period for Sweden) and during COVID period, (h) the strong correlation is observed for both pre-COVID and COVID period.

Based on the above findings, it can be concluded that COVID-19 disrupted the linkage of wind energy with air quality, but the disruption was minimal for solar and nuclear electricity generation. Therefore, some important policy implications for Sweden, which can help the country achieve its renewable energy goals in the post-COVID-19 world, are provided. The wind power generation in Sweden seems to have been disrupted due to COVID-19 induced restrictions irrespective of the nature of the restrictions imposed. The wind industry in Sweden is now facing several challenges, including lack of space as well as social opposition. The wind industry development in Sweden has been possible mostly due to financial benefits received by this industry in the form of green certificate schemes. However, current studies have also pointed out that wind power development may face a challenge as local private investments are pivotal in developing the social acceptance of wind projects. But due to COVID, financial risks associated with this industry increased as well. Therefore, to increase the financial investment and social acceptance, the government must put some strategies. To minimize the landscape interference that results because of the wind development, the government can concentrate on building more offshore winds as they are minimal in terms of recreation disruption which will be causing less landscape interference.51 Sweden mostly depends on nuclear and hydropower. Given that Sweden has vast coastlines, there is a need to utilize the potential of the offshore wind industry in Sweden. According to Ambrose,52 global offshore wind industry investment more than quadrupled during the first half of 2020. This is another indication that the offshore wind industry is less prone to pandemic events and should be prioritized by this Nordic economy.

For the solar power generation, the result indicated that it could be hampered due to air pollution which is in line with Bergin et al.15 and Li et al.20 Hence, effective policies to minimize air pollution is recommended. Therefore, although the AQI of Sweden is lower than other European counties, it must still invest in controlling air pollution if it wants to increase its renewable production. As Sweden wishes to become a 100% renewable country by 2040, it is of the highest necessity for this country to implement measures that can control AQI. Moreover, in some urban cities, the concentration of PM10, PM2.5 as well as NO2 exceed the air quality standards. Implementing measures also has benefits in terms of health since the country loses approximately 7600 people annually due to PM and nitrogen oxide exposure.53 Air quality improvement policies should be implemented at both the local and regional level. Since solar power has also been seen to improve the air quality, Sweden should invest more in solar power generation. If renewables can be developed in their full capacities, they are sufficient enough to improve the air quality throughout the world including Sweden. Renewable energy development has a wide range of benefits in terms of economic growth, employment generation, and reduction in carbon emissions, but the findings of this analysis show that the production of renewable electricity can help Sweden prevent a lot of premature deaths occurring in the country every year and also reduce the disability diseases associated with the air pollution.

Furthermore, the result also showed that nuclear energy got disrupted as well due to COVID-induced air pollution. But higher pollution can also trigger a country to produce more electricity from different sources of renewables including nuclear and wind energy as has been demonstrated by the results from different frequencies. Therefore, the addition of more renewable infrastructure investment in Swedish economy can significantly impact the energy efficiency of this country and the government should focus on these investments by taking short, medium as well as long term action plans.

Future research can further delve into these issues by looking at how Sweden’s renewable energy production during COVID-19 can be compared to other Scandinavian countries. In addition, the direct measures of COVID-19, such as stringency of the lockdown measures as well as the daily incidents occurring from COVID-19, can be compared with air quality to see if there is any direct linkage among these variables. Although various other techniques to handle the daily data can be used, the wavelet approach will certainly help analyse these relationships.
CONFLICT OF INTEREST
The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT
Data available on request from the authors.

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