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The impacts of COVID-19 on clean energy labor markets: Evidence from multifaceted analysis of public health interventions and COVID-health factors

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ABSTRACT

COVID-19 pandemic has affected clean energy labor market. Using real-time job vacancy data, this study analyzes the impacts of the pandemic on the U.S. clean energy labor market in 2020, including biomass, energy efficiency (EE), electric vehicle (EV), power/microgrid, solar, and wind industries. This study identifies how COVID-health factors and public health interventions influence clean energy job availability during the early COVID pandemic. Overall, California had the most energy jobs and experienced a significant decrease in April 2020. EV and solar had the highest percentages of job vacancies during the pandemic in general. Still, lockdowns had the most severe influence on EE and wind jobs. Stay-at-home orders negatively affected clean energy job vacancies in biomass, EV, power/microgrid, and wind. Social-gathering restrictions, however, did not have much influence. Increased COVID tests at the state level had the strongest and most positive influence on clean energy job postings, indicating the importance of a state’s ability to manage public health infrastructure or crisis issues. COVID hospitalizations negatively influenced the job vacancies in biomass and wind but did not affect the other four sectors; conversely, as COVID death numbers increased, the number of jobs in biomass, EV, power grid, solar, and wind decreased, but not in EE jobs.

1. Introduction

The U.S. Bureau of Labor Statistics defines clean jobs as those assisting the environment, protecting natural resources, or transforming a business’s operations to be more environmentally friendly (E2 and Clean Jobs America 20, 2020). These jobs include renewable energy, energy efficiency (EE), pollution clean-up or remediation, natural resource conservation, and environmental compliance (Schneer and McGinn, 2019). Like most economic sectors, the COVID-19 pandemic has affected the clean energy sector (C and Assessing the impact, 2020). For example, layoffs and stay-at-home orders have decreased energy demand and affected clean energy output (Sovacool et al., 2020), such as negative supply chain impacts on power generation (Turk and Kamiya, 2020). Additionally, many of the materials necessary for clean energy, such as solar panels and wind turbines, come from China and have also experienced significant economic disruptions (Ferroukhi et al., 2020). China’s solar products production fell by at least 20% in the first few months of 2020, leading to many delays in solar production projects (Ferroukhi et al., 2020). Despite the influence of the COVID pandemic, the U.S. solar industry had a record year in 2020 and added 19.2 GW of new capacity-a 43% increase from 2019 (P. & RenewablesSo, 2021).

One way to measure economic activity is through the number of job vacancies. Job postings tend to increase when labor market demand increases and fall when labor demands fall; therefore, an analysis of job postings can reflect the state of the economy (Dias et al., 2020). For example, in the U.K., job postings almost ceased entirely at the beginning of the first lockdown in 2020, initially affecting both blue and white-collar jobs. Still, most growth has been in jobs requiring intensive training or employment in wealthy areas (Dias et al., 2020). Similarly, a study in the United States discovered that nearly all industries observed
a decline in job postings, with no significant difference between those deemed “essential” or with “work-from-home” capability (Forsythe et al., 2020).

This study’s primary analysis focuses on the online clean energy job market during the pandemic in 2020. In addition, it aims to identify how COVID health indicators (i.e., cases, deaths, hospitalizations) and public health interventions (e.g., stay-at-home orders) impacted U.S. clean energy jobs in 2020. Clean energy is defined as energy that generates from renewable, zero emission sources that do not pollute the atmosphere when used, and energy saved by energy efficiency measures (The Welding Institute and Wh, 2022; Department of Energy, 2022). For example, clean energy resources generally include solar, wind, water, geothermal, bioenergy and nuclear. Clean energy jobs here are defined as work relating to renewable energy, sustainability, energy efficiency or environmental management. Specifically, this study is interested in analyzing jobs in business that produce goods or provide services that are related to renewable energy or beneficial to the environment or conserve natural resources.

1.1. Impacts of the COVID-19 pandemic on clean and energy efficiency sectors

Several years before the COVID pandemic, clean energy generation steadily grew in capacity and consumption (International Energy Agen, 2020a). In 2019, most clean energy jobs increased in the United States; for example, solar energy jobs rose by 2.3%, while wind energy jobs grew by 3.2%. About 510,000 people were employed by clean energy generation sectors, less than half the amount used by fossil fuel jobs. EE jobs employed almost twice the amount of fossil fuel workers, with 2.3 million people working in design, installation, and manufacturing (Barrett and Yudken, 2020). Among all clean energy jobs, women typically made up about 30% of workers and racial minorities made up 20–25% (Barrett and Yudken, 2020). In 2018, approximately 11 million people worked in clean energy generation and fuels worldwide; China employed four million people, and the European Union employed 1.2 million people, compared to 850,000 in the United States (Schneer and McGinn, 2019). Wind energy, which accounted for $652 billion in global investments from 2015 to 2019, was one of the highest employing fields, according to the Global Wind Energy Council (Global Wind Energy Counci, 2020)

During the early stages of the pandemic, most energy sectors, including clean energy, were affected as businesses closed, transportation lessened, and people stayed at home. In the second quarter of 2020, the residential solar industry was affected more than any other part of the solar industry; for example, the rate of residential solar installations fell 23% from the first quarter. States that enforced stronger stay-at-home orders, such as California and the Northeast U.S., experienced more significant declines in solar installations in the second quarter of 2020 than states with less strict orders, such as Florida and Texas (Perea et al., 2020). Approximately 594,300 clean energy jobs were lost from the beginning of the pandemic until the end of 2020- a 17% drop (E2 and Clean Jobs America 2020). The cumulative 2020 losses were more than double the past three years of clean energy employment growth.

Other countries’ renewable energy sectors have also experienced the impacts of the COVID pandemic. For instance, in China, renewable energy subsidy budgets have been cut by 50%. In India, solar deployment in 2020 fell by 23% compared to 2019, and wind energy is estimated to decrease by 50% through 2022 (International Energy Agen, 2020b). In Europe, shutdowns, policy changes, and other economic impacts related to COVID have led to an 18% reduction in the predicted number of solar installations compared to 2019. In addition, COVID-related delays and cancellations in European wind power industries resulted in Germany, Sweden, Spain, the U.K., and the Netherlands failing to meet their expected growth targets in 2020 (International Energy Agen, 2020c).

Electric vehicles (EVs) have taken an enormous hit from lockdowns, and in China, EV sales fell by 79% in February (Ferroukhi et al., 2020). Investments in clean energy have also fallen globally by 2.6% from the same period in 2019; however, clean energy investments have surpassed fossil fuel investments in 2020 (Ferroukhi et al., 2020). Minority populations in the United States have been a large part of clean energy job losses from February to April 2020, as 25% of those who lost jobs in U.S. clean energy were Black and/or Hispanic, and 19% were women. These two groups make up 25% and 27% of the clean energy workforce, respectively (Jordan, 2020). According to the American Wind Energy Association (AWEA), wind energy generation stands to lose $35 billion in investments, with over $8 billion of that money directly affecting rural communities that rely on wind energy generation (American Wind Energy Asso, 2020).

1.2. Purpose of this study and contributions

The majority of studies in 2020 have either looked at one or a few sectors of the clean energy industry or examined the impacts of COVID on the renewable energy sector as a whole; therefore, further analysis regarding clean energy industry changes and the influential factors during COVID pandemic is needed. This study addresses the research gap by comparing six primary sectors of the clean energy industry (i.e., biomass, EE, EE, wind, solar, and power grid) to determine how specific state-level sectors have been affected. In addition, we also identify the potential factors influencing these clean energy jobs during the COVID pandemic in 2020. Therefore, this study attempts to answer the following research questions:

1) What were the overall impacts and trends of the clean energy labor market in 2020?
2) Are there variations in terms of different sectors of the clean energy labor markets? Which sector of the clean energy industry experienced the most impacts?
3) Which states’ clean energy jobs suffered the most from the COVID pandemic?
4) How did health intervention policies (e.g., social distancing, stay-at-home orders) and COVID-related health indicators influence the clean energy labor market?

This paper is critical to the analysis of the current clean energy industry and policies. First, we provide evidence of the overall impacts of COVID on the clean energy labor market and the trends of these impacts in 2020. Instead of examining the total industry sale record, this study analyzes job vacancy postings because job vacancy data enables the tracking of local economies disaggregated by geography, occupation, and industry. Second, the analysis of job vacancy data provides a unique opportunity to measure the changes in employees’ skill requirements, both across and within clean energy occupations. Third, this work focuses on the spatial dynamics of health intervention policies and health indicators of COVID disease spread and deaths, contributing to the literature on socio-spatial mechanisms (American Wind Energy Asso, 2020). This interconnected analysis has not previously been studied in renewable or clean energy industries. Finally, although researchers have used aggregate vacancy data, and even vacancy microdata from the Bureau of Labor Statistics Job Openings and Labor Market Turnover (JOLTS) survey, these data provide little details on the characteristics of a given vacancy or the firm that is posting (Labor Insight Market Data, 2021); therefore, we use data from Burning Glass Technologies Labor Insights, which provides characteristic information, to address this gap.

2. Method

2.1. Data preparation

This study obtained data on job postings from Burning Glass Technologies Labor Insights (Labor Insight Market Data, 2021). The Burning
Glass data aggregates nearly all job advertisements posted online daily from approximately 40,000 online job boards in the United States by scraping, cleaning, and coding online job vacancies. It also removes duplicate postings across sites and assigns attributes to the positions, including posting time, geographic location, required job qualifications (e.g., education level and skills), and industry. This dataset provides rich and timely data on the clean energy labor market during the COVID crisis. It is generally viewed as a valid dataset for the job vacancies representing the private sector labor demand in the United States. The job posting data have been used to study various labor market phenomena (e.g., the Great Recession) (Hershbein and Kahn, 2018; Deming and Kahn, 2018), as well as the job market during the pandemic (Forsythe et al., 2020). This study analyzed the job posting data in six sectors of the clean energy industry from January to December 2020. We exploited detailed information on occupation, geography, skill requirements, and firm identifier to identify clean energy job categories.

2.2. Selection of clean energy industry and job categories

This study focuses on biomass, EE, EV, power, or microgrid generating clean energy sources and solar and wind sectors (Department of Energy, 2021). We sampled the posted job vacancy from Burning Glass with certain keywords to identify specific clean energy labor industries (Table 1). The selection of relevant keywords was based on recent jobs published by the U.S. Department of Energy (DOE) (Department of Energy, 2021).

To validate our definitions of clean energy sector jobs, we first looked at the top employers with the most job postings in each clean energy sector (Appendix Table 1). For example, in the solar energy sector, we observed that the top industry employers are all related to solar energy. We also observe that the top ten employers accounted for a large portion of the overall solar job postings (27.8%). Similar patterns exist for other clean energy sectors. These results show that our definition captures the most employees in their respective clean energy sectors.

Additionally, we looked at the most common occupations per clean energy sector (Appendix Table 2). Again, we observed that the top occupations were highly relevant to the tasks in each clean energy sector. For example, the most common occupation in the wind sector is “Wind Turbine Service Technicians,” while occupations such as “Electricians” and “Electrical Engineers” appear as top occupations in many other clean energy sectors. In addition, similar to the leading firms, the principal occupations also account for a large proportion of the job postings in each sector. Overall, these results provide further justification of the clean energy sector definitions.

2.3. Measures

This study focuses on state-level unit analysis because many counties did not have clean energy job postings during the pandemic. The following sections describe specific measures for dependent and independent variables.

Table 1: Selection of clean energy industry and keywords.

| Clean energy industry | Keywords |
|------------------------|----------|
| Biomass                | Bioenergy and Biomass |
| Solar                  | Solar, Solar panels, Solar energy, Solar farm, P.V. |
| Wind                   | Wind energy, Wind power, Wind turbine, Windfarm |
| Power grid with clean sources | Smart grid, Microgrid, Grid modification, Grid with clean energy sources |
| Energy Efficiency (EE) | Energy Star appliances, Energy efficiency |
| Electric Vehicle (EV)  | All-electric vehicles, Battery electric vehicles, Fuel cell electric vehicles, Plug-in hybrid electric vehicles, EV charging, Type 1 plug, Type 2 plug, Type 3 plug, Type 1 charging, Type 2 charging, Type 3 charging |

2.3.1. Dependent variables: job postings

There are six dependent variables in this study. For each selected sector of the clean energy industry, we estimated the total number of job postings by week in each state for the state-level job vacancies from January to December 2020.

2.3.2. Independent variables

The independent variables include the health indicators of COVID cases, hospitalization and deaths, stay-at-home policies, socioeconomic vulnerability, and racial diversity. We also have two control variables, location and season, to control for temporal and spatial effects.

2.3.2.1. Health indicators. The health indicators include three COVID related variables: the number of total COVID tests, average daily hospitalizations, and total COVID deaths per week. We used three ratios in the regression model by dividing the total tests, deaths, and hospitalizations by the total population of each state. Our data source was an open-source COVID-19 data hub (Guidotti and Ardia, 2020; Guidotti, 2020), and their COVID related information was based on Johns Hopkins’s University Coronavirus Research Center (Johns Hopkins University, 2021).

2.3.2.2. Health intervention policies. This study used stay-at-home and social gathering restrictions to measure the effects of health intervention policies. The data source was the Oxford COVID-19 Government Response Tracker (OxCGRT), which provides a systematic cross-national and -temporal measure of government responses to the COVID spread (Hale et al., 2020). Primarily, the two measures were coded as below:

(1) Level of stay-at-home restriction: 0 - No measures; 1 - Recommend not leaving the house; 2 - Required, only “essential” trips; and 3 - Required, not leaving the house with minimal exceptions (e.g., allowed to leave only once every few days, only one person can leave at a time, etc.). A higher number indicates stricter stay-at-home requirements.

(2) Level of social gathering restriction: 0 - No restrictions; 1 - Restrictions on huge gatherings (limit is above 1000 people); 2 - Restrictions on gatherings between 100–1000 people; 3 - Restrictions on gatherings between 10 and 100 people; and 4 - Restrictions on gatherings of less than ten people. A higher number indicates more significant restrictions on social gathering.

3. Results

3.1. State distribution of clean energy jobs and spatial effect analysis

Spatially, clean energy job postings were distributed unevenly across the United States (Fig. 1). California (C.A.), Texas (T.X.), Florida (F.L.), New York (N.Y.), and Colorado (C.O.) had the highest number of clean energy jobs. In contrast, West Virginia (W.V.), North Dakota (N.D.), Alaska (A.K.), Wyoming (W.Y.), and Vermont (V.T.) ranked the lowest. The top five states accounted for more than 40% of all jobs in the six sectors of the clean energy industry. However, their neighboring states did not show a similar pattern, indicating spatial heterogeneity; for instance, T.X. had many more clean energy jobs than New Mexico (N.M.), Oklahoma (O.K.), Arkansas (A.R.), and Mississippi (M.S.).

We considered the spatial effect analysis of clean energy jobs using Moran’s I index, which computes global spatial autocorrelation by taking into account feature locations and attribute values of a single attribute simultaneously (Moran, 1950). It can be calculated as:

$$I = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})(x_j - \bar{x})$$

where, $n$ is the number of the spatial features; $x_i$ is the attribute value of feature $i$; $x_j$ is the attribute value of feature $j$; $\bar{x}$ is the mean of this
attribute; \( w_{ij} \) is the spatial weight between feature \( i \) and \( j \); and \( \sum_{i} \sum_{j} w_{ij} \) is the aggregation of all spatial weights.

The results show that the Moran’s I global spatial autocorrelation was not significant, \( p = 0.47 \) (Fig. 2), indicating negligible spatial effects in the data. This finding is not a surprise because clean energy jobs at the state level show substantial heterogeneity. In the future, county-level clean energy jobs in states with the highest clean energy jobs (e.g., C.A.) can be analyzed by considering the spatial effects.

### 3.2. Trends in time and type of clean energy jobs

We further examined time and clean energy job type distributions during the pandemic. Specifically, the uneven distribution of clean energy jobs is also reflected in the effects of months and different job types (Fig. 3). Overall, January and February 2020 had the fewest clean energy jobs, followed by a sharp increase in March (depending on the states), then a significant decrease in April due to the impacts of the pandemic. Afterward, the number of clean energy jobs slowly rebounded due to the re-opening of the economy. Compared with Season 2 during the pandemic, C.A. continued to increase clean energy jobs in

### Table 2

| Before lockdown (Mar. 11) | After lockdown (minimum) | Reduced | Maximum Percentage change (%) | Average Percentage change (%) |
|---------------------------|---------------------------|---------|-------------------------------|------------------------------|
| 33                        | 21                        | 12      | -36.4                         | 2.4                          |
| 801                       | 385                       | 416     | -51.9                         | -38.1                        |
| 1776                      | 985                       | 791     | -44.5                         | -21.2                        |
| 762                       | 409                       | 353     | -46.3                         | -23.2                        |
| 1368                      | 763                       | 605     | -44.2                         | -16.0                        |
| 601                       | 295                       | 306     | -50.9                         | -38.1                        |
| 5341                      | 2940                      | 2401    | -45.0                         | -24.4                        |

### Note

The maximum percentage change was the week in the lockdown period, which has the last decrease in job postings.

![Fig. 1. Choropleth map of the different types of clean energy jobs per state during COVID-19.](image1)

![Fig. 2. The Moran’s I plot for global spatial autocorrelation test.](image2)
Fig. 3. Clean energy jobs in the U.S. by month and state in 2020: (a) clean energy jobs in different states and (b) distribution of clean energy jobs in different months.

Fig. 4. Percentages of different types of clean energy job postings in the U.S.: (a) monthly clean energy job postings and (b) different types of clean energy jobs.
Seasons 3 and 4, while T.X. and F.L. did not increase in Seasons 3 and 4. As for different types of clean energy jobs, EV jobs (35.05%) had the most postings, followed by solar (27.93%), EE (12.81%), grid (13.98%), wind (9.4%), and biomass (0.84%; Fig. 4). This result might occur because the U.S. is transitioning from gas-driven vehicles to EVs. As a result, there is an increasing need for engineers and researchers in EV-related professions. On the other hand, biomass jobs had the least number of postings. After growing from 2004 through 2014, expansion in electricity generation from biomass and waste ended in recent years (Mayes, 2019). In 2018, electricity generation from biomass was 2% below its peak generation of 71.7 million MWh in 2014 (Mayes, 2019). This halt on industry growth appears to have similarly impacted the job postings.

3.3. Impacts of COVID-19 lockdown on clean energy jobs

During the first nine weeks of 2020, there were few clean energy job postings (Fig. 5a), and this may be due to clean energy companies recruiting new employees later in the year. This result was reflected by the sharp increase of clean energy job posting after the first nine weeks. However, the U.S. economy lockdown between the twelfth week (March 18) and the twenty-fourth week (identified by the region enclosed by a dashed, black rectangle) dramatically influenced clean energy jobs. Clean energy job postings during the lockdown reduced about 40%. The first re-opening occurred at the seventeenth week (April 22), and clean energy job postings slowly began recovering to pre-lockdown levels. Almost all six clean energy labor markets experienced certain levels of decrease during the lockdown and the following six weeks after (Fig. 5b). The most significant reductions in job postings were in EV and solar, where before lockdown (March 18), there were 1776 and 1368 jobs, respectively, which decreased to 791 and 605 jobs (Table 2). Overall, lockdowns had the most severe influence on EE and wind jobs, with a 38.1% decrease in job postings for both industries. This finding is followed by power grid and EV jobs, which experienced an average reduction of 23.2% and 21.2%, respectively. On the other hand, the lockdown had negligible influence on biomass jobs mainly due to the

Fig. 5. (a) Weekly different types of clean energy jobs (where the total clean energy jobs are marked as the right y-axis, while the remaining clean energy jobs were marked as left y-axis), and (b) percentage changes of clean energy jobs.
overall low job posting.

3.4. Results of multiple linear regression analysis

To analyze the factors influencing the job posting of the six sectors of the clean energy industry by weeks since the start of stay-at-home-orders, we used six multiple ordinary least square (OLS) linear regression models to examine the relationship between clean energy jobs, health intervention policies (e.g., stay-at-home and social gathering), and COVID hospitalizations, tests, and deaths (Table 3). Overall, the five main independent variables explained each clean energy industry’s job postings well, with a higher percentage of variance and $R^2$ ranging from 0.65 to 0.89, after accounting for the effects of location and time. The purpose of using the control variables of states and time is to account for the impact of local socioeconomic differences and time effects of COVID-related issues. All variables were log-transformed to normalize the variables.

Stay-at-home orders negatively affected the number of jobs in four sectors of the clean energy industry, including biomass, EV, power/microgrid, and wind, suggesting that during the weeks with fewer stay-at-home restrictions, there were more clean energy jobs. For example, in the weeks with a 1% stay-at-home order policy increase, there were 0.15% fewer jobs posted in EE, followed by 0.14% fewer in biomass, 0.12% in power or micro-grid, and 0.12% in wind jobs. Social gathering policy, however, did not affect most clean energy jobs.

Overall, health indicators of COVID disease spread and death had significant effects on clean energy labor markets. Increased COVID tests at the state level positively influenced the number of jobs in all six sectors of clean energy industry, indicating a state’s ability to manage public health infrastructure or crisis issues. For example, in the weeks with 1% more COVID tests per state, there were 0.43% more wind jobs and 0.40% more EE jobs. Among all the independent variables, COVID tests were the strongest positive predictor of job postings. The number of COVID hospitalizations at the state level negatively influenced the number of jobs in the biomass and wind industries but did not affect the other four sectors. As the number of COVID deaths increased, the number of jobs in biomass, EV, power/microgrid-related, solar, and wind decreased; there was no relationship between COVID deaths and EE jobs. Specifically, the weeks with 1% more COVID deaths had fewer job postings in the solar (−0.08%), wind (−0.06%), power/microgrid (−0.05%), EV (−0.04%), and biomass (−0.03%) sectors.

Since C.A. had the highest numbers of clean energy jobs in 2020, we further conducted regression analysis on the factors influencing the six clean energy job postings in C.A. (Table 4). Our results indicate that social-gathering restriction did not have any effect. Still, stay-at-home orders had a negative impact on the number of jobs in biomass, EE, EV, power/microgrid, and solar but not in the wind industry. COVID tests only affected the EV industry, with a positive relationship to the number of EV jobs. While COVID deaths did not influence clean energy jobs, COVID hospitalization rate negatively impacted five clean energy jobs, including EE, EV, power/microgrid, solar, and wind. The hospitalization rate was not related to the number of biomass jobs.

4. Discussion

4.1. Relationship between COVID-19 and clean energy jobs

Our results show a clear relationship between COVID and reductions in clean energy labor market. The only sector not impacted during the weeks from March through April 2020 was the biomass sector due to the low number of job postings. Reductions in clean energy labor markets due to the pandemic by themselves are not surprising results, as we would expect to see a reduction of labor markets as a result of the overall economic impacts of the COVID pandemic. Prior research, however, has identified that not all labor markets were impacted equally by the COVID pandemic (Dalton, 2020). For example, industries with the lowest ability to “telework” or those affected by a lack of consumers saw reduced labor markets. Therefore, industries like leisure and hospitality were negatively impacted, while finance and insurance were not.

Additionally, specific industries, such as construction and transportation, were more affected by localized virus incidences than by national trends. Therefore, if patterns are generalized to “all industries,” we only see the overall negative trend and lose nuanced identification of inter-industry variance. As such, it is essential to analyze each sector individually. It is interesting how immediate these effects were on job vacancies in the clean energy industry. The job posting reductions appear to coincide almost immediately, with no apparent lag, with the significant events of the pandemic. As the United States began to impose more severe restrictions in March, job postings saw a rapid drop-off. However, after April, we note job postings regained momentum. According to research by the U.S. Bureau of Labor Statistics, most industries impacted by COVID maintained reductions through the end of 2020, and impacts were most noticeable from June onward (Handweker et al., 2020).

These clean energy results differ in immediacy and elasticity (i.e., ability to regenerate growth patterns quickly). This result shows two things: 1) clean energy employment tracks in tandem with the socio-environmental phenomenon, such as pandemics, and 2) the clean energy sector can stabilize relatively quickly compared to the overall economy. After COVID lockdown restrictions were eased, both the EV and solar sectors showed the highest increases in job postings. According to the Solar Energy Industries Association (SEIA)’s review, the solar industry appears to have been able to sustain growth, although the impacts of COVID and solar installations grew 43% in 2020 (P.& Renewables and The U, 2020). Similarly, Deloitte Insights report that, despite the short-term effects of the pandemic, the EV market is expected to continue growing throughout the 2020’s (Woodward et al., 2020). Both sectors appear to be maintaining momentum because of the increased focus on carbon reductions and the improvements and cost reductions in technology development and deployment. The labor market growth of the solar and EV sectors despite the effects of COVID could also explain why our results indicate that C.A. had the lowest

Table 3

| Independent variable | Number of job postings in each industry |
|----------------------|----------------------------------------|
|                      | Model 1 Biomass_b | Model 2 EE_b | Model 3 EV_b | Model 4 Grid_b | Model 5 Solar_b | Model 6 Wind_b |
| Stay-at-home         | −0.14**          | −0.15***     | −0.05        | −0.12**        | −0.04          | −0.12**        |
| Social gathering     | 0.03             | −0.00        | 0.02         | −0.01          | 0.03*          | 0.01           |
| COVID tests          | 0.41***          | 0.40***      | 0.31***      | 0.42***        | 0.35***        | 0.43***        |
| Hospitalizations     | −0.05**          | −0.01        | −0.01        | −0.01          | −0.01          | −0.04***       |
| COVID deaths         | −0.03*           | −0.02        | −0.04*       | −0.05**        | −0.08***       | −0.06***       |
| N                    | 725              | 1987         | 2215         | 1993           | 2090           | 1980           |
| $R^2$                | 0.65             | 0.87         | 0.89         | 0.85           | 0.88           | 0.80           |

*p < 0.05, **p < 0.01, ***P < 0.001, Coefficients of categorical variables including the total of 50 states and 44 weeks (since the week of stay-at-home orders) were considered as controlled variables, and therefore, were not listed here. EE = Energy Efficiency and EV = Electric Vehicles. Each variable’s coefficient (b) was standardized. All variables have been log-transformed.
reduction in the job postings of the six clean energy industries in 2020. As both sectors had the highest concentration of job postings in C.A., their strength had a positive net effect on the overall clean energy job postings.

Wind and EE were hit hardest by the effects of COVID in March and April 2020, with both suffering from the most significant drop in job postings. The EE industry saw the results of two phenomena combining: March and April saw historically low energy use, as moderate weather patterns allowed for energy savings. In addition, due to COVID restrictions, commercial buildings had reduced energy consumption as office workers were forced to work from home (Marohl and Comstock, 2020). The second of these phenomena produced lasting effects as companies realized that many positions could continue to work remotely beyond the COVID restrictions and allow them to cut the costs of commercial office or workspace (Parker et al., 2020). This situation impacted the EE industry twofold, with a traditional seasonal decline in demand combined with a lasting change in the retail office sector. First, the wind industry suffered from job layoffs due to wind turbine construction being deemed non-essential. Although wind turbine installations reached a record high in 2020 (Bowers and Comstock, 2020), projects’ pausing during the pandemic put a lull in job postings. For example, there were strict COVID restrictions in T.X., the state with the most wind turbine capacity, in March and April. In N.Y., an enormous offshore wind construction operation was halted (Office of the Texas Governor, 2020; Cuomo, 2020).

Regarding the relationship between clean energy jobs, health intervention policies (i.e., stay-at-home and social gathering), COVID health indicators (i.e., tests, hospitalizations, and deaths), we would expect these factors to impact industry growth for all variables that resulted in negative economic results. However, what is interesting is the relationship between COVID testing and job postings. These results show that testing had a positive effect on job postings. Logically, increased testing results in fewer hospitalizations and deaths and increases individual perceptions of safety, thus allowing for more favorable economic and industry trends. This is an important finding because it highlights the need to focus on testing infrastructure, not only as a health mechanism but as an economic one. Our results are consistent with several studies that concluded the economic crisis impacted every clean energy sector from the COVID pandemic (e.g., Jordan, 2020), which tracked job losses from unemployment data; however, they found record job losses in all clean energy jobs in April 2020, while we found these jobs slowly recovered. An increase in job postings as industries attempt to re-employ the positions lost during the pandemic is expected and explains why we observed an increase in job postings after April 2020. In essence, our results support and add a unique dimension to previous research by examining an alternative set of labor data and focusing on job postings rather than job losses.

4.2. Limitations and future studies

Several limitations to this research need to be addressed, though they also highlight potential challenges for future research. First, our database only covers vacancies posted on the internet, not those in printed newspapers or other sources. Previous studies, however, have pointed out that job posting distributions in required skills are relatively stable across time, and the aggregate and industry trends in the number of vacancies are similar to other sources (Hershbein and Kahn, 2018). Second, the keywords used to narrow down job titles in clean energy industry might not cover all the relevant jobs. Future research should continue to expand the scope of clean energy jobs. Third, this study did not find spatial effects in the regression analysis, which might be because our analysis focuses on states instead of counties or census tracts. Future research could use similar datasets available at a more refined level to identify the differences of labor markets in rural or urban areas or areas with diverse populations.

5. Conclusion and policy implications

The Biden administration has committed to making a historic investment in energy and climate research. This plan includes energy innovation and clean, resilient infrastructure and communities; therefore, clean energy job creation is essential for achieving this goal (Limon and Aguilar, 2021). Our study focuses on the impacts of the COVID pandemic on clean energy labor market to emphasize the connection between achieving renewable energy and sustainability goals. We also point out the following policy recommendations:

The concentration of clean energy labor in a limited geographic area is an industry concern. If an industry is contained to specific geographies, it is vulnerable to adverse events within these localities. In contrast, sectors with more geographic spread are less impacted by events that occur within isolated areas. Of course, this becomes less of an issue in a global pandemic because every geographic area is affected. However, more isolated crisis scenarios, such as hurricanes or earthquakes, could significantly affect industries concentrated in certain regions. Our data show clean energy jobs are very geographically concentrated in a small number of states. Both industry and policymakers should prioritize increasing clean energy labor market in the currently underrepresented areas to protect the industry from the effects of geographically-isolated crisis scenarios. For example, T.X.’s geographically-constrained power grid caused a near-total collapse during Winter Storm Uri in February 2021, which caused nearly 4.5 million homes to go without power for several days (Energy Information Adm, 2021). To achieve universal clean energy, it will be necessary for policymakers to target under-performing regions. Several states identified in this study have little to no presence in the clean energy labor market, which will not only affect these states economically as more energy jobs transition to the clean and renewable sector but also will affect their ability to produce clean energy and avoid reliance on energy from other locations. Much is made of national “energy independence”; however, policymakers also need to ensure that there is a diversity of “clean energy” sources regionally.

One of the most significant impacts of the COVID pandemic was the pausing of projects in T.X. and N.Y. for the wind energy industry. Although clean energy industry workers were eventually included in
essential worker criteria, this clarification did not happen until August 2021 (D. ofecurity and Ad, 2021). To pre-empt future pauses of projects, it will be necessary for policymakers to formalize clean energy workers as "essential" in the form of stated rules and approved statutes rather than informal and ad-hoc memoranda.

The importance of health infrastructure—mainly testing and vaccination resources—is also critical to mitigating the negative impacts of the COVID pandemic scenarios. Several studies have identified that testing resources were both an indicator of investment in healthcare infrastructure and a predictor of a region’s ability to mitigate the effects of the pandemic (Lai et al., 2021; Tromberg et al., 2020; Kavanagh et al., 2020). Researchers should not just focus on the spread of COVID-19 cases; many organizations have invested in their testing infrastructure to maintain employee productivity during the pandemic. Looking ahead, the clean energy industry should make sure it has sufficient infrastructure in place ahead of any impending health crisis to self-mitigate adverse effects. Additionally, this highlights the importance of adequate health support within the clean energy industry, including quality healthcare services, insurance coverage, and other health benefits, to maintain employee health and avoid loss of productivity due to employee absence.

In considering future energy sector predictions, there should be a focus on improving clean energy sector growth, particularly biofuel and biomass. Our results showed insignificant impacts of COVID-19 on the biofuels and biomass sectors, mainly due to the low volumes of the overall job vacancies. To increase competition and promote choice in the marketplace, it will be essential to diversify clean energy market. Biofuels and biomass both present opportunities for sector growth that could provide alternatives to solar and wind generation. Currently, the U.S. Energy Information Administration (EIA) predicts that solar and wind will continue to be the dominant clean energy producers through 2022 (Energy Information Adm, 2021).

Studies suggest both state and local clean energy policies have moderate and positive effects on the number of clean or green energy jobs (Yi, 2013), indicating that state and local governments that take green or clean jobs seriously are somehow rewarded with more robust clean energy labor market, compared with other regions. Communities need to invest in clean energy industry and develop more resilient plans to improve clean energy labor market to respond appropriately and mitigate the effects of public health and the natural disaster crisis.

CRediT authorship contribution statement

Chien-fei Chen: Writing – original draft, Writing – review & editing, conceives the research ideas, writes, edits and oversees the entire manuscript. Yuanyang Liu: Formal analysis, Writing – original draft, leads the statistical analysis and result writing, and defines the measurement. Jamie Alexander Greig: Writing – original draft, Writing – review & editing, lead the literature review, policy recommendations, and overall manuscript writing. Zhenglai Shen: Data curation, Formal analysis, compiles data, conducts geospatial analysis, writes results and designs graphs. Yunye Shi: helps with the classifications of clean energy industry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix Table 1

Top employers for each clean energy sector examined in this study

| Solar (N = 67251) | Wind (N = 21602) | Grid (N=32497) |
|------------------|-----------------|---------------|
| Employer         | P               | Employer      | P            | Employer    | P            |
| Republic Services Incorporated | 6.2% | General Electric Company | 4.6% | National Grid | 5.2% |
| Tesla            | 5.7%            | NextEra Energy, Inc. | 3.7% | Reading & Math, Inc | 2.8% |
| Sunrun           | 3.7%            | Siemens       | 3.4% | Rotech Healthcare | 1.7% |
| Vivint Solar     | 3.2%            | Vestas        | 2.9% | Sargent & Lundy    | 1.7% |
| Solar Transport Company | 2.8% | Black & Veatch | 2.3% | Guidehouse       | 1.6% |
| Sunrun Inc       | 1.8%            | Avaingrid     | 2.2% | First Solar       | 1.6% |
| Lg Electronics Usa Incorporated | 1.3% | DNV GL        | 2.0% | Vmware Incorporated | 1.4% |
| Sunpower Corporation | 1.3% | Stantec, Inc. | 1.6% | Portland General Electric | 1.3% |
| Sunrun, Inc      | 1.0%            | Westwood Professional Services Incorporated | 1.4% | Lodging Enterprises Incorporated | 1.3% |
| Sunpro           | 0.9%            | Mastec Incorporated | 1.3% | Memorial Healthcare System | 1.3% |
| **Total**        | **27.8%**       | **Total**     | **25.5%**    | **Total**    | **19.9%**    |

| Biomass (N=1942) | Energy Efficiency (N=31578) | Electric Vehicle (N=83204) |
|------------------|-----------------------------|----------------------------|
| Employer         | P                           | Employer                  | P            |
| HNI Corporation  | 5.1%                        | Verizon Communications Incorporated | 6.5% | Aldi | 8.3% |
| Impossible Foods | 5.1%                        | Praxair                   | 2.6% | Tesla | 3.8% |
| University of Illinois | 4.0% | Checkers Drive In Restaurants | 1.8% | Usic | 2.9% |
| Lawrence Berkeley National Laboratory | 3.9% | Sunpower Corporation | 1.2% | Penske | 2.2% |

(continued on next page)
Appendix Table 1 (continued)

| Employer | P  | Employer | P  | Employer | P  |
|----------|----|----------|----|----------|----|
| Die Energy | 3.5% | Tesla | 1.2% | Pike Electric Incorporated | 1.5% |
| National Renewable Energy Laboratory | 2.8% | Waste Management | 1.1% | Sears | 1.5% |
| Sandia Corporation | 2.5% | Southern Company | 0.9% | Polars Industries | 1.0% |
| Poet Software | 2.3% | Siemens | 0.9% | Black & Veatch | 0.9% |
| Oak Ridge National Laboratory | 2.0% | Kenmanetal Incorporated | 0.8% | Osmose Incorporated | 0.7% |
| Enviva | 1.7% | Peter Kazella & Associates, Inc | 0.8% | Syesco Corporation | 0.7% |
| Total | 33.0% | Total | 17.9% | Total | 23.6% |

Appendix Table 2

Top occupations for each clean energy sector examined in this study

| Solar | Wind | Grid |
|-------|------|------|
| SOC-6 Occupation | P  | SOC-6 Occupation | P  | SOC-6 Occupation | P  |
| Sales Representatives, Wholesale and Manufacturing | 10.92% | Wind Turbine Service Technicians | 7.12% | Miscellaneous Computer Occupations | 6.61% |
| Sales Representatives, Wholesale and Manufacturing, Technical and Scientific Products | 10.00% | Miscellaneous Managers | 5.93% | Software Developers, Applications | 6.01% |
| Heavy and Tractor-Trailer Truck Drivers | 5.46% | Maintenance and Repair Workers, General | 5.34% | Registered Nurses | 4.57% |
| Electricians | 4.42% | Miscellaneous Computer Occupations | 3.01% | Electrical Engineers | 4.30% |
| Miscellaneous Managers | 3.56% | Electrical Engineers | 2.76% | Miscellaneous Managers | 3.53% |
| Solar Photovoltaic Installers | 3.18% | Construction Managers | 2.08% | Miscellaneous Teachers and Instructors | 3.28% |
| Wind Turbine Service Technicians | 2.78% | Civil Engineers | 2.00% | Electricians | 2.84% |
| Sales Managers | 2.36% | Miscellaneous Engineers | 1.82% | Database Administrators | 2.49% |
| Retail Salespersons | 2.02% | Software Developers, Applications | 1.80% | Customer Service Representatives | 2.35% |
| Miscellaneous Computer Occupations | 1.96% | Electricians | 1.54% | Miscellaneous Engineers | 1.75% |
| Total | 46.65% | Total | 33.40% | Total | 37.73% |

| Biomass | Energy Efficiency | Electric Vehicle |
|---------|-----------------|-----------------|
| SOC-6 Occupation | P  | SOC-6 Occupation | P  | SOC-6 Occupation | P  |
| Natural Sciences Managers | 6.13% | Retail Salespersons | 4.80% | Retail Salespersons | 6.64% |
| Operations Research Analysts | 5.36% | Food Service Managers | 3.57% | Wind Turbine Service Technicians | 5.23% |
| Miscellaneous Managers | 4.58% | Miscellaneous Managers | 3.57% | Electrical Power-Line Installers and Repairers | 4.58% |
| Laborers and Freight, Stock, and Material Movers, Hand | 3.09% | Wind Turbine Service Technicians | 3.57% | Automotive Service Technicians and Mechanics | 4.37% |
| Miscellaneous Life Scientists | 2.83% | Miscellaneous Computer Occupations | 3.04% | Laborers and Freight, Stock, and Material Movers, Hand | 3.54% |
| Chemical Engineers | 2.68% | Software Developers, Applications | 2.44% | Heating, Air Conditioning, and Refrigeration Mechanics and Installers | 3.44% |
| Medical and Clinical Laboratory Technicians | 2.37% | Customer Service Representatives | 2.37% | Electricians | 3.12% |
| Miscellaneous Computer Occupations | 2.32% | Electrical Engineers | 2.34% | First-Line Supervisors of Retail Sales Workers | 2.97% |
| Physical Scientists | 2.21% | Sales Representatives, Wholesale and Manufacturing | 2.18% | Heavy and Tractor-Trailer Truck Drivers | 2.97% |
| Power Plant Operators | 2.11% | Mechanical Engineers | 2.11% | Farm Equipment Mechanics and Service Technicians | 2.47% |
| Total | 33.68% | Total | 30.00% | Total | 39.34% |

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