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Impact analysis of COVID-19 pandemic on the future green power sector: A case study in the Netherlands

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1. Introduction

In 2020, the outbreak of the coronavirus disease 2019 (COVID-19) produced a striking global crisis. According to the World Health Organization (WHO), 1.2 billion confirmed cases of COVID-19 and over two million deaths occurred, affecting almost all countries around the world by the end of March 2021 [1]. Moreover, through domestic and international trade limitations, the pandemic created enormous economic damage. It has been confirmed that the global economy shrank by 4.3% in 2020 and may lead to 130 million people falling into extreme poverty [2,3]. In terms of global emissions, a drastic reduction occurred in CO2 [4], NO2 [5], PM [6], and other chemicals compared with their 2019 levels. This decreasing trend varied from region to region. In short, the change brought about by the COVID-19 pandemic in all aspects marks it as a new and severe challenge.

Energy is the cornerstone of economic development and social operation. The energy sector faced huge shocks from both the supply and demand sides during the pandemic [7]. It is predicted by the International Energy Agency (IEA) that global energy demand in 2020 will decrease by nearly 6% compared to 2019 levels [8]. Traditional fossil fuels such as oil [9,10] and natural gas [11] have suffered a significant decline in both demand and price. Meanwhile, lockdown measures applied during the pandemic led to a huge shift in the power sector in terms of electricity demand and its hourly distribution. Statistically speaking, the average electricity production in 16 European countries was reduced by almost 9% in April 2020 compared with the mean value for the identical period from 2015 to 2019 [12]. The fossil fuel electricity supply decreased by 28%, whereas the renewable electricity supply increased by 15% during this period [13,14]. It can be observed that this decreasing trend of electricity demand was common across all countries.

The pandemic has also strongly influenced renewable energy integration in the power sector. On the one hand, global trade restrictions and economic shrinkage have led to budget reductions in most countries, posing a hurdle for the manufacturing, installation, and deployment of renewable energy technologies. However, the huge uncertainties in fossil fuel prices (e.g., oil and natural gas)
Nomenclature
COVID-19 Coronavirus disease 2019
WHO World Health Organization
IEA International Energy Agency
ENTSO European Network of Transmission System Operators for Electricity
CBS Central Bureau of Statistics
PV Photovoltaic
N-gas Natural gas
LSTM Long and short-term memory
RNN Recurrent neural network
REF Reference 2019 scenario
BAU Business-as-usual 2035 scenario
NEV National Energy Outlook 2035 scenario
HW High wind 2035 scenario
HS High solar 2035 scenario
COM Combination 2035 scenario
O&M Operation and management
CEEP Critical excess electricity production

Provided a prominent opportunity for renewable energy to be adopted as an alternative in the future power sector [15,16]. Moreover, investment in renewable energy is deemed an effective measure for promoting sustainable economic growth and creating more employment opportunities during the post-pandemic period [17]. The impact of the COVID-19 pandemic on renewable energy technology is complex and far-reaching. In this context, exploring what will happen in the future green power sector if a similar pandemic appears will be instructive and meaningful. It will help identify the appropriate path for renewable energy technology development and can be used to formulate novel policies to withstand the possible long-term shocks of such urgent events. Taking the Netherlands as a case study, the main objective of this exploratory investigation is to develop and summarize the methodological steps for evaluating the impact of lockdown measures implemented in response to similar pandemics in the future power sector. Two key processes contribute heavily to the results: 1) the impact simulation of lockdown measures on electricity demand, and 2) the design of the future power sector.

First, the simulation of lockdown measures plays a vital role in representing the impact of similar events to the COVID-19 pandemic. Previous studies have employed people’s behavior (with a time resolution of 1 h) during the pandemic, to reflect the impact of lockdown measures [18,19]. This assumption emphasizes the hourly distribution of behavior in evaluations. Another study summarized and formulated the hourly distribution of occupancy profiles under different confinement policies for all building types [20]. The impact of confinement on electricity and heat demands was measured by assuming this hourly distribution of occupancy profiles in buildings. In short, these studies aim to indirectly simulate the impact of lockdown measures on energy use, by first assuming an hourly distribution of people’s behaviors or occupancy profiles under the measures and then identifying the impacts of these behaviors on energy use. This method indirectly simulates the influence of lockdowns by assuming that the hourly distribution curve is effective and widely used. However, looking more specifically at the power sector, the questions of how to simulate the impact of lockdown measures and under what conditions an hourly distribution curve is applicable for this impact have not yet been addressed.

Second, the green power sector is essential in the low-carbon transition of the entire energy system, and renewable energy integration has become the dominant direction in future power sectors [21]. In the Netherlands, because of the government’s general 49% reduction target, the primary goal of the power sector is to reduce CO2 emissions by at least 20.2 Mt by 2030 [22]. Increased renewable energy integration and investment in renewable energy have a strong influence on the achievement of this goal. Offshore wind power and photovoltaic (PV) power represent key green power resources for future societies and economies. Studies have been conducted to formulate a suitable energy transition pathway in the power sector [23–25]. Nevertheless, to the best of our knowledge, transition pathways mainly covering different renewable energy sources in the power sector in the medium-term (2035) have not been designed and compared in the Netherlands. Furthermore, a future power sector dominated by different renewable electricity types may respond differently during pandemics. Onshore wind power, offshore wind power, and PV power differ significantly in terms of the electricity supply curve and investment cost. The differences in all the above aspects could have a strong influence on performance under lockdown measures; however, these considerations have not been discussed in current COVID-19 related research [26,27].

This study summarizes and develops methodological steps to explore the impact of lockdown measures during similar pandemics in the future green power sector. First, two lockdown levels for the electricity demand were defined. The difference curve of electricity demand was applied to represent the specific impact of lockdown measures on the power sector under the two lockdown levels. When obtaining the difference curve of electricity demand, the long-and short-term memory (LSTM) model was employed to extend this curve across the entire year. For the future power sector, four renewable scenarios and a business-as-usual (BAU) scenario were formulated to show the green transition in the Netherlands power sector up to 2035. Finally, a multidimensional analysis from technical, environmental, and economic perspectives was conducted. The proposed methodological steps were found to be generic and applicable to the power sectors in other countries, especially those that have or will have a high share of renewable energy in the power supply mix.

The main contributions of this study are summarized as follows:

1) It explores the green transition pathways in the Netherlands power sector toward the medium-term goal (2035).
2) It quantifies the impact of lockdown measures brought about by similar pandemics in the future Netherlands power sector.
3) It contributes to formulating policies that develop renewable energy and can withstand such emergencies in the future, and the methods are generic and applicable to the power sector of other countries.

The remainder of this paper is organized as follows: Section 2 gives a brief introduction to the Netherlands, including its performance during the COVID-19 pandemic and its current power sector; Section 3 comprehensively shows our methodological steps, including the simulation of lockdown measures, scenario development, and power system modeling; Section 4 provides results from the technical, economic, and environmental analyses; Section 5 presents a discussion; and Section 6 concludes the paper.

2. Background- The Netherlands

The Netherlands was selected as a case study for the following two reasons: (1) It is one of the countries most affected by the COVID-19 pandemic; that is, its electricity demand, supply, and hourly distribution were significantly changed, and hence sufficient data can be found. (2) The current electricity supply mix in the
Netherlands is dominated by fossil fuels. Green economic requirements require a rapid low-carbon transition in the future power sector.

The Netherlands is a western European country (Fig. 1) with a total population of 17.4 million. Its population density is nearly 515 people/km². The first case of COVID-19 was confirmed on February 27, 2020. Lockdown measures (e.g., closing schools and universities, mandatory national lockdowns and bans on meetings, and other public activities) were implemented by the government [28]. These stringent lockdown measures were initially proposed to be extended to April 28, 2020. After the complete lockdown period, the national economy and citizens’ normal lives were seriously affected. The government announced that some lockdown measures would begin to be relaxed from June 1. They allowed people to travel by public transport, though they needed to wear masks. However, the second wave of the COVID-19 pandemic began in September 2020. The government raised the national pandemic risk level and announced that it would “partially close the city” nationwide and further tighten epidemic prevention measures in the following month [29].

Natural gas (N-gas) has always been the most important fuel in the Netherlands’ power supply mix. The Dutch gas market is one of the largest in Europe [30]. Under the pressure of domestic energy intensive industries, gas-based fossil fuels have dominated the energy supply for electricity generation. However, the anti-gas sentiment caused by strong earthquakes in Groningen, in combination with climate change policies, has raised doubts about future N-gas development [31,32].

The government has set ambitious emission reduction goals and formulated a national policy framework to move towards a low-carbon economy. The deployment of renewable energy technologies is relatively low though is progressing under policy protection [30]. Renewable energy (e.g., wind, PV, and bioenergy) has developed rapidly in the Netherlands in recent years. It is estimated that renewable electricity growth could convert the Netherlands from a net importer to an exporter of energy. The share of renewable electricity from 2005 to 2019 is shown in Fig. 2a, and the proportion of electricity generation in technology in 2019 is shown in Fig. 2b.

3. Methodology

3.1. Methodological steps

The methodological steps aim to simulate the impact of lockdown measures on the future green power sector. The first step involves simulating the impact of lockdown measures. This step requires us to define different lockdown levels during the COVID-19 pandemic period, analyze their impact upon electricity demand, and simulate the impacts using the difference curve of this demand. In this step, the electricity demand curves under different levels of lockdown measures are obtained. The second step serves as a future scenario development, showing green transition pathways in the power sector. This step considers the growth in future electricity demand attributable to population expansion and industrial development.

The electricity demand curve obtained in the first step can be applied in the second step to represent the impact of a lockdown implemented under a similar pandemic in the future power sector. All the above data are inputted into the third step. An appropriate simulation tool is required in this step to perform power sector modeling and analysis. The final step aims to quantify the impact of different lockdown levels on future power sector scenarios and quantify what will happen if a similar emergency occurs. This step includes an analysis from technical, environmental, and economic perspectives. The structure of the methodology is illustrated in Fig. 3.

3.2. Simulation of the impact of lockdown measures

3.2.1. Lockdown level definitions

As previously described, the COVID-19 pandemic outbreak was repeated in the Netherlands, and the lockdown measures differed by period. In response to this crisis, the government initially adopted a series of stringent lockdown measures in early March 2020. These measures included a ban on public activities and travel, daytime curfews, and so on. Considering the dramatic electricity demand decline that occurred after applying these stringent lockdown measures, the lockdown level during this period was regarded as a “Complete lockdown” and is defined as Lockdown Level 2 in this study.

Since June 2020, many countries have chosen to ease lockdown measures and have tried to enforce mask-wearing instead of restricting travel. With the exception of certain educational institutions and schools, which remained closed, other lockdown measures were alleviated. The lockdown level after moderate alleviation is referred to as “Partial lockdown” and is defined as Lockdown Level 1 in this study. Clearly, the electricity demand immediately picked up once these measures were relaxed. However, the electricity demand during this period still remained lower than the mean value during the same period in 2019. To summarize, lockdown levels, the main measures implemented in different levels, and the corresponding periods in the Netherlands are provided in Table 1. A reference level (no COVID-19) is established for comparison.

3.2.2. Analysis of the impact on electricity demand

The reduction in electricity demand during the corresponding period (compared with the reference period in 2019) is presented in Table 2. The electricity demand under Lockdown Level 1
decreased by 0.52 TWh compared with the 2019 level. Electricity demand under Lockdown Level 2 decreased by 1.08 TWh, accounting for 12.01% of the 2019 electricity demand level.

The changes in electricity demand caused by the lockdown measures appear in both the total amount and hourly distribution.

![Development of renewable electricity in the Netherlands.](image1)

**Fig. 2.** Development of renewable electricity in the Netherlands. a Share of renewable electricity to the total electricity supply from 2005 to 2019. b Proportion of electricity generation of each technology in 2019.

![Structure of the methodological steps in this study.](image2)

**Fig. 3.** Structure of the methodological steps in this study.

| Level          | Simple description       | Main Measures                                                                 | Corresponding period |
|----------------|--------------------------|-------------------------------------------------------------------------------|----------------------|
| Reference level| No pandemic              | No restriction                                                                | 2019                 |
| Lockdown Level 1| Partial lockdown     | 1 Close some national borders and restrict international travel.               | June 1, 2020–June 28, 2020 |
|                |                          | 2 Some schools and education institutions (e.g., primary schools) resume classes. |                      |
|                |                          | 3 Outdoor restaurants, theaters, music venues, museums and cinemas gradually open, though a certain social distance must be maintained. |                      |
|                |                          | 4 Require people to wear masks on public transport.                           |                      |
|                |                          | 5 Ban of public gatherings >100 [33].                                         |                      |
| Lockdown Level 2| Complete lockdown   | 1 Close schools, universities, restaurants and other public buildings within the country. | April 6, 2020–May 3, 2020 |
|                |                          | 2 Mandatory national lockdown and require people to stay at home.              |                      |
|                |                          | 3 Ban of meetings of three or more people.                                   |                      |
|                |                          | 4 Enforce social distancing >1.5 m [33].                                     |                      |

The electricity demand curve during the corresponding period (June 1, 2020–June 28, 2020; four weeks) of Lockdown Level 1 is shown in Fig. 4a, along with that of the similar period (June 3, 2019–June 30, 2019; four weeks) of 2019. For better comparison, the weekends of 2020 and 2019 were made to coincide. Because the
variation in electricity demand also differs according to the type of day, the average electricity demand curve of the corresponding period was divided into workdays (Fig. 4b) and weekends (Fig. 4d) in this study. The difference curve of electricity demand for the two types of days between Lockdown Level 1 and 2019 is shown in Fig. 4c and e.

The average electricity demand and its hourly distribution on workdays and weekends were all significantly modified by the COVID-19 pandemic. Regarding the difference curve on workdays under Lockdown Level 1, the reduction in electricity demand occurred at all hours of the day. However, the most significant decline occurred between 12:00 and 15:00. The period from 12:00 to 15:00 h (the “afternoon valley”) was almost 12% lower than the 2019 level. This is mainly attributable to decreased industry and commercial activities, such as the closure of clubs, cafes, and restaurants. These two types of activities are responsible for a large proportion of the electricity demand in this period. Morning and evening peaks on work days were maintained, indicating that normal activities in the morning and evening continued but remained less active than before. During this period, the electricity demand decreased from 5% to 10%. The two periods before 5:00 h and after 22:00 h were the least affected by the lockdown measures. The decline proportion in these two periods was maintained at ~3%. Because most people’s work ends at the same time during a workday, the ratio of residential electricity demand started to rise. The decline in electricity demand in the industrial and service sectors during these periods was not as clear as that in the daytime.

Regarding the difference curve of electricity demand during the weekend under Lockdown Level 1, the most apparent difference between the workday and weekend was the disappearance of the morning load peak. Typically, the electricity demand around 8:00 h exceeded the night load and represented the first load peak. However, the morning load peak did not occur during lockdown. One likely reason is that people tended to get up later when the lockdown took effect. This also brought forward the greatest decline in electricity demand. The most significantly decreased share also occurred in the afternoon valley, a reduction of ~10%. Unlike the morning peak, the evening peak at the weekend remained and served as the most prominent characteristic of the electricity consumption. This is plausible because most people tend to use electricity-based entertainment at night. The difference in electricity demand during this period was only 3%.

Identical pictures of the electricity demand curves between the 2019 level and Lockdown Level 2 are presented in Fig. 5. The average electricity demand curve was also distinguished by the type of day: workdays (Fig. 5b) and weekends (Fig. 5d). The difference curves of electricity demand for these days are shown in Fig. 5c and e, respectively.

In terms of the decreasing share in the workday, the order of the affected period during one day under Lockdown Level 2 resembled that of Lockdown Level 1; that is, the most significantly affected period was the afternoon valley, followed by the morning and evening peak, and finally night-time. However, the decreasing share of all periods under Lockdown Level 2 was more serious: afternoon valley: 20%; morning and evening peak: approximately –15%; and night-time: 5%. As mentioned before, the industrial and commercial sectors even halted their activities under Lockdown Level 2. This produced a significant decline in electricity demand during all hours of the day. For the decreasing share at the weekend under Level 2, the decline in electricity demand exceeded that under Level 1. The “Get up later” effect in the morning peak at the weekend was still present.

By analyzing the impact of lockdown on electricity demand, it becomes easy to see that the difference curve of electricity demand can intuitively reflect the influence of different lockdown measures on the power sector. Considering the method of indirectly simulating the impact of lockdown (by assuming an hourly distribution curve), the difference curve of electricity demand was utilized in this study to represent and simulate the impact of different lockdown levels on the power sector.

Table 2
Electricity Demand Reduction during Different Lockdown Levels (Compared with the reference period in 2019) [34].

| Corresponding period | Electricity demand (TWh) | Reference period | Electricity demand (TWh) | Difference (%) |
|----------------------|--------------------------|----------------|--------------------------|---------------|
| Lockdown Level 1     | June 2020                | 8.13           | June 2019                | 8.65          | –6.01         |
| Lockdown Level 2     | April 2020               | 7.89           | April 2019               | 8.97          | –12.04        |
3.2.3. Simulation of the impacts across one year

After determining the role of the electricity demand difference curve when simulating the impact, the problem became one of obtaining the annual electricity demand difference curve.

To summarize, the year can be roughly divided into two stages (according to the total electricity demand and its hourly distribution): summer (from April to September) and winter (from January to March and from October to December). For the summer stage, the difference curves in the corresponding periods of the two lockdown levels could be directly applied to transform the unaffected electricity demand curve into the affected one under lockdown conditions. For the winter stage, using the difference curve in the summer stage was unsuitable because the share of electricity demand for each industry in this stage differed from that in the summer stage. Thus, it is unrealistic to simulate the impact using only the actual difference curve.

In this study, long short-term memory (LSTM) was employed to forecast the electricity demand during the winter stage under different lockdown levels. Then, the electricity demand difference curve between the 2019 level and LSTM forecast was obtained and utilized in the winter stage. In this way, the annual electricity demand difference curve was obtained, and the unaffected electricity demand curve of any year could be converted into the electricity demand curve under lockdown measures. To summarize, the impact of different lockdown measures on the power sector can be simulated. A schematic of the annual electricity demand difference curve is shown in Fig. 6.

LSTM is a common and established approach that uses time-sequence data to forecast future occurrences [35,36]. A typical LSTM unit consists of an input and output gate, forget gate, unit input, and cell state. LSTM includes abundant network units and employs these to store values of long$ and short durations. The structure of LSTM is illustrated in Fig. 7. This approach can overcome the shortcomings of vanishing gradients in recurrent neural networks (RNN), and it is better at learning characteristics from sequential data [37,38].

The modeling procedure and forecasting process when using the LSTM method to forecast the affected electricity demand in the winter stage are as follows:

1. Data collection: The key input data of the standard demand forecasting approach are timing information (e.g., day of the week, time of day, and day of the month), weather data, and previous demand data. However, significant changes in electricity consumption pose significant challenges to standard forecasting approaches. These input data cannot precisely reflect sudden and large differences in human behavior. In this study, mobility data were introduced and served as an essential complementary input to the LSTM model. The mobility data included information regarding retail and recreation, grocery and pharmacy, parks, transit stations, workplaces, and residential areas. Such data can show how visits to different places vary compared to the baseline once the lockdown measures are implemented; thus, they are suitable for reflecting the extent of different lockdown levels.

The input data of the LSTM model can therefore be divided into several categories: (a) Previous electricity demand data. These data were gathered from the Transparency Platform of the European Network of Transmission System Operators for Electricity (ENTSO) [39]. The collected data included the electricity demand records...
from September 2019 to November 2020 and were based on hourly sampling time. (b) Timing information. Information regarding the day of the week and the month of the day were employed. (c) Weather information. Meteorological data were collected for five cities in the Netherlands: Amsterdam, Utrecht, Hogeveen, Groningen, and Middelburg. The average daily temperature, precipitation, humidity, and dew point of each city were obtained from the Weather Underground website [40]. (d) Mobility data. Daily mobility data in the Netherlands are available from Google mobility reports [41]. In general, all data collections have credible support and ensure the correctness of the collected data.

(2) Processing method and network architecture: To accelerate the training process, all variables were normalized before the forecasting process. The Z-score normalization method was applied to normalize the data to the range of 0–1. The hidden layers (LSTM layer and fully connected hidden layer) and nodes in each layer serve as two main parameters supporting the LSTM network architecture. In this study, one LSTM layer and two fully connected hidden layers were employed, and the node number of the fully connected hidden layers was approximately twice that of the input layer. For each tuple, its input was composed of the electricity demand record, the characteristics of the previous seven days, and the characteristics of the targeted day. The characteristics were the timing, weather, and mobility data. The output of each tuple was the forecast electricity demand for the target day. The data-correspondence relationship during the forecasting process in the LSTM model is shown in Fig. 8. The electricity demand record employed in the model includes days in the winter and days under different lockdown levels. The LSTM network can identify and learn the influence of electricity demand characteristics by constantly training on these data. The electricity demand under different lockdown levels during the winter stage can be obtained by flexibly applying mobility data.

(3) Modeling apps and facilities: In this study, all the above procedures were programmed in the Python programming language. The proposed method was implemented in Python using TensorFlow. The results were obtained by running the procedures on a workstation with an Intel Xeon W-2123 CPU and 64 GB memory.

This model could predict the hourly electricity demand of any day in the winter stage, using mobility data from during the lockdown period. The forecasted electricity demand not only conformed to the features of electricity demand in the winter stage but was also affected by the lockdown measures. Taking one week in the winter stage (from November 2 to November 8, 2020) as an example, the results of the forecasted daily electricity demand under Lockdown Level 1 are given in the left-hand side of Fig. 9. The average electricity demand curve on workdays and weekends and the difference curves on workdays and weekends are shown in Fig. 9a, b, 9c, and 9d, respectively. The results under Lockdown Level 2 are given in the right-hand side of Fig. 9. The average electricity demand curve during the workday and weekend and the difference curves on workdays and weekends are shown in Fig. 9e, f, 9g, and 9h. It can be seen that the forecasted daily electricity demand during the winter stage exhibits the same characteristics as the electricity demand in the summer stage, and it was affected by the lockdown [as shown in Figs. 4 and 5].

Taking Lockdown Level 1 as an example, the annual electricity demand difference curve is obtained by applying the difference curves in Fig. 4c and e to all workdays and all weekends, respectively, in the summer stage; applying the difference curves in Fig. 9b and d to all workdays and all weekends, respectively, in the winter stage.

Note that the lockdown levels defined in this study did not occur in winter; thus, no actual electricity demand data are available to verify the results of the forecast model. With the second outbreak of the COVID-19 pandemic in the Netherlands, several lockdown measures were implemented again at the end of October. The levels of these lockdown measures resembled those adopted in June (i.e., Lockdown Level 1). The annual electricity demand difference curve was applied at the 2019 level to produce the yearly electricity demand curve under Lockdown Level 1. The affected electricity
demand difference curve was compared with the actual electricity demand curve for November 2020, to verify the effectiveness of using the difference curve to simulate the lockdown impact. The simulated results of the affected electricity demand difference curve and actual electricity demand curve for 2020 are shown in Fig. 10.

Very little difference can be observed between the actual electricity demand and simulated demand, both in terms of total amount and hourly distribution. Thus, this simulated method of using the difference curve is regarded as credible for simulating the impact of different lockdown levels on electricity demand during the winter stage. Moreover, the assumption of using the LSTM model to forecast electricity demand is further discussed in the discussion section.

3.3. Future scenario development

The European Union promised that its emissions could be reduced by 80–95% by 2050, compared to the 1990 level [42,43]. Climate policies in the Netherlands have established similar targets and focused more on short- and medium-term plans. The “Energy Agenda” [44] and “National Energy Outlook” [45] have been proposed, with an emphasis on energy saving, gas consumption reduction, and more renewable energy investments. The application of current and planned policies in these national publications is mainly assessed in terms of the medium-term goals.

The increase in electricity demand in 2035 forms a common assumption in all future scenarios. The Netherlands is soon expected to become a net power exporter, rather than an importer. This provides additional requirements for electricity production. Meanwhile, deeper electrification in the industry and transport sectors will also increase electricity demand. Considering these factors, electricity demand has grown from 118 TWh in 2019 to 140 TWh in 2035 [45].

3.3.1. Reference 2035 scenario

The Reference 2035 scenario closely resembles the 2019 scenario. It simulates the development of the power sector in the Netherlands according to the current situation and policies. Changes in power production technologies and energy preferences are negligible. The installed capacities of thermal power (including coal- and gas-fired power, PV power, onshore wind power, and offshore wind power) all increased at a similar ratio.
This scenario was built from the National Energy Outlook (NEV), presented by the government of the Netherlands. The key aspect of NEV focuses on renewable targets between 2016 and 2035. To achieve the goal of a renewable electricity share of more than 16%, this scenario emphasizes the construction of offshore wind farms and solar photovoltaic panels, with the installed capacities of offshore wind power and PV power exceeding 10 GW and 20 GW, respectively. Meanwhile, coal is reduced in the electricity supply mix, and its share is replaced by renewable energy sources. Natural gas exhibits a moderate decrease because gas changes from the current baseload to the backup of renewable energies in 2035. It is worth mentioning that all nuclear power plants are phased out in the NEV plan.

The High wind 2035 scenario is based on the NEV 2035 scenario but sharply increases the installed capacity of onshore and offshore wind power. Onshore wind power is regarded as one of the most effective renewable energy sources for achieving emission-reduction targets. However, its potential for use in the Netherlands is limited. According to the “Clean Economy by 2050” [40], the theoretical potential of onshore wind power across the entire country is estimated to be 10 GW. The potential of offshore wind power is large, reaching ~34 GW. In this scenario, onshore wind power technology is added to its maximum potential, and the installed capacity of offshore wind power is set at 15 GW in 2035.

The High solar 2035 scenario is also built from the NEV 2035 scenario, though it increases the installed capacity of PV power. Solar panels can be well integrated into the roofs of public infrastructure, and PV power generation implemented on the roofs of suitable utilities in the Netherlands shows promising potential. According to the “Clean Economy by 2050” [46], The Netherlands is expected to have a total roof area of over 300 km². The theoretical installed capacity of PV power in the Netherlands is predicted to be 90 GW in 2035. In this scenario, the installed PV power capacity is 42 GW, nearly half of the maximum potential. The installed capacity of offshore and onshore wind power exhibits a slight reduction, with the proportion of these two technologies maintained at the NEV level.

This scenario presents a more ambitious deployment of renewable energy technologies than the NEV 2035 scenario. It aims to demonstrate the effect of increasing the installed capacity of wind power and PV power. The capacities of these two power generation technologies do not exceed those of the high-and high-solar scenarios, respectively. Compared with the NEV scenario, the installed capacity of thermal power decreases slightly. Further details of the installed capacity for various technologies in the 2035 scenarios and 2019 reference scenario are provided in Table 3.

### 3.4. Power sector modeling

#### 3.4.1. Modeling tool

The power sector simulation and scenario construction processes must consider the types of conventional and renewable electricity generation technologies. Meanwhile, analysis of scenarios from technical, environmental, and economic perspectives requires a diversity of modules in the tool. In addition to the requirements of these modules, the simulation tool also requires an hourly basis to calculate the hourly, weekly, monthly, or yearly balance between the electricity supply and demand.

The EnergyPLAN tool has been widely applied to evaluate power sector strategies, validate the feasibility of advanced technologies, and explore the appropriate penetration share of renewable electricity [47–49]. This tool can assess the development of future power sectors at regional, national, or even EU levels. Regarding endogenous logic, the EnergyPLAN tool is a deterministic input/output tool that depends more upon manual heuristics. Furthermore, this tool can quickly produce results with a time resolution of 1 h. Therefore, this tool was selected to simulate the power sector and develop different scenarios in the Netherlands. A schematic of the EnergyPLAN tool is provided in Fig. 11.

#### 3.4.2. Technical and economic data

The hourly distribution data for electricity demand in the Netherlands were obtained from ENTSO [39], and the power generation data (e.g., nuclear, wind, offshore wind, and PV power) were also used. These applied a time resolution of 15 or 60 min. Furthermore, the installed capacity of each electricity generation technology and the fuel consumed in the power sector in 2019 were obtained from the Netherlands Central Bureau of Statistics (CBS) [34].

The cost profile of the EnergyPLAN tool includes the investment cost of each technology, fuel cost, fixed and flexible operation and management (O&M) costs, and electricity and CO₂ prices. In addition, certain annual factors (e.g., the period of technology and interest rate) were required to calculate the total yearly cost. As for the investment cost, the costs of different conventional and
renewable electricity generation technologies were taken from research findings [50–52]. These cost data have been widely used in numerous studies at the EU level and were considered suitable for conducting economic analysis in this study. The investment costs are listed in Table 4. The future fuel costs were based on projections calculated in previous studies [53,54]; they are presented in Table 5. The CO2 price was obtained from [55]. The interest rate in this study was assumed to be 3%.

### Table 3
Description of The Alternative Scenarios For The Netherlands in This Study.

| Scenario abbreviation | Reference 2019 | Business-as-usual 2035 | NEV 2035 | High wind 2035 | High solar 2035 | Combination 2035 |
|-----------------------|----------------|------------------------|----------|----------------|----------------|------------------|
| Electricity demand    |                |                        |          |                |                |                  |
| Total electricity demand (TWh/year) | 118.35 | 140 | 140 | 140 | 140 | 140 |
| Electricity import/export (TWh/year) | 0.86 | 0 | 0 | 0 | 0 | 0 |
| Technologies | | | | | | |
| Nuclear (GW) | 0.45 | 0.54 | 0 | 0 | 0 | 0 |
| Central thermal power (N-gas) (GW) | 10.5 | 12 | 8.9 | 8.9 | 8.9 | 8.4 |
| Distributed thermal power (N-gas) (GW) | 5.07 | 6 | 3.07 | 3.07 | 3.07 | 2.5 |
| Thermal power (Coal) (GW) | 4.63 | 5.5 | 3.35 | 3.35 | 3.35 | 1.1 |
| Onshore wind power (GW) | 3.669 | 4.5 | 7.26 | 10 | 6 | 10 |
| Offshore wind power (GW) | 0.957 | 1.2 | 10.61 | 15 | 8 | 12 |
| PV power (GW) | 6.924 | 8.4 | 20.1 | 8.4 | 42 | 25 |
| Biomass power (GW) | 1.24 | 1.5 | 2.23 | 2.23 | 2.23 | 4 |

Fig. 11. Schematic of the EnergyPLAN tool.

for the Netherlands' power system was simulated with an hourly time resolution over 2019. The simulation results were compared with actual data, to confirm the consistency and reliability of the reference model. The balance between electricity production and consumption was the most important indicator for validating the model. A comparison of the electricity balance between the actual value in 2019 and the EnergyPLAN simulation is provided in Table 6. The simulated electricity production from hydro, thermal, wind, and PV was entirely within the expected margins (less than 1% difference), as were the electricity exports and imports. The maximum difference between the actual data and simulation was 0.89%, for the exported electricity. The results presented in this

3.4.3. Model validation

Once the input electricity demand and supply data were obtained and the fuel distribution was identified, the reference model
Table 4
Investment costs of different technologies and fixed O&M costs.

| Technologies      | Investment costs (ME/MW) | Lifetime (Year) | Fixed O&M costs (% of investment) | VO&M costs (€/MWh) |
|-------------------|--------------------------|-----------------|-----------------------------------|-------------------|
|                   | 2019 | 2035 | 2019 | 2035 | 2019 | 2035 | 2019 | 2035 |
| Power plant-coal  | 1.8  | 1.7  | 40   | 1.3  | 1.3  | 2.6  | 2.4  |
| Power plant-N-gas | 0.9  | 0.85 | 30   | 1.2  | 1.2  | 1.8  | 1.6  |
| Power plant-biomass| 2.62 | 2.2  | 25   | 2.8  | 2.8  | 4.5  | 4.2  |
| CHP—N-gas         | 1.02 | 1    | 20   | 1.3  | 1.3  | 1.8  | 1.6  |
| Individual boiler | 0.06 | 0.05 | 25   | 3.2  | 3.2  | 1.1  | 1    |
| Onshore wind      | 1.1  | 0.95 | 25   | 1.8  | 1.6  | 3    | 3    |
| Offshore wind     | 2.2  | 1.9  | 25   | 3.2  | 3    | 3    | 3    |
| PV                | 0.88 | 0.7  | 30   | 1.3  | 1.2  | 2    | 2    |
| Nuclear           | 5.6  | 5.5  | 50   | 2    | 1.8  | —    | —    |

Table 5
Fuel costs of different fuels and CO₂ in the Netherlands.

| €/GJ  | Coal | Crude oil | Diesel | Petrol | Natural gas | LPG | Biomass | CO₂ price (€/ton) |
|-------|------|-----------|--------|--------|-------------|-----|---------|-----------------|
| 2019  | 3    | 9         | 34     | 48     | 6           | 28  | 6.9     | 8.9             |
| 2035  | 3.5  | 17.5      | 45     | 56     | 9.2         | 34  | 7.2     | 24.8            |

Table 6
Comparison of electricity balance between actual value in 2019 and EnergyPLAN simulation.

| Plant Type  | Electricity generation (TWh) | Difference (TWh) | Difference (%) |
|-------------|------------------------------|------------------|----------------|
| Actual Data 2019 | EnergyPLAN Simulation |
| Onshore wind | 7.935 | 7.935 | 0 | 0 |
| Offshore wind | 3.573 | 3.573 | 0 | 0 |
| PV           | 2.813 | 2.813 | 0 | 0 |
| Nuclear      | 3.7   | 3.7   | 0 | 0 |
| Biomass      | 5.06  | 5.06  | 0 | 0 |
| Thermal      | 89.823| 90.16 | 0.337| 0.38 |
| Import       | 20.403| 20.503| 0.1| 0.49 |
| Export       | 19.548| 19.988| 0.44| 0.89 |

Table provide an accurate simulation of the Netherlands’ power system and verify the accuracy of the model. The construction of the 2019 reference scenario serves as an essential step in developing future scenarios for the Netherlands.

4. Results

To show the results more comprehensively, this section performs a multidimensional analysis from the technical, environmental, and economic perspectives. In the technical analysis, the energy consumption and supply in future power sector scenarios under different lockdown levels were presented, with the hourly distribution of electricity demand and supply. Then, the CO₂ emissions for different scenarios were provided in the environmental analysis to show the impacts of lockdown levels on emissions. Finally, the economic analysis aims to show the power sector cost change brought about by the lockdowns. An analysis from these three perspectives can provide a complete picture of the influence of different lockdown levels on the future power sector.

4.1. Technical analysis

First, in the technical analysis, the annual primary energy supply for future power sector scenarios under lockdown levels is shown in Fig. 12. Electricity production by technology type is shown in Fig. 13.

For the future power sector in the Netherlands, all renewable scenarios exhibit a reduction in the primary energy supply compared with the BAU scenario. This is because of the decreasing installed capacity of thermal power plants, including coal-fired and gas-fired power plants. However, because of the long-term use of N-gas for electricity generation, it remains a huge share of the total primary energy supply in all renewable scenarios. The share of renewable electricity from the total electricity production in the COM scenario was highest among all future scenarios, reaching almost 67%.

When it comes to the technical impact of lockdown measures, electricity production decreases with demand reduction in all future scenarios. The decline in electricity production under different lockdown levels was similar for each scenario. This can reflect the extent of the electricity demand reduction caused by the different lockdown levels in 2035 (i.e., 19.07 TWh in Lockdown Level 1 and 17.25 TWh in Lockdown Level 2). Furthermore, the implementation of lockdowns also improved the share of renewable electricity. The 7% increase indicates that renewable electricity will play a more important role in electricity supply during the future pandemic period. This is consistent with the electricity supply trends during the COVID-19 outbreak in 2020.

As mentioned previously, all future scenarios simulated in the EnergyPLAN model were set to island mode. Excess electricity production is a vital indicator of the imbalance between electricity demand and supply when a change is introduced in the power sector. The critical excess electricity production (CEEP) (caused by the introduction of different lockdown measures) in future power sector scenarios is shown in Fig. 14. Under the lockdown level upgrade, the CEEP in all renewable scenarios showed an increasing trend. This indicates that the lockdown measures worsened the electricity imbalance caused by renewable energy integration in
Fig. 12. Annual primary energy supply of future power sector scenarios under different lockdown levels.

Fig. 13. Electricity production by generation technology type for different future scenarios under different lockdown levels.

Fig. 14. CEEP in future scenarios under different lockdown levels.
the power sector. However, the magnitude of the growth differed by scenario.

The CEEP was originally 7.47 TWh in the HW scenario; this increased by 2 TWh under Lockdown Level 1 and increased by 2.3 TWh again under Lockdown Level 2. A heavier lockdown can increase CEEP growth in Scenario HW but has the opposite effect in Scenario HS. Changing from Lockdown Level 1 to 2 only results in an increase of 1.8 TWh in the HS scenario, which is less than the growth realized by the implementation of Lockdown Level 1. This can be attributed to the hourly distribution of supply curves in the HW and HS scenarios. Here, the period of one typical week in these two scenarios was selected as an example to show the electricity supply and demand under different lockdown levels. The results were as follows: HS scenario (Fig. 15) and HW scenario (Fig. 16).

The electricity supply and demand of a typical week in the HS scenario are shown in Fig. 15a; these correspond to the CEEP provided in Fig. 15b. Similarly, the electricity supply and demand in the HW scenario and the CEEP in the HW scenario are shown in Fig. 16a and b, respectively. For the electricity demand daily curves, the electricity demand change caused by lockdown measures primarily focuses on the sharp decline in electricity demand between 11:00 and 15:00 h. It is easy to see that this change places more obstacles against PV power integration than wind power, because the most active PV power generation period extends from 13:00 to 15:00 h. However, CEEP growth from Lockdown Level 1 to 2 in the HW scenario exceeds that in the HS scenario.

The main reason for this is the time concentration and fluctuation of wind-power generation in the Netherlands. Time concentration refers to intensive and large quantities of wind power within a month or season. This situation is shown in Fig. 16b, where more serious lockdown measures forced the power sector to abandon excess electricity production. The change in electricity demand leads to the abandonment of excess wind power production during the entire period of one day. Thus, for the entire year, the amount of abandoned wind power exceeds that of abandoned PV power, which appears only in a certain period of one day (as shown in Fig. 15b). From the perspective of electricity supply, the implementation of lockdown measures will more significantly affect the power system with a higher proportion of wind power integration.

4.2. Environment analysis

Second, an environmental analysis is conducted in this section, following the energy supply and demand analysis. The CO₂ emissions of the future power sector scenarios under lockdown levels are shown in Fig. 17.

For the future power sector in the Netherlands, CO₂ emissions in the BAU scenario reach 61.6 Mt. Clearly, the low-carbon transition in the power sector can significantly decrease CO₂ emissions. CO₂ emissions in Scenarios NEV, HW, and HS were all around 31 Mt, and the lowest occurred in the COM scenario (24.4 Mt). Compared with the BAU scenario, a reduction of 65% in emissions under the COM scenario is attributable to the large-scale utilization of wind, PV, and biomass power.

In terms of the environmental impact of lockdown measure implementation, lockdown measures can result in CO₂ emission reductions across all future power sector scenarios. Compared with the case of no lockdown, the implementation of lockdown measures under Lockdown Level 1 leads to an emission reduction of 4.9 Mt in the BAU scenario and a reduction of 2.7 Mt in the COM scenario. The difference in emission reduction was attributable to the different electricity supply structures between the two scenarios. In the BAU scenario, the decline in demand caused by lockdowns can reduce the electricity supply, most of which is satisfied by coal- and gas-fired power plants. Thus, the reduction in
electricity generation decreases fossil energy use more in the BAU scenario than in the COM one. This can also be proven in the implementation of lockdown measures under Lockdown Level 2: a reduction of 9.3 Mt in scenario BAU and 5 Mt in scenario COM. To summarize, Lockdown Level 1 brings about a reduction of 8–12% in CO₂ emissions, and Lockdown Level 2 brings about a reduction of 15–21% in CO₂ emissions in all future power sector scenarios.

4.3. Economic analysis

Third, economic analysis is an indispensable element for understanding the impact of lockdows on the future power sector. The power sector cost and share of each cost type (e.g., investment cost and fuel cost) serve as the key indicators to present the economic influence of low-carbon transition, lockdown measure...
implementation, and the mixture thereof. The annual power sector cost by cost type for future power sector scenarios is presented in Fig. 18. In the REF scenario, the total power sector cost was nearly 8.9 BEUR. Approximately 7% of the total power sector cost is from O&M cost, 23.7% from investment cost, and 64.4% from fuel cost.

For the future power sector in the Netherlands, the costs in the BAU scenario in 2035 significantly increased compared with the REF scenario in 2019. The huge increase can be attributed to two causes: 1) Electricity demand will increase from 118 TWh in 2019 to 140 TWh in 2035, and 2) higher fuel and carbon prices are expected in the future. The share of fuel costs to total costs in the BAU scenario improves to 65%, making it the most significant contributor to power sector cost expansion. Meanwhile, the CO2 cost increases by 3.5 times compared to the REF scenario. Compared with BAU, all future renewable scenarios exhibit a reduction in total power sector costs, owing to renewable energy integration. Replacing fossil electricity with renewable electricity can prevent the expansion of fuel costs caused by the rising fossil fuel prices. Scenario HW has the lowest power sector of 10.9 BEUR, nearly 19.4% lower than scenario BAU. Regarding the cost type, investment cost (instead of fuel cost) is the main contributor to the power sector cost. Owing to the rapid development of renewable electricity installed capacity, the investment cost is responsible for 30% of the total system cost in the NEV scenario, 33% in the HW scenario, 32% in the HS scenario, and 33% in the COM scenario, respectively.

Regarding the economic impact of lockdown measure implementation, lockdown measures result in a fuel cost reduction, and the extent of this reduction increases with the improvement in lockdown levels. A decline in demand leads to lower utilization of fossil fuels in electricity generation. The fuel cost in all future power sector scenarios underwent a reduction from 720 to 883 MEUR under Lockdown Level 1 and 1287 to 1601 MEUR under Lockdown Level 2. As for the total power sector cost, compared with the case of no lockdown, the lockdown measures applied under Level 1 in the COM scenario can reduce the total cost by 7.8%. Applying lockdown measures under Level 2 could reduce the total cost by 14.1%. In addition, when lockdown measures are adopted, the higher investment and O&M cost share in future power sector scenarios indicate that lockdown may lead to the idleness of electricity generation equipment and the expansion of renewable investment burden.

5. Discussion

In this study, the LSTM model was applied to forecast electricity demand during winter under different lockdown levels. However, these lockdown levels were defined from April or June 2020, and no actual electricity demand data were available in the winter stage to verify the results. Two main reasons support the employment of the LSTM model when no data are available to verify the forecast: (1) The LSTM model’s performance in predicting the electricity demand in November under Lockdown Level 1. Owing to the implementation of lockdown measures, the electricity demand data in November can be treated as a dataset with which to verify Lockdown Level 1. Little difference can be seen between the actual electricity demand and forecasted demand, both in terms of the total amount and hourly distribution. This proves the effectiveness of using the forecast approach to simulate the impact of lockdowns in the winter stage. (2) The forecasted approach applied here is more akin to a means to roughly simulate the electricity demand change under lockdown measures than to precisely forecast hourly electricity demand, as in other existing forecast algorithms. Thus, this approach is regarded as a reasonable assumption in this study.

In terms of future scenarios in the Netherlands, all scenarios are technically feasible for satisfying the electricity demand in 2035. Renewable scenarios exhibit a CO2 emission reduction of 42–65% when compared with the BAU scenario. Meanwhile, owing to the high fuel and carbon prices, the system costs of all renewable scenarios were lower than those of the BAU scenario. When considering the lockdown measures, their impacts on the power sector differed according to the lockdown level in terms of electricity supply, emission reduction, and power sector cost. With the implementation of lockdown measures, electricity production significantly decreased along with electricity demand in all scenarios. This also led to further emission reductions and a decline in fuel costs. Changing the lockdown level from 1 to 2 can deepen these effects in all the above aspects. Owing to the different renewable electricity supplies, the change in the electricity demand curve caused by lockdown measures produced a more temporary electricity imbalance in the HW scenario than in other renewable scenarios. Thus, a heavier lockdown level has a greater influence on the wind power supply than PV power in the Netherlands. To prevent potentially harmful electricity imbalances in a future
pandemic, the power sector must take adequate measures during the extensive integration of wind power (e.g., by increasing the transmission line capacity).

In this analysis, the impact of different lockdown levels on the future power sector in the Netherlands was evaluated based upon methods for simulating the lockdown level throughout the year and constructing different development scenarios of the power sector. These methods are universal, and most can be applied to evaluate the impact of lockdown measures in other counties. The scope of this study was limited to investigating the impact on the Netherlands’ future power sector, because electricity demand varies in different regions and countries, and the impact of lockdowns may lead to different changes in electricity demand because of the local economic and cultural contexts. Despite these differences, this method is effective and can be used across various cases.

Furthermore, this study focuses on changes in the power sector during the emerging pandemic period. However, the energy supply in the future power sector cannot comprehensively reflect the influence of lockdown measures on the energy demands of the energy system. Changes in different lockdown levels in the future transport and industry sectors are also key elements when evaluating energy use at the local level. The impact of lockdowns in future energy systems (including the power, transport, and industry sectors) will be investigated in future studies.

6. Conclusion

The outbreak of the COVID-19 pandemic has caused a massive change in the power sector, especially in electricity demand. This study explored the impact of lockdown measures implemented in response to similar pandemics in the future power sector. Taking the Netherlands as an example, two lockdown levels for electricity demand were defined and simulated to distinguish the influence of the pandemic on the power sector. For the future power sector, four renewable scenarios and a BAU scenario were designed, to portray a green transition pathway up to 2035. These renewable scenarios were formulated based upon official publications in the Netherlands. All future power sector scenarios were modeled in the EnergyPLAN tool with two lockdown levels. Future scenarios under different lockdown levels were assessed from technical, environmental, and economic perspectives.

Compared with the BAU scenario, all renewable scenarios performed better in terms of CO2 emission reduction and system cost-effectiveness. In the optimal scenario, the green transition can achieve a reduction of 65% in CO2 emissions and 20% in power sector costs in the Netherlands. With the implementation of lockdown measures in 2035, Lockdown Level 1 produces an electricity demand decline of 8.75 TWh and an emission reduction of 8–12% among all scenarios. Lockdown Level 2 leads to an electricity demand decline of 16.65 TWh, with emissions decreasing from 15 to 21% and power sector costs reducing by 11–13%. Furthermore, the heavier lockdown level can influence wind power integration, owing to the change in the hourly electricity demand curve caused by lockdown measures.

This is an exploratory study that aims to advance knowledge regarding what will happen to the future power sector if a similar pandemic arises. These methods are generic and applicable to the power sectors in other countries. This study serves as the first step in understanding the impact of the COVID-19 pandemic on the total energy system, and it will help in the formulation of novel policies to withstand long-term shocks in the future.

Credit author statement

Shihua Luo: Conceived and designed the experiments; Performed the experiments; Analyzed the data; Contributed materials/analysis tool; Wrote the paper.

Weihao Hu: Conceived and designed the experiments; Analyzed the data; Contributed materials/analysis tool.

Wen Liu: Conceived and designed the experiments; Analyzed the data; Contributed materials/analysis tool.

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Zhe Chen: Conceived and designed the experiments; Contributed materials/analysis tool.

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.

Acknowledgments

This study was supported by the National Key Research and Development Program of China (2018YFE0127600).

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