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Flexibility enhancement measures under the COVID-19 pandemic — A preliminary comparative analysis in Denmark, the Netherlands, and Sichuan of China

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ABSTRACT

The COVID-19 pandemic affects all the aspects of modern society worldwide, especially in the power sector. Measures of flexibility enhancement are regarded as solutions to guarantee reliable and flexible electricity supply in such an emergency. This study aims at investigating the impact of flexibility enhancement measures (electricity storage and flexible demand) in different situations of the preliminary COVID-19 pandemic. Case studies in different regions (Denmark, the Netherlands, and the Sichuan province of China) are conducted and assessed using the hourly simulation tool EnergyPLAN. These regions own different electricity supply mix and level of renewable electricity. It is found that the flexible demand measure within one day or one week can hardly eliminate the electricity imbalance caused by either the pandemic or the increasing renewable electricity. The monthly flexible demand is effective for balancing, but its potential in these regions is not enough. However, electricity storage measure enhances the electricity balance even during the most extreme situation of the pandemic. From the economic perspective, electricity storage measure leads to an increase of up to 15% in total system costs, while flexible demand measure has a negligible effect on costs. This study serves as the first step to understand the performance of flexibility enhancement measures in the power sector under the shock of a pandemic.

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1. Introduction

1.1. Background

The outbreak of Coronavirus disease 2019 (COVID-19) changes the lifestyle and work manner in 2020. According to the World Health Organization (WHO), 75 million confirmed cases of COVID-19 and over 1.6 million deaths are reported globally, affecting over 210 countries and territories as of the end of November [1]. In addition to the health damage, this pandemic also created an unpredictable economic crisis worldwide. The global gross domestic product (GDP) is forecast to fall by 4.9% in 2020 in the latest report of the International Monetary Fund (IMF) [2]. Even after a strong recovery, the global economic size in 2021 might be well below the 2019 level [3].

Governments apply stringent restrictions to slow the spread of the pandemic. These restrictions are mainly concentrated in the bans of travel [4], daytime curfews [5], and partial or full lockdown [6,7]. Around 4.2 billion people (54% of the global population) were restricted in their actions, and almost all the global population was affected by the pandemic response measures in one way or another [8]. Global energy demand in the first quarter of 2020 decreased by 3.8% compared to the identical period in 2019, and it is expected to drop by 6% in the whole year [9]. As the first region facing the pandemic, China owned the most considerable energy decline after the two months of lockdown, accounting for 7% of total energy demand and the United States (US) and European countries followed, accounting for over 5%.

Regarding the energy demand by type rather than region, coal demand was the most affected (decrease by 8%) compared with the first quarter of 2019 [9]. Global oil demand was also hit strongly, falling by almost 5% since the road transport activity was nearly 50%
doubling below the 2019 level and 60% dropping in aviation [10].

Electricity, the most common energy form in modern society, also suffered a significant curtailment during the COVID-19 pandemic. With people confined to their homes, working and studying online, the electricity demand related to home appliances rose. Nevertheless, the decrease in industrial and commercial activities exceeded the increase in residential demand. The lockdown measures could reduce electricity demand significantly [11]. However, due to the easing restrictions in the post-COVID, electricity demand began to recover and may rebound to a higher level than last year. For instance, approximately a 3% demand increase is confirmed in July 2020 in China [9]. The shock of electricity demand fluctuation would impose serious challenges to the power sector.

Except for the shock of the pandemic in the power sector, increased integration of renewable energy sources (RES) could significantly influence the electricity demand and supply. The requirements of low-carbon and sustainable energy systems (such as the Paris Agreement [12]) prompt the rapid development of renewable energy in the past decades. For example, the growth of renewable energy generation is responsible for nearly two-thirds of the growth of global power generation [13,14]. Meanwhile, the share of wind power and PV reached 45% in Denmark and 20% in Spain by the end of 2016, and it is expected to double to higher than 10% in large power systems (such as China and the US) by 2022 [15]. However, strong dependence on the weather results in the intermittence of renewable electricity. A higher penetration share of renewable electricity in the power sector can aggravate the electricity imbalance.

A reliable and resilient electricity supply plays an essential role during this kind of emergency. Maintaining a sustainable electricity supply and its contribution to people’s regular lives should be an urgent priority. Measures of ensuring flexibility in the power sector are considered a good choice. They include supply-side and demand-side management, grid-side and system-wide storage measures [16,17]. For the demand side, flexible electricity demand measure provides opportunities for reducing or temporally defer some load to extend the flexibility of electricity demand. The importance of providing demand-side flexibility is highlighted in the power system regarding electricity balance and system costs. It is estimated by International Energy Agency (IEA) that nearly 185 GW of flexible demand can realize cost-effectively by 2040 [18].

Electricity storage measure serves as one of the most mature and widely used flexibility enhancement measures. It includes different types of technologies such as pumped hydro storage, utility-scale battery, compressed air energy, and so on [19]. The existing analyses on the impact of these flexibility enhancement measures on electricity supply and demand focused mainly on the individual measure and less on the comparison between flexible demand and electricity storage measures on electricity balance, especially in the context of COVID-19.

1.2. Own contribution

Flexibility enhancement measures could reduce the temporal electricity imbalance caused by both the shock of pandemic and the expansion of renewable electricity. Researches concerning renewable energy integration and flexibility enhancement measure over the world widely exist [20,21]. However, it is not clear the extent to which the COVID-19 pandemic affects the power sector in terms of renewable electricity supply, especially the impacts on an hourly basis. Our hypothesis is that the renewable power supply share will increase because of COVID-19. The level of changes varies in different types of supply and different power systems. It is interesting to investigate and compare the change of renewable power supply in power systems with different renewable power share. Second, the role of electricity storage and flexible electricity demand measures in securing the electricity balance has not been evaluated in the context of the COVID-19 pandemic. The effectiveness of these measures in promoting large-scale renewable energy integration in a pandemic situation is not apparent.

Based on the discussion above, the purpose of this paper is twofold: 1) to investigate the impacts of the COVID-19 pandemic on the existing power sectors in regions with different electricity supply mix and level of renewable electricity and 2) to evaluate the capability of two measures in ensuring the electricity balance under the influence of two factors, i.e., renewable electricity integration and the COVID-19 pandemic.

Three regions are selected as case studies, namely Denmark, the Netherlands and the Sichuan province of China. Hourly simulations for the electricity supply and demand are conducted for these regions by the EnergyPLAN model. First, the impact of the preliminary COVID-19 pandemic in the power sector in the above regions is simulated and analyzed, emphasizing the influence on renewable electricity. Second, we investigate how flexibility enhancement measures (electricity storage and flexible demand) could affect the electricity balance and determine the capacity requirement of these measures under the impact of higher renewable electricity penetration shares and more difficult pandemic situations.

The main novelty and contribution of this work are listed below:

- It quantitively presents and compares the impacts of COVID-19 on the renewable power supply in different power systems.
- It is the first attempt to evaluate the effectiveness of two measures in securing electricity balance in the context of COVID-19.
- It facilitates the decision-making process for energy suppliers and policy-makers in a similar urgent crisis.

The rest of this paper is organized as follows. Section 2 displays the case areas and their lockdown measures during the preliminary COVID-19 pandemic. Section 3 presents the methodology including the modeling tool and relevant methods. Section 4 shows the data and impact analysis of preliminary COVID-19 pandemic on the power sector. Section 5 displays the results of the two measures. The discussion and conclusion are shown in Section 6 and Section 7, respectively.

2. Case areas and their lockdown measures

The reasons for taking the regions can be summarized as follows: 1) The three regions are all affected by the COVID-19 pandemic in 2020; 2) The three regions have different renewable electricity shares, which represents that these regions are in different stages of renewable energy development; 3) The three regions have different electricity supply mix. This is helpful to the flexibility enhancement analysis under different situations. A brief introduction of these reasons is provided as follows.

2.1. Denmark

Denmark is one of the northern European countries, owns an area of 43,000 km². In 2018, the total population in Denmark was around 5.7 million and the population density reached 135.6 people/km² (Fig. 1a). In the past two decades, the electricity supply in Denmark had a significant change: the considerable decline of coal electricity generation and the rapid expansion of wind power. Moreover, Denmark is excellent at integrating variable renewable energy due to the high interconnection and flexible power system [22] (see Fig. 1d). The proportion of electricity generation of each technology in Denmark in 2019 is shown in Fig. 1g.
The first medical case of the COVID-19 pandemic in Denmark was confirmed on February 27th, and then the pandemic rapidly spread in early March. Lockdown measures such as temporary border control, traffic restriction and closure of public places were claimed by the government to curb the rise of infected people. Daycare, schools, and educational institutions have been closed since March 13th, and the closure period was originally two weeks, which has been extended to April 13th [23]. The number of infected people started to fall at the end of April and the daily number only reached 22 on May 31st. However, due to the relaxation of restrictions, the situation of the pandemic was likely to worsen again and the total infected patients in Denmark were around 16600 by the end of August [24]. The period from March to May in 2020, which was most affected by the lockdown measures, is selected as the sample.

2.2. The Netherlands

Located in the western part of the European continent, the Netherlands has an area of 41,000 km² and the total population was 17.4 million in 2019, with a population density of nearly 515 people/km² (Fig. 1b). The electricity supply in the Netherlands relies heavily on fossil fuels. Natural gas serves as the most crucial fuel in the energy supply mix and accounts for a large share of electricity generation. Renewable energy in the Netherlands developed rapidly, and the share of renewable energy to total energy supply doubled between 2008 and 2019 [25]. The share of renewable electricity to the electricity generation from 2005 to 2019 is presented in Fig. 1e, along with the proportion of electricity generation of each technology in the Netherlands in Fig. 1h.

Similar to Denmark, the first case of the pandemic in the Netherlands occurred on February 27th. Lockdown measures were implemented by the government in Netherland. Different from Denmark as the first European country to ease the restriction, the Netherlands extended the effective period of stringent lockdown measures to April 28th [26]. In short, the number of infected people in the Netherlands shares a similar increase tendency with that of Denmark. The daily number decreased in April and was only 185 on May 31st [27]. Thus, the period from March to May in the Netherlands is chosen as the sample for the same reason.

2.3. Sichuan, China

Sichuan is one of the largest provinces in China with an area of 486,000 km² and its population has reached 83.8 million by the end of 2019 (Fig. 1c). The electricity supply in the power sector of Sichuan province is hydro-dominated, because of the rich hydro-power resources. Other renewable energy resources such as wind power and solar power are also abundant, but they are not fully exploited in the present [28]. It is worth mentioning that renewable electricity penetration in Sichuan has passed the stage of rapid development and reached a very high share of 88.4% in 2018 (see Fig. 1f). The proportion of electricity generation of each technology to the whole electricity supply in Sichuan in 2018 is provided in
The first medical case in Sichuan appeared on January 11th. The government advocated behaviors (such as wearing masks) and implemented stringent lockdown measures as soon as possible to prevent the further spread of the epidemic [29]. After around three months of epidemic control and management, the medical cases related to the COVID-19 pandemic in Sichuan province reduced to zero. This indicates that people’s lives affected by the pandemic gradually returned to normal. The number of infected people reached its peak in early February and the total number of COVID-19 pandemic patients in Sichuan was 660 as of the end of August [30]. Thus, the most serious period (from January to March) of the pandemic in Sichuan is selected to compare with the same period in 2019 to show the impact of the preliminary COVID-19 pandemic.

3. Methodology

3.1. Simulation steps

The simulation steps intend to explore the performance of the flexibility enhancement measures under the background of the COVID-19 context and increased renewable electricity. The first step is scenario design in the three regions. It aims at simulating the impact of the preliminary COVID-19 pandemic on the power sector, and it also considers the electricity demand uncertainty. The second step is the renewable electricity penetration in the three regions. The critical factor in this step is the determination of the maximum renewable electricity penetration share.

The third step is the implementation of flexibility enhancement measures in the modeling tool. In this step, two measures, namely the electricity storage and flexible electricity demand are utilized to ensure electricity balance in the power sector. The final step serves as the results of flexibility enhancement measures analysis from the capacity requirement and economic perspective. In addition, the impact of the preliminary COVID-19 pandemic on electricity demand and supply in the three regions is summarized and evaluated. The flowchart of the analysis steps is shown in Fig. 2.

3.2. Scenario design

The lockdown measures implemented by governments led to a significant impact on the actual power system. The most significant impact of the preliminary COVID-19 pandemic on the power sector is the change in electricity demand and hourly distribution. Due to the lack of extensive storage measures in the power system, it is required that the electricity supply and demand be the same in real-time. As a result, the electricity supply is required to change during the period of this pandemic, which may result in an imbalance of electricity. Actually, how the COVID-19 pandemic affects the power sector is complicated. Many studies utilized the changes in electricity demand and hourly distribution to reflect the impact of the pandemic by comparing the electricity demand in 2019 and 2020 [31,32]. Thus, the data of electricity demand and hourly distribution in the three regions are collected and summarized to explore the effectiveness of flexibility enhancement measures in the context of COVID-19.

However, it is not certain that whether the electricity demand will fall or rise in the power sector facing the next pandemic outbreak as the measures will vary. Considering this uncertainty, four alternative scenarios are constructed with the electricity demand increased or decreased by 5% and 10%, respectively. In addition, a reference scenario is established for the purpose of comparison. Details of the above scenarios in regions are presented in Table 1. Note that the reference scenario in different regions are based on the same time range but different months: Denmark and the Netherlands (Mar.–May) and Sichuan (Jan.–Mar.).

3.3. Renewable electricity integration

As indicated in the introduction, the current renewable electricity penetration shares in regions are different: Denmark (60%), the Netherlands (25%) and Sichuan (88%). Here, the renewable electricity penetration share is identified as the proportion of renewable electricity to the total electricity supply. In this study, it is essential to determine the maximum renewable electricity penetration share based on the electricity supply structure in each region.

A certain percentage of thermal electricity production in the total electricity production has been assigned to ensure grid stabilization. In general, thermal electricity production will decrease if renewable electricity increases in the electricity supply. However, owing to the intermittency of renewable electricity and the requirement of grid stabilization, a larger renewable electricity share may inversely increase thermal power production. In this case, renewable electricity should not be added to the system because the increase of renewable electricity will increase the need for thermal power and cannot realize the decrease of CO2 emissions. Thus, marginal thermal electricity production is chosen as the factor in this study, influencing the feasible penetration share of renewable energy. The maximum renewable electricity penetration share is determined by formula (1) as below:

\[
MTE(\alpha) = \frac{TE(\alpha) - TE(\alpha - 5\%)_i}{C_0}
\]

where \(MTE(\alpha)_i\) refers to the marginal thermal electricity production of the power sector under the renewable electricity share of \(\alpha\) (%) in scenario \(i\); \(TE(\alpha)\) and \(TE(\alpha - 5\%)\), represent the thermal electricity production of the power sector in scenario \(i\) when the renewable electricity share reaches \(\alpha\) and \(\alpha-5\%\), respectively; \(\alpha\) indicates the renewable electricity penetration share, its initial value serves as the penetration share when a mismatch of electricity supply and demand first occurs. The maximum share is identified as \(\alpha\) before the \(MTE(\alpha)\) becomes positive during the increase of renewable energy penetration.

The \(MTE(\alpha)_i\) of scenarios in the three regions is calculated when the renewable electricity penetration share (i.e. \(\alpha\)) increases from its initial value. The results are shown in Appendix A. The indicator of marginal thermal power production is created to illustrate the comprehensive effects of increasing renewable electricity, including the benefits of decreasing thermal power production and CO2 emissions. The result of maximum renewable share cannot reflect the future renewable electricity penetration in the actual power system but aims at displaying the possibility of renewable electricity expansion based on the current power system structure. This indicator is discussed further in the Discussion section. The maximum penetration share of scenarios for three regions is provided in Table 2.

3.4. Flexible demand potential estimation

In the three regions, electricity demand is divided into individual sectors, namely the residential sector, the commercial and the industrial sector. Firstly, electricity demand is uniformly classified by sector to assess the flexible demand potential in each sector.

Then, a technical method pioneered and proposed in Refs. [33,34] is applied to assess the flexible demand potential. This method divides the electricity demand into several processes firstly and estimates the flexible electricity demand potential by determining whether the electricity demand of individual processes can
be transferred temporally. Storability and controllability are identified as two main factors that determine the value of flexible electricity demand in the residential and commercial sectors. Particularly, the processes in the industrial sector account for an additional criterion: independence. An industrial process that is closely related to other processes rather than independent may be a hurdle for the flexibility of electricity demand.

For the residential sector, the electricity demand of refrigerator and washing equipment is responsible for a large share of electricity demand in this sector and have the potential of being converted to flexible demand. Electrical processes linked to the behavior of consumers meet neither of the requirements of storability and controllability. Their electricity demand is regarded as inflexible. For the commercial sector, the demand for refrigerators, ventilation and space heating can be transferred to flexible electricity demand. As for the industrial sector, ventilation, fans and refrigerator processes have the possibility of being flexible demand. However, ventilation and refrigerator processes in the industrial sector have other uses, which are related mainly to other industrial processes. Thus, only half the electricity demand of this kind of process can be classified as flexible demand.

A summary of flexible electricity demand types by sector is shown in Fig. 3.

EnergyPLAN tool can simulate the flexible electricity demand in the power sector with three frames: one day, one week and one week.
month (4 weeks). The flexible demand is distributed evenly by the time frame and is not allowed to delay from one to another. Actual flexible electricity demand is mainly determined within a time frame of some hours or one day, and rarely one week and one month.

The share of the electricity demand of individual sectors to total electricity demand for each region is collected to quantify the flexible electricity demand potential. For the share of electricity demand that can be transferred into flexible demand in each sector, industrial investigations and correlation researches are employed to obtain and summarize the transferred share in Denmark, the Netherlands and Sichuan, respectively. Key assumptions of the above shares are provided in Appendix B. The estimated flexible electricity demand potentials of the three regions during the three months period of the COVID-19 pandemic are presented in Table 3.

### 3.5. Power system simulation

#### 3.5.1. EnergyPLAN tool

The energy system simulation and analysis tool EnergyPLAN are widely used to formulate energy system strategies, determine the appropriate penetration share of renewable energy and evaluate the feasibility of advanced technologies [35,36]. The reasons for taking the EnergyPLAN tool are listed as following: 1) It includes various conventional and advanced electricity generation technologies to meet the need of the power sector simulation; 2) It supports the implementation of flexibility enhancement measures such as electricity storage and flexible electricity demand in the power sector; 3) It simulates the power sector on an hourly basis, and calculate the hourly, weekly, monthly and yearly electricity balance between supply and demand.

As for the endogenous logic, EnergyPLAN is a deterministic input/output tool that relies on manual heuristics rather than iteration, and it can obtain the simulation results in a few seconds with a time resolution of 1 h [37–39]. The schematic diagram of the EnergyPLAN tool is shown in Fig. 4.

#### 3.5.2. Technical and economic inputs

The hourly profile of electricity demand and supply in Denmark and the Netherlands is gathered from the Transparency Platform of the European Network of Transmission System Operators of Electricity (ENTSO) [40], as well as the installed capacity of electricity generation technologies. The installed capacity and hourly distribution data of electricity supply in Sichuan are obtained from Ref. [41].

The cost data in the EnergyPLAN tool includes fuel cost, investment cost, fixed and flexible operation and maintenance (O&M) cost. The investment cost of different technologies in Denmark and the Netherlands is summarized on the basis of studies of the Danish Energy Agency [42,43]. The investment cost of different technologies in Sichuan is gathered from industrial reports and researches [44]. The investment and O&M cost of technologies in the three regions are also presented in Table 4. The fuel cost is based on the projection of IEA [45], and the fuel cost of each region is shown in Table 5. In addition, the interest rate in this study is set at 6%.

#### 3.5.3. Model validation

The validation of the reference model of the three regions plays a vital role in the flexibility enhancement measure analysis. The simulation results are compared with the actual data to verify the
accuracy of the EnergyPLAN tool. The comparison of electricity supply and demand between the actual value and EnergyPLAN simulation in Denmark, the Netherlands and Sichuan are given in Appendix C. It can be seen that the modeled electricity generation from thermal plants, wind and PV are all within the expected margins (lower than 1% difference). Therefore, the reference model can correctly simulate the power system in the above regions.

4. Data and impact analysis of preliminary COVID-19 pandemic on the power sector in Denmark, the Netherlands and Sichuan

4.1. The impact of preliminary COVID-19 pandemic on the power sector in Denmark

Results for the impact of the preliminary COVID-19 pandemic on the power sector in Denmark are shown in Fig. 5. The comparison of electricity demand in each month and the electricity supply of each electricity generation technology is displayed in the panels on the left, with the proportion of the above factors to the whole demand or supply presented on the right. For the electricity demand in these three months in Denmark, minor differences occur compared with the same period in 2019. The proportion of each month in electricity demand is also consistent with the level of last year. This may occur because of the short and relaxed period of lockdown
measure implementation. As for the electricity supply, thermal electricity production represents the largest reduction among all the electricity generation technologies, decreasing by 13.7% (Fig. 5c). A reduction in onshore wind power (decrease by 0.2 TWh) and offshore wind power (decrease by 0.13 TWh) appeared while the PV power ushered in a slight increase of 0.1 TWh. As a whole, the electricity supply in Denmark owns a reduction of 0.63 TWh, accounting for 8.25% of the supply of the 2019 level.

4.2. The impact of preliminary COVID-19 pandemic on the power sector in the Netherlands

Changes in the power sector in the Netherlands in terms of the electricity supply and demand, and concrete proportions during the COVID-19 pandemic are illustrated in Fig. 6. The electricity demand in the Netherlands has an apparent reduction each month during the pandemic: March contributes 0.53 TWh (decrease by 5.1%), April 0.7 TWh (7.7%) and May 0.9 TWh (9.3%). The reduction in electricity demand is increasing with the spread of the pandemic. This tendency causes the share of electricity demand in May to reduce to 32.36%, with the largest decline among these three months (Fig. 6b). In addition, the total electricity demand decreases by 2.13 TWh, which is 7.3% lower than the electricity demand in the same period in 2019.

Thermal electricity production in the Netherlands during the pandemic gains a massive decline of 3.3 TWh, reaching 14.3% of the thermal electricity in 2019. Natural gas remains the most effective source of thermal electricity supply from March to May in 2020, but the power production of coal-fired power plants is shrunk dramatically. Renewable electricity fills up the part of the demand originally belonging to coal electricity. The PV power in the Netherlands has a dramatic expansion of 1.21 TWh, which is responsible for 75.6% of the PV power generation in the same period in 2019. This is mainly because of the electricity demand decline caused by the lockdown measures and the reduction of power plants using fossil fuels. As mentioned before, the lockdown measures lead to a significant decrease in electricity demand. Meanwhile, the power production from fossil-fired power plants falls during the period owing to low operating costs and priority access to the grid through regulations. Thus, renewable electricity such as PV power and wind power increased and played an important role than before.

4.3. The impact of preliminary COVID-19 pandemic on the power sector in Sichuan, China

Results for the impact of the preliminary COVID-19 pandemic on the power sector in Sichuan are displayed in Fig. 7. The electricity demand in Sichuan has an obvious reduction in each month during the pandemic: January contributes 0.39 TWh (decrease by 1.7%), February 0.75 TWh (4.1%) and March 0.58 TWh (3%). The most significant electricity demand decline in the three months in Sichuan occurs in February, which is the time when the lockdown measures were most strictly implemented.

The hydropower in Sichuan suffers a considerable curtailment of 4.39 TWh, and this is because the high hydropower share (more than 75%) in electricity supply leaves little room to increase its penetration share in the spring season. In addition, unlike the previous two regions, conventional power plants would take precedence to satisfy the remaining electricity demand. The reduction of thermal electricity is therefore far below that of hydropower, reaching only 0.38 TWh. Benefiting from the policy support and huge investment, wind power and PV power in Sichuan still maintain a sustainable growth trend even with the electricity demand drop during the pandemic.
5. Results

Critical excess electricity production (CEEP), caused by the temporal mismatches of electricity demand and supply, performs the key indicator in evaluating the electricity balance. CEEP of these scenarios under different renewable electricity penetration share is illustrated in Fig. 8. Note that the transmission lines connected to neighboring countries or provinces are allowed in this study.
Electricity imbalance will occur when excess electricity production has no choice of exporting or storage.

From the perspective of renewable electricity, the amount of CEEP increases with the improvement of renewable electricity penetration share in each scenario. It indicates that higher renewable electricity integration will lead to a huge electricity imbalance in all three regions. On the other hand, CEEP in the scenario with greater electricity demand is higher than the scenario with less demand in the same renewable penetration share. This is because renewable electricity production is required to increase to reach the same penetration share in a scenario with greater electricity demand.

The CEEP is not proportional to the renewable electricity share and the electricity demand but increases growth rate. Meanwhile, the growth rate of CEEP differs by region. As indicated in Fig. 8a, CEEP increases from 0.01 TWh to 0.03 TWh when the penetration share of renewable electricity increases from 55% to 60% in scenario EDD-c. However, the growth of CEEP is 0.19 TWh with the share increasing from 60% to 65% and the growth comes to 0.7 TWh in the next increase in the penetration share. When looking at different regions, the Netherlands has the highest CEEP of 12.08 TWh in scenario EDN-e after realizing the significant growth in renewable energy integration. Despite the most minor power system among these regions, Denmark’s CEEP growth is higher than Sichuan, and the highest CEEP occurs in the EDD-b scenario, reaching 8.16 TWh at 80% renewable electricity penetration. Due to the minor increase in penetration share (increase only by around 5%), the CEEP growth in Sichuan is the lowest.

One week of the period (the third week in May in Denmark) is selected as an example to show the impact of electricity storage and flexible demand measure on electricity balance. The electricity supply and demand, along with the electricity balance in the scenario EDD-b under a renewable penetration share of 65%, are shown in Fig. 9a. An electricity storage capacity of 12 GWh is added to the power system and results for the electricity supply and demand are displayed in Fig. 9b. Moreover, 2.1 TWh of flexible electricity demand within the time frame of one day and one week is introduced in the power sector respectively to explore the impact of flexible demand within different time frames, which are illustrated in Fig. 9c and d. With the implementation of electricity storage, CEEP in the power sector is significantly decreased by shifting excessive renewable electricity production to meet the demand where the electricity generation is short. In contrary to electricity storage measure, flexible demand is not good at ensuring electricity balance but serves as a more effective measure in reducing electricity import and export. If assuming the same amount of flexible demand in different time frames, the flexible demand within a larger time scope can further decrease CEEP, electricity importation and exportation. For example, the flexible demand of 2.1 TWh within one week can reduce the CEEP of 16 GWh to 0 this week, resulting in an electricity export reduction of 33.78 GWh. When the flexible demand of 2.1 TWh within one day is introduced, the CEEP reduction is 7.69 GWh, and the electricity export reduction only reaches 5.62 GWh.

5.1. Electricity storage measure

The capacity requirements of electricity storage for achieving the electricity balance in three regions under different shares of renewable electricity penetration are presented in Fig. 10. Specific values of the capacity requirement of electricity storage measure are provided in Appendix D. Given that the CEEP in the Netherlands is relatively small in the early stage of renewable penetration, a feasible storage capacity of below 15 GWh can ensure the electricity balance with a CEEP of 0.1 TWh. When the penetration share exceeds 40% in each scenario in the Netherlands, the electricity storage capacity increases significantly with an increasing installed capacity to cope with the CEEP over 1 TWh. These additional storage capacities are obliged to store excess electricity and allocate it during off-peak hours. It means that the storage measure can provide an opportunity to temporally storing excessive renewable electricity, contributing to further CEEP curtailment. Moreover, the highest storage capacity in the Netherlands occurs in the EDN-e scenario at 55% renewable electricity penetration, reaching 291 GWh and the highest capacity in Denmark occurs in the EDD-b scenario at 80% penetration, 410 GWh.

Compared with the Denmark scenarios (Fig. 10a), the storage capacity requirement in Sichuan is more minor, even with a higher CEEP in the power sector (Fig. 10c). When faced with a similar CEEP of about 0.2 TWh (0.21 TWh in scenario EDD-c at 65% renewable penetration, 0.22 TWh in scenario EDS-d at 85% renewable penetration), the storage capacity in Sichuan serves as only 10 GWh, lower than that in Denmark by 5 GWh. This is because the transmission line capacity in Sichuan is far beyond the line capacity in Denmark and the Netherlands. Consequently, the reduction of CEEP can be realized in Sichuan by few storage capacities, as shown in Fig. 10c.
Fig. 9. Hourly dispatch for the electricity demand and supply, and electricity balance of the third week in May in the scenario EDD-b at the renewable electricity penetration share of 65%. a Without any measure. b Assuming the electricity storage measure with the capacity of 12 GWh. c Assuming the flexible electricity demand measure with the flexible demand of 2.1 TWh within one day. d Assuming the flexible electricity demand measure with the flexible demand of 2.1 TWh within one week.

Fig. 10. The capacity requirement of electricity storage measure for achieving the electricity balance in three regions corresponding to different shares of renewable electricity penetration: Denmark (a), the Netherlands (b) and Sichuan (c). For better understanding, all storage capacity requirements are marked with specific values in the figure.
5.2. Flexible demand measure

Specific values of the demand requirement of flexible electricity demand measure within one day are presented in Fig. 11. Like the electricity storage measure, the flexible electricity demand requirement increases with CEEP. However, this measure cannot deal with large CEEP. Once the CEEP increases to more than 0.1 TWh in the power sector, flexible electricity demand measure within one day fails to maintain the electricity balance, i.e. reduce the CEEP to 0, even without considering the limitation of flexible demand potential. In addition, when the flexible electricity demand requirement that ensures the electricity balance exceeds its potential, applying flexible demand is considered infeasible in the scenario. Thus, the feasibility level of flexible electricity demand (one day) measure is also shown in Fig. 11, i.e. The color of the dot indicates the feasibility of the flexible demand measure; purple indicates feasibility, while gray indicates infeasibility.

For further exploring the effect of flexible demand measure, flexible demand measure within one week and one month are also implemented in each scenario. Specific values of the demand requirement of flexible electricity demand measure within one week and one month are provided in Appendix Tables D2 and D3. Flexible demand within one week works better than daily flexible demand, but it is also powerless in decreasing large CEEP in the power sector. As for the flexible demand within one month, it has the best performance in ensuring electricity balance than daily and weekly flexible demand. However, the monthly flexible demand requirement is responsible for nearly 28.6% in Denmark, 17.9% in the Netherlands and 9.3% in Sichuan of total electricity demand. Actual monthly flexible demand cannot account for such a high share, and it is considered unsuitable for eliminating electricity imbalance.

5.3. Cost analysis

The system cost by cost types of each scenario after introducing electricity storage is provided in Fig. 12. The cost growth rate due to the introduction of electricity storage is shown in Fig. 13. In Denmark and the Netherlands, compressed air energy storage (CAES) is an ordinary and mature electricity storage measure. Pumped hydro storage serves as the more cost-effective one in Sichuan. Thus, these two technologies are selected in the cost analysis and their costs are provided in Section 3.5. Obviously, the investment and O&M costs grow rapidly with the increase of renewable electricity penetration share. This is mainly because of the expansion of the installed capacity of renewable electricity generation technologies. Meanwhile, the expansion of renewable electricity decreases the fuel and CO2 costs in each region. The cost growth rate of electricity storage measures is obtained by comparing the cost of the original power system with the power system implementing electricity storage measures. It can be seen that the cost growth of electricity storage in Denmark can reach nearly 15%, which is the highest among all the regions. The highest cost growth rate in Sichuan is 13.5%, while that in the Netherlands is approximately 11.5%.

Different from the electricity storage measures, flexible electricity demand can make effects without adding extra devices. It contributes to electricity balance mainly by flexibly arranging the use of flexible demand devices. This can result in negligible costs in the existing power system. Therefore, the cost of the power system after applying flexible demand measures is considered the same as the original power system. From an economic perspective, the flexible demand measure performs better than electricity storage.

6. Sensitivity analysis

6.1. Interconnection capacity

Interconnection capacity can strongly influence the storage requirement of flexibility enhancement measures. For each region, the impact of different interconnection capacities is evaluated. In the sensitivity analysis, the interconnection capacity is changed from 0.9 times of actual capacity to 1.1 times. An overview of values in the sensitivity analysis is presented in Table 6.

The scenario of decreasing electricity demand by 5% in the three regions (i.e. EDD-b, EDN-b and EDS-b) is selected. The different interconnection capacity is applied in each scenario for conducting this sensitivity analysis. The results of sensitivity analysis for interconnection capacity are provided in Fig. 14 and Fig. 15.

It can be seen from the figures that a lower interconnection capacity leads to the growth of capacity requirements of flexibility enhancement measures. In comparison, a higher interconnection capacity leads to the reduction of capacity requirements. Taking Denmark as an example, increasing the interconnection capacity from 3500 MW to 3850 MW results in a reduction of storage capacity of electricity storage measure from 35 GWh to 24 GWh at the renewable share of 70%, which is responsible for nearly 31.43%. However, the reduction of the interconnection capacity from 3500 GWh to 3150 GWh results in an expansion of storage capacity by 23 GWh, accounting for 65.71% of the initial storage capacity requirement. The difference of storage capacity fluctuation between the interconnection capacity expansion and reduction is because of the hourly distribution of excess electricity production.

Fig. 11. The feasibility of flexible electricity demand (one day) measure for achieving the electricity balance in three regions under different shares of renewable electricity penetration: Denmark (a), the Netherlands (b) and Sichuan (c). The color of the dot indicates the feasibility of the flexible demand measure; purple indicates feasibility, while gray indicates infeasibility. For better understanding, all capacity requirements of flexible demand are marked with specific values in the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
The expansion of excess electricity production due to lower interconnection capacity is larger than the decrease due to higher interconnection capacity. Therefore, decreasing the interconnection capacity in each scenario brings a more significant change in storage capacity requirements.

Meanwhile, a similar tendency occurs in the performance of flexible demand measure under such situations. Increasing the interconnection capacity from 6130 MW to 5520 MW leads to decreased flexible demand by 2.3 TWh in scenario EDN-b at the renewable share of 35% while decreasing the interconnection capacity from 6130 MW to 5520 MW leads to an expansion by 3.2 TWh. This should also be attributed to the distribution of excess electricity distribution. Considering that the daily flexible demand requirement is relatively small, changing the interconnection capacity...
capacity can cause a more significant influence on flexible demand measure than electricity storage measure in ensuring the electricity balance.

In summary, lower interconnection capacity rather than higher interconnection capacity has a more apparent effect on the capacity requirement of flexibility enhancement measures. Compared with electricity storage measure, flexible demand measure reacts more significantly to a change in interconnection capacity.

6.2. Seasonal hydro in Sichuan

The hydropower in Sichuan has seasonal features based on its generation. Seasons can correspond to three periods, namely low-water period (Jan.–Mar.), normal-water period (Apr.–June) and high-water period (Jul.–Spt.). A sensitivity analysis of seasonal hydro in Sichuan is conducted to assess the influence on flexibility enhancement measures. The data of actual hydropower generation in Sichuan during different periods are collected and utilized in the scenarios, as shown in Table 7. It is worthwhile to mention that the data used in previous scenarios in Sichuan is in the low-water period, since the research time range in this paper is from January to March. The results of sensitivity analysis for interconnection capacity are provided in Tables 8 and 9.

Obviously, varying from the low-water period to the other two periods significantly increases the capacity requirements of Sichuan’s two flexibility enhancement measures. In the low-water period, the storage capacity requirement of electricity storage measure in scenario EDS-a for eliminating electricity imbalance is 3 GWh. The capacity requirement in the normal-water period serves as 25 GWh, increased by 22 GWh and the capacity requirement in the high-water period is 310 GWh, increased by 307 GWh. The capacity requirement of different periods doesn’t increase proportionally but increases with a dramatic growth rate. Improving the hydropower generation only with electricity demand unchanged will lead to more significant excess electricity production as the time of hydropower generation is concentrated and the power generation per unit time is huge, which easily exceeds the electricity demand.

The seasonal hydro can affect the capacity requirement of electricity storage measure and strongly influence that of flexible demand measure. For example, changing the low-water period to the normal-water period raises the capacity requirement of flexible demand from 6.4 TWh to 21 TWh in scenario EDS-a. In the high-water period, abundant hydropower makes the renewable electricity share in Sichuan reaching nearly 100%. Electricity storage measure can ensure electricity balance in the high-water period with a higher storage capacity, while flexible demand measure is powerless. From the perspective of technical feasibility, the electricity storage measure performs better than the flexible demand measure facing the condition of seasonal hydro in Sichuan. The higher storage capacity requirement of electricity storage measure translates into more reliability and flexibility in the Sichuan power system.

7. Discussion

The influence of the preliminary COVID-19 pandemic on the power sector varies greatly in different regions. The electricity demand in the Netherlands and Sichuan reduce significantly while electricity demand in Denmark is minor. For countries like the Netherlands, the pandemic increases renewable electricity production. Especially the PV technology, considering its falling price in recent years, the rapid expansion of PV power is considered to be sustainable in the Netherlands. As for the regions owning a high share of renewable penetration, such as the Sichuan province of China, the decline in electricity demand and the implementation of confinement measures may reemphasize the importance of thermal electricity production. The requirement of grid stabilization in such emergencies and the seasonal fluctuation of renewable electricity can result in the idleness of electricity generation equipment and the increase of renewable investment burden.

As for the impact of flexibility enhancement measures on the power sector during the preliminary COVID-19 pandemic, it is found that the flexible electricity demand measure has a limited effect on eliminating the electricity mismatch under high renewable electricity penetration and severe pandemic situations. Both the flexible electricity demand within one day and one week contribute little to maintain the electricity balance. The monthly flexible electricity demand is helpful but unrealistic due to its poor potential in all regions. Nevertheless, more electricity demand flexibility can release the strong dependence of electricity supply on neighboring regions by decreasing electricity importation and exportation. More importantly, this measure can be realized without infrastructure establishment and huge investment costs, which performs a more cost-effective option.

Electricity storage measure is a more effective measure to guarantee the electricity balance in different regions. Even in a scenario suffering the most severe pandemic influence, electricity

Table 7
Hydropower generation of different periods in Sichuan.

| Season       | Period    | Hydropower generation (TWh) |
|--------------|-----------|-----------------------------|
| Jan.–Mar.    | Low-water | 52.95                        |
| Apr.–June    | Normal-water | 73.52                       |
| Jul.–Spt.    | High-water | 128.85                       |

Fig. 15. The influence of interconnection capacity changes on flexible demand measure in the three regions: Denmark (a), the Netherlands (b) and Sichuan (c).
storage with a storage capacity of 420 GWh can reduce the CEEP to zero. Moreover, increasing the transmission line capacity, though it can diminish storage capacity requirement, is not regarded as the solution to ensure the electricity balance. The harm of electricity imbalance has not been eliminated or solved by exporting electricity but is shifted to neighboring regions.

The assumption of maximum renewable electricity penetration share in scenarios plays an important role in the flexibility enhancement analysis. The indicator for determining the maximum penetration share is the change in thermal electricity production. The technical assumption of maximum renewable electricity has been conducted in many studies [48,49]. The difference between this study and previous studies is the indicator. Previous studies use the COMP (namely, the ratio between the marginal primary energy supply (PES) to the marginal critical electricity excess production (CEEP)) as the indicator to determine the feasible penetration level of renewable electricity. These two indicators are similar, and their difference occurs in: The indicator of marginal thermal electricity production focuses on the change in thermal electricity and CO2 emission. The indicator of COMP focuses on the change in the primary energy supply and system fuel efficiency. Thus, the marginal thermal electricity production indicator in evaluating the maximum share of renewable electricity is regarded as a reasonable assumption in this study.

It needs to be noted that this paper is exploratory simulation research aiming at advancing more knowledge of flexibility enhancement measures if the pandemic becomes more severe and the renewable electricity increases rapidly. This study focuses more on the flexibility enhancement analysis based on the actual data of electricity demand and hourly profile during the pandemic in the three regions. The initial findings at the regional level can help policy designers and electricity suppliers to understand the performance of flexibility enhancement measures under severe crisis and higher renewable energy integration. The study results are helpful to have a benchmark for the setup of a secure electricity supply system and infrastructure to withstand the extreme crisis in the future.

8. Conclusion

The COVID-19 pandemic greatly affected the electricity supply and demand over the world. This study shows the impact of the preliminary period of the pandemic on the power sectors in Denmark, the Netherlands and Sichuan. The electricity supply decline in Denmark and the Netherlands concentrates on the thermal electricity production of conventional power plants. However, the renewable electricity generation in these two regions only has a slight drop or even increase compared with the same period in 2019. PV and wind power play a more important role in satisfying electricity demand in Denmark and the Netherlands. The most affected power generation technology in Sichuan is hydro-power, which accounts for the most significant decrease in the local electricity supply.

This study mainly investigates the performance of flexibility enhancement measures (electricity storage and flexible demand) in the preliminary COVID-19 pandemic. Three regions are selected as case studies: Denmark, the Netherlands and China’s Sichuan province. Hourly simulations for the electricity supply and demand are conducted for these regions by the EnergyPLAN model. It is found that allowing more electricity demand flexibility within one day or one week, though with a limited effect on eliminating the electricity mismatch, serves as a cost-effective solution to reduce the exported and imported electricity in the pandemic. Flexible demand measure within one month can maintain the electricity balance, but the need for monthly flexible demand far exceeds its potential. The results indicate that flexible demand measures can be more effective in a more extensive power system (like Sichuan) as its electricity demand is large enough to provide rich flexibility potential.

Electricity storage is the more practical measure in realizing the goal of electricity balance. In the scenario under the maximum renewable electricity penetration share, electricity storage measure can ensure electricity balance between electricity supply and demand under the extreme situation of a similar crisis. More importantly, this measure eliminating the electricity mismatch with a capacity lower than 410 GWh (i.e. Denmark 410 GWh, the Netherlands 291 GWh and Sichuan 58 GWh), which is affordable for the three regions considering the rapid development of storage.
capacity and types of electricity storage measure in the near future. From an economic perspective, the introduction of electricity storage measure brings about cost expansion in the three regions. The highest cost growth due to the implementation can reach nearly 15%, which occurs in Denmark. Meanwhile, flexible demand measure results in a negligible cost expansion in the existing power system as it makes effects without adding extra devices. Considering the sensitivity analysis of interconnection capacity and seasonal hydro, flexible demand measure reacts more significantly to a change in interconnection capacity in the three regions compared with electricity storage measure. Flexible demand measure cannot deal with the extensive excess electricity production due to seasonal hydro, while electricity storage measure can ensure electricity balance in the high-water period with a higher storage capacity.

To sum up, flexible demand measure is more economically effective and is helpful to reduce the exported and imported electricity. However, electricity storage measure performs better than flexible demand measure in terms of ensuring electricity balance when facing similar crises like the preliminary COVID-19 pandemic and facing changes in interconnection capacity and seasonal hydro. Therefore, the long-term plan for deploying more electricity storage measures, especially in regions with low development levels of renewable energy, should be prioritized if more renewable electricity integration is to be accomplished in the power sector.

**Credit author statement**

Shihua Luo: Conceived and designed the experiments; Performed the experiments; Analyzed the data; Contributed materials/analysis tools; Wrote the paper. Weihao Hu: Conceived and designed the experiments; Contributed materials/analysis tools. Wen Liu: Conceived and designed the experiments; Contributed materials/analysis tools; Wrote the paper. Zhou Liu: Performed the experiments; Analyzed the data; Wrote the paper. Qi Huang: Conceived and designed the experiments. Zhe Chen: Conceived and designed the experiments; Contributed materials/analysis tools.

**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 A. The marginal thermal electricity production of each renewable penetration share**

| Table A1 | Results for the marginal thermal electricity production of each renewable penetration share in Denmark. |
|----------|---------------------------------------------------------------------------------------------------------------|
| EDD-a Penetration share (%) | Marginal thermal production (TWh) | EDD-b Penetration share (%) | Marginal thermal production (TWh) | EDD-c Penetration share (%) | Marginal thermal production (TWh) | EDD-d Penetration share (%) | Marginal thermal production (TWh) | EDD-e Penetration share (%) | Marginal thermal production (TWh) |
| 60 | 60 | 55 | – | 55 | – | 55 | – |
| 65 | 60 | 60 | – | 65 | – | 60 | – |
| 70 | 70 | 70 | – | 70 | – | 70 | – |
| 75 | 75 | 75 | – | 75 | – | 75 | – |
| 80 | 80 | 80 | – | 80 | – | 80 | – |

| Table A2 | Results for the marginal thermal electricity production of each renewable penetration share in the Netherlands. |
|----------|---------------------------------------------------------------------------------------------------------------|
| EDN-a Penetration share (%) | Marginal thermal production (TWh) | EDN-b Penetration share (%) | Marginal thermal production (TWh) | EDN-c Penetration share (%) | Marginal thermal production (TWh) | EDN-d Penetration share (%) | Marginal thermal production (TWh) | EDN-e Penetration share (%) | Marginal thermal production (TWh) |
| 35 | 35 | 35 | – | 35 | – | 35 | – | 35 | – |
| 40 | 40 | 40 | – | 40 | – | 40 | – | 40 | – |
| 45 | 45 | 45 | – | 45 | – | 45 | – | 45 | – |
| 50 | 50 | 50 | – | 50 | – | 50 | – | 50 | – |
| 55 | 55 | 55 | – | 55 | – | 55 | – | 55 | – |

| Table A3 | Results for the marginal thermal electricity production of each renewable penetration share in Sichuan. |
|----------|---------------------------------------------------------------------------------------------------------------|
| EDS-a Penetration share (%) | Marginal thermal production (TWh) | EDS-b Penetration share (%) | Marginal thermal production (TWh) | EDS-c Penetration share (%) | Marginal thermal production (TWh) | EDS-d Penetration share (%) | Marginal thermal production (TWh) | EDS-e Penetration share (%) | Marginal thermal production (TWh) |
| 86.06 | 86.06 | 85 | – | 85 | – | 85 | – | 85 | – |
| 90 | 90 | 90 | – | 90 | – | 90 | – | 90 | – |
Appendix B. Flexible electricity demand estimation

TABLE B1
The proportion of electricity demand of each sector to the total demand and the share that can be converted into flexible electricity demand [33,34]

| Region        | Sector      | The share to the total electricity demand (%) | The share that can be converted into flexible electricity demand (%) |
|---------------|-------------|-----------------------------------------------|---------------------------------------------------------------|
| Denmark       | Residential sector | 21.74                                       | 15                                                          |
|               | Commercial sector  | 28.26                                       | 2.3                                                         |
|               | Industrial sector  | 50                                          | 5.6                                                         |
| The Netherlands| Residential sector | 20                                         | 15                                                          |
|               | Commercial sector  | 20                                          | 4                                                           |
|               | Industrial sector  | 60                                          | 7                                                           |
| Sichuan       | Residential sector | 23.7                                        | 12                                                          |
|               | Commercial sector  | 17.13                                       | 3                                                           |
|               | Industrial sector  | 59.17                                       | 5                                                           |

Appendix C. The validation of EnergyPLAN model in the simulation of the power sector

TABLE C1
Comparison of electricity generation in the period with the EnergyPLAN simulation in Denmark.

| Plant Type       | Electricity generation (TWh) | Difference (TWh) | Difference (%) |
|------------------|------------------------------|------------------|----------------|
| Actual Data 2020 | EnergyPLAN Simulation        |                  |                |
| Onshore wind     | 2.46                         | 2.46             | 0              | 0.00           |
| Offshore wind    | 1.569                        | 1.569            | 0              | 0.00           |
| PV               | 0.446                        | 0.446            | 0              | 0.00           |
| Thermal          | 2.533                        | 2.553            | 0.02           | 0.79           |
| Export           | 3.073                        | 3.093            | 0.02           | 0.65           |

TABLE C2
Comparison of electricity generation in the period with the EnergyPLAN simulation in the Netherlands.

| Plant Type       | Electricity generation (TWh) | Difference (TWh) | Difference (%) |
|------------------|------------------------------|------------------|----------------|
| Actual Data 2020 | EnergyPLAN Simulation        |                  |                |
| Onshore wind     | 2.249                        | 2.249            | 0              | 0.00           |
| Offshore wind    | 0.799                        | 0.799            | 0              | 0.00           |
| PV               | 2.813                        | 2.813            | 0              | 0.00           |
| Nuclear          | 1.018                        | 1.018            | 0              | 0.00           |
| Biomass          | 1.831                        | 1.831            | 0              | 0.00           |
| Thermal          | 17.867                       | 17.873           | 0.006          | 0.03           |
| Export           | 5.516                        | 5.524            | 0.008          | 0.15           |

TABLE C3
Comparison of electricity generation in the period with the EnergyPLAN simulation in Sichuan.

| Plant Type | Electricity generation (TWh) | Difference (TWh) | Difference (%) |
|------------|------------------------------|------------------|----------------|
| Actual Data 2020 | EnergyPLAN Simulation        |                  |                |
| Hydro      | 55.34                        | 55.34            | 0              | 0.00           |
| Thermal    | 13.016                       | 13.0175          | 0.0015         | 0.01           |
| Wind       | 2.892                        | 2.892            | 0              | 0.00           |
| PV         | 0.779                        | 0.779            | 0              | 0.00           |
| Export     | 15.021                       | 15.0175          | –0.0035        | –0.02          |
Appendix D. Specific values of storage capacity requirement of electricity storage in the three regions

**TABLE D1**
Specific values of electricity storage capacity in the three regions.

| Storage capacity (GWh) | Renewable electricity penetration level (%) |
|------------------------|---------------------------------------------|
|                        | Region | Scenario abbreviations | 55 | 60 | 65 | 70 | 75 | 80 |
| Denmark                |        | EDD-a                  | 2  | 7  | 26 | 85 | 229 |
|                        |        | EDD-b                  | 3  | 12 | 35 | 110| 410 |
|                        |        | EDD-c                  | 1  | 4  | 18 | 52 | 140 |
|                        |        | EDD-d                  | 1  | 6  | 24 | 72 | 173 |
|                        |        | EDD-e                  | 2  | 9  | 31 | 92 | 213 |
| Region                 |        | Scenario abbreviations | 30 | 35 | 40 | 45 | 50 | 55 |
| Netherland             |        | EDN-a                  | 7  | 20 | 51 | 95 | 168 |
|                        |        | EDN-b                  | 1  | 9  | 24 | 57 | 105| 196 |
|                        |        | EDN-c                  | 2  | 12 | 21 | 65 | 115| 228 |
|                        |        | EDN-d                  | 3  | 14 | 32 | 74 | 125| 260 |
|                        |        | EDN-e                  | 5  | 17 | 36 | 81 | 135| 291 |
| Region                 |        | Scenario abbreviations | 85 | 90 |
| Sichuan                |        | EDS-a                  |    | 0.2| 1  | 5  | –  | –  |
|                        |        | EDS-b                  |    | 0.3| 2  | 7  | –  | –  |
|                        |        | EDS-c                  |    | 0.1| 0.6| 3.1| –  | –  |
|                        |        | EDS-d                  |    | 0.2| 0.9| 4.8| –  | –  |
|                        |        | EDS-e                  |    | 0.3| 1.6| 6.3| –  | –  |

**TABLE D2**
Specific values of Flexible electricity demand (one week) in the three regions.

| Flexible demand-one week (TWh) | Renewable electricity penetration level (%) |
|---------------------------------|---------------------------------------------|
|                                 | Region | Scenario abbreviations | 55 | 60 | 65 | 70 | 75 | 80 |
| Denmark                         |        | EDD-a                  | 0.2| 1  | 5  | –  | –  |
|                                 |        | EDD-b                  | 0.3| 2  | 7  | –  | –  |
|                                 |        | EDD-c                  | 0.1| 0.6| 3.1| –  | –  |
|                                 |        | EDD-d                  | 0.2| 0.9| 4.8| –  | –  |
|                                 |        | EDD-e                  | 0.3| 1.6| 6.3| –  | –  |
| Region                          |        | Scenario abbreviations | 30 | 35 | 40 | 45 | 50 | 55 |
| The Netherlands                 |        | EDN-a                  | 0.5| 2  | 5.1| –  | –  |
|                                 |        | EDN-b                  | 0.04| 0.7| 2.5| 6.6| –  | –  |
|                                 |        | EDN-c                  | 0.11| 0.9| 3  | 8.6| –  | –  |
|                                 |        | EDN-d                  | 0.2| 1.1| 3.6| –  | –  | –  |
|                                 |        | EDN-e                  | 0.3| 1.4| 4.2| –  | –  | –  |
| Region                          |        | Scenario abbreviations | 85 | 90 |
| Sichuan                         |        | EDS-a                  | –  | –  |
|                                 |        | EDS-b                  | 0.6| –  | –  |
|                                 |        | EDS-c                  | 1  | –  | –  |
|                                 |        | EDS-d                  | 1.8| –  | –  | –  |
|                                 |        | EDS-e                  | 2.2| –  | –  | –  |
| Region      | Scenario abbreviations | Flexible demand—one month (TWh) | Renewable electricity penetration level (%) |
|------------|-----------------------|----------------------------------|--------------------------------------------|
|            |                       | 55                               | 60                                         | 65   | 70    | 75    | 80    |
| Denmark    | EDD-a                 | 0.04                             | 0.04                                       | 1.9  | 7.1   | –     | –     |
|            | EDD-b                 | 0.1                              | 0.6                                        | 2.7  | 10.4  | –     | –     |
|            | EDD-c                 | 0.02                             | 0.2                                        | 1.2  | 3.9   | –     | –     |
|            | EDD-d                 | 0.04                             | 0.3                                        | 1.7  | 5.5   | –     | –     |
|            | EDD-e                 | 0.06                             | 0.6                                        | 2.4  | 7.4   | –     | –     |
| The Netherlands | EDN-a               | 0.19                             | 1                                           | 2.71 | 14.2  | –     | –     |
|            | EDN-b                 | 0.01                             | 0.27                                       | 1.3  | 4.9   | 18.4  | –     |
|            | EDN-c                 | 0.03                             | 0.4                                        | 1.7  | 6.2   | –     | –     |
|            | EDN-d                 | 0.05                             | 0.6                                        | 2.1  | 8.1   | –     | –     |
|            | EDN-e                 | 0.08                             | 0.7                                        | 2.6  | 10.3  | –     | –     |
| Sichuan    | EDS-a                 | World economic outlook update    | 6.1                                        |     |       |       |       |
|            | EDS-b                 | 0.2                              |                                            | 10.3 |       |       |       |
|            | EDS-c                 | 0.5                              |                                            | 13.8 |       |       |       |
|            | EDS-d                 | 0.8                              |                                            | 17.6 |       |       |       |
|            | EDS-e                 | 1.1                              |                                            | 21.3 |       |       |       |

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