Towards Carbon Neutrality: Optimizing Generation and Storage Capacities in Germany and Carbon Pricing in China

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Abstract: We propose a model for economic optimization of electricity generation and storage capacities given ecological economic objectives and conditions, including carbon pricing. Conventional as well as wind and solar power generation in China and Germany are simulated for 2030 and 2045. We used wind and solar power data of the year 2020 and 2019, respectively, taking into account the changing technical parameters and changing production costs. The focus of this paper is to calculate 1) a reasonable carbon price facilitating China's emission reduction in 2030, and 2) the most economical allocation of wind and solar power generation capacities and chemical and mechanical energy storages for Germany to achieve carbon neutrality in 2045. For a 100% renewable energy supply in the future, we recommend the use of synthetic natural gas (SNG) as the main energy carrier for storage and pumped storage hydropower as a supplement.

Notice: The views expressed in this article are those of the authors and do not necessarily reflect the official views of their respective institutions.

Keywords: Carbon neutrality, power supply, power storage, SNG (synthesized natural gas), carbon pricing, LCOE (levelized cost of electricity)

1. Introduction

Climate change is one of the biggest challenges facing humankind. This systemic, comprehensive, and global issue has extensive and far-reaching impacts on economic and social development. To achieve the 2°C temperature control goal of the Paris Agreement, the world must achieve carbon neutrality by 2050 [24]. More than 120 countries and regions around the world have made carbon neutrality commitments [48]. Among them, German legislation established the goal of achieving carbon neutrality in 2045 [6]. China announced that it would strive to achieve carbon peaking by 2030 and carbon neutrality by 2060 [15].

For Germany, achieving carbon neutrality means electrifying the entire energy supply and meeting society's entire energy needs with wind and solar power alone [see, e.g., 12]. The power industry is China's largest carbon-emitting industry, accounting for more than 40% of the country's total carbon emissions. It will be the main driver of energy growth in the next 10 years and will be an important guarantee of supporting China's economic transformation and modernization and improving the living standards of residents in the future. Its carbon emission peak and peak time will directly determine whether China's 2030 carbon peak goal can be achieved [60].

The core question in this paper is whether and how Germany can achieve carbon neutrality in 2045 and whether China can reach the carbon peak in 2030 through carbon pricing alone. Modeling and simulating China's and Germany's different stages of emission reduction with a single system dynamics model may help to better explain and optimize the emission reduction paths. We propose a model for economic optimization of electricity generation and storage capacities given ecological economic objectives and conditions, including carbon pricing. Conventional, as well as wind and solar power generation in China and Germany, are simulated for 2030 and 2045. To do so, we used wind and solar power data for the year 2020 and 2019, respectively, taking into account the changing technical parameters and changing production costs.

We first briefly introduce the relevant research work and latest progress of China and Germany on climate neutrality. The structural details and main variables of the model will then be introduced step-by-step, and the settings of the parameters will be presented. For China to achieve its carbon peak in 2030, we calculate the effects by carbon pricing, and for Germany to achieve carbon neutrality in 2045, we also conduct simulation and scenario analyses for different power capacity combinations. We conclude with a discussion of parameter uncertainty and an introduction to a stress testing method provided by the model.

2. Related Research and Data Sources

In 2021, China released its "Action Plan for Carbon Peaking by 2030" [58]. China's national carbon market has officially launched transactions. In the first compliance cycle, 2162 key emission companies in the power generation industry were included, covering about 4.5 billion tons of carbon dioxide emissions. It is the carbon market with the largest carbon dioxide emissions in the world [64]. By the end of 2022, the cumulative transaction volume of carbon emission allowances (CEA) reached 233 million tons, and the cumulative transaction value was ￥10.12B [53]. In 2020, the installed capacity of coal power accounted for less than 50% of the total installed capacity of China's electric power for the first time, but there were and are still 1110 GW of coal-fired power units in operation across the country [54]. China's coal power capacity is expected to reach its peak before 2030, and the peak value will be below 1300 GW [51] and decline rapidly after 2030 [61]. China's power sector must achieve zero emissions by 2050 and negative emissions on a certain scale by 2060 in order to support the entire energy sector to achieve carbon neutrality [63, 55].

In recent years, China's new renewable power generation capacity has increased rapidly. In 2021, China's annual total power generation was 8534 TWh, of which wind power and solar power generation were 656 TWh and 327 TWh respectively, a year-on-year increase of 40.5% and 25.2% respectively. Thermal power generation was 5806 TWh [59]. According to relevant forecasts, the electricity consumption of China's whole society will increase from 7.5 PWh in 2020 to 9.2 PWh and 10.7 PWh in 2025 and 2030 respectively. The expected value in 2050 and 2060 will reach 16 and 17 PWh [57, 23].

Because of fluctuations in power demand and supply, the most economical allocation and use of different energy structures to ensure uninterrupted power supply are major challenges for the power industry. New power generation such as wind and solar, have considerable volatility and uncertainty, and extreme weather conditions affect the operation safety of the power grid [see, e.g., 5]. Taking Germany as an example, the potential installed capacity of wind power and photovoltaics is 390 GWp and 8600 GWp respectively [30]. The investment cost of large-scale photovoltaic power plants has been reduced to a level of around 1 €/Wp, which is similar to that of wind power [28, 45, 35]. Wind power and photovoltaics accounted for 28.8% of total power generation in Germany in 2021 [see 47]. Göke et al. presented a feasibility analysis of meeting Germany's annual energy demand of 1209 TWh with all renewable energy [12]. However, as shown in Figure 1, the demand for electric energy and the power generation of wind and solar power have obvious seasonal and daily fluctuations. With the increase in the proportion of electricity generation from renewable sources, the power industry needs more and more energy storage capacity to reduce wind and solar energy curtailment [3] and to achieve the effect of emission reduction and energy saving [see, e.g., 33]. With the help of geographical advantages, the specific construction cost of pumped storage plants can be lower than €1/kWh [see, e.g., 37]. When the corresponding geographical resources are lacking or far away [21, 25], such specific cost can be as high as €200/kWh [20, 16, 62, 38]. In contrast, hydrogen energy technology that uses synthetic natural gas (SNG) as an energy carrier and can directly use Germany's existing storage [see 9] and transportation infrastructure will play an increasingly important role. This technology uses surplus power to electrolyze water to produce hydrogen, absorb carbon dioxide through methanisation to generate SNG for storage, and use it for power generation when necessary [42, 43, 22, 26, 14, 17].

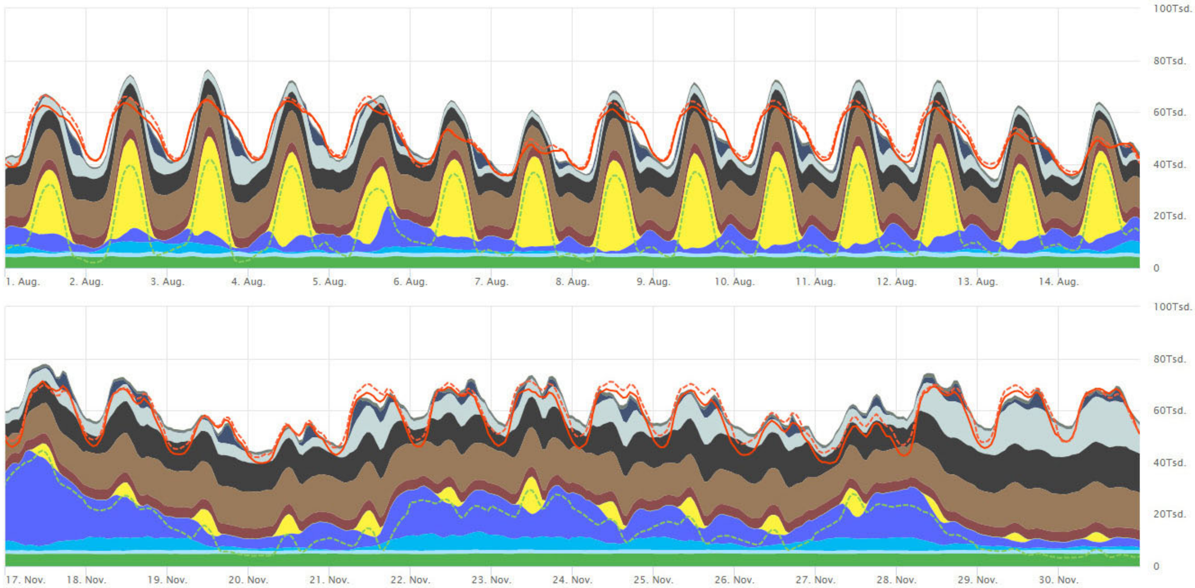

Figure 1: Example of power generation and demand in Germany in 2022. Top: August 1-14, bottom: November 17-30. The red solid line is demand, and the yellow and blue areas are photovoltaic and wind power generation respectively [41]

System dynamics is an ideal tool for solving problems of energy complexity. Beginning in the 1970s, Naill analyzed the energy transition in the United States by developing a series of system dynamics models from the perspective of limited global resources. The United States National Energy Policy Plan of 1983 was formulated based on the FOSSIL2 system dynamics model [31]. Optimizing the mix of different generation and storage can improve security of energy supply while reducing fuel costs and emissions [see, e.g., 2, 52]. Different portfolio concepts of electricity generation in Germany were evaluated considering various technological parameters by comparing their production costs and their CO2 emissions mitigation potential [1]. Ntsoane et al. evaluated the feasibility of modifying the existing hydro pumped storage facilities to increase their capacity [34]. Happach et al. identified several key factors for the investment decisions into energy storage technologies [19]. Happach & Tilebein analyzed electrical storage technologies and assessed the capabilities of energy storage technologies in the Germany electricity market [18]. Mashhadi found out that the German power system would see renewables as the main generation source by 2050. Conventional plants will be less involved in the daily energy production as gas gets a minor role as a flexibility provider and coal will be outcompeted from the energy mix [29].

Despite academic criticism of the ways in which higher carbon prices can reduce emissions [39, 8], it has become an important means of emission reduction [see, e.g., 13], among which determining a reasonable carbon price becomes the core issue in solving carbon emission reduction [see, e.g., 36]. In addition, consumer-side load shifting through measures such as dynamic electricity prices can also promote users to contribute to energy conservation and emission reduction [see, e.g., 50, 65].

3. A Model for Capacity Optimizing and Carbon Pricing

To find the optimal path of the power industry's carbon peak in China and Germany's carbon neutrality, this paper modifies, extends and reparameterizes the 2012 model [1]. The aim is to describe the mechanism of electricity production and consumption, the characteristics of wind, solar and thermal power generation, combine mechanical and chemical energy storage methods, and economically optimize electricity production and storage under the premise of ensuring electricity supply security and climate protection standards. The model specifically incorporates a carbon price calculation module to help decision makers promote emission reductions by increasing the cost of carbon emissions.

3.1 Model Structure

The key output results of the model for capacity optimizing and carbon pricing are shown in Table 1, among which three calculation results are the most critical: `Shortage` shows the annual average power of the total electricity imported from the external grid due to insufficient supply in the grid. The lower the value, the more stable the grid supply. `CO2 G` is the total emissions of the power industry for the year. The purpose of this model is to provide the most economical power supply configuration, i.e. to find the one with the lowest `LCOE`, under the premise of ensuring a stable power supply at a certain carbon price or emission cap.

Table 1: The main output results

030width:600px; Name	Type	Unit	Description
Average U		1	Dispatchable power utilization
CO2		B[€|¥]	Total cost for CO2 emission allowances
CO2 G		GtCO2	Total CO2 emissions
Demand	S	GWh	Cumulative demand of electricity
Fuel		B[€|¥]	Total cost of chemical fuels
Invest M		B[€|¥]	Total investment
LCOE		[€|¥]/MWh	Levelized cost of electricity
Operation M		B[€|¥]	Total operating cost
PV Utilities	S	1	Photovoltaic utilization
Shortage		GW	Average power supply shortage
Total M		B[€|¥]	Total cost
WD Utilities	S	1	Wind power utilization
Description: Type S: Stock			

The model is mainly composed of three parts: power generation and power consumption, power storage subsystems (mainly pumped storage), synthetic natural gas (SNG) and new technology solutions such as load shifting.

For simplicity, the first part of this model only distinguishes four power generation categories: wind power generation (`WD`), photovoltaic power generation (`PV`), `Dispatchable` thermal power generation, and `Other` power generation methods (including nuclear power, hydropower, biomass power generation, etc.). These are represented in the model as three inflows (Figure 2).

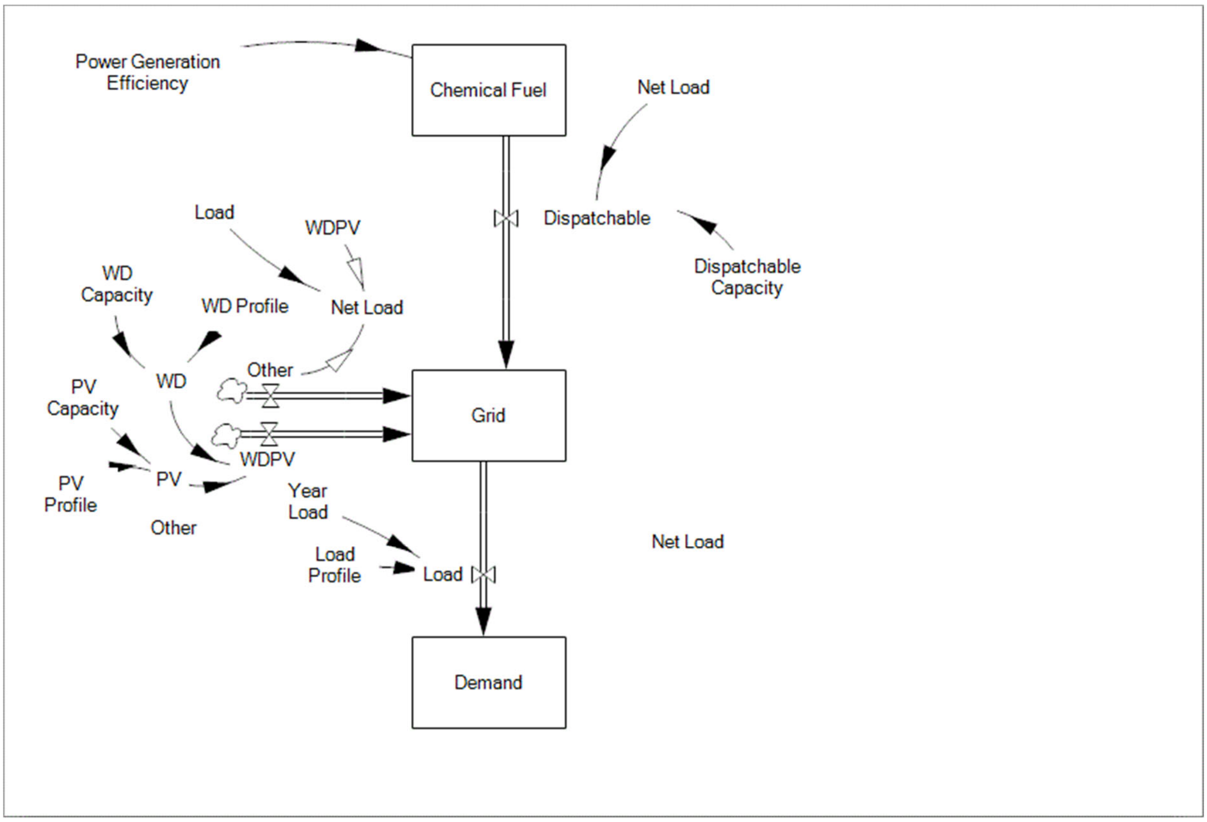

Figure 2: Wind, solar, dispatchable power generation and other methods meet the needs of the grid

The variables for this part of the model are listed in Table 2. `Grid` is a pseudo stock, its function is to calculate the surplus or shortage of power supply in each cycle (hour), and it is set to zero at the beginning of each cycle. In addition to the three inflows mentioned above, there is also an outflow representing `Load` in each hour of the year. `Other` is a constant. `WD`, `PV` and `Load` change with time throughout the year, and are given by multiplying the annual total or installed capacity with the time curve:

```
Load = Load Profile x Year Load / 8.76

WD = WD Capacity x WD Profile

PV = PV Capacity x PV Profile
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Additionally, `Net Load`, also known as residual load, is the gap between demand and the sum of `WD`, `PV`, and `Other` power generation. `Dispatchable` needs to bridge this gap to ensure a balance between supply and demand.

Table 2: Main variables describing electricity supply and demand

030width:600px; Name	Type	Unit	Description
Chemical Fuel	S	GWh	Chemical fuel stocks
Dispatchable	F	GW	Dispatchable power
Dispatchable Capacity	P	GW	Installed capacity of dispatchable power
Grid	S	GWh	Balance of power generation and demand
Load	F	GW	Actual power demand

Load Profile		1	Load curve
Net Load		GW	Residual load
Other	F, P	GW	Generating power of nuclear power, hydropower, etc.
Power Generation Efficiency	P	1	Efficiency of dispatchable power generation
PV		GW	Photovoltaic power
PV Capacity	P	GW	Installed photovoltaic capacity
PV Profile		1	Photovoltaic power generation curve
WD		GW	Wind power generation power
WD Capacity	P	GW	Installed wind power capacity
WD Profile		1	Wind power generation curve
WDPV	F	GW	Wind and photovoltaic power
Year Load	P	TWh	Annual power generation
Description: Type D: Data, F: Flow; P: Scenario parameter; S: Stock			

As wind and solar capacity increases, so does the likelihood that more electricity could be generated than needed. This often results in voluntary or mandatory curtailment of wind and solar power to ensure grid stability [3]. A more environmentally friendly and economical option than the usual curtailment is to capture and store excess electric energy through storage facilities such as pumped storage, and use the stored electric energy later when needed to reduce the dispatchable generation, as shown in the second part of our model (Figure 3).

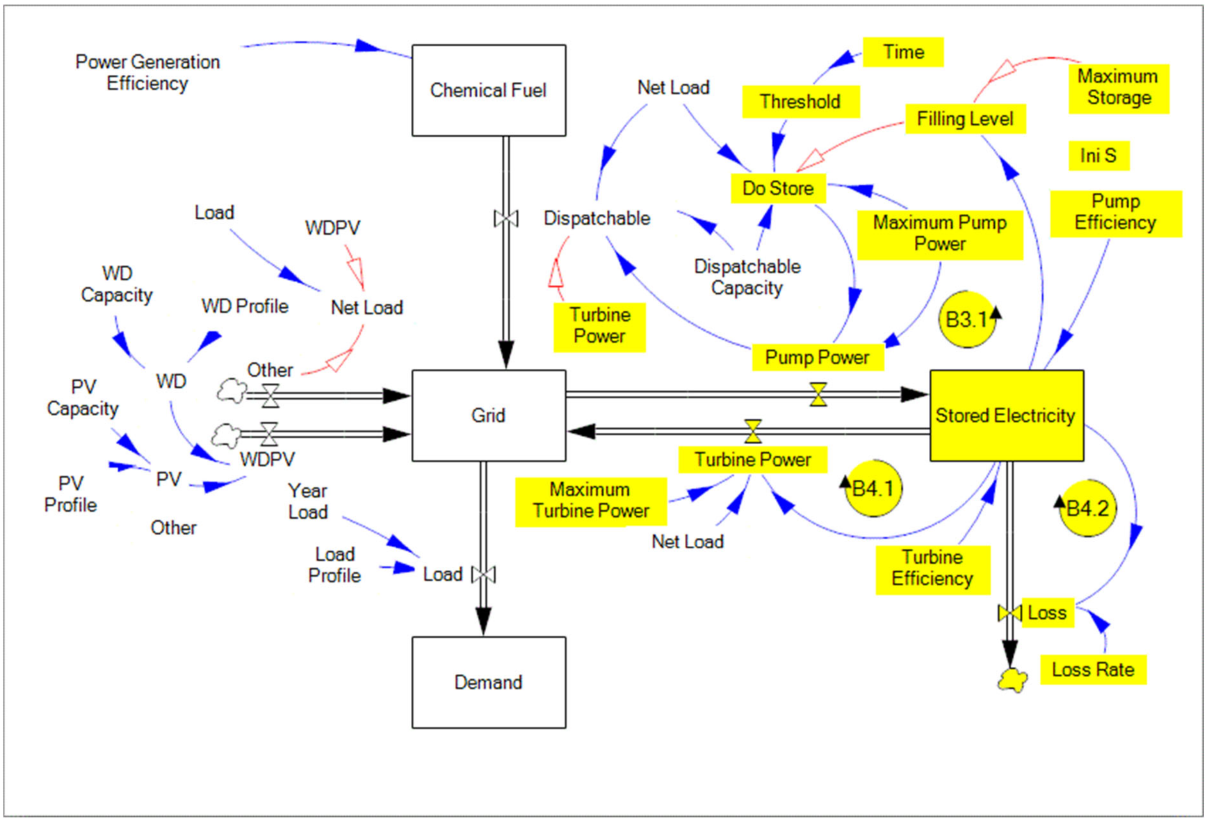

Figure 3: With the growth in installed capacity of wind and solar power, the importance of energy storage methods such as pumped storage power plants is becoming increasingly evident

The variables of this part of the model are listed in Table 3. Three variables, `Maximum Pump Power`, `Maximum Storage` and `Maximum Turbine Power` describe the storage capacity of the entire network. Normally, pumped storage is only filled up when the Net Load is negative. Threshold, however, defines the seasonal minimum Filling Level below which the pumped storage should be filled even if the Net Load is positive. That means, in such cases, the pump storage is filled with the electricity from Dispatchable.

Table 3: Main variables describing pumped storage

030width:600px; Name	Type	Unit	Description
Do Store		0/1	Storing power from the grid, binary value (0/1)
Filling Level		1	Actual filling level of pumped storage
Ini S	P	1	Initial values of Filling Level
Loss	F	GW	Power of energy loss
Loss Rate	P	1	Loss rate of energy storage
Maximum Pump Power	P	GW	Maximum pump power
Maximum Storage	P	GWh	Maximum storage capacity
Maximum Turbine Power	P	GW	Maximum turbine power
Pump Efficiency	P	1	Pump efficiency
Pump Power	F	GW	Pumping power
Stored Electricity	S	GWh	Electricity stored
Threshold	L	1	Lowest Filling Level before filling storage using dispatchable power
Turbine Efficiency	P	1	Power generation efficiency
Turbine Power	F	GW	Power generation
Time	I	h	
Description：Type F: Flow; I: Vensim's special variable; L: Time profile; P: Scenario parameter; S: Stock			

The main disadvantage of all mechanical storage methods such as pumped storage is that the maximum capacity and duration of storage are limited to hundreds of GWh and several days for economic reasons (see Sections 2 and 4.2). As a result, chemical electricity storage methods such as SNG have emerged, which can reach a maximum capacity of hundreds of TWh and a storage time longer than one year [43]. Figure 4 shows the model including the third part. Shown at top left is the mechanism by which SNG produces chemical fuels. Note that CO2 emissions for the entire power industry can be calculated from the net consumption of chemical fuels due to the absorption of CO2 during SNG production.

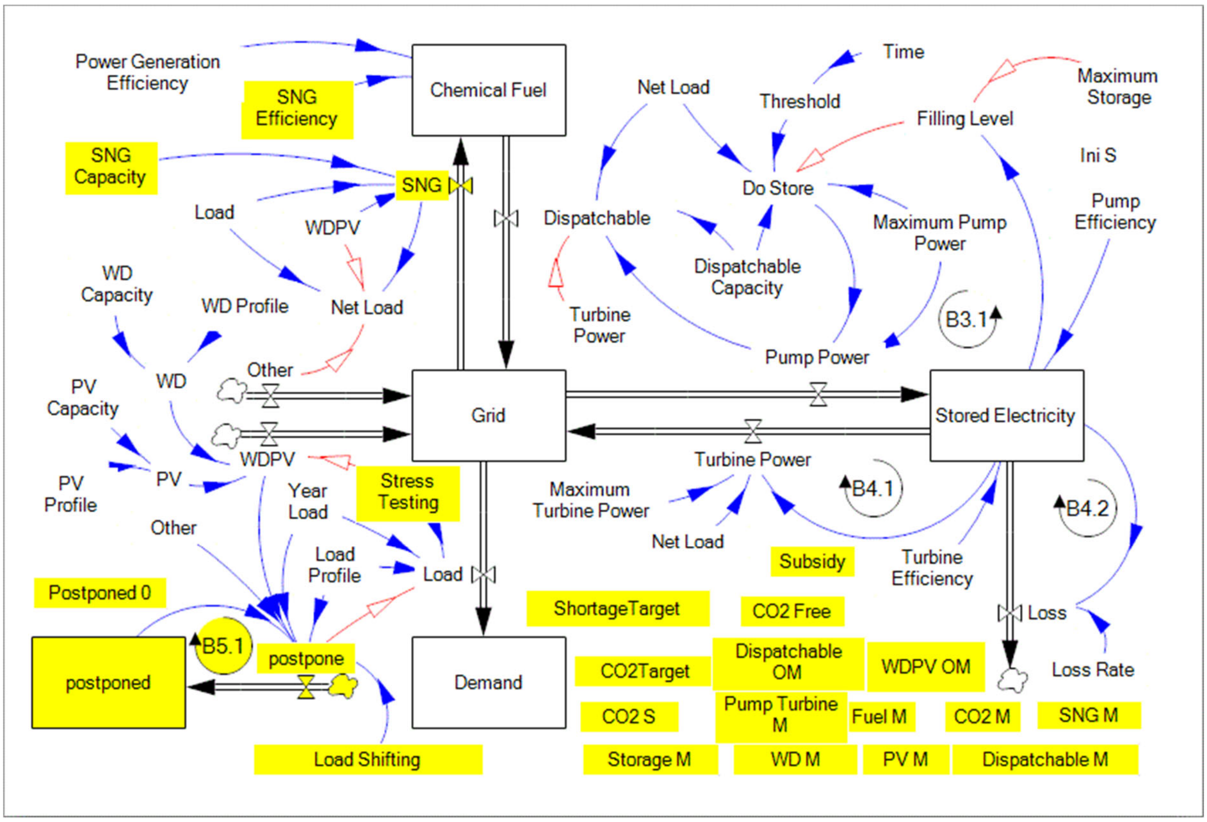

Figure 4: The key to achieving carbon neutrality in the power industry lies in the construction of `SNG Capacity`, the implementation of consumer-side `Load Shifting`, and the economic optimization of capacity allocation based on scene parameters

Another core technology for future power supply is consumer-side load management that matches wind and solar power generation (the lower left part of the model in Figure 4). The variables are listed in Table 4. Among them, `Load Shifting` refers to the amount of power in the consumer's load that can be postponed for several days when necessary according to the wind and solar power generation. `Postponed` shows the accumulation of delayed electricity demand. `Postponed` is then depleted by a negative value of `Postpone` when the wind and solar power becomes sufficient. `CO2 M` and `CO2Target` are important parameters to promote emissions reduction. The model also include a simple `Stress Testing` function (see Section 4.3).

Table 4: Main variables of new technologies and other parameters

030width:600px; Name	Type	Unit	Description
CO2 Free	P	GtCO2	Free quota of carbon emission allowances
CO2 M	P	B[€|¥]	Price of CO2 emission allowances
CO2 S	P	tCO2/GWh	Emission coefficient of dispatchable power generation
CO2Target	P	GtCO2	CO2 emission limit
Dispatchable M	P	B[€|¥]/GW	Dispatchable power investment costs
Dispatchable OM	P	B[€|¥]/GWh	Operating costs of dispatchable power
Fuel M	P	[€|¥]/MWh	Chemical fuel costs
Load Shifting	P	GW	Power under control by consumer-side load shifting
Postpone	F	GW	Postponing power usage

Postponed	S	GWh	Postponed energy consumption
Postponed 0		GWh	Postponed energy consumption at the beginning of the year
Pump Turbine M	P	B[€|¥]/GW	Investment costs for pumps and turbines
PV M	P	B[€|¥]/GW	Photovoltaic investment costs
ShortageTarget	P	GW	Power shortage limit
SNG	F	GW	Actual power used for SNG production
SNG Capacity	P	GW	Maximum power for SNG production
SNG Efficiency	P	1	SNG production efficiency
SNG M	P	B[€|¥]/GW	SNG investment costs
Storage M	P	B[€|¥]/GWh	Investment costs for storage capacity
Stress Testing	P	1	Grid stress test index
Subsidy	P	B[€|¥]	Electricity price subsidy
WD M	P	B[€|¥]/GW	Wind power investment costs
WDPV OM	P	B[€|¥]/GWh	Operating costs of wind and solar power
说明：Type F: Flow; P: Scenario parameter			

Using various economic and technical parameters in Table 4, our model can simulate and calculate the `LCOE`, carbon emissions `CO2 G` and `Shortage` for supply safety and stability. The goal of optimizing various power and storage capacities is to minimize the `LCOE` at a given total CO2 emission limit or at a CO2 price under the premise of safety of supply. In concrete terms, the process can be carried out by the Vensim DSS function "Optimize" [49], with subsequent manual fine-tuning if necessary.

3.2 Parametrization

A total of 90 variables (see Appendix), of which 66 are core variables (see Section 3.1) are in the model. In this section, we insert German power grid data from 2019 [46, 41] into the model for verification. The calculated results basically agree with the actual situation (Table 5).

Table 5: Model simulation using German power grid data in 2019 [46, 41]

030width:600px; Name	Value	Unit
Average U	39.7%	1
CO2 S	452	tCO2/GWh
CO2 G	0.223	GtCO2
Demand	528	TWh
- w/o Other	379	TWh
LCOE	106.82	€/MWh
PV Capacity	45.8	GW
PV Util	10.6%	1
Shortage	0.265	GW
WD Util	25.7%	1
WD Capacity	59.4	GW

Figure 5 shows the sensitivity analysis results of `Shortage` and `LCOE` relative to `Dispatchable Capacity`, `PV Capacity` and `WD Capacity` using a scatter plot. It clearly shows that `Dispatchable Capacity`, in contrast to `PV Capacity` and `WD Capacity`, can make an important contribution to supply safety. At the same time, a higher `WD Capacity` can reduce `LCOE` to a considerable extent. For more sensitivity and extreme value analysis, see Sections 4.1, 4.2 and 4.3.

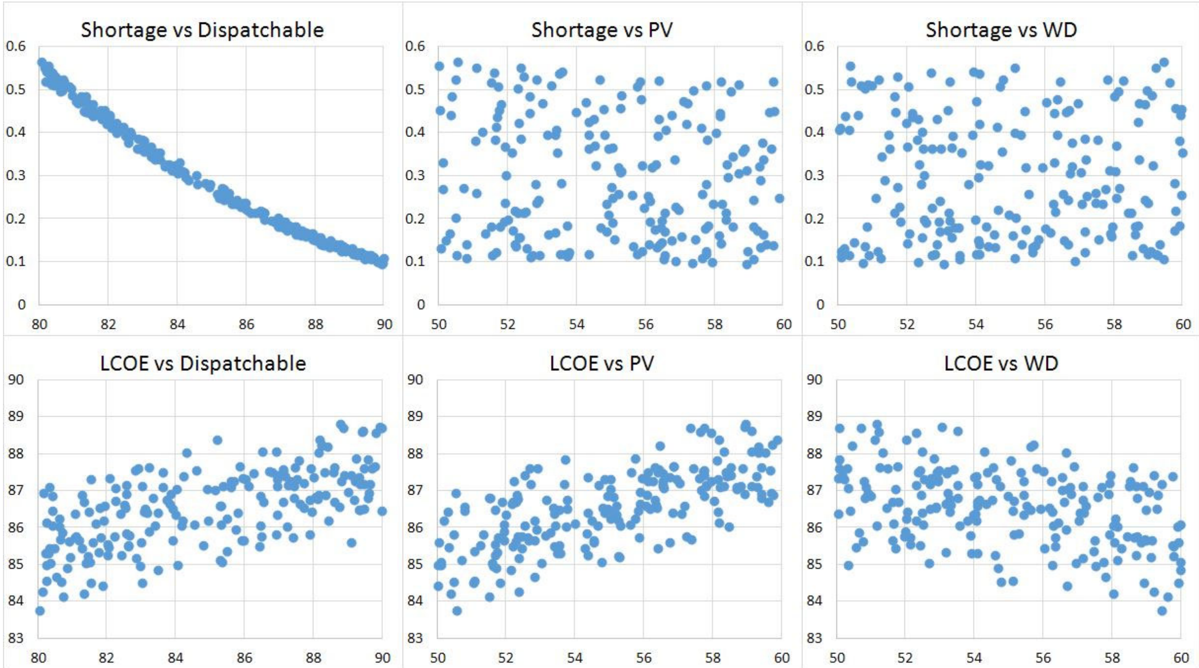

Figure 5: Scatterplots of `Shortage` *and* `LCOE` *versus* `Dispatchable`*,* `PV Capacity` *and* `WD Capacity`

4. Model Application and Discussion

4.1 Carbon Pricing for China's Carbon Peak in 2030

In 2030, China's power industry is expected to generate 10700 TWh. We apply the model proposed in this paper to find the most economical allocation of various generation capacities under different carbon prices, and calculate the corresponding total carbon emissions. The calculation is parameterized using the data on installed capacity and power generation of various types of power generation in 2020 [see, e.g., 32] and currently collected construction cost information [4, 7]. Figure 6 shows the results.

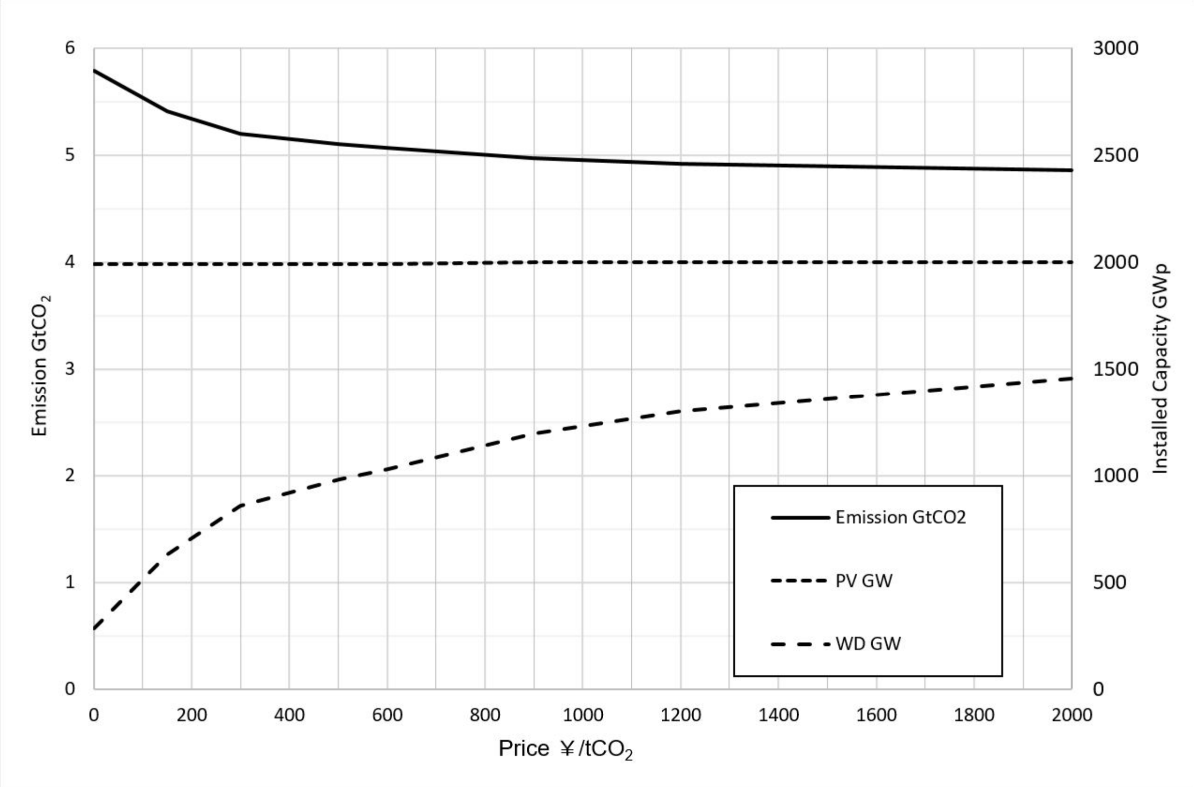

Figure 6: Relationship between carbon price and total carbon emissions of China's power industry

It is worth noting that the effect of emissions mitigation brought about by raising the carbon price has nonlinear characteristics. The installed solar capacity can contribute to the reduction of emissions and costs at the same time, regardless of the carbon price. Regarding the installed wind power capacity, the emission reduction effect is obvious, as long as the carbon price is below ￥300/tCO2. Further increases in the carbon price will have diminishing returns [see 39]. To achieve the emission target of 50.7 GtCO2 until 2030, the cumulative construction of wind and solar power required by this model is 1022 GWp and 1991 GWp respectively. The carbon price should be set around ￥600/tCO2 if no other measures are to be adopted.

Table 7: Wind and solar power generation capacity and investment amount completed by the end of 2022 [56] and expected to be completed by 2030

030width:600px;	Wind Power (GWp)	Photoelectric (GWp)	Investment (￥B)
Cumulative installed capacity by the end of 2022	365	393	
New installed capacity in 2022	37.6	87.4	
2030 model calculation cumulative installed capacity	1022	1991	10192
2023-2030 need new increments every year	82.1	199.8	1274

Table 7 lists the wind and solar power generation capacity and investment amount completed by the end of 2022 and expected to be completed by 2030 according to our model simulations. Among them, the annual investment from 2023 to 2030 is only about 1% of China's GDP, which will not become an obstacle to the realization of carbon peaking. However, it is necessary to strengthen vigorously the construction and operation of wind and solar power to ensure the realization of the goal of carbon peaking in 2030.

4.2 Germany's Carbon Neutrality in 2045

Germany aims to become carbon-neutral by 2045. We apply the model proposed in this paper to find the most economical allocation of various power generation and storage capacities under the premise of supply safety and carbon neutrality. The calculation is parameterized using the data from Sections 2 and 3.2. Table 8 shows the optimization results for four selected scenarios.

Table 8: Germany's carbon neutrality in 2045

030width:600px; Scenario	I	II	III	IV	Unit		General parameters		unit
Load shifting	**0**	**0**	**30**	**65**	GW		Power generation	1300	TWh
Maximum storage	**23500**	**660**	625	580	GWh		Storage construction	0.20	€/Wh
SNG capacity	**0**	**445**	375	264	GW		SNG construction	2.00	€/W
Dispatchable capacity	0	189	160	124	GW		Dispatchable construction	1.00	€/W
Wind power installed capacity	390	390	390	390	GW		Wind power construction	1.00	€/W
Photovoltaic installed capacity	1400	1460	1145	900	GW		Photovoltaic construction	1.00	€/W
Pump capacity	220	6	6	6	GW		Pump power	0.20	€/W
Turbine capacity	197	40	32	20	GW		Turbine power	0.20	€/W
Marginal cost of SNG	-	214	188	161	€/MWh		Round trip efficiency SNG	35%	1
Total investment	**6573**	**3070**	**2578**	**2063**	B€		Power generation efficiency	50%	1
Levelized Cost of Electricity	**435.54**	**237.39**	**198.63**	**159.08**	€/MW		Round trip efficiency pumped storage	81%	1

Scenario I only envisages the use of pumped storage power plants. To cover the higher demand in winter with sufficient electricity, the excess electricity generated in summer must be stored. The `Maximum Storage` capacity required for pumped storage is 23.5PWh and the construction costs for this alone amount to €4.7T. This means that investments in the energy sector exceed the sum of €5T to €6T that German opinion groups believe is necessary for the energy turnaround in society as a whole by 2045 [see, e.g., 44, 40, 10]. In this case, the LCOE exceeds €400/MWh and the economic feasibility is low.

Scenario II also envisions the deployment of SNG (or PtM, Power-to-Methane) energy storage technology [see 17], which converts excess wind and solar power into methane for chemical energy storage. Favorable for this scenario is that development cost of natural gas storage is incomparably low [see 11] because of methane's high energy density, and Germany already has sufficient storage [9] and transport capacity today, and therefore also for SNG. Figure 6 shows simulated power generation and demand in 2045 under this scenario. Compared with Scenario I, Scenario II saves more than 97% of the pumped storage capacity, and the total investment is reduced from €6.6T to €3.1T. The total cost of power generation is correspondingly reduced by nearly half to the cost range of gas-fired power generation in Germany in 2021 [see 27], economically and technologically (see Section 2) have shown considerable feasibility.

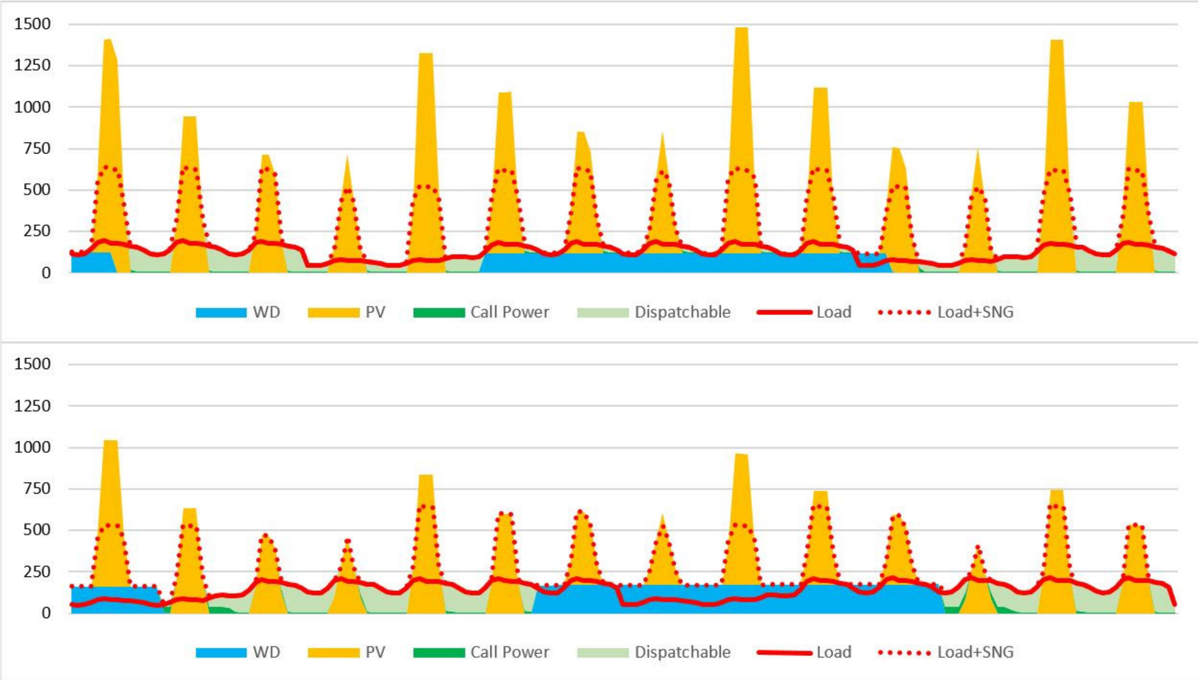

Figure 6: Simulation of power generation and demand in 2045. Top: August 1-14, bottom: November 17-30. The red solid line is the demand, the area between the red dotted line and the solid line is the power used for SNG production, the yellow and blue areas are photovoltaic and wind power generation respectively, and the dark and light green are water storage and thermal power generation respectively

To further reduce the LCOE, Scenario III relies on consumer-side load shifting. During periods of low wind and solar generation, consumers defer partial loads for up to a week to help reduce the need for dispatchable power. When the amount of wind and solar power generation is large, consumers have to increase the load to make up for the previously delayed load to absorb electricity, thereby reducing the demand for installed capacities of SNG and pumped storage (see Figure 7). Compared with Scenario III, Scenario IV intensifies consumer-side load shifting and greatly reduces LCOE, but requires more consumer-side technology and management.

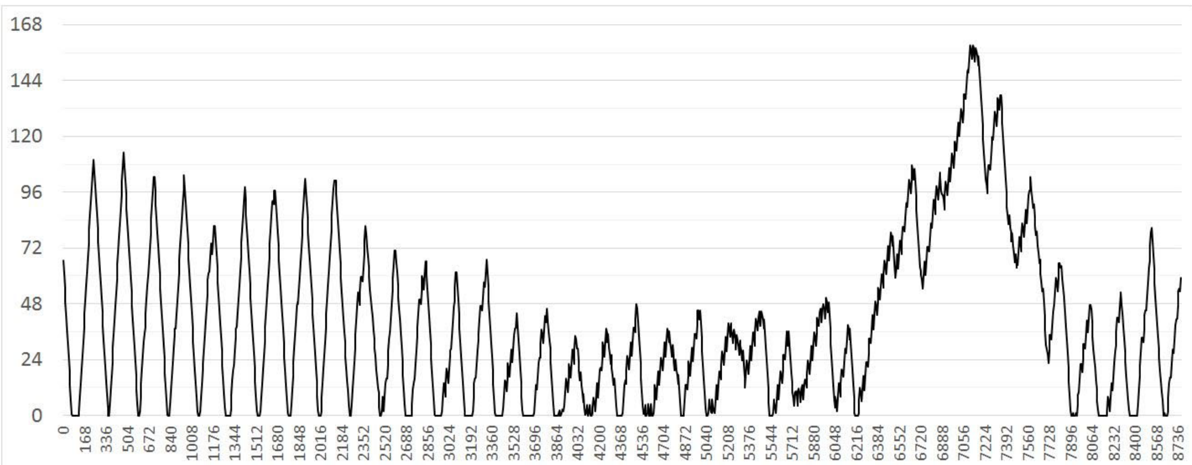

Figure 7: The consumer-side load shifting latency can be up to almost a week in Scenario III. The horizontal axis in the figure is time (8760 hours per year) and the vertical axis is latency (hours)

Note that the economic and technical feasibility of consumer-side load shifting is beyond the scope of this paper. However, the model optimization offers the electricity industry the space to advance the development of this technology and organization through price advantages.

4.3 Discussion: Wind and Solar Power Curves, Load Demand Curve and Stress Testing, Limitations

The core of the model is to allocate and use power generation and storage resources in the most economical way possible under the premise of ensuring safety of power supply and meeting emission reduction requirements under given load demand curves as well as wind and solar power curves (see Figure 2 and Table 2 in 3.1). Sections 4.1 and 4.2 calculate the load demand curve and the wind and solar power curve in China in 2030 and Germany in 2045 using the monthly data of China in 2020 and Germany in 2019, respectively. Several periodic variables are introduced to simplify the simulation (see Table 8).

Table 8: Electricity supply and demand time curve

030width:600px; Name	Type	Unit	Description
Load Profile		1	Load demand curve
Load Profile 7Day			7-day cycle load demand curve
Load Profile Day			24-hour cycle load demand curve
Load Profile Year			Monthly load demand curve
PV Profile		1	Solar power curve
PV Profile 4Day		GW	Solar power 4-day cycle curve
PV Profile Year	P	GW	Monthly solar power curve
WD Profile		1	Wind power curve
WD Profile 10Day	F	GW	237-hour cycle curve of wind power
WP Profile Year	P	TWh	Monthly wind power curve
Description: Type D: Data, F: Flow; P: Scenario parameter; S: Stock			

The specific algorithm of wind, solar and load curve is:

```
Load Profile = Load Profile Day x Load Profile 7Day x Load Profile Year

WD Profile = WD Profile 10Day x WD Profile Year

PV Profile = PV Profile 4Day x PV Profile Year
```

The periodic variables for wind and solar power production are set to represent more of the situations that place a higher demand on grid stability. For example, Figure 6 shows that the wind power curve used for the simulation is set in such a way that strong and windless phases alternate. A bigger challenge for renewable power supply than ensuring power supply stability within a day, a week or a month is to ensure power supply stability over quarters and years. From today's perspective, the wind and solar power curves in 2045 obviously have considerable uncertainty. This represents one of the main limitations of the model statements. For this reason we introduce the `Stress Testing` parameter (see Figure 4 and table 4 in Section 3.1) which is convenient for simulating the situation when the wind and solar power curves drop by a certain percentage across the board and the load curve rises by the same percentage across the board. Figure 9 shows the scatterplots of `Shortage` and `CO2 G` versus `Stress Testing`, `SNG Capacity` and `Dispatchable Capacity` for the sensitivity analysis. It is apparent that the risk of power grid instability or excessive emissions under different conditions can be reduced by increasing the installed capacity of SNG and dispatchable power generation.

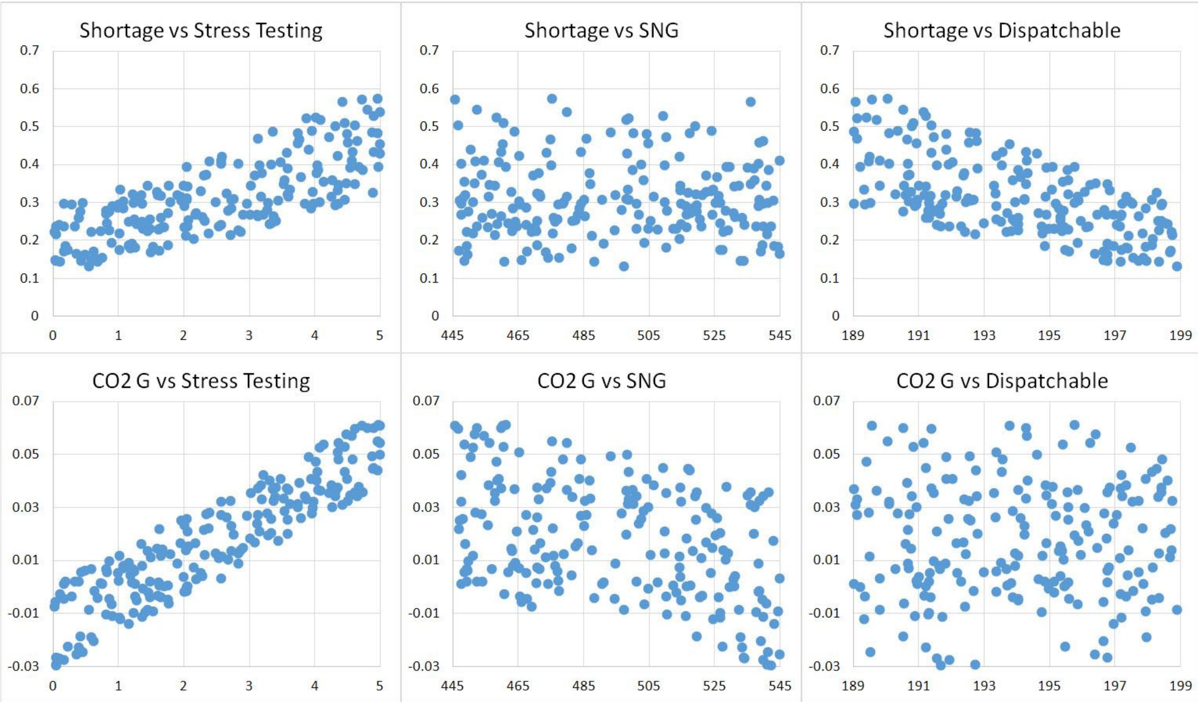

Figure 9: Scatterplots of Shortage and CO2 emission versus Stress Testing, SNG and Dispatchable capacities

If the `Year Load` is reduced by a certain amount, then a certain amount of SNG is expected to remain at the end of the year. Theoretically, this quantity of SNG can be sold at the price which does not cause any change of `LCOE` in the aggregate and thus reflects the marginal cost of SNG. These marginal costs for the scenarios that have SNG capacities are listed in Table 8.

In addition to wind, sunshine and load curve conditions, the cost optimization calculation results of the model in this paper are directly related to the construction costs of various technical facilities. These cost data not only vary significantly over time, but also correlate with the total amount of various technical facilities built (see Section 2). The fact that this is not taken into account in the current version represents further limitations of the model. Future versions of the model in this paper not only need to update the parameters, but also consider setting the relevant parameters as variables of the total construction volume to generate more accurate optimization results.

5. Summary

On the basis of several relevant studies and technical and economic data (Section 2), we proposed a model for economic optimization of electricity generation and storage capacities given ecological economics objectives and conditions. The model is mainly composed of three parts: power generation and power consumption, pumped storage, synthetic natural gas (SNG) and consumer-side load shifting (Section 3.1). We used data of power generation and consumption of Germany for necessary parameter calibration and verification (Section 3.2).

The simulation of China's power industry showed that it is economically feasible to achieve carbon peaking by 2030 through a higher carbon price alone which needs to be set at ￥600/tCO2 or higher (Section 4.1).

The simulation of Germany's fully renewable and fully electrified energy supply in 2045 showed that the economic feasibility of large-scale pumped storage is poor. For a 100% renewable energy supply in the future, we recommend the use of synthetic natural gas (SNG) as the main energy carrier for storage and pumped storage hydropower as a supplement. The levelized cost of electricity is controlled below €240/MWh, which is economically feasible. In addition, the possibility of further cost reduction through consumer-side load shifting can be considered (Section 4.2).

This paper also discussed the uncertainty of wind and solar power generation as well as the uncertainty of demand. This and other uncertainties regarding various technological parameters represent limitations of the model statements. The model provides a simple method for stress testing (Section 4.3).

System dynamics provides a good way for us to deepen our understanding of power supply and energy transition. We will continue to optimize the model structure and adjust various model parameters as needed to provide better support for energy transition decisions.

Appendix: Model Variables

030width: 600px;680 Name	Type	Unit	Description
a PV	F	1	Photovoltaic utilization
a WD	F	1	Wind power utilization
Average U		1	Dispatchable power utilization
Chemical Fuel	S	GWh	Chemical fuel stocks
CO2		B[€|¥]	Total cost for CO2 emission allowances
CO2 Free	P	GtCO2	Free quota of carbon emission allowances
CO2 G		GtCO2	Total CO2 emissions
CO2 M	P	B[€|¥]	Price of CO2 emission allowances
CO2 S	P	tCO2/GWh	Dispatchable power emission coefficient
CO2Accept		B[€|¥]	Variables for CO2 emission optimization
CO2Target	P	GtCO2	CO2 emission limit
Cumulative Utilization	S	h	Cumulative utilization
Demand	S	GWh	Cumulative demand of electricity
Dispatchable	F	GW	Dispatchable power
Dispatchable Capacity	P	GW	Installed capacity of dispatchable power
Dispatchable M	P	B[€|¥]/GW	Dispatchable power investment costs
Dispatchable OM	P	B[€|¥]/GWh	Operating costs of dispatchable power
Do Store		0/1	Storing power from the grid, binary value (0/1)
Duration		h	Total hours per year
Exchange Rate	P	¥/€	Renminbi and Euro exchange rate
Filling Level		1	Actual filling level of pumped storage
FINAL TIME	I	h	
Fuel		B[€|¥]	Total cost of chemical fuels
Fuel M	P	[€|¥]/MWh	Chemical fuel costs
Grid	S	GWh	Balance of power generation and demand
Grid2	F	GW	Power supply and demand gap
Ini S	P	1	Initial values of Filling Level
INITIAL TIME	I	h	

Invest M		B[€|¥]	Total Investment
LCOE		[€|¥]/MWh	Levelized cost of electricity
Load	F	GW	Actual power demand
Load Profile		1	Load curve
Load Profile 7Day	L, P	1	Seven-day load curve
Load Profile Day	L, P	1	Daily load curve
Load Profile Year	L, D	1	Annual load curve
Load Shifting	P	GW	Power under control by consumer-side load shifting
Loss	F	GW	Power of energy loss
Loss Rate	P	1	Loss rate of energy storage
Maximum Pump Power	P	GW	Maximum pump power
Maximum Storage	P	GWh	Maximum storage capacity
Maximum Turbine Power	P	GW	Maximum turbine power
Net Load		GW	Residual load
Operation M		B[€|¥]	Total operating cost
Other	F, P	GW	Nuclear power, hydropower, etc.
per year	P	1	Annualized investment cost
Postpone	F	GW	Postponing power usage
Postponed	S	GWh	Postponed energy consumption
Postponed 0		GWh	Postponed energy consumption at the beginning of the year
Power Generation Efficiency	P	1	Efficiency of dispatchable power generation
Production		GWh	Cumulative dispatchable power generation
PV		GW	Photovoltaic power
PV Capacity	P	GW	Installed photovoltaic capacity
PV M	P	B[€|¥]/GW	Photovoltaic investment costs
PV Profile		1	Photovoltaic power generation curve
PV Profile 4Day	L, P	1	Photovoltaic four-day power generation curve
PV Profile Year	L, D	1	Photovoltaic monthly power generation Curve
PV Utilities	S	1	Photovoltaic utilization
Pump Efficiency	P	1	Pump efficiency
Pump Power	F	GW	Pumping power
Pump Turbine M	P	B[€|¥]/GW	Investment costs for pumps and hydropower turbines
SAVEPER	I	1	
Shortage	S	GW	Average power supply shortage
ShortageAccept		B[€|¥]	Variables for power shortage optimization
ShortageTarget	P	GW	Power shortage limit
SNG	F	GW	Actual power used for SNG production
SNG Capacity	P	GW	Maximum power for SNG production
SNG Efficiency	P	1	SNG production efficiency
SNG M	P	B[€|¥]/GW	SNG investment costs
Storage M	P	B[€|¥]/GWh	Storage investment costs
Stored Electricity	S	GWh	Electricity stored
Stress Testing	P	1	Grid stress test index
Subsidy	P	B[€|¥]	Electricity price subsidy
Threshold	L	1	Lowest Filling Level before filling storage using dispatchable power

Time	I	h	
TIMESTEP	I	1	
Total M		B[€|¥]	Total cost
Turbine Efficiency	P	1	Power generation efficiency
Turbine Power	F	GW	Power generation
Usage		GWh	Net chemical fuel consumption
Utilization	F	1	Utilization rate of thermal power (dispatchable power)
WD		GW	Wind power generation power
WD Capacity	P	GW	Installed wind power capacity
WD M	P	B[€|¥]/GW	Wind power investment costs
WD Profile		1	Wind power generation curve
WD Profile 10Day	L, P	1	Ten-day power generation curve of wind power
WD Profile Year	L, D	1	Monthly wind power generation curve
WD Utilities	S	1	Wind power utilization rate
WDPV	F	GW	Wind and photovoltaic power
WDPV OM	P	B[€|¥]	Operating costs of wind and solar power
Year Load	P	TWh	Annual power generation
Description: Type D: Data, F: Flow; I: Vensim's special variable; L: Time profile; P: Scenario parameter; S: Stock			

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