清华大学气候变化与可持续发展研究院
Institute of Climate Change and Sustainable Development,Tsinghua University

GAUC
Global Alliance of Universities on Climate

AFFORDABLE CARBON NEUTRALITY

Decarbonization pathways for China and its power sector

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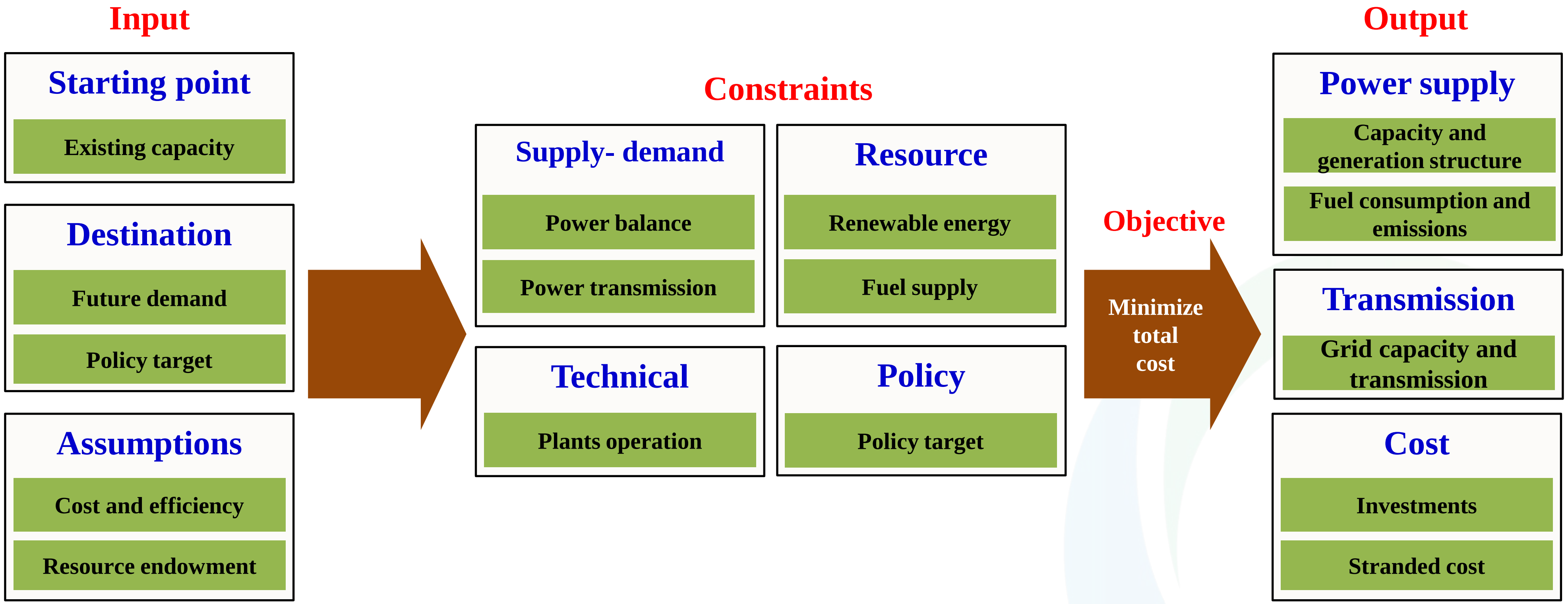
Outline

1. Methodology
2. Scenario analysis
3. Policy recommendations

LoMLoG: bottom-up energy system model integrating both long-term planning and short-term operation

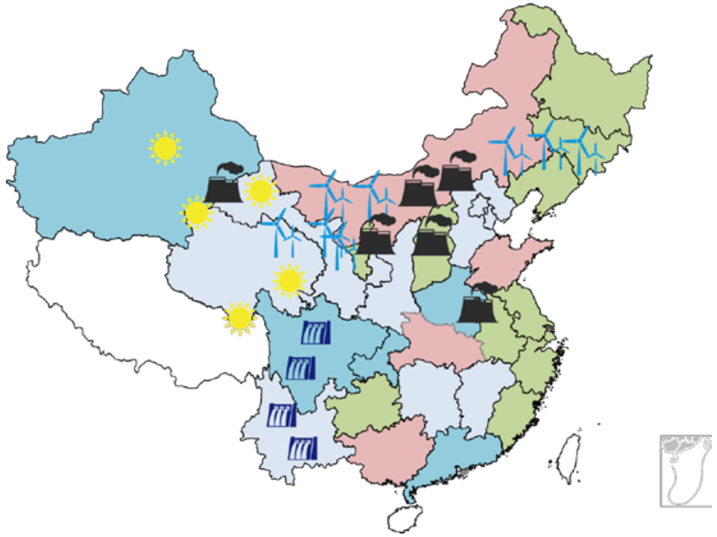
- **Model framework**



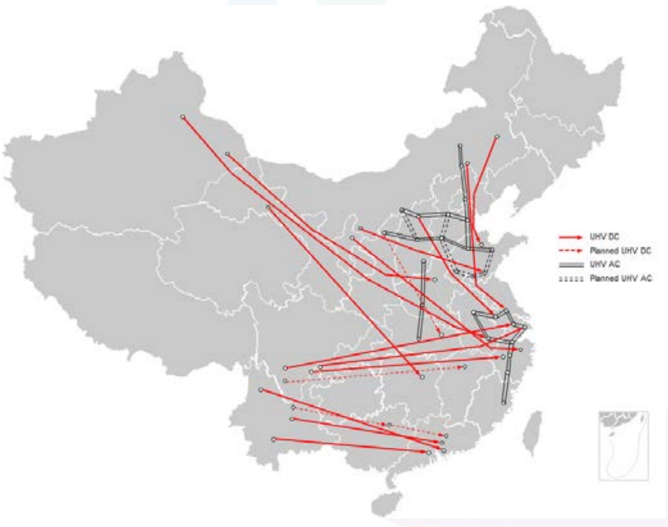
- **Settings**
  - Planning horizon: 2018 - 2050
  - 14+1 power generation technologies
  - Spatial-temporal resolution: 17 regions, 96 time slices

Model description: Spatial module

- **Region division: 17 regions based on resources and grid structure**
  - Resource-rich regions: Inner Mongolia, Xinjiang, Ningxia, Shanxi, Guizhou, Sichuan & Chongqing, Hubei, Yunnan, Northeast, Northwest
  - Load-centered regions: Jing-Jin-Ji, Shandong, East, Guangdong
  - Power transmission intersections: Jing-Jin-Ji, Henan, Hubei
- Existing and short-term planned **cross-region transmission lines** are included
- **Transmission lines and capacity** in the long-term are set as variables to be optimized along with power generation capacity



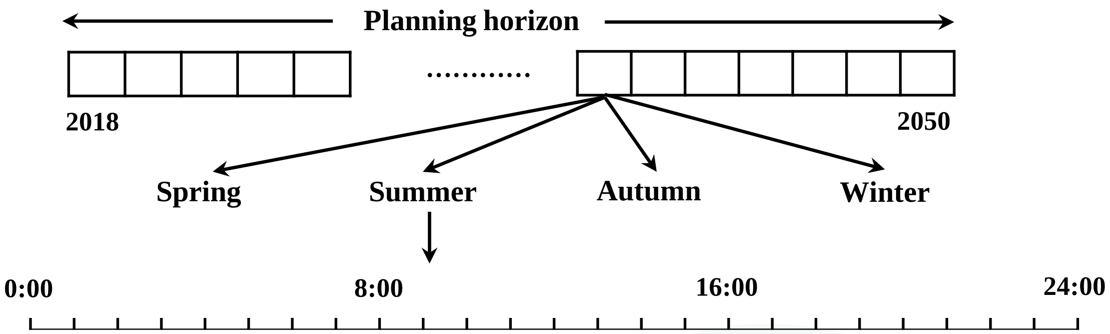
Region division

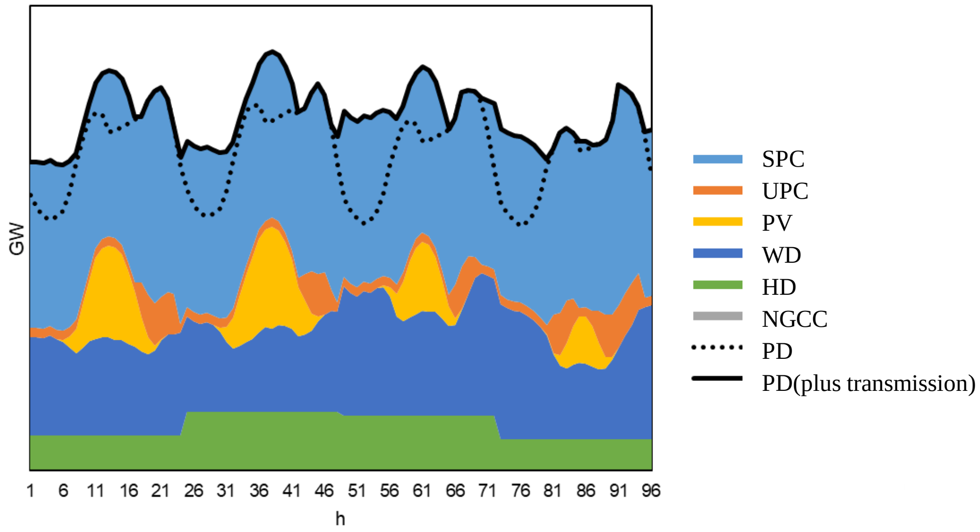


Ultra-high-voltage transmission lines

Model description: Temporal module

- **Time slices**
  - One year → 4 seasons
  - One day → 24 hours
  - 96 time slices in total
- **Seasonal and daily fluctuation**
  - Power demand profile
  - Renewable energy variability
- **Unit commitment**
  - Integrating variable RE requires more flexibility in the power system
  - Thermal power plants have operation constraints for load-dispatch
  - Capacity factor limits
  - Start-up and shut-down decisions
  - Ramp up and down limits

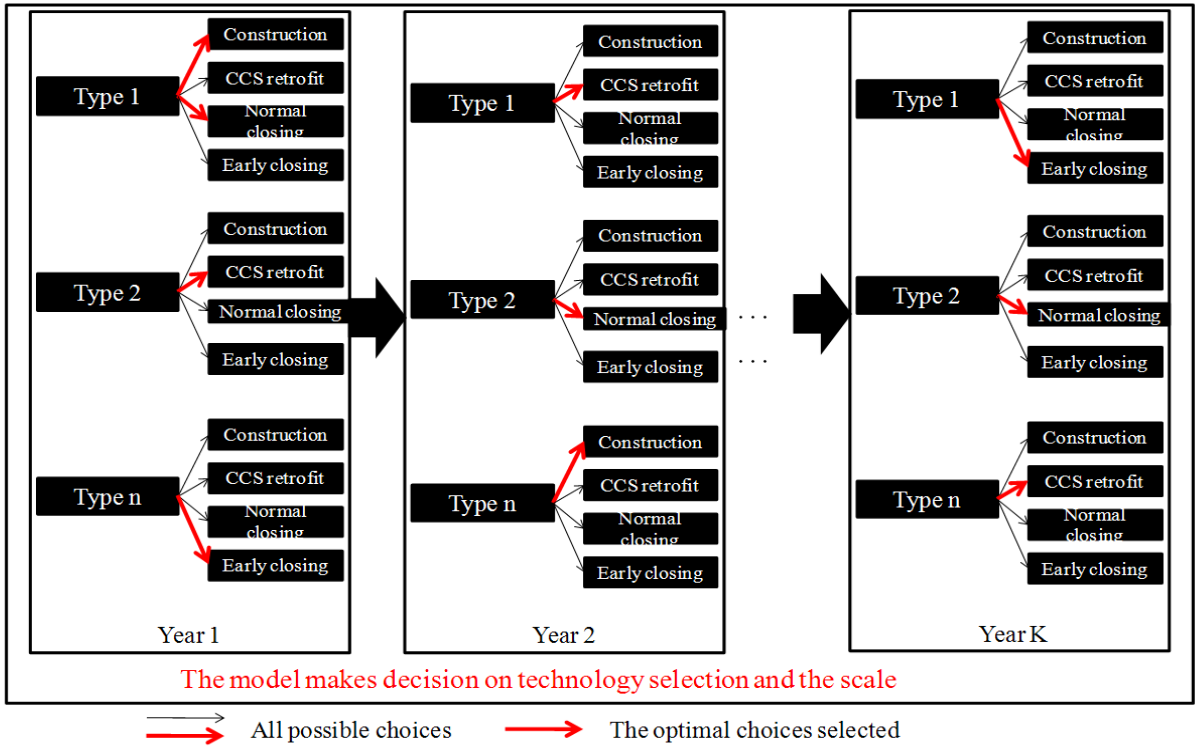




Load dispatch

Long-term planning: Super-structure model

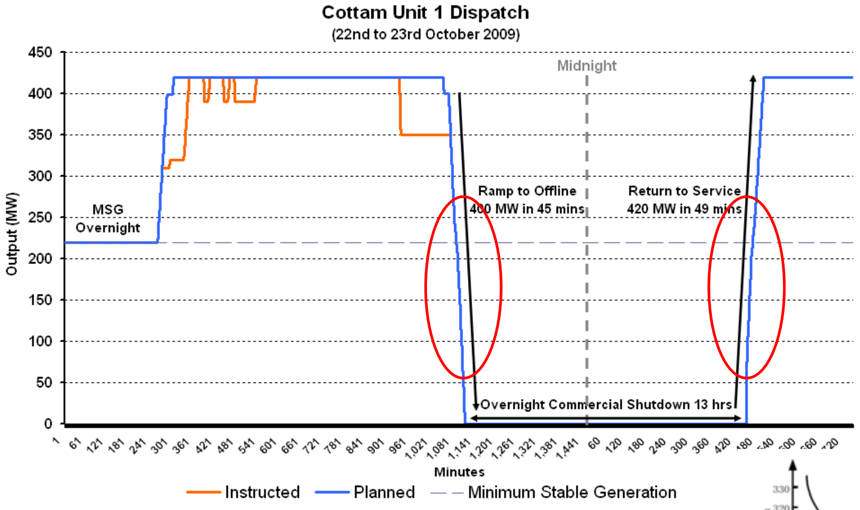
Notation	Plant type
SPC	Sub and super-critical coal
UPC	Ultra-supercritical coal
SPCC	Sub and super-critical coal with CCS
UPCC	Ultra-supercritical coal with CCS
SPCCOC	Sub and super-critical coal-biomass co-firing power plants with CCS
UPCCOC	Ultra-supercritical coal-biomass co-firing power plants with CCS
NGCC	Natural gas combined cycle
NU	Nuclear
HD	Hydro
WDON	Wind onshore
WDOFF	Wind offshore
PVCEN	Centralized solar photovoltaic
PVDIS	Distributed solar photovoltaic
BE	Biomass

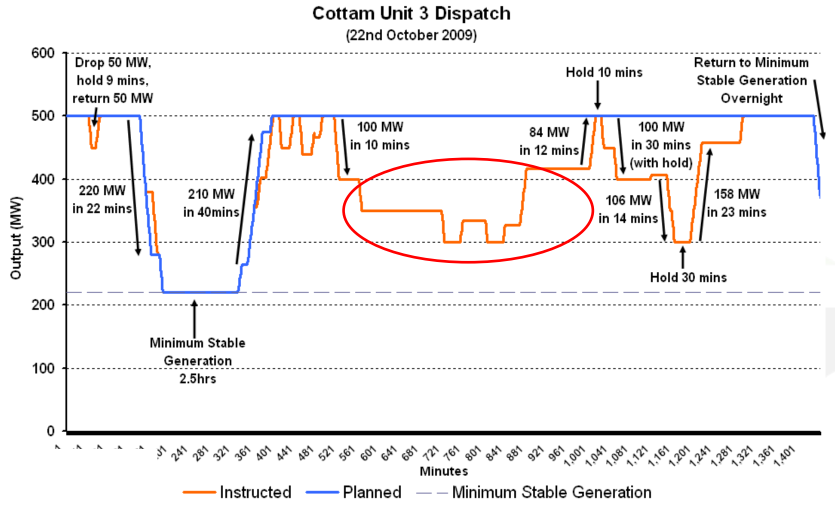


- **Investment decision**
  - All alternative investment decisions are included (**All the arrows**)
    - Time, scale and location of plants construction
    - For coal plants: could retire before the end of lifetime or retrofitted with CCS
  - The optimal choice is selected based on the objective function (**Red arrows**)

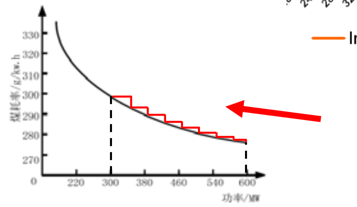
Short-term scheduling: coal plants operation

Modelling the operational details of coal plants





Start-up/shut-down, operation and ramping constraints



Efficiency change at part load

$$oc^{s+1}_{g,t,r} = oc^{s}_{g,t,r} + st^{s}_{g,t,r} - sh^{s}_{g,t,r}$$

$$pg^{s+1}_{g,t,r} - pg^{s}_{g,t,r} \le (oc^{s+1}_{g,t,r} - st^{s+1}_{g,t,r}) \cdot RP^{up} + (st^{s+1}_{g,t,r} - sh^{s+1}_{g,t,r}) \cdot MINOH_g$$

$$pg^{s+1}_{g,t,r} - pg^{s}_{g,t,r} \ge (oc^{s+1}_{g,t,r} - st^{s+1}_{g,t,r}) \cdot RP^{down} + (sh^{s+1}_{g,t,r} - st^{s+1}_{g,t,r}) \cdot MINOH_g$$

$$oc \cdot OHMIN_i - M(1 - x_i) \le pgs \le oc \cdot OHMAX_i + M(1 - x_i)$$

$$pgs \cdot FCR_i - M(1 - x_i) \le fd \le pgs \cdot FCR_i + M(1 - x_i)$$

$$\sum_i x_i = 1$$

Short-term scheduling: energy storage

Modelling the energy storage process

Balance the supply and demand by charge and discharge cycles

Power and capacity constraints

Charge and discharge constraints

$$
\begin{cases}
load_{t,s} = PD_{t,s} + charge_{t,s} - discharge_{t,s} \\
storage_{t,s+1} = storage_{t,s} + charge_{t,s+1} \cdot \eta_{charge} - discharge_{t,s+1} / \eta_{discharge} \\
charge_{t,s} \le y1_{t,s} \cdot M \\
discharge_{t,s} \le y2_{t,s} \cdot M \\
y1_{t,s} + y2_{t,s} = 1 \quad y1, y2 \in \{0,1\}
\end{cases}
$$

Capacity constraints

$$ices_t \cdot SL_{\min} \le storage_{t,s} \le ices_t \cdot SL_{\max}$$

Power constraints

$$
\begin{cases}
charge_{t,s} \le ices_t \cdot CHG \\
discharge_{t,s} \le ices_t \cdot DCHG
\end{cases}
$$

Powerful functions of our model

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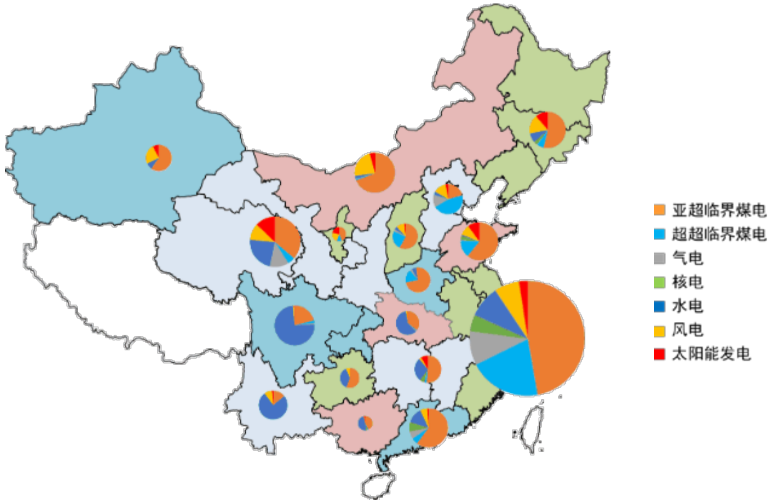
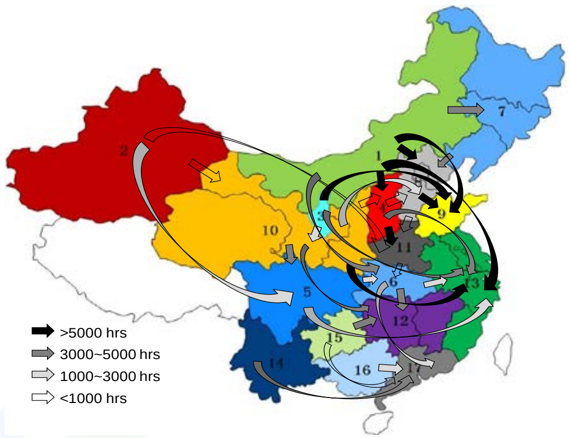
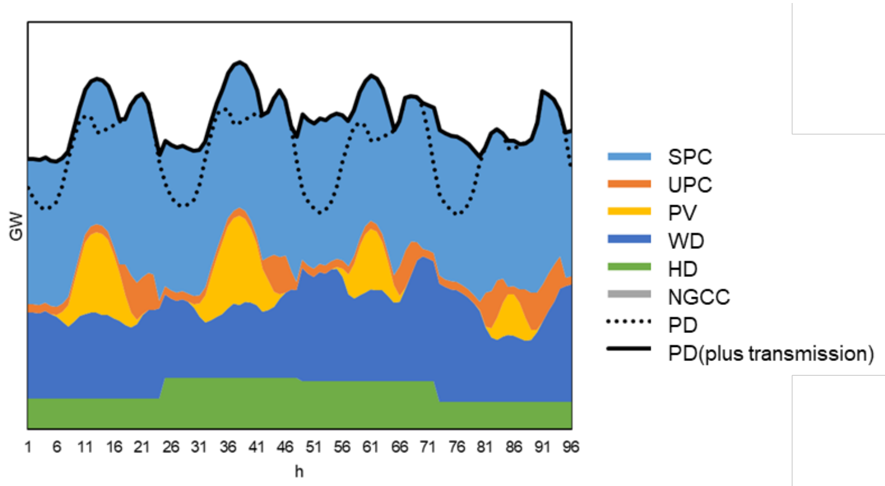
Regional capacity expansion



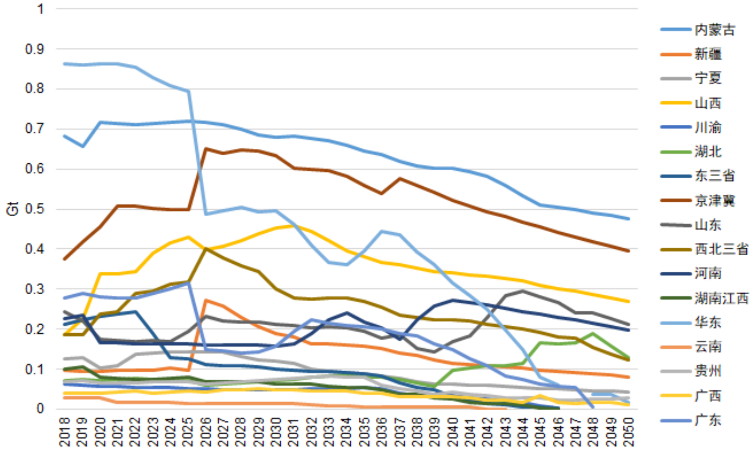
Inter-region power transmission



Power dispatch profile



Regional CO_2 emissions



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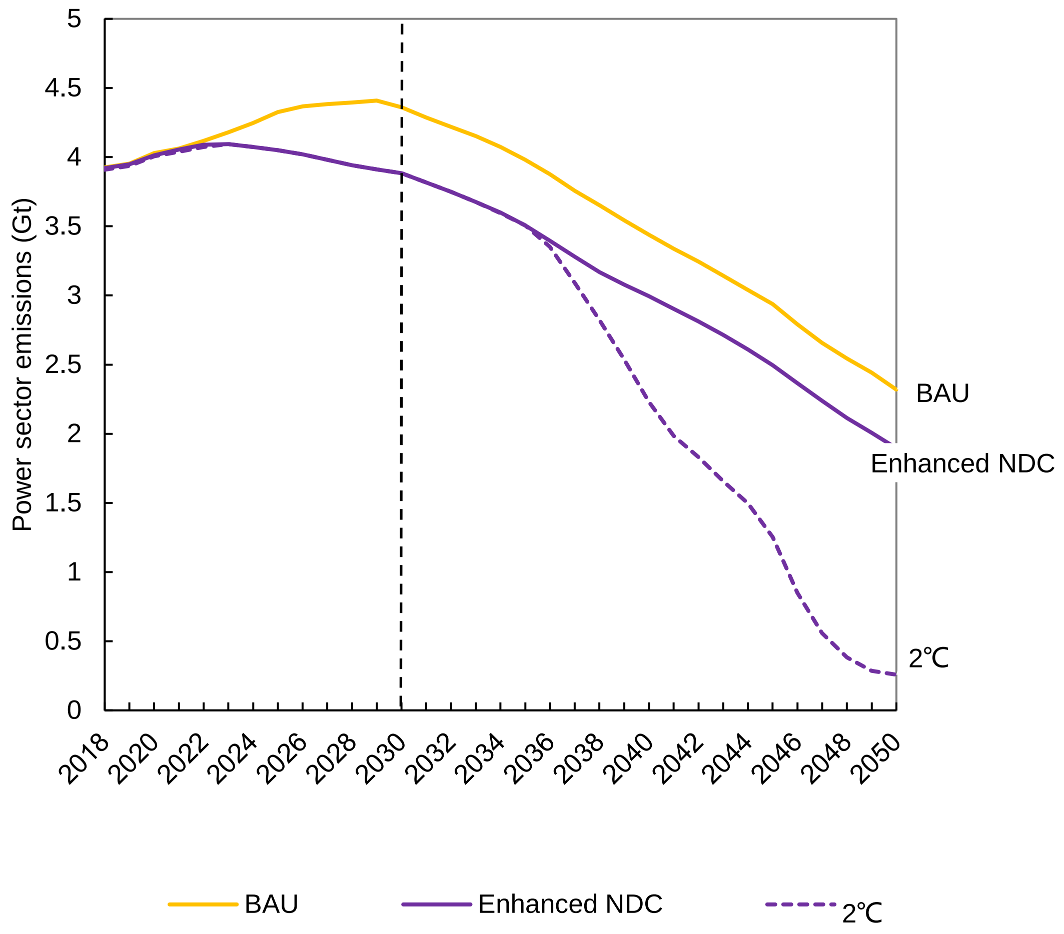
Scenarios setting

	2020	2030	2050
Business as Usual scenario (BAU)	Non-fossil share: 15%	Non-fossil share: 20%	
Enhance NDC scenario	Non-fossil share: 15%	Non-fossil share: 25%	Non-fossil share: 50%
2°C Scenario (2DS)	Carbon budget (2018-2050): 94.7Gt		
1.5°C Scenario (1.5DS)	Carbon budget (2018-2050): 76.4Gt 2050 net-zero emission		

Carbon emission trajectories: Policy

- Policy scenario and enhanced policy scenario both cannot realize 2D temperature control target
- In 2DS, the delay-action pathway has a very sharp drop of emissions. In contrast, the early-action pathway saves sufficient reduction space for post-2030.
- In 1.5DS, power sector has reached net-zero emissions since 2046.



Carbon emission trajectories: 2D

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- Policy scenario and enhanced policy scenario both cannot realize 2D temperature control target
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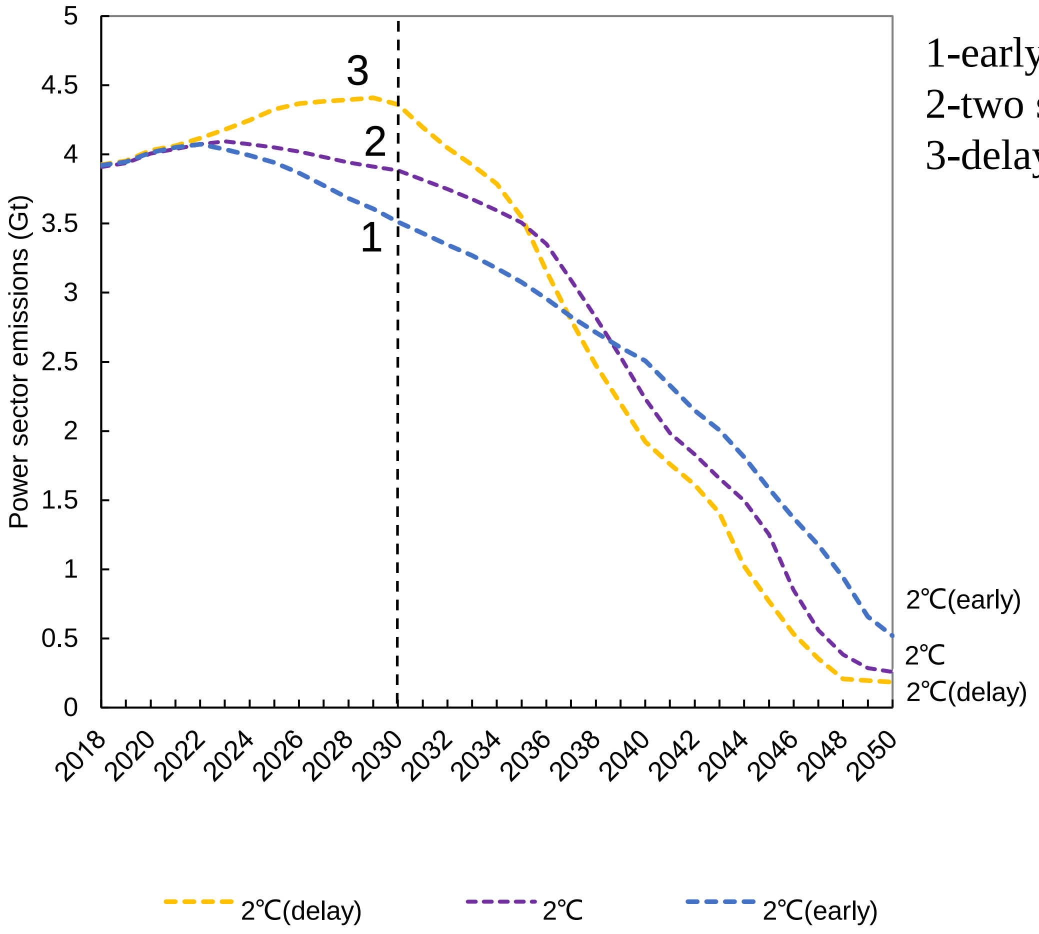
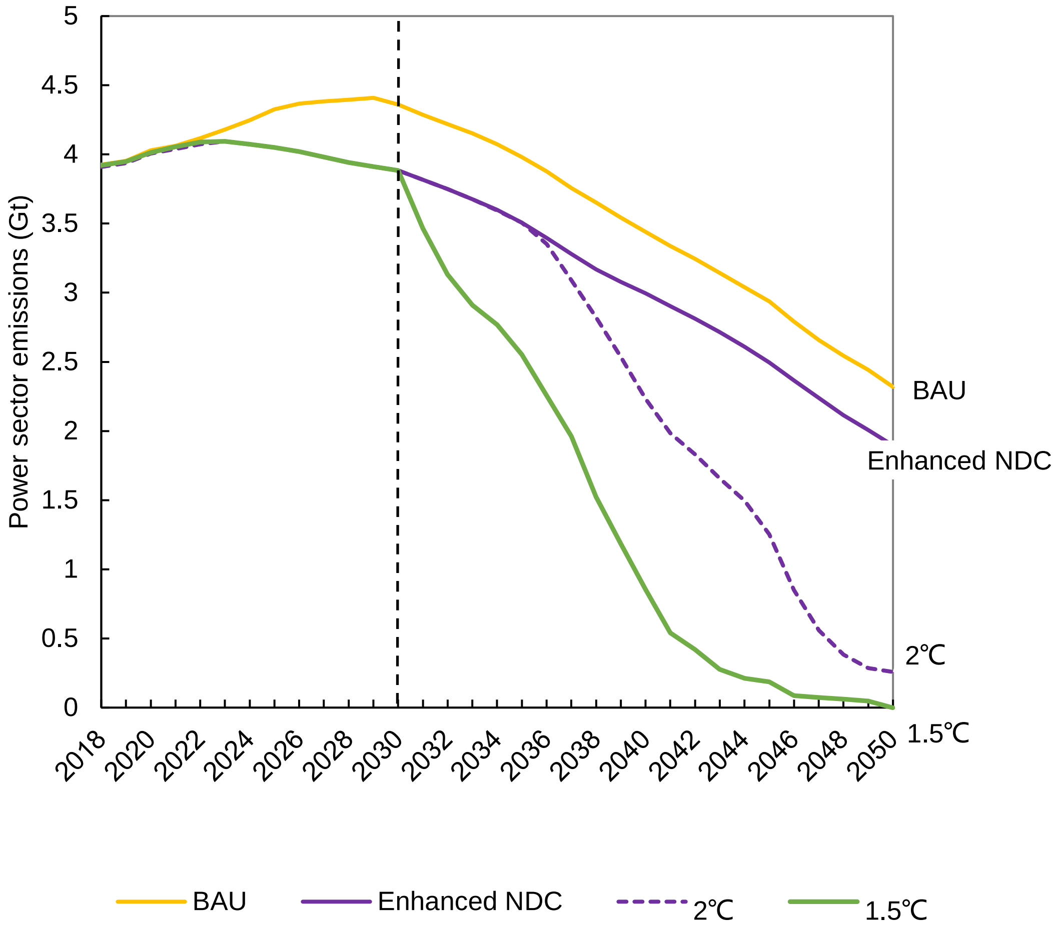


Carbon emission trajectories: 1.5D

- Policy scenario and enhanced policy scenario both cannot realize 2D temperature control target
- In 2DS, the delay-action pathway has a very sharp drop of emissions. In contrast, the early-action pathway saves sufficient reduction space for post-2030.
- In 1.5DS, power sector has reached net-zero emissions since 2046.



2050 capacity mix

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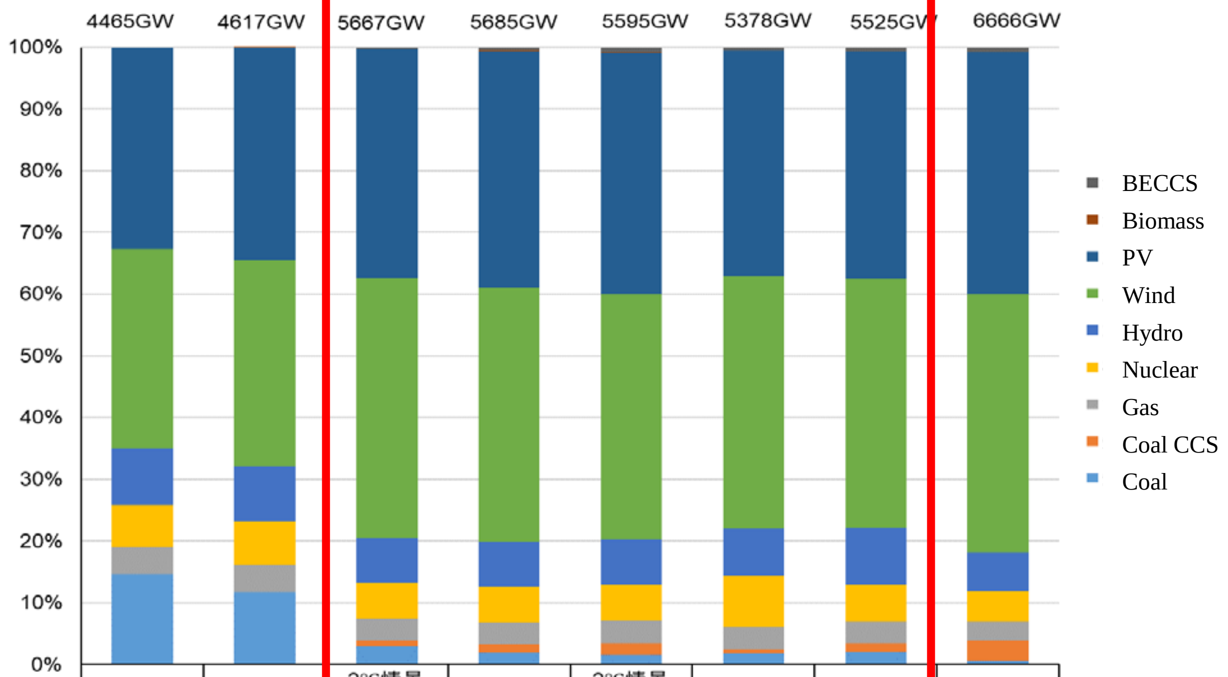
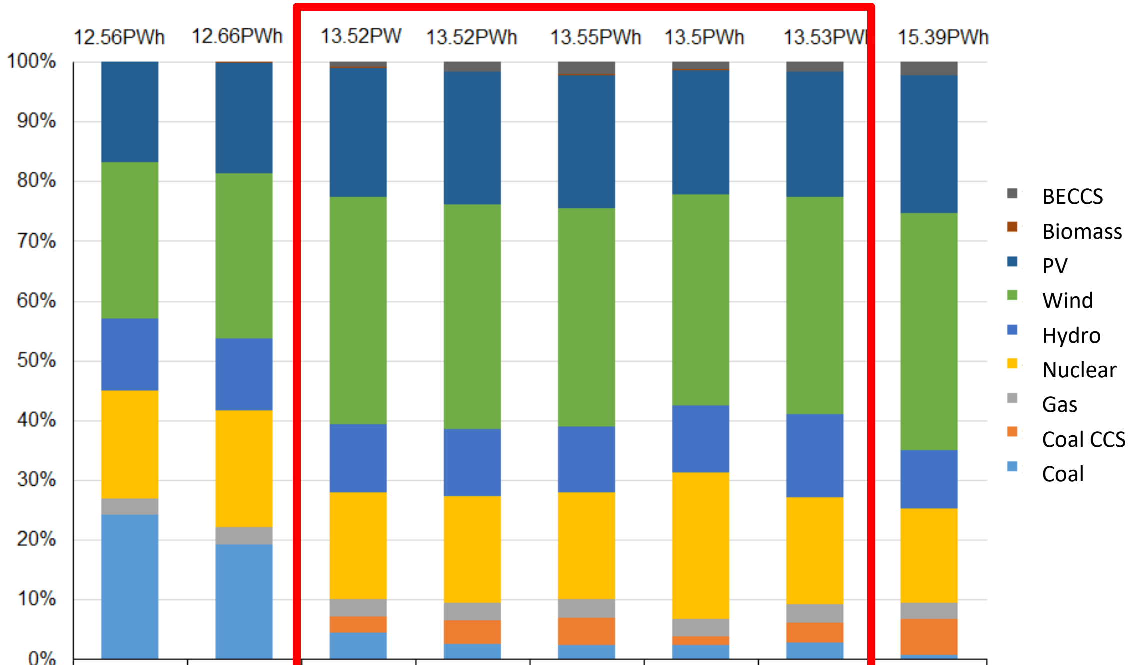


		政策情景	强化减排情景	2°C情景（提前减排）	2°C情景	2°C情景（延后减排）	2°C情景（高核电）	2°C情景（高水电）	1.5°C情景
BECCS	生物质CCS	0	0	15	33	45	27	34	53
Biomass	生物质发电	0	3	4	3	8	4	2	0
PV	太阳能发电	1459	1592	2100	2182	2187	1965	2035	2611
Wind	风电	1444	1539	2381	2336	2223	2194	2231	2790
Hydro	水电	410	412	414	414	410	414	508	420
Nuclear	核电	301	327	327	327	327	445	327	327
Gas	气电	200	200	200	200	200	200	200	200
Coal CCS	煤电CCS	0	0	60	83	104	31	74	230
Coal	煤电	651	544	166	108	90	98	113	35

2050 capacity mix

- 2050 capacity
  - Total capacity range：4000-6000GW
  - Non-fossil share:80.9%, 83.9%, 93.1% and 93%
  - VRE share:65%, 67.8%, 79.5% and 81%
- Residual coal capacity
  - Policy：500-600GW
  - 2DS：100GW
  - 1.5DS：tiny
- BECCS and coal+CCS
  - CCS is essential for coal power
  - Trade-off between BECCS and coal power

2050 power generation mix



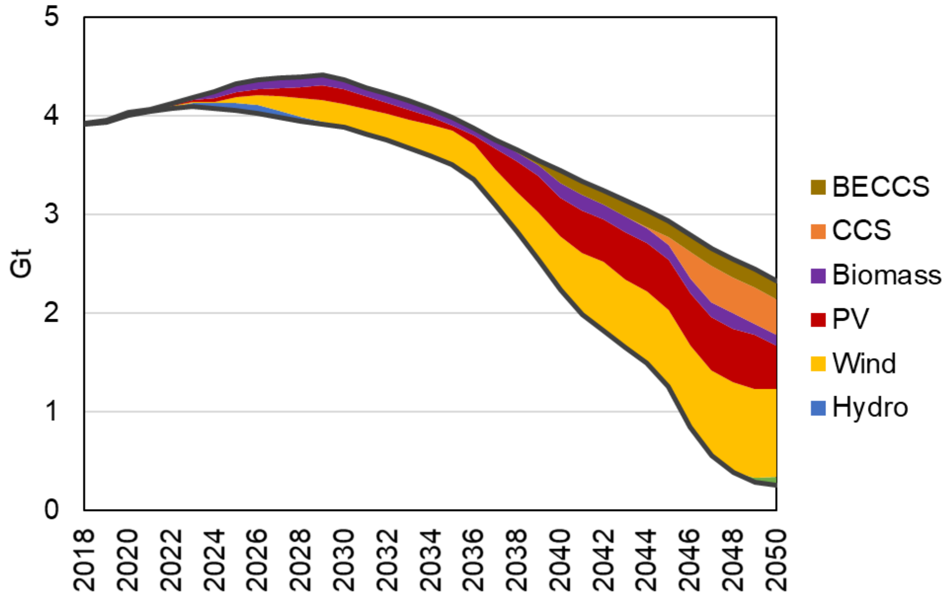
		政策情景	强化减排情景	2°C情景（提前减排）	2°C情景	2°C情景（延后减排）	2°C情景（高核电）	2°C情景（高水电）	1.5°C情景
BECCS	生物质CCS	0	0	0.09	0.20	0.26	0.16	0.21	0.33
Biomass	生物质发电	0	0.02	0.03	0.02	0.05	0.03	0.01	0.002
PV	太阳能发电	2.09	2.33	2.93	3.00	2.99	2.81	2.81	3.56
Wind	风电	3.29	3.51	5.14	5.09	4.98	4.75	4.93	6.10
Hydro	水电	1.52	1.53	1.53	1.50	1.49	1.52	1.86	1.51
Nuclear	核电	2.26	2.45	2.42	2.42	2.42	3.30	2.42	2.42
Gas	气电	0.35	0.37	0.38	0.40	0.41	0.40	0.41	0.40
Coal CCS	煤电CCS	0	0	0.37	0.51	0.62	0.20	0.46	0.92
Coal	煤电	3.04	2.45	0.62	0.38	0.33	0.34	0.39	0.14

2050 generation mix

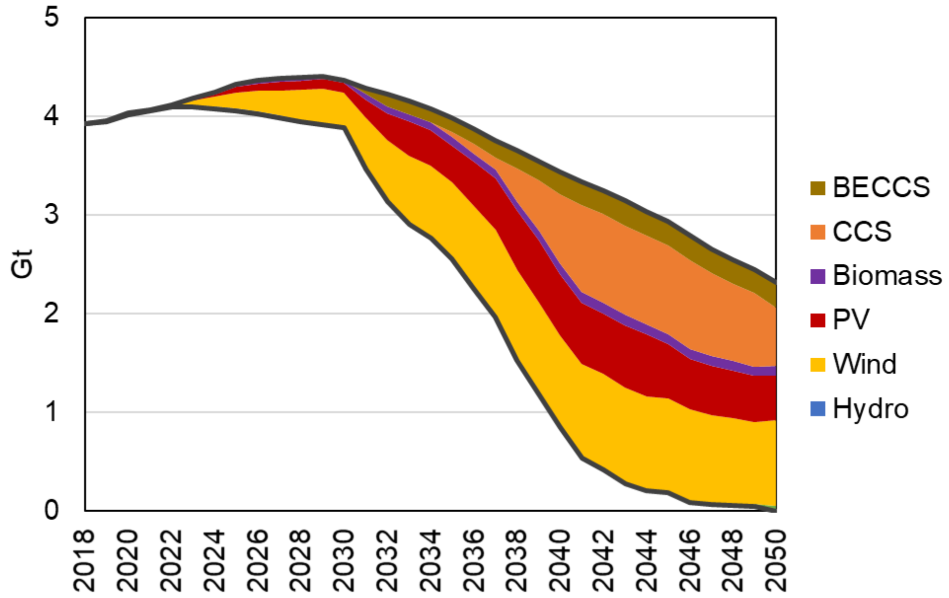
- 2050 Generation
  - Non-fossil share: 73%, 73%, 91% and 91%
  - VRE share: 43%, 46%, 60% and 63%
- In 2DS, VRE share is very high (56%-60%) in 2050, raising big challenges for system balance and grid flexibility.

CCS is inevitable

- Renewables, coal+CCS and BECCS will play the key role
- In 2DS, capacity of coal+CCS and BECCS in 2050 will be 83GW and 33GW. The captured CO_2 will reach 0.39Gt and 0.19Gt.
- In 1.5DS, capacity of coal+CCS and BECCS in 2050 will be 230GW and 53GW. The captured CO_2 will reach 0.71Gt and 0.31Gt.



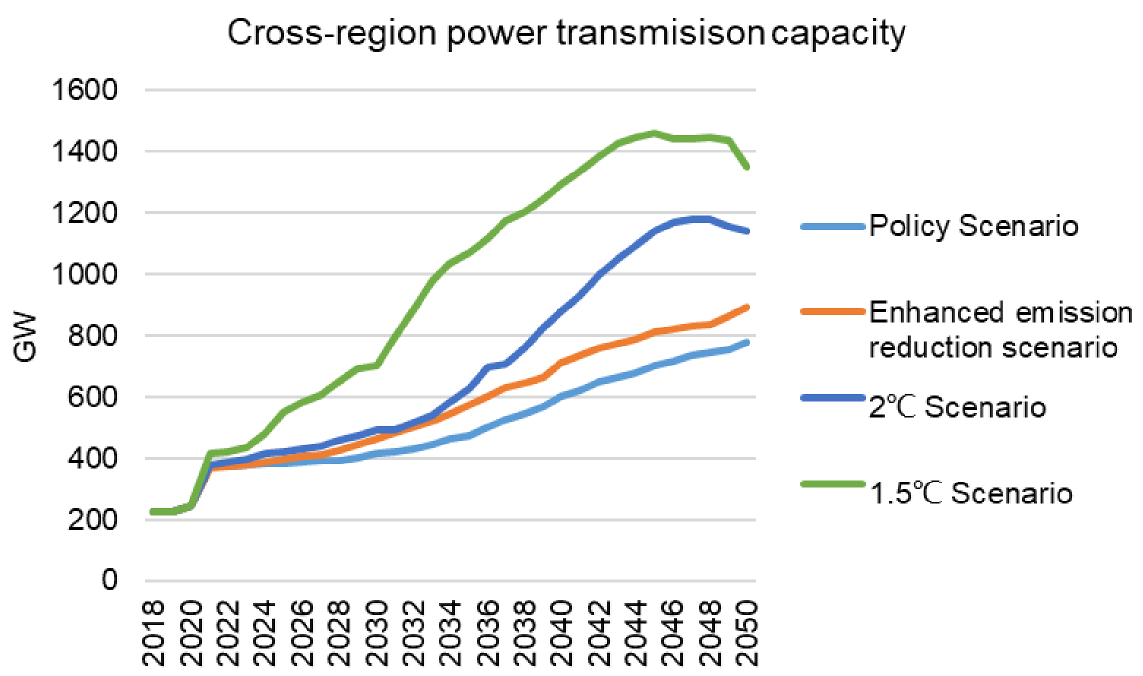
BAU vs 2°C

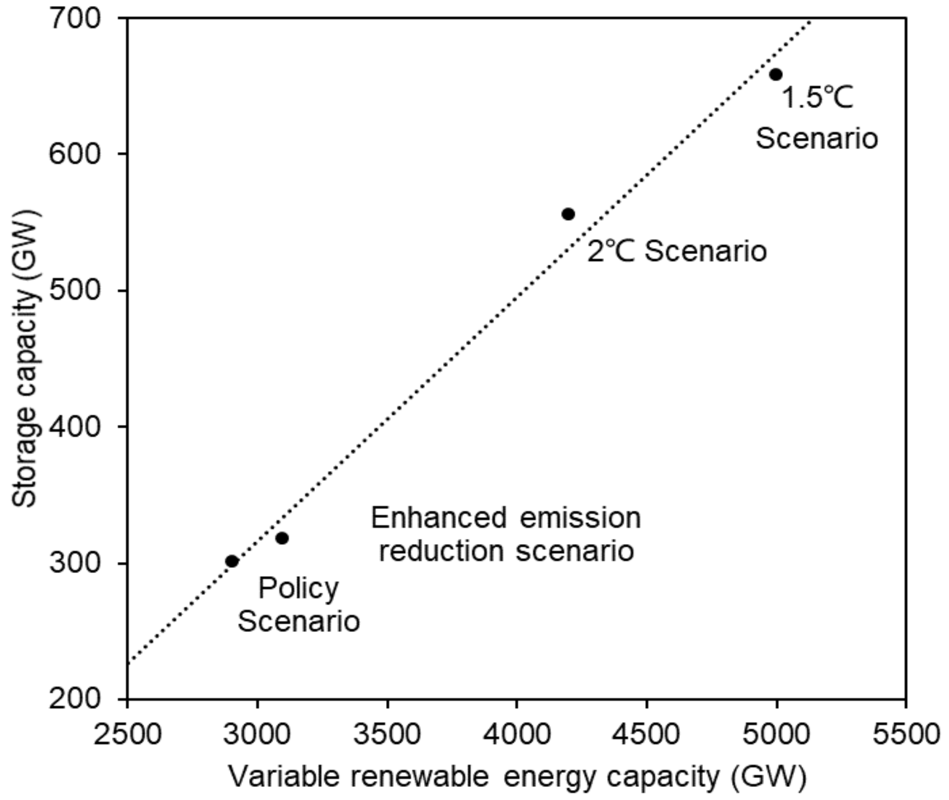


BAU vs 1.5°C

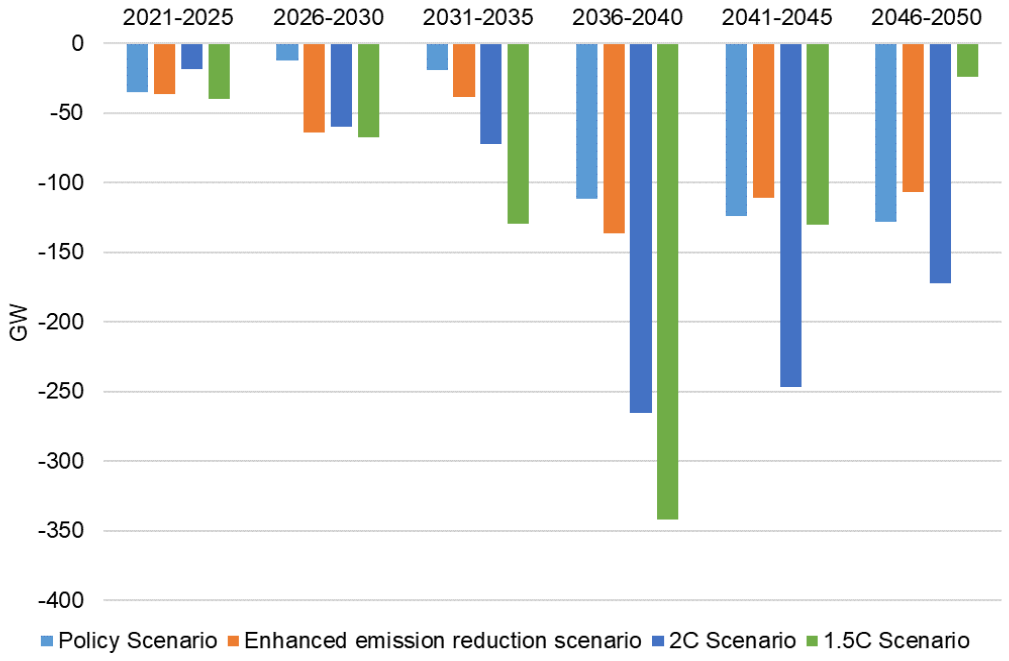
Long distance Power transmission & power storage

- **Investments:** Cross-region power transmission and energy storage capacity would increase.

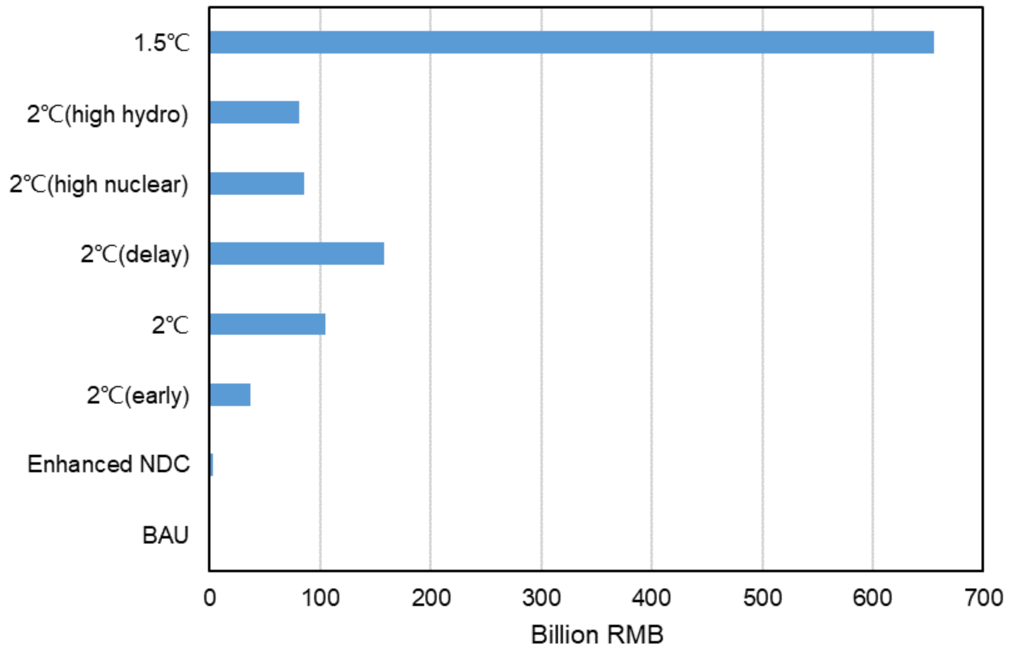




Big economic loss due to early retirement of coal plants



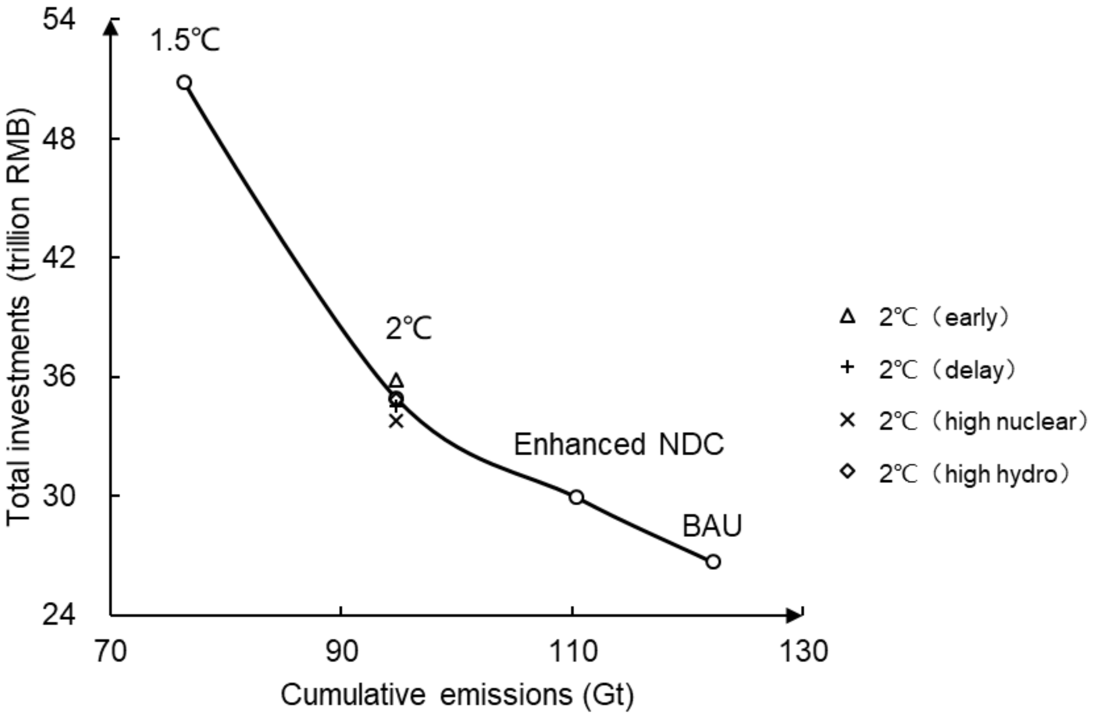
Coal power retirement plan



Stranded cost

- With stricter climate targets, coal plants decommissioning scale increases and the decommissioning time is earlier.
- Implication: building new coal power plants should be very cautious.

Investments

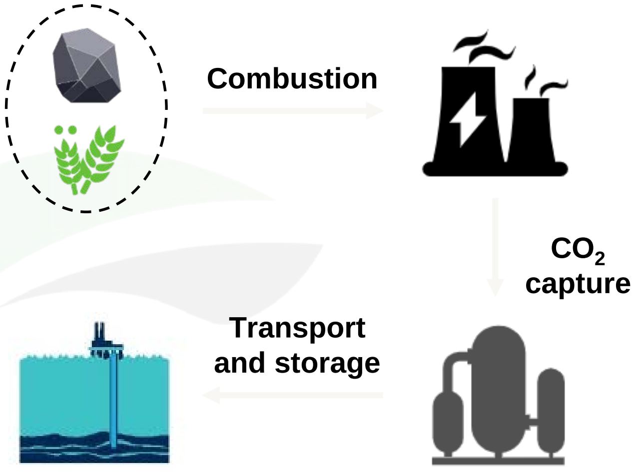


- Compared to Policy Scenario, investments in Enhanced NDC, 2DS and 1.5DS will increase by 12%, 31% and 90%
- In 2DS and 1.5DS, the annual incremental investment is 1058.5 and 1539.1 billion RMB, equivalent to 1.3 and 1.9 times of 2018 investment.
- There is no significant differences in the investment of different pathways in 2DS. It is acceptable that emission reduction action is deployed in advance.

Further thoughts on coal power: PBECCS

- **PBECCS**: Partial Bioenergy Carbon Capture and Storage
  - Co-firing up to 20% carbon neutral biomass with coal
  - Could reach negative emission when combined with CCS
  - Solution to solve the emission and stranded value dilemma

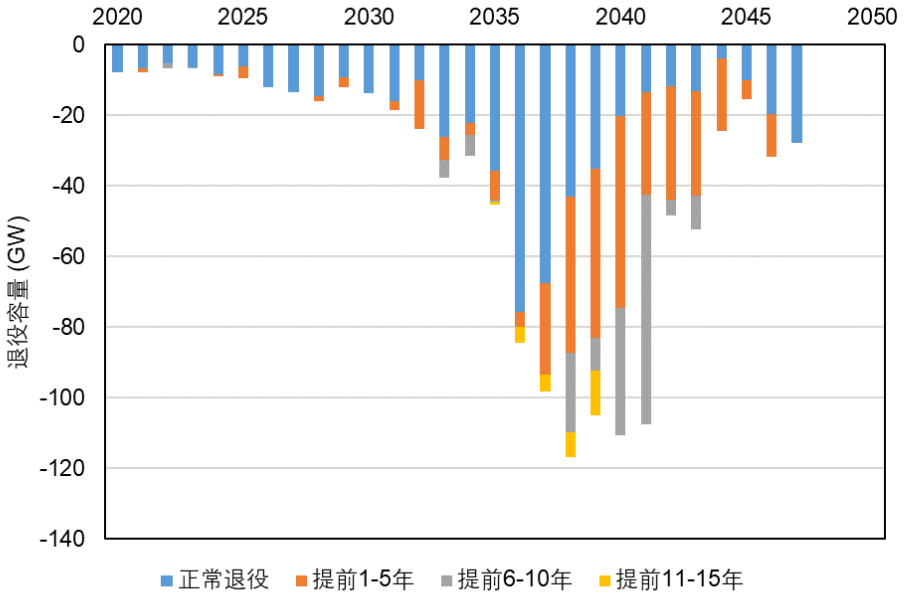
- **Scenario analysis**
  - Baseline scenario: equivalent to the above-mentioned 1.5DS
  - PBECCS scenario: PBECCS technology is introduced



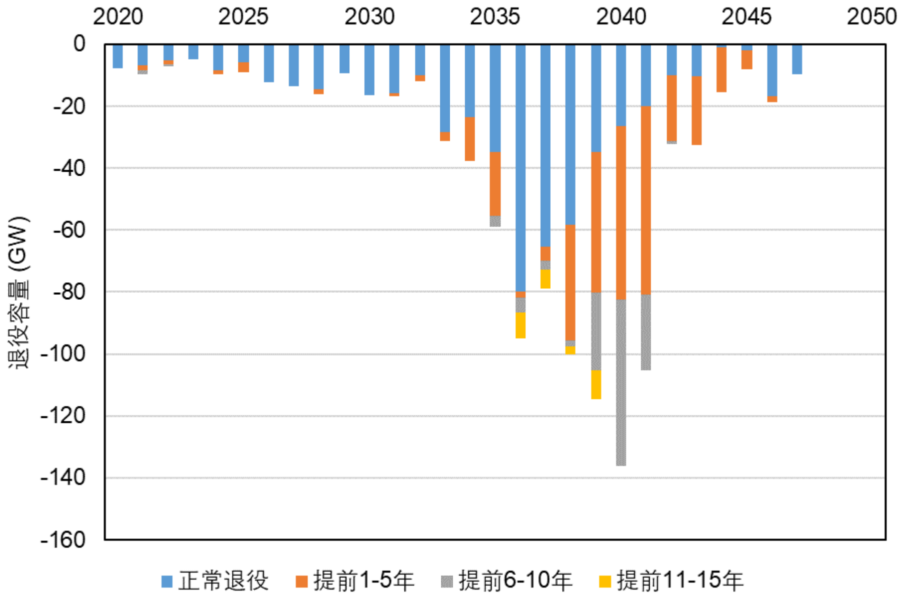
PBECCS diagram

Results comparison: less pre-mature retirement

- **Early-retired capacity：** 539GW → 467GW
- **Average lifetime：** 27.88y → 28.07y
- **2050 capacity：** 265GW → 351GW
- **Stranded cost：** 655.1 billion → 577.3 billion



Baseline



PBECCS

Results comparison: less wind, PV and storage

- **2050 wind capacity：** 2790GW → 2711GW
- **2050 PV capacity：** 2611GW → 2287GW
- **2050 storage capacity：** 1417GWh → 1339GWh

Comparison of wind, PV and storage between two scenarios

	Baseline	PBECCS
2050 wind capacity（GW)	2790	2711
2020-2050 annual addition（GW/y)	86	83
2050 PV capacity（GW)	2611	2287
2020-2050 annual addition（GW/y)	80	69
2050 storage capacity（GWh)	1417	1339

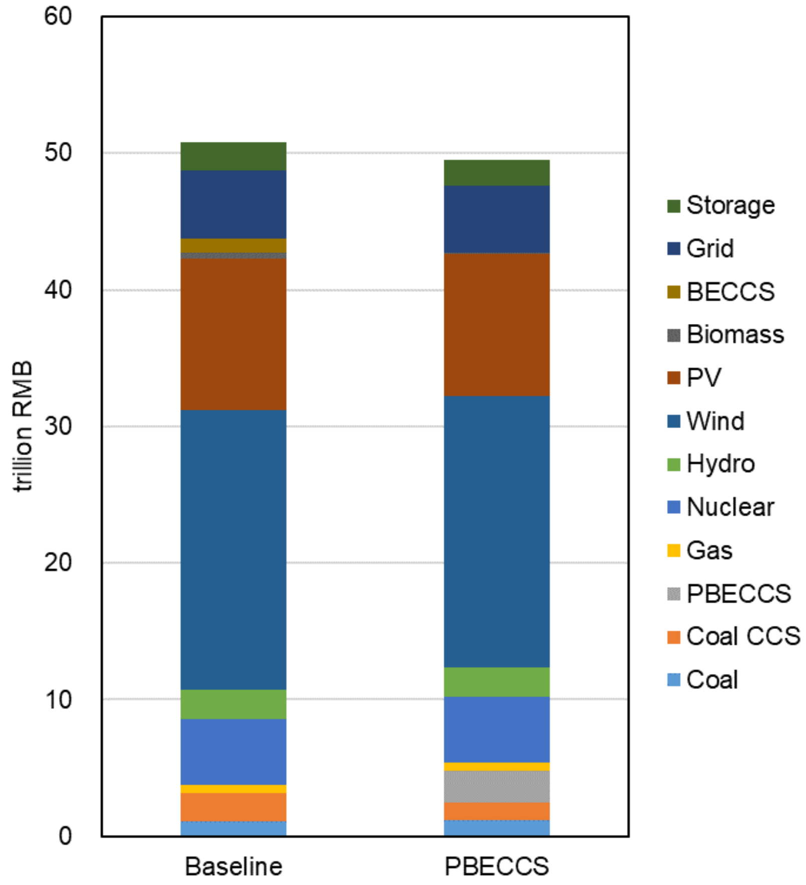
Results comparison: lower flexibility demand

- **2050 VRE share**： 62.8% → 59.1%
- **PBECCS scenario**: lower VRE share causes lower flexibility demand of power system, which increases the possibility of transition pathway.

Comparison of VRE share between two scenarios

	2025	2030	2035	2040	2045	2050
Baseline	22.0%	31.1%	44.3%	54.7%	60.5%	62.8%
PBECCS	23.1%	31.9%	42.7%	52.2%	57.0%	59.1%

Results comparison: lower investments



Comparison of investments between two scenarios

- **Coal-related investment:**

  1.6 trillion+

- **Wind, PV and storage investment:**

  2.8 trillion -

- **Total investment:**

  50.79 trillion → 49.49 trillion RMB

  reduced by 2.6%

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Policy recommendations

- **Continuous expansion of renewable energy**
  - Supportive policies and incentives for the renewable energy industry should be formulated to ensure the speed of renewable energy expansion.
  - Inter-regional power transmission should be promoted to guarantee the regional matching of resource and demand.
  - Research and development of grid-related technologies should be actively deployed to ensure the stable operation of power grids.
- **Orderly phase-out of coal power**
  - Additional coal-fired power plants should be strictly controlled and an orderly phase-out mechanism for existing coal-fired power plants should be established.
  - The reemployment of coal industry workers should be properly guided to reduce economic and social risks.
- **Acceleration of CCS and PBECCS deployment**
  - More efforts should be put into R&D of CCS/PBECCS to get ready for the large-scale deployment.
- **Guarantee of required investment**
  - The green investment and financing mechanisms need to be established and improved to support China's power sector decarbonization as soon as possible.

Many Thanks！

Q & A