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Sizing renewable power plant in a hydro-based hybrid generation system

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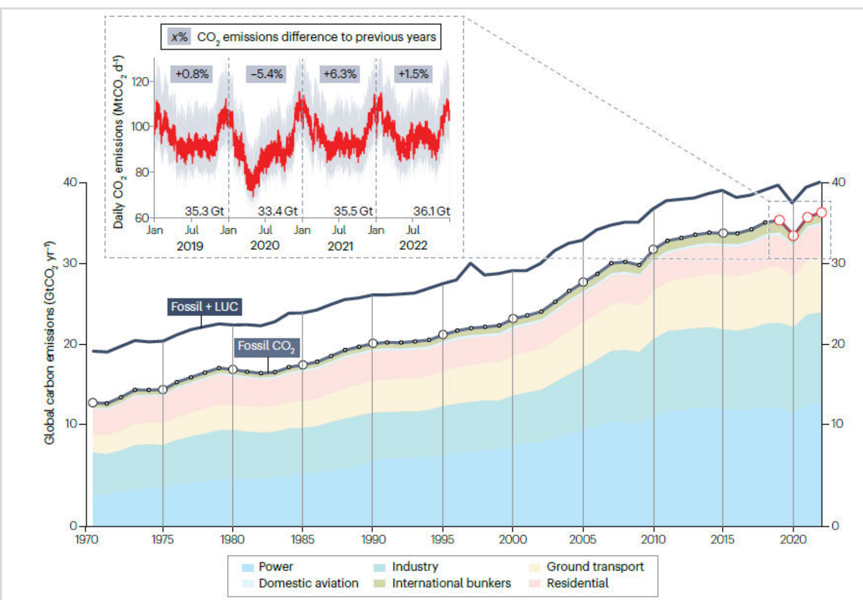
Outline

1. *Background*
2. *Techno-economic analysis framework*
3. *Long- and short -term nested operation model*
4. *Case study*
5. *Results and discussion*
6. *Summary*

1 Background: global carbon emissions

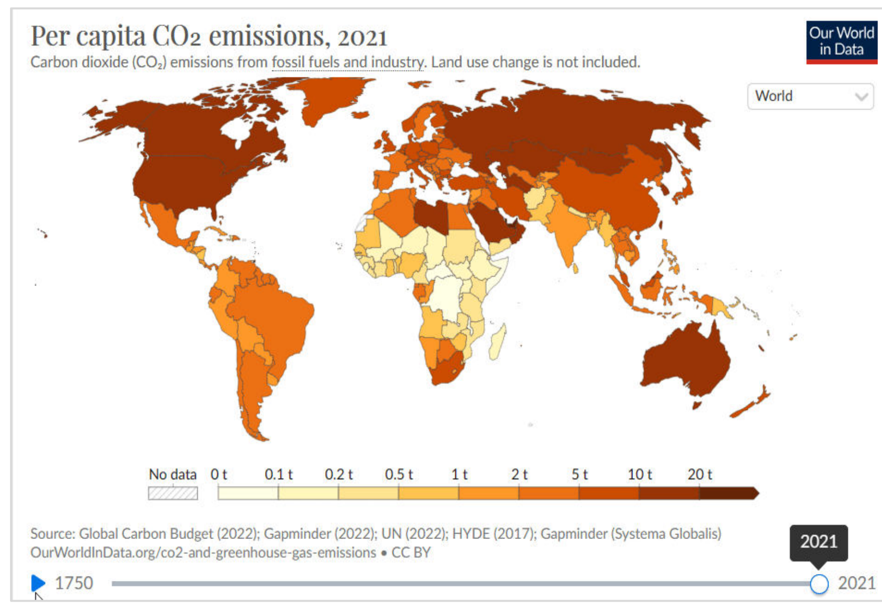
- In 2022, global CO_2 emissions from fossil fuel combustion and cement production reached 36.1 ± 0.3 billion tons.
- Power accounted for 39.3% of the CO_2 emissions total, industry 28.9%, ground transportation 17.9%, residential 9.9%, and others 10%.

Global CO_2 emissions 1970–2022



[by Liu Zhu et al.2023, Nature reviews earth & environment]

Per capital CO_2 emissions 1750–2021

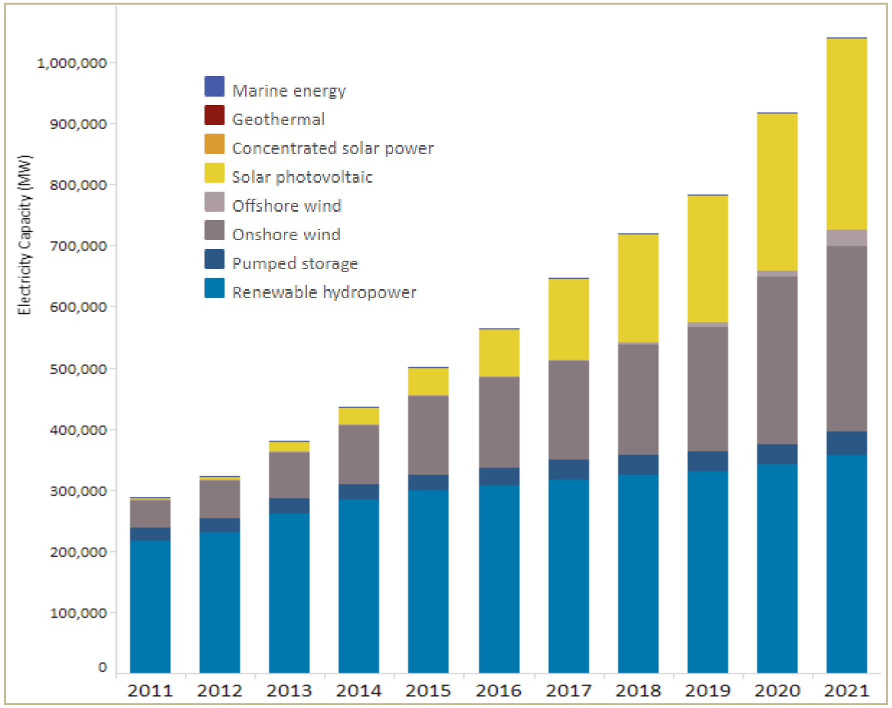


[**Source**: *https://ourworldindata.org/co2-emissions*]

1 Background: clean energy development

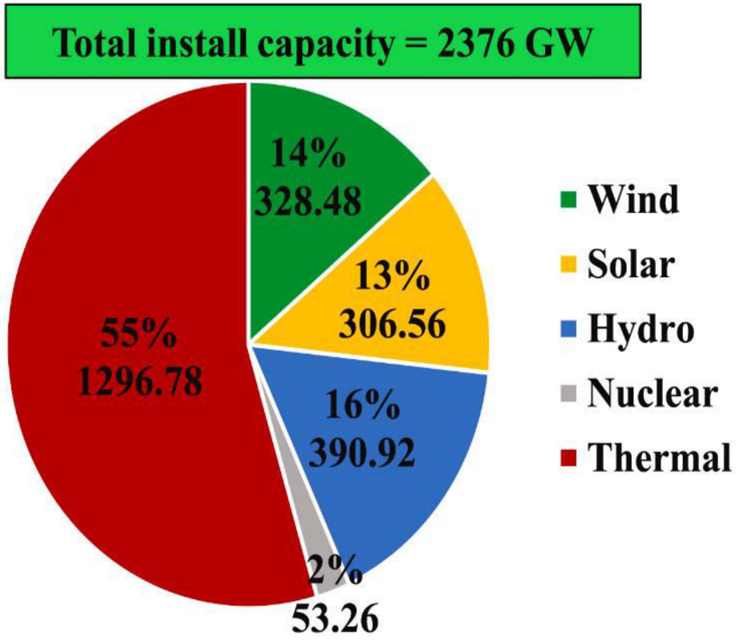
- China proposed Carbon Peaking and Carbon Neutrality goals in 2020, namely, achieving peak carbon before 2030 and carbon neutrality in 2060.
- To achieve the carbon neutrality goal, a new power system dominated by clean energy (e.g., hydro, solar, and wind) should be constructed.

Electricity capacity trend (2011-2021)



[**Source:** *https://www.irena.org/Energy-Transition/Technology/Solar-energy*]

Installed capacity of different power sources in China (2021)



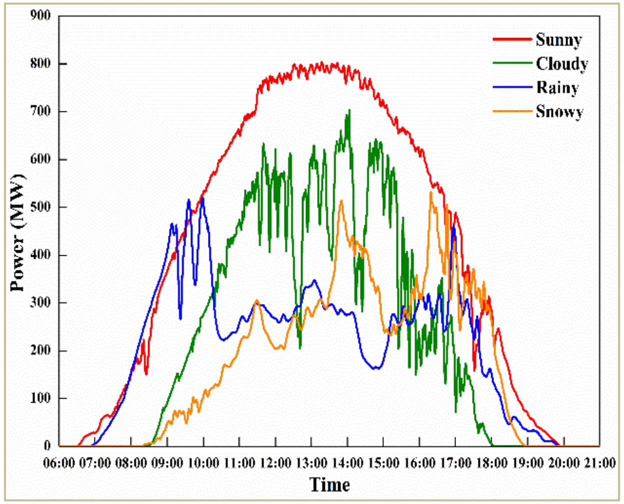
[by Zhang et al.2022, Energy]

1 Background: Hybrid generation system (HGS)

- However, high penetration of renewables may lead to high risk of electricity curtailment rate and low power supply reliability for the power system.

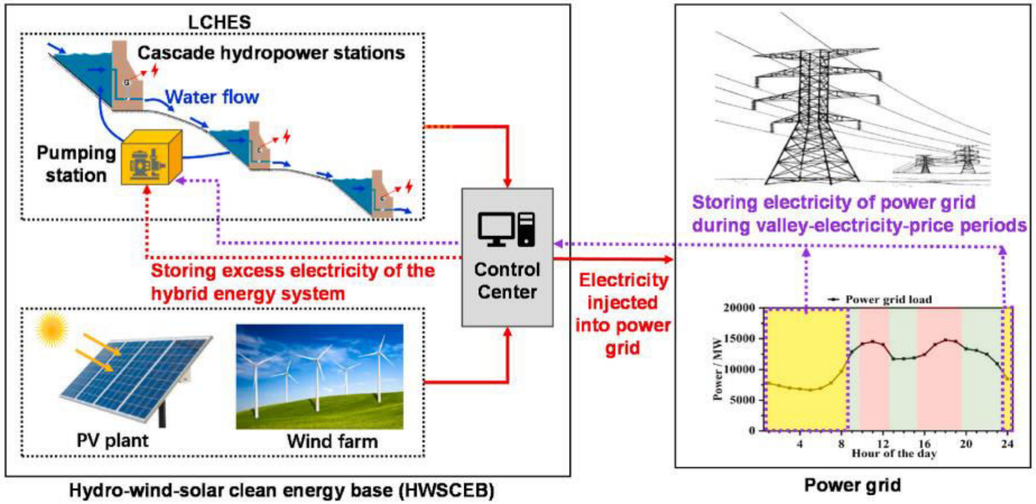
- Taking advantage of the flexible hydropower and complementary aspects of the resources, complementary management of wind, solar and hydropower is an effective way to improve the energy use efficiency.

Power output fluctuation



[by Ma et al., 2019, Applied Energy]

Hydro-based hybrid generation system



[by Zhang et al., 2022, Energy]

1 Background: Capacity configuration of the HGS

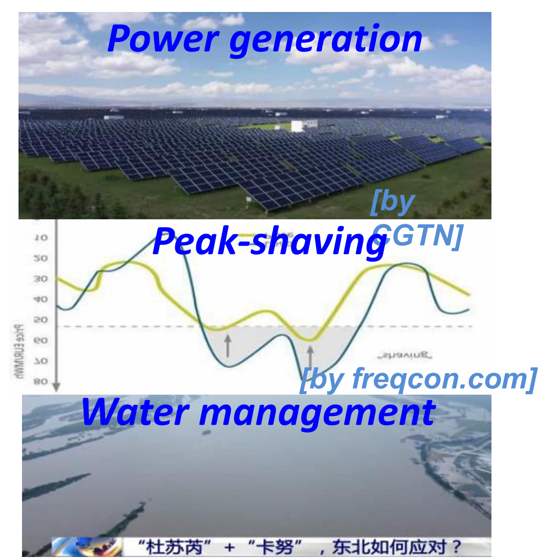
- **Capacity configuration of the HGS plays a critical role in increasing the synergy between different power sources.**

- **The capacity configuration process itself relies on system operation simulation during the techno-economic analysis.**

- **However, accurately simulating the operation of the HGS over their lifespan is challenging due to following reasons:**

(1) Coordinate multiple objectives covering different timeframes, such as long-term water management and short-term renewable accommodation.

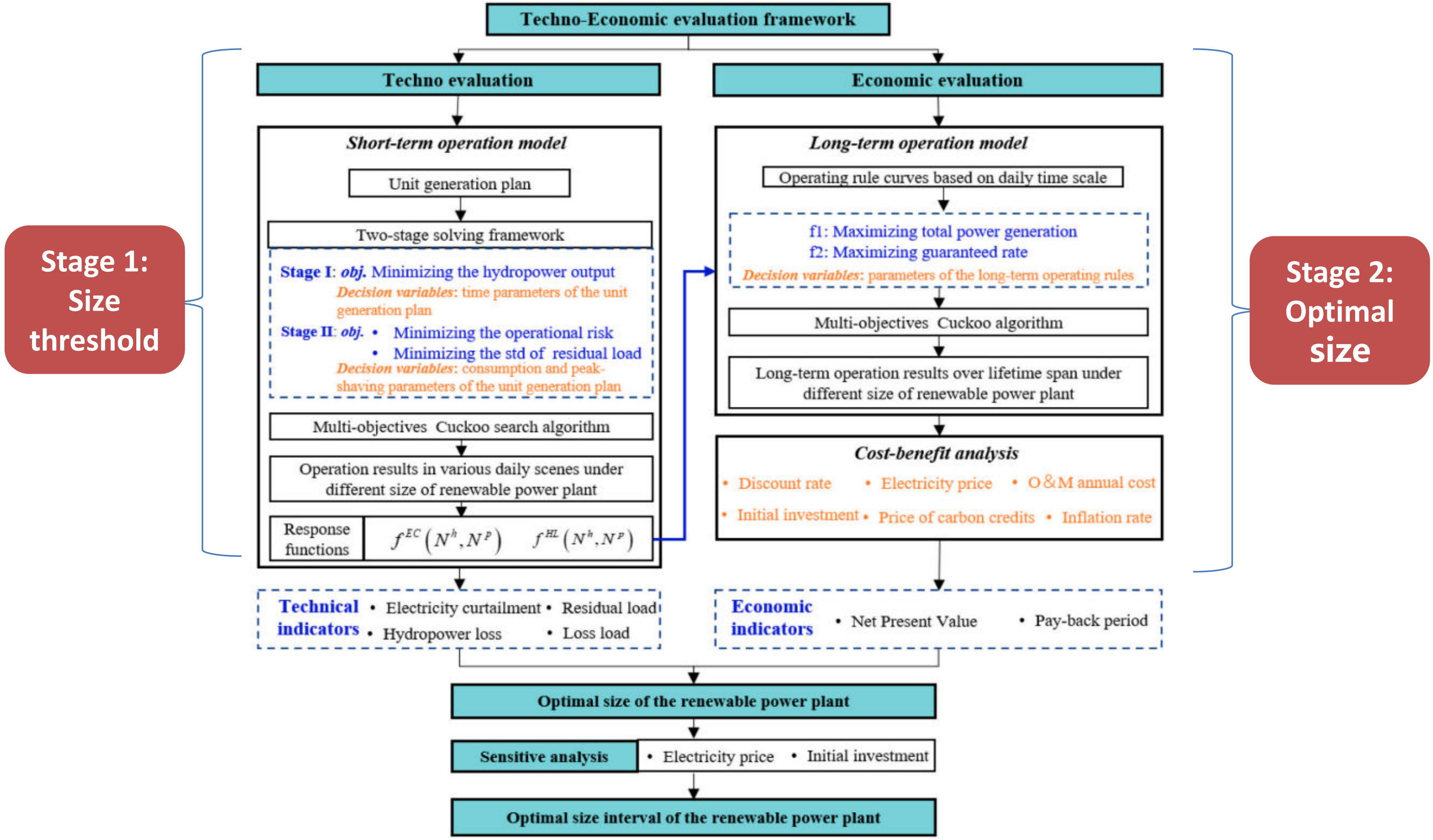
(2) Solve complex nonlinear optimization model with millions of decision variables.



[by CCTV, 2023]

2 Techno-economic analysis framework

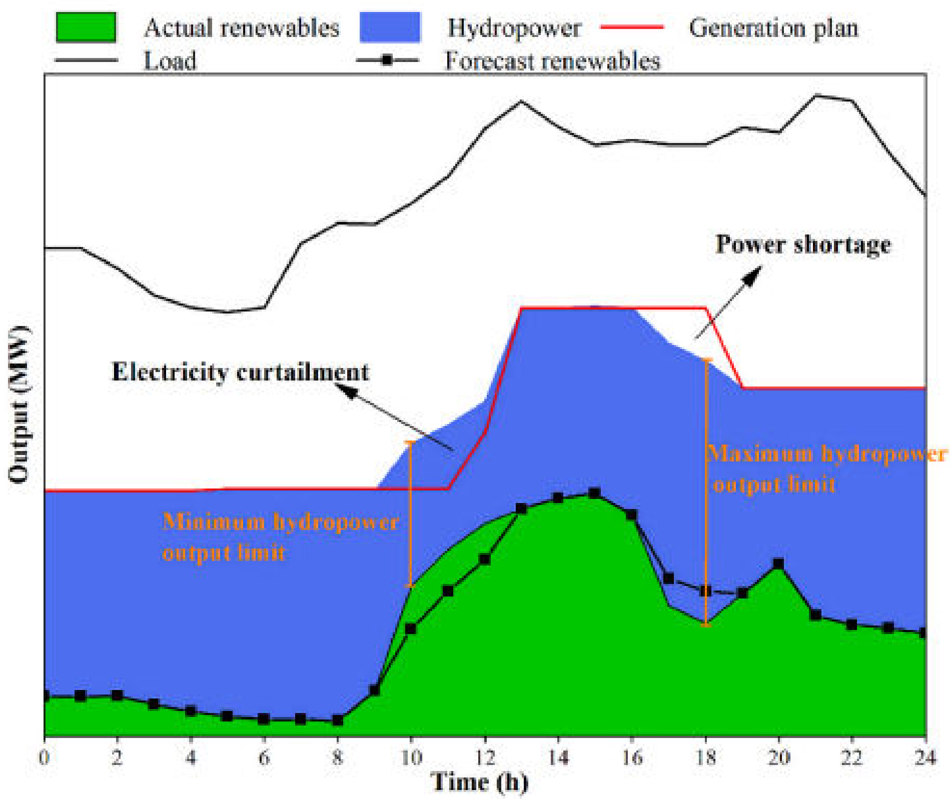
A two-stage sizing framework based on techno-economic analysis



2 Techno-economic analysis framework

Technical evaluation

Daily generation plan of the HGS



[by Jiang et al. 2023, Renewable Energy]

Electricity curtailment rate (EC)

$$\mathrm{EC}(x) = \frac{1}{T}\sum_{t=1}^{T}\frac{N_t^{\mathrm{h}} + N_{t,x}^{\mathrm{p}} - N_t^{\mathrm{plan}}}{N_{t,x}^{\mathrm{p}}}, \quad N_{t,x}^{\mathrm{plan}} < N_t^{\mathrm{h}} + N_{t,x}^{\mathrm{p}}$$

Load Loss rate

$$\mathrm{LR}(x) = \frac{1}{T}\sum_{t=1}^{T}\frac{N_t^{\mathrm{plan}} - N_t^{\mathrm{h}} - N_{t,x}^{\mathrm{p}}}{N_{t,x}^{\mathrm{plan}}}, \quad N_{t,x}^{\mathrm{plan}} > N_t^{\mathrm{h}} + N_{t,x}^{\mathrm{p}}$$

Hydropower loss rate

$$\mathrm{HL}(x) = \frac{\sum_{t=1}^{T} N_t^{\mathrm{h}}}{\sum_{t=1}^{T} N_t^{\mathrm{h'}}} = \frac{\sum_{t=1}^{T} kQ_t^{\mathrm{e}}h_t}{\sum_{t=1}^{T} k\cdot min\left[Q_t^{\mathrm{e}} + Q_t^{\mathrm{spi}}, Q^{\mathrm{e},max}\right]h_t}$$

Standard deviation of the residual load

$$\begin{cases} \mathrm{RL}(x) = \mathrm{std}(L^{\mathrm{re}}) = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(L_{t,x}^{\mathrm{re}} - \overline{L_{\mathrm{x}}^{\mathrm{re}}}\right)^2} \\ L_{t,x}^{\mathrm{re}} = L_{t,x} - N_{t,x}^{\mathrm{plan}} \end{cases}$$

2 Techno-economic analysis framework

Economic evaluation

- The cost-benefit framework includes two economic indicators: **Net Present Value** and **Pay-back period**

Net Present Value Formula

$$\mathbf{NPV} = \Sigma \frac{CF_n}{(1+i)^n} - \text{Initial Investment}$$

(1) Net Present Value of the HGS with x size PV and wind power plant

$$\max_{x \in (0, P_{\max}]} C_{NPV}(x) = \sum_{y=1}^{Y} \frac{\left[B^{p} E^{p}(x,y) + B^{C}(x,y) - B^{h} E^{hl}(x,y) - C^{OM}(x,y)\right](1+d)^{(y-1)}}{(1+d_r)^{y}} - C^{in}(x)$$

$$x^{opt} = argmax(\mathrm{NPV}(x)), x \in [0, P_{\max}]$$

$$\text{Payback Period Formula} = \frac{\text{Initial Investment OR Original Cost of the Asset}}{\text{Cash Inflows}}$$

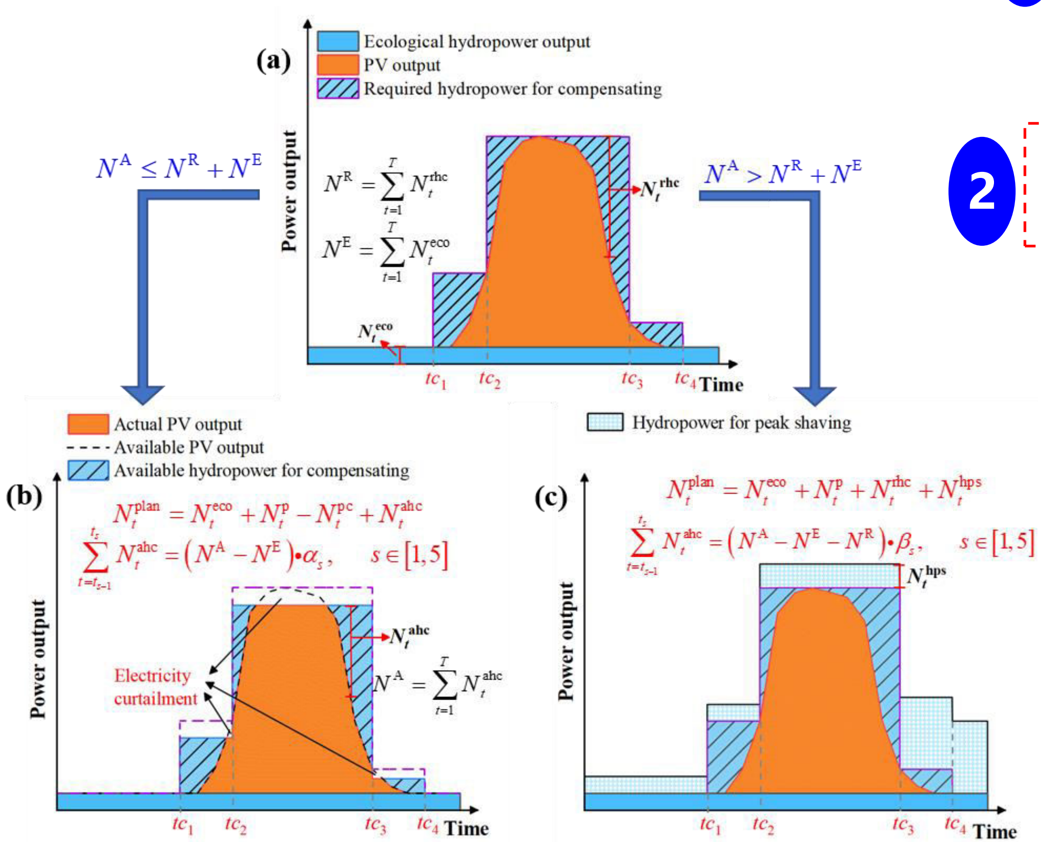
(2) Pay-back Period of the HGS with x size PV and wind power plant

$$\sum_{y=1}^{PBP} \frac{\left[B^{p} E^{p}(x,y) + B^{C}(x,y) - B^{h} E^{hl}(x,y) - C^{OM}(x,y)\right](1+d)^{(y-1)}}{(1+d_r)^{y}} - C^{in}(x) = 0$$

3 Long- and short -term nested operation model

Short-term operation model: unit generation plan

Steps for deriving the UGP



[by Jiang et al. 2023, Applied Energy]

1 Compensate generation curve into a multi-segment shape by time parameters [tc_1,..., tc_4] (Fig. 2(a))

2 Judge: Whether the available hydropower is enough for compensation

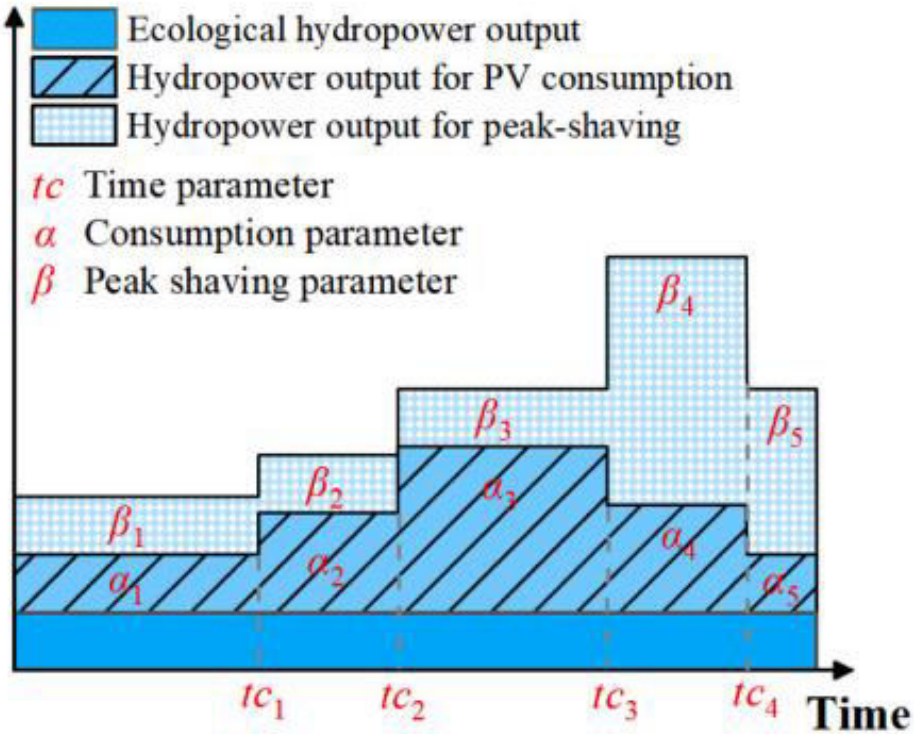
3 No: Distribute available hydropower into each stage by consumption parameters (Fig. 2(b))

4 Yes: Distribute the available hydropower into each stage by peak-shaving parameters (Fig. 2(c))

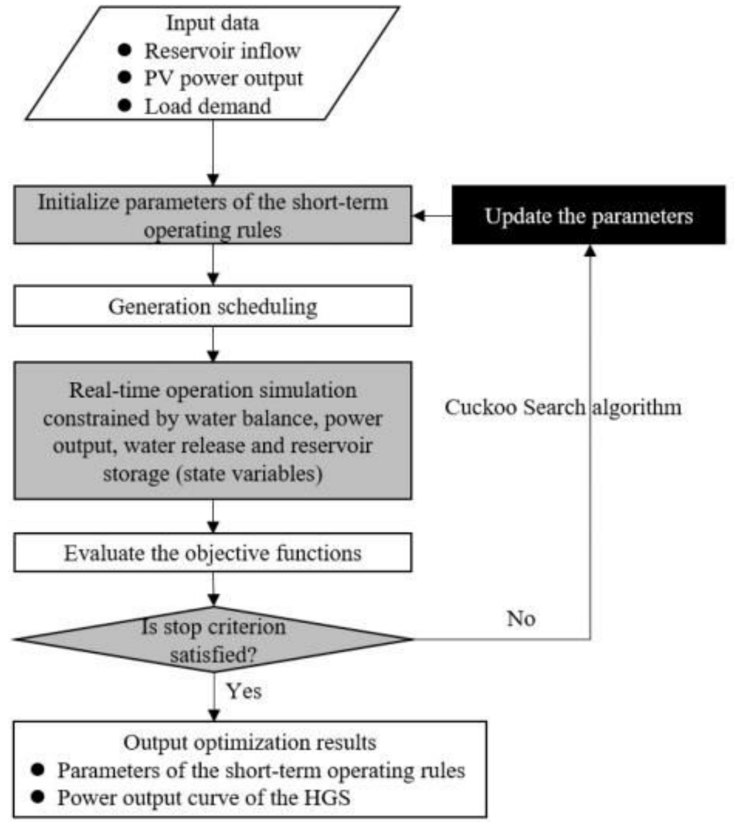
3 Long- and short -term nested operation model

Short-term operation model: solution process

Parameters of the unit generation plan



Flowchart of the short-term optimal operation process

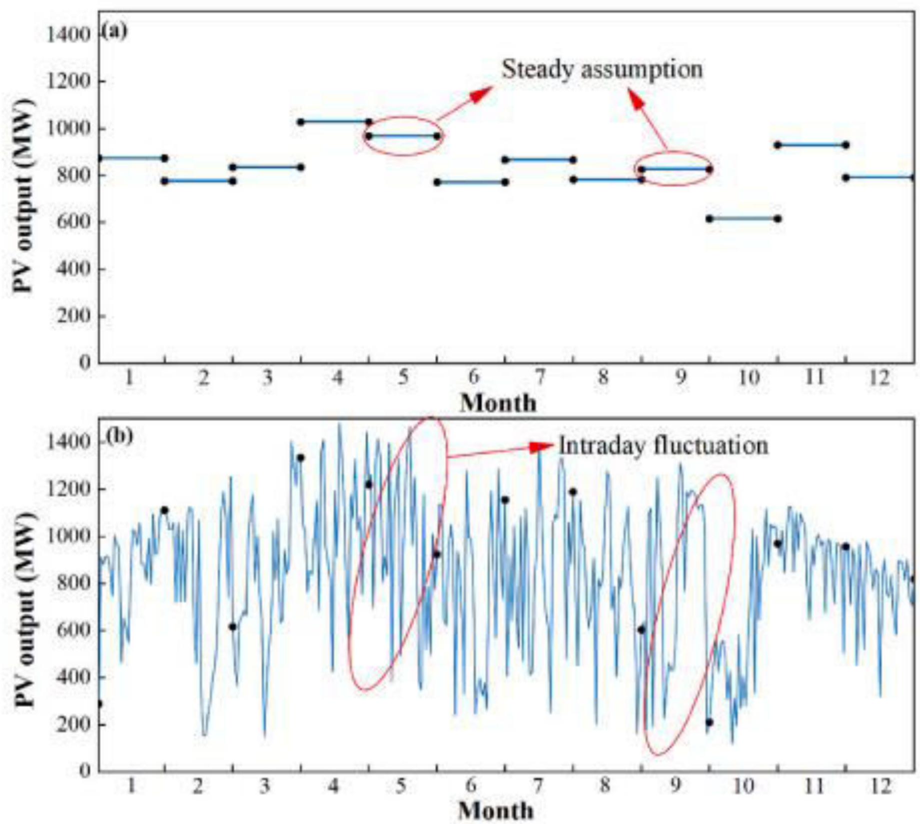


[by Jiang et al. 2023, Applied Energy]

3 Long- and short -term nested operation model

Response functions

Steady assumption of long-term operation



[by Jiang et al. 2023, Renewable Energy]

- **Steady assumption may lead to the overestimation of the generation performance**

Electricity curtailment response function:

$$\mathrm{EC}_t = f^{\mathrm{EC}}\left(N_t^{\mathrm{h}}, N_t^{\mathrm{p}}\right)$$

Electricity curtailment rate ⟷ **response** ⟷ **Hydropower output PV output**

Hydropower loss rate response function.

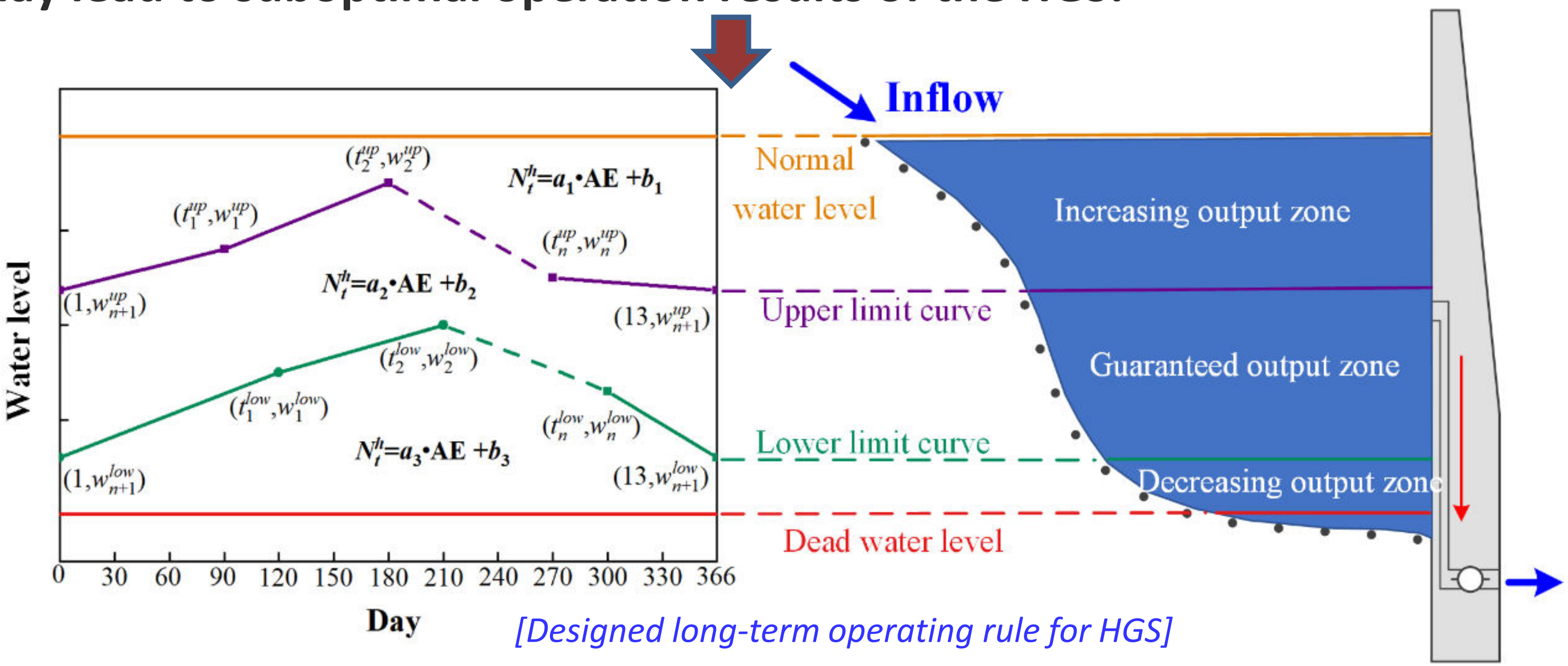
$$\mathrm{HL}_t = f^{\mathrm{HL}}\left(N_t^{\mathrm{h}}, N_t^{\mathrm{p}}\right)$$

Hydropower loss rate ⟷ **response** ⟷ **Hydropower output PV output**

3 Long- and short -term nested operation model

Long-term operation model

- Conventional operating rules without incorporating PV and wind forecasts may lead to suboptimal operation results of the HGS.



[Designed long-term operating rule for HGS]

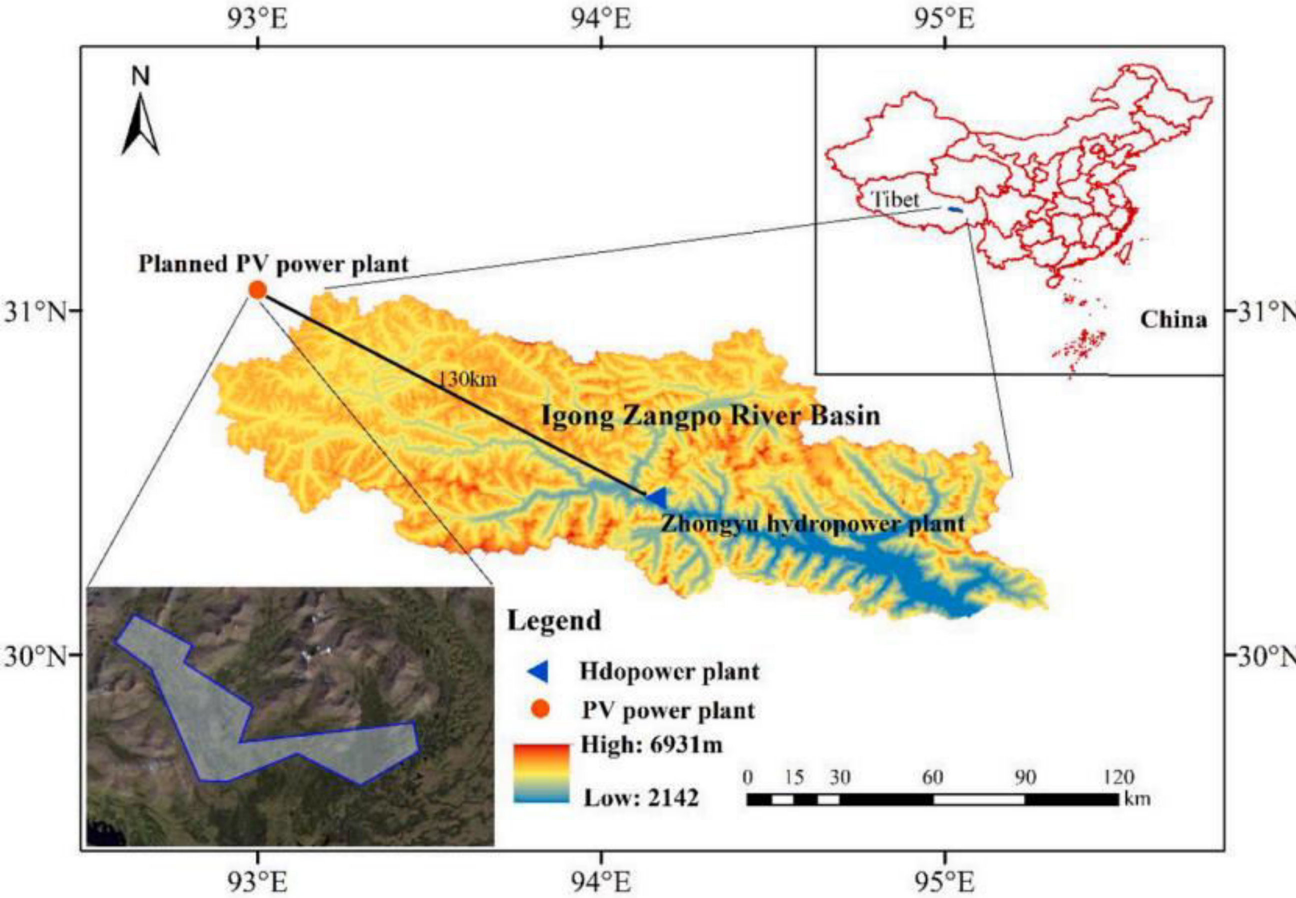
Available energy=
Stored energy + Forecast renewable energy

$$AE_t=\left[\left(V_t-V_{\min}\right)+I_t\Delta T\right]\rho g\overline{H_t}+\left(N_t^p+N_t^w\right)\Delta T$$

Input: Available energy
Output: Hydropower output
Parameters: a, b and key points

4 Case study

Zhongyu hydro–PV HGS

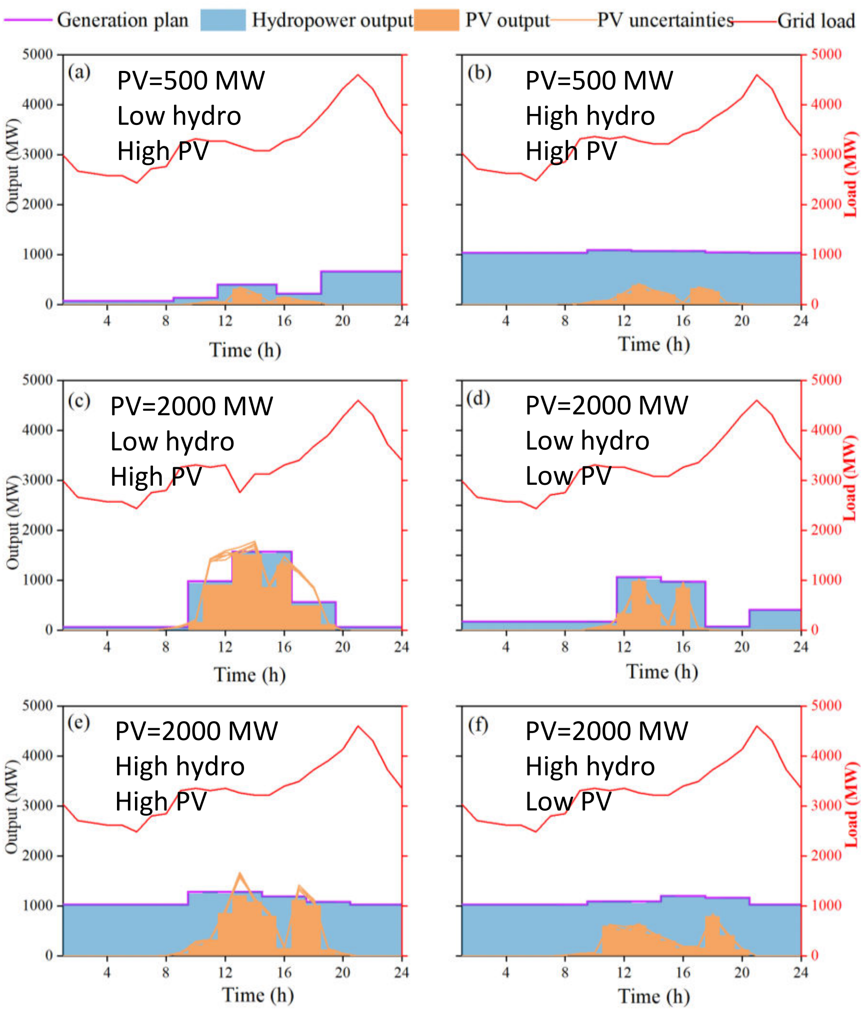


- **Hydropower plant: normal turbine:960 MW ecological turbine: 70 MW**
- **Soar PV plant: maximum installed potential of 5500 MW**
- **EHV DC channel (Lhasa-Zhongyu-Cangdu): 6000 MW**
- **PV power has a higher priority for integration into the power grid compared to hydropower**

5 Results and discussion

Short-term operation results

Daily operation results in six typical scenarios



- **When PV size is low, HGS performs well in minimizing the operational risk (electricity curtailment and power shortage)**
- **As the PV size increased, electricity curtailment and load loss rates increased, due to insufficient hydropower capacity to complement the fluctuations in PV power**

The increase of PV size significantly reduced the consumption level of PV energy

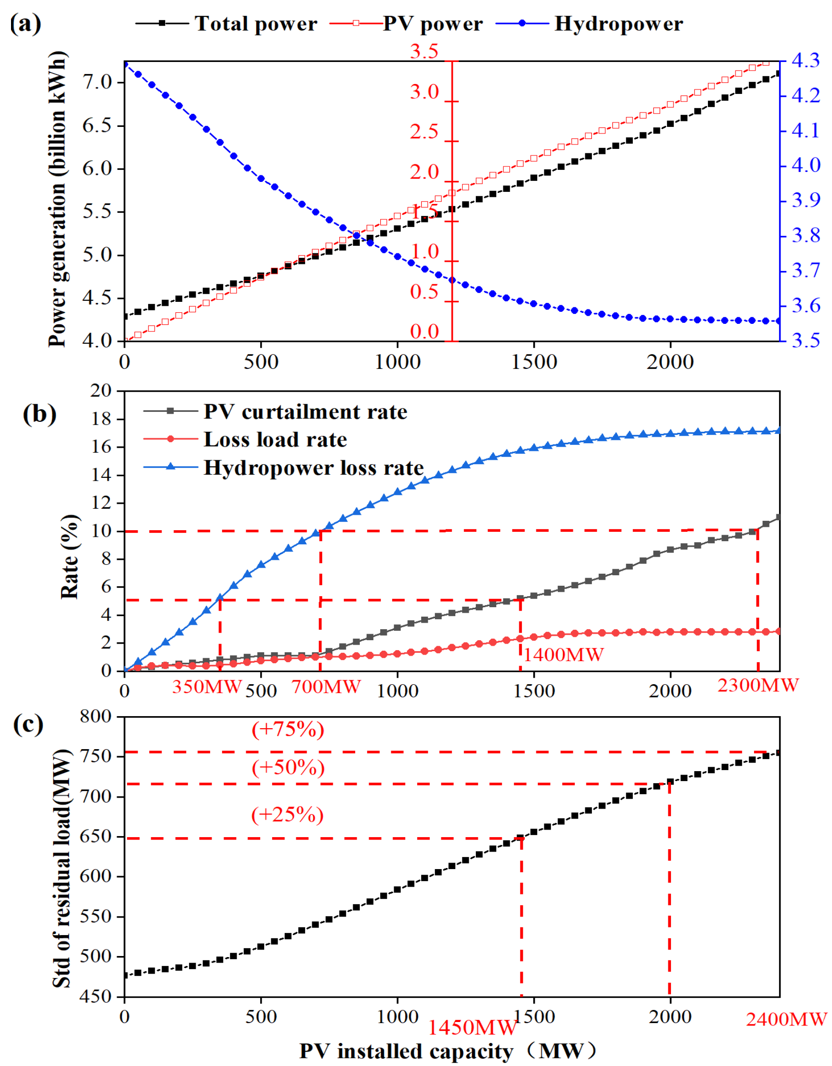
5 Results and discussion

Technical evaluation results

As PV size increased from 0 to 2400 MW

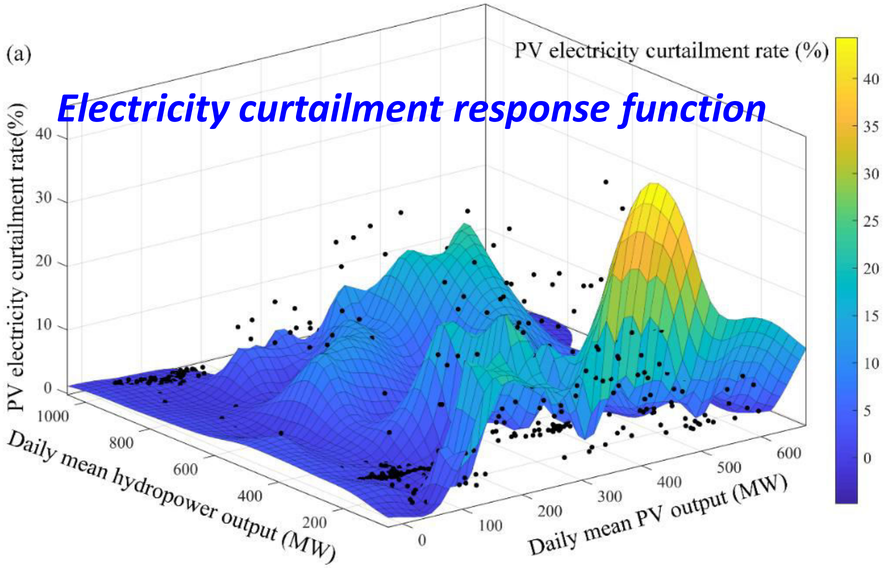
- **Power generation indicators:** PV and total power generation increased but hydropower generation decreased by 17%.
- **Operational risk indicator:** PV curtailment, load loss, and hydropower loss rate all increased, but the hydropower loss rate was significantly higher than the PV curtailment rate.
- **Peak-shaving indicator** : peak-shaving performance decreased by 58.3%

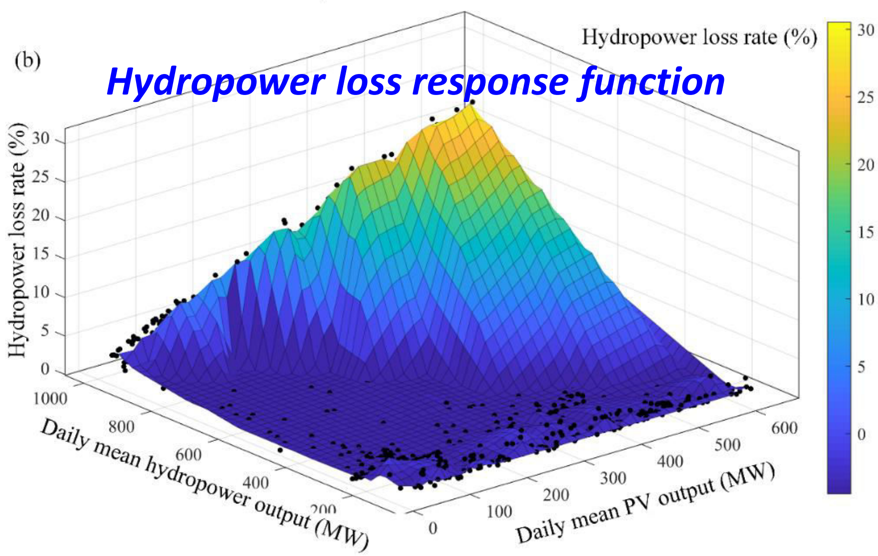
Technical evaluation indicators in all PV size



5 Results and discussion

Multidimensional response functions





- **Low hydropower and high PV power : high PV curtailment rate**

  Flexibility of hydropower plants was insufficient

- **Increased hydropower and decreased PV power reduced PV curtailment rate;**
- **Further increased hydropower resulted in high curtailment rate**

  Due to the limitation of the reservoir storage capacity

- **High hydropower and high PV power output: high hydropower loss rate.**

  Mainly occurred in flood season, indicating that competition existed between hydropower and PV power

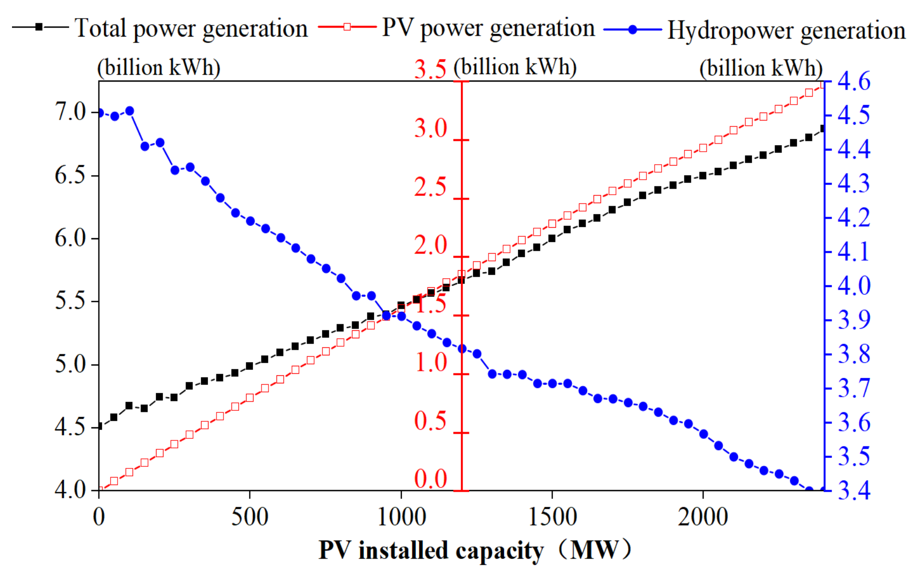
5 Results and discussion

Long-term operation results

- As PV size increased, the PV power generation and total power generation exhibited a significant rise. Conversely, hydropower generation decreased.
- Notably, power generation efficiency of the HGSs declined due to the higher PV curtailment rate and hydropower loss rate associated with larger PV size.

PV size：	0	→	2400MW
PV generation：	0	→	3.47 billion kWh
Hydropower generation：	45.1	→	3.4 billion kWh
Total power generation：	45.1	→	6.81 billion kWh

Energy production in all PV size

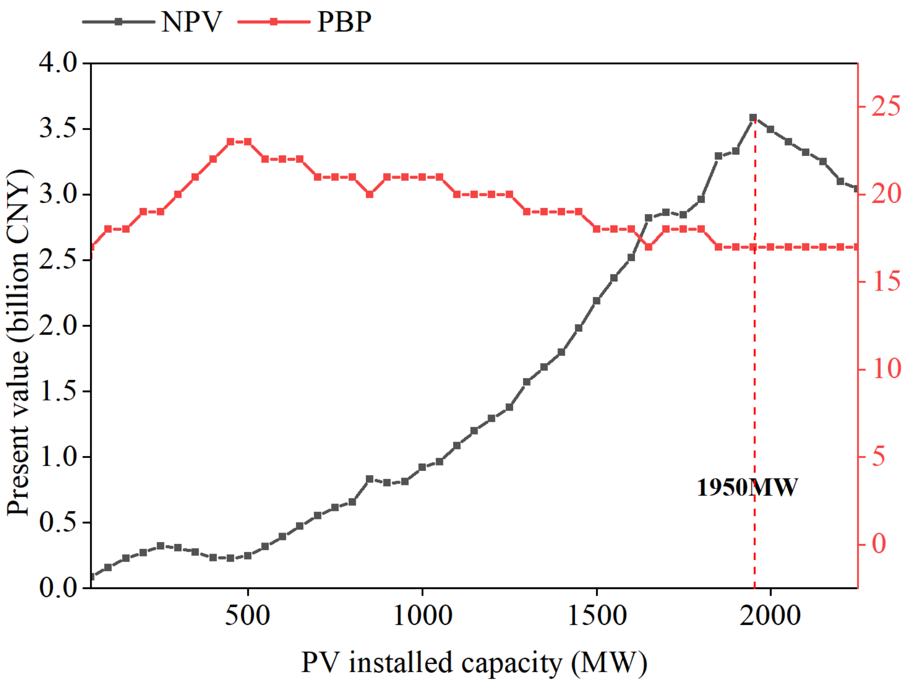


5 Results and discussion

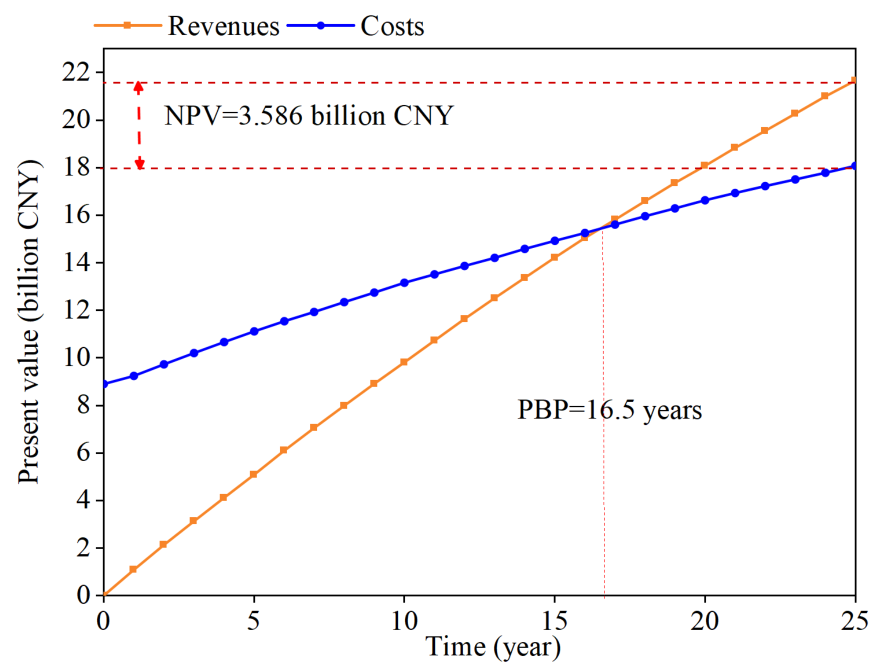
Economic evaluation indicators

- **Maximum NPV was achieved when the PV size reached 1950 MW with 16.5 years PBP.**
- **Beyond this threshold, NPV decreases due to the increase in hydropower loss rate and electricity curtailment rate associated with larger PV sizes.**

NPV and PBP in all PV sizes



Revenues and costs of the HGSs with optimal PV size

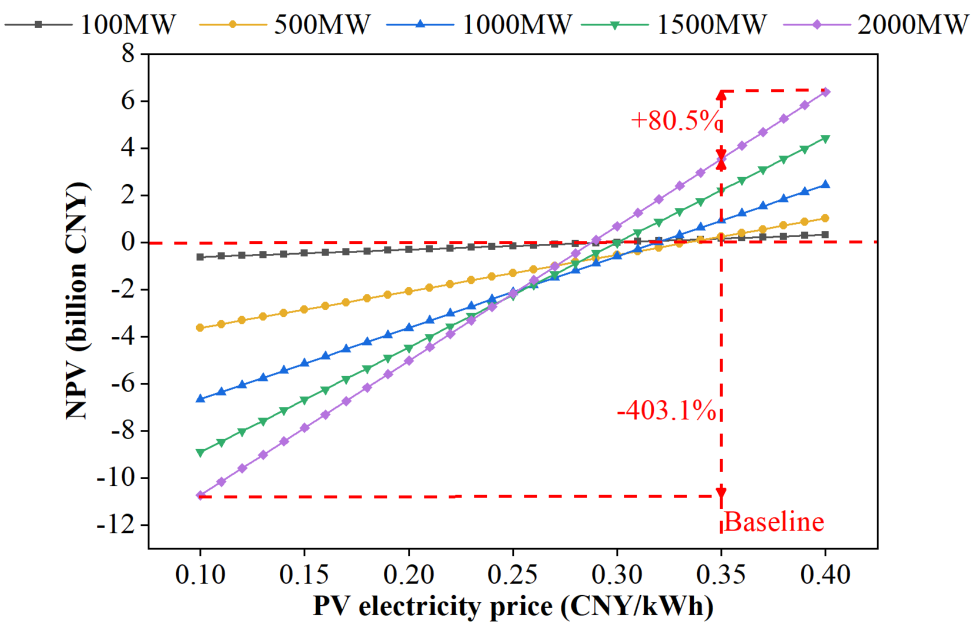


5 Results and discussion

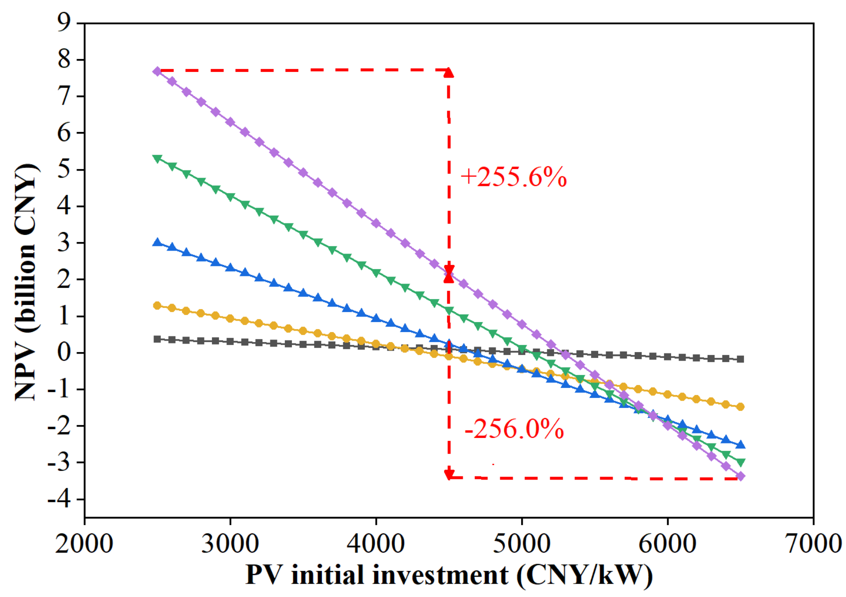
Sensitivity analysis

- **NPV for all PV sizes increased with increasing PV price, and the larger the PV size, the more sensitive the NPV was to changes in PV price.**
- **PV initial investment increased from 4.5 to 6.5 × 10^6 CNY/MW or decreased to 2.5 × 10^6 CNY/ MW, the NPV for the optimal PV size decreased by 256.0% and increased by 255.6%, respectively.**

Sensitivity analysis of NPV to PV electricity



Sensitivity analysis of NPV to initial investment

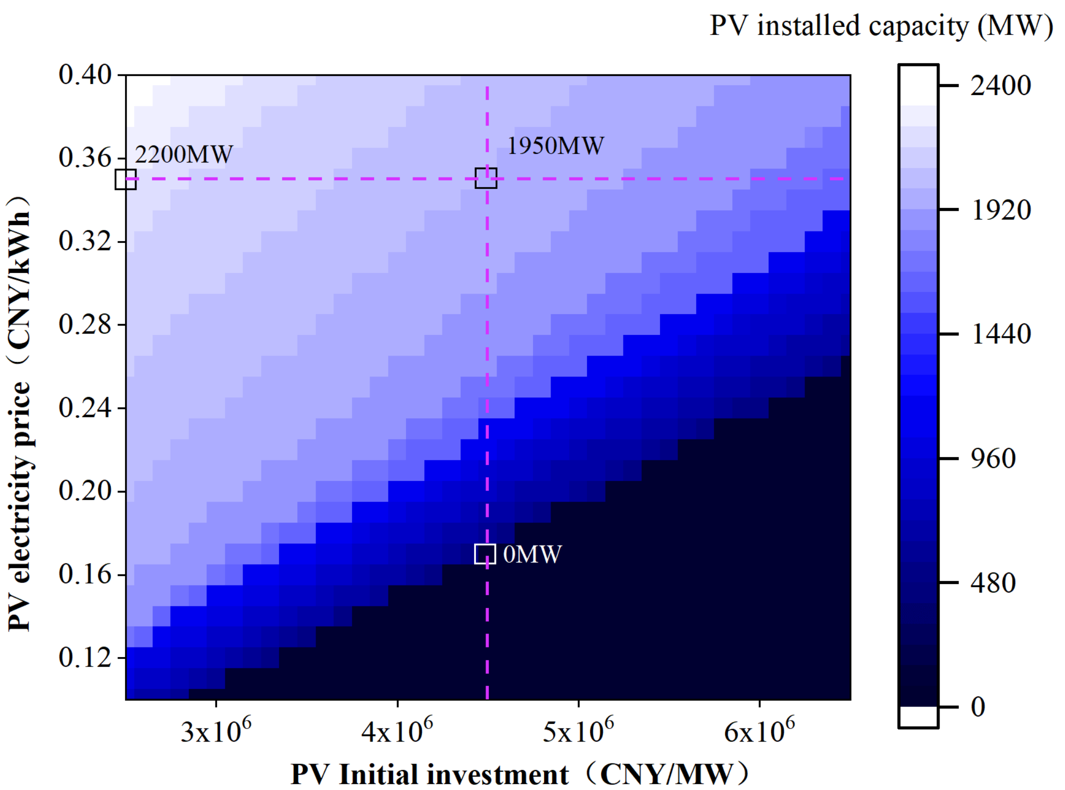


5 Results and discussion

Sensitivity analysis

- **The sensitivity analysis not only illustrate the impact of changes in PV price and initial investment on the optimal PV size, but also help stakeholders to identify a feasible region that contains various economic parameter combinations.**

Sensitivity analysis of optimal PV size to economic parameters



6 Summary

- **A long- and short-term nested operation model was constructed to accurately simulate the lifetime-span operation of the HGS with high temporal resolution.**

- **A holistic techno-economic framework for sizing the HGS was established to consider both technical performance (such as electricity curtailment, hydropower loss, and peak-shaving) and economic performance over a lifetime span.**

- **The proposed framework was effective to determine the size of the renewable power plant within a HGS, and it can be extended to a larger system that contains multi-reservoirs and various renewable power plants.**

Appreciation for your listening!

Thank you !