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Toward a sustainable megalopolis by reconciling power system decarbonization and urban health resilience

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Main credits to my student:

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- PhD student at University of Macau (since 2022)
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- Master in Electrical Engineering, Chongqing University (2022)
- Bachelor in Electrical Engineering, Nanjing University of Posts and Telecommunications (2019)

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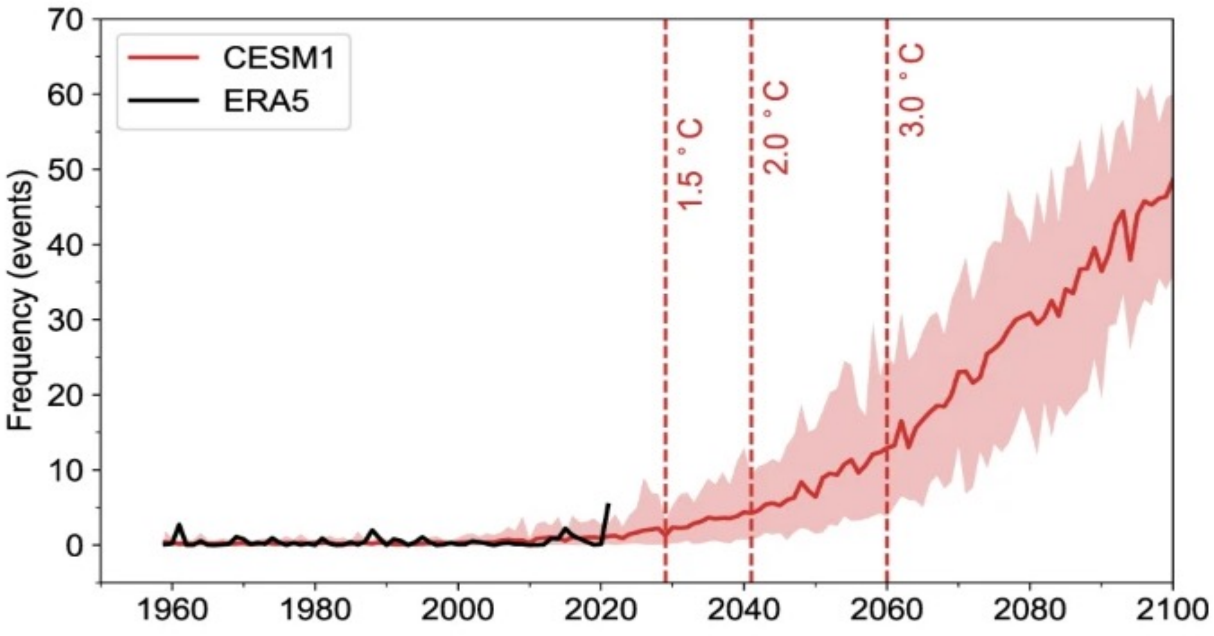
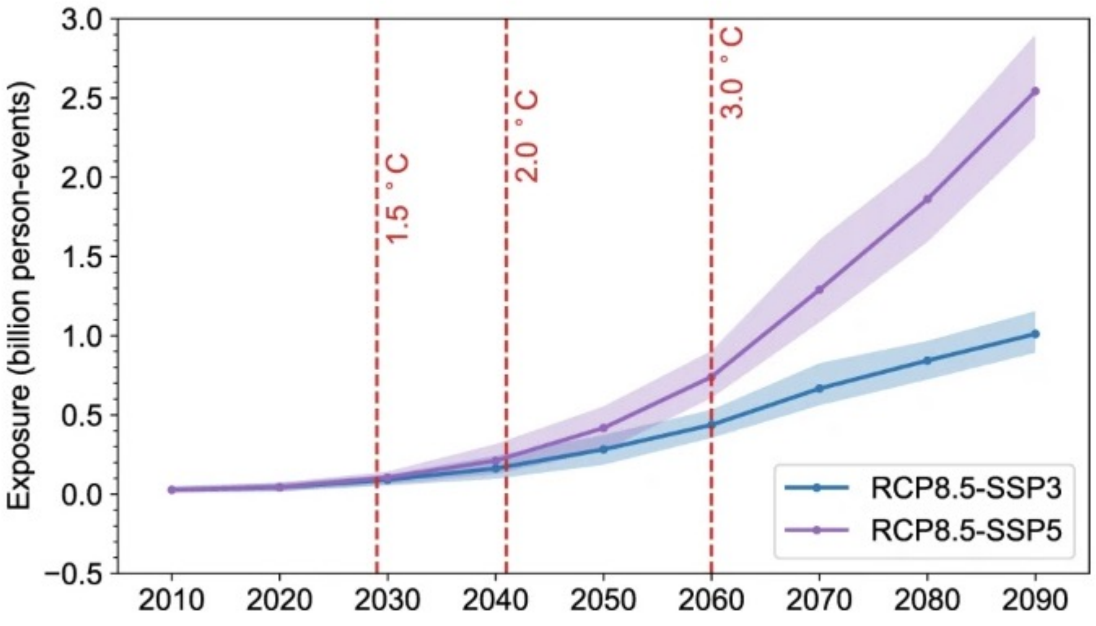
Global climate change increases heatwaves

- **Climate change** is increasing the **frequency of heatwaves** and **heat exposure**.
- Extreme heat frequency: +4.1times (1.5 °C) → +9.4times (4 °C) [1]
- Population heat exposure: ~30%(present) → 48–76% (by 2100) [1]



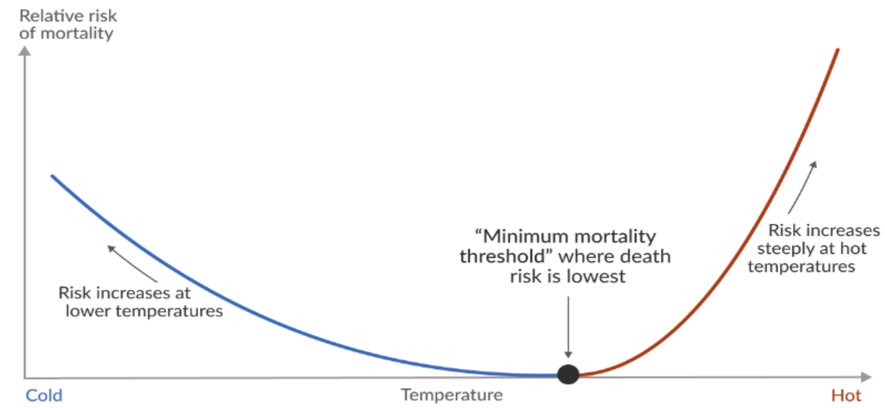


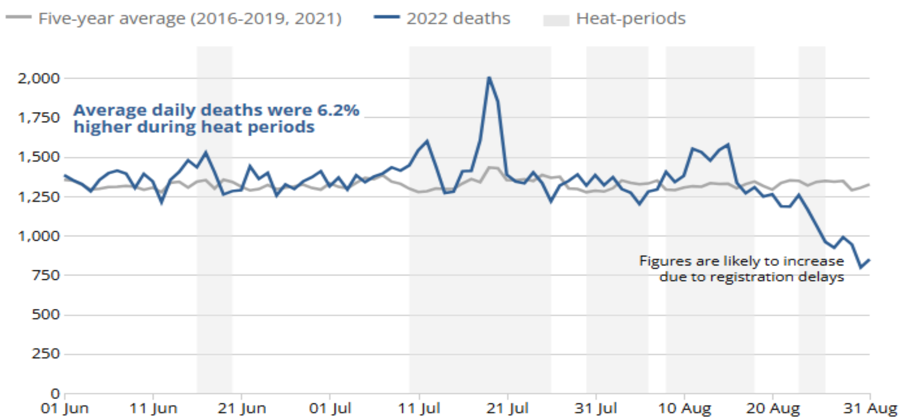
Increase in frequency of heat waves and population heat exposure [2]

[1] IPCC, *Climate Change 2021: The Physical Science Basis (AR6 WGI)*, Summary for Policymakers, Fig. SPM.6, Cambridge University Press, 2021
[2] Zhang, X., Zhou, T., Zhang, W., Ren, L., Jiang, J., Hu, S., ... & Man, W. (2023). Increased impact of heat domes on 2021-like heat extremes in North America under global warming. *Nature Communications*, *14*(1), 1690.

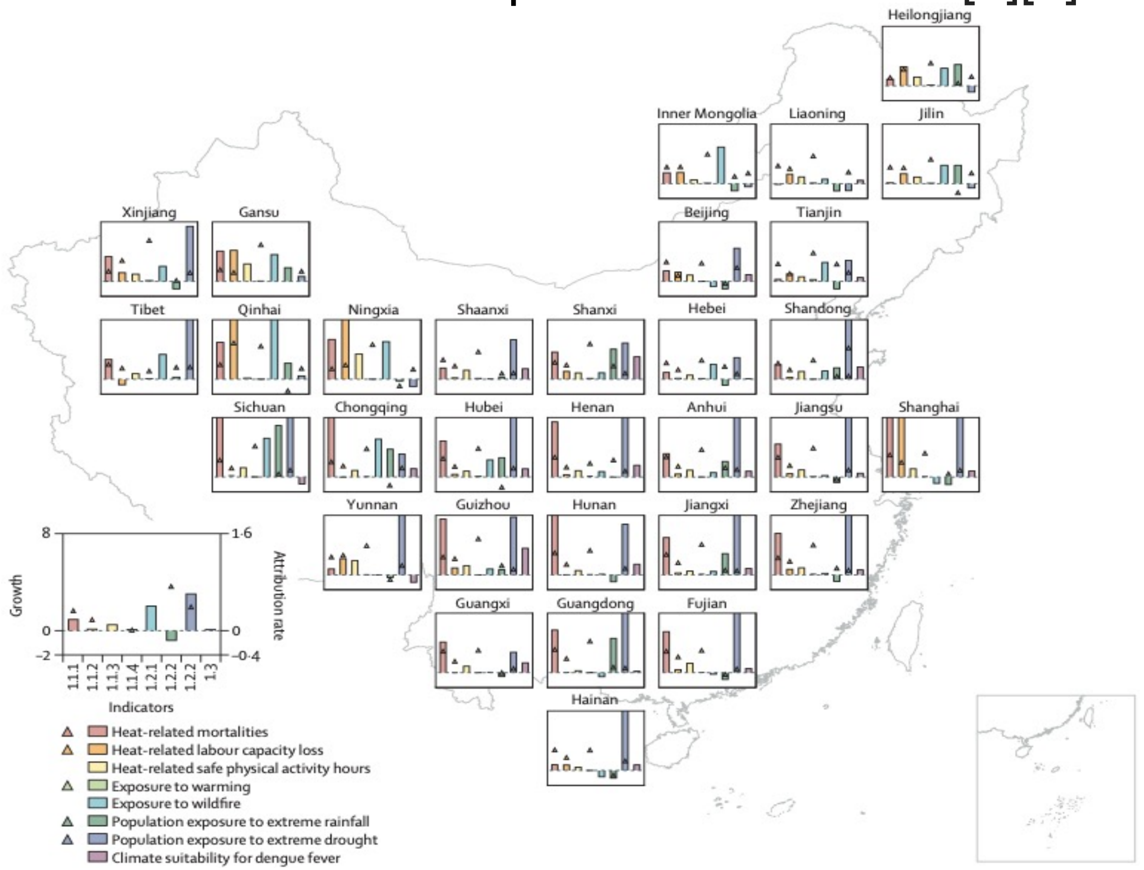
Growing heatwaves lead to heat exposure & mortality

- Prolonged **heat exposure** increases **health risks**, leading to excess mortality
- In 2022, record-breaking heatwaves caused ~ **62k deaths** in Europe & **51k in China** [3][4]





Excess mortality surge induced by heatwave

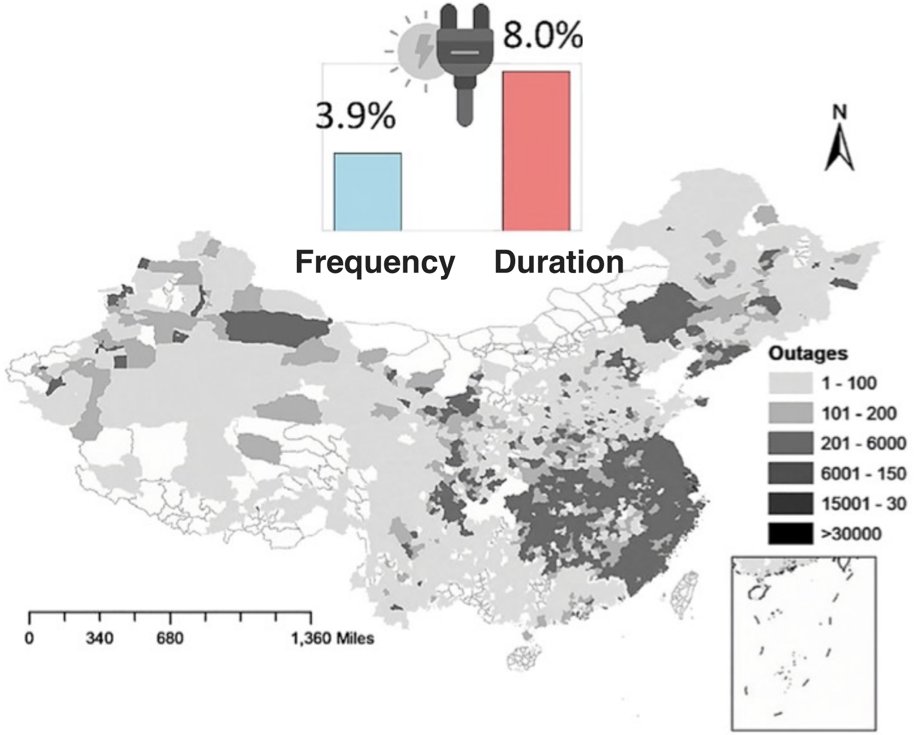


Growth of health risks from the historical baseline (mostly 1986–2005) to the current level (mostly in 2022) [4]

[3] Ballester, Joan, et al. "Heat-related mortality in Europe during the summer of 2022." *Nature medicine* 29.7 (2023): 1857-1866.
[4] Zhang, Shihui et al. "The 2023 China report of the Lancet Countdown on health and climate change: taking stock for a thriving future", The Lancet Public Health, 2023: 8.

Growing heatwaves cause power outages

- Extreme heatwaves bring up **cooling demand** & lead to power outages
  - increases summer peak loads by **10%–25%** relative to historical levels
  - leads to **electricity shortages** or even **widespread outages**



Heatwaves significantly increase the risk of power outages in China (2019-2021) [4]

Rolling Blackouts Hit Several Cities as Heat Wave Scorches Mexico

Cities were plunged into darkness as scorching temperatures strained the national energy grid.

Listen to this article · 2:10 min Learn more

Share full article

The electrical grid in Mexico has been strained after soaring temperatures, leading to blackouts on Tuesday. Daniel Becerril/Reuters

Long Blackouts Hit India as Heatwave Stokes Power Use

- Outages ranging from 2-12 hours, LocalCircles survey says
- Peak demand surged past 235 GW Tuesday, exceeding predictions

A vendor sells air coolers in New Delhi on May 20. *Photographer: Money Sharma/AFP/Getty Images*

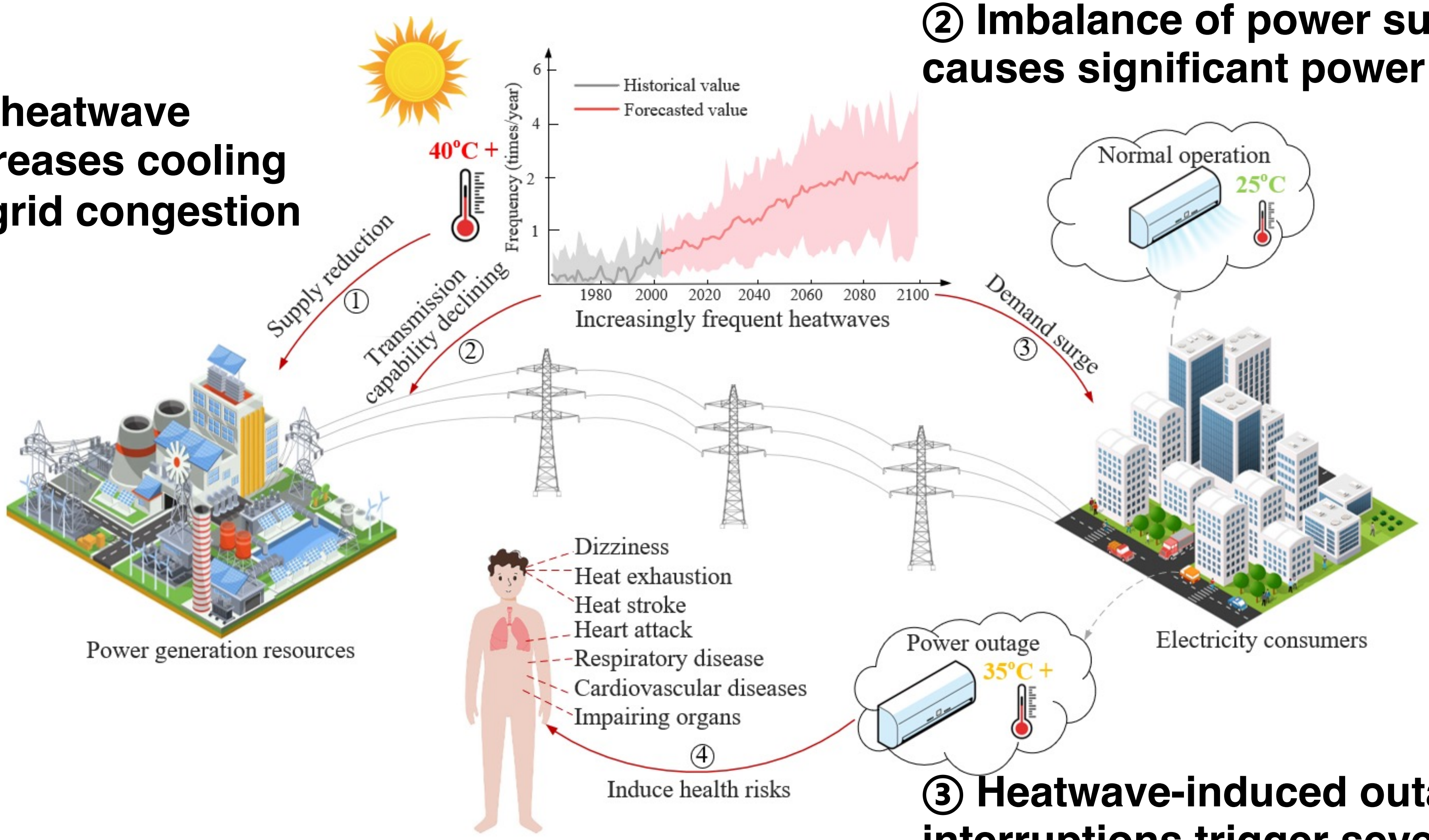
Heatwave-induced large-scale power outages in Mexico and India

[4] Liang, Jing, et al. "Impacts of heatwaves on electricity reliability: Evidence from power outage data in China." *Iscience* 28.2 (2025).

Coupling of climate-power-health systems

① **Extreme heatwave sharply increases cooling demand & grid congestion**

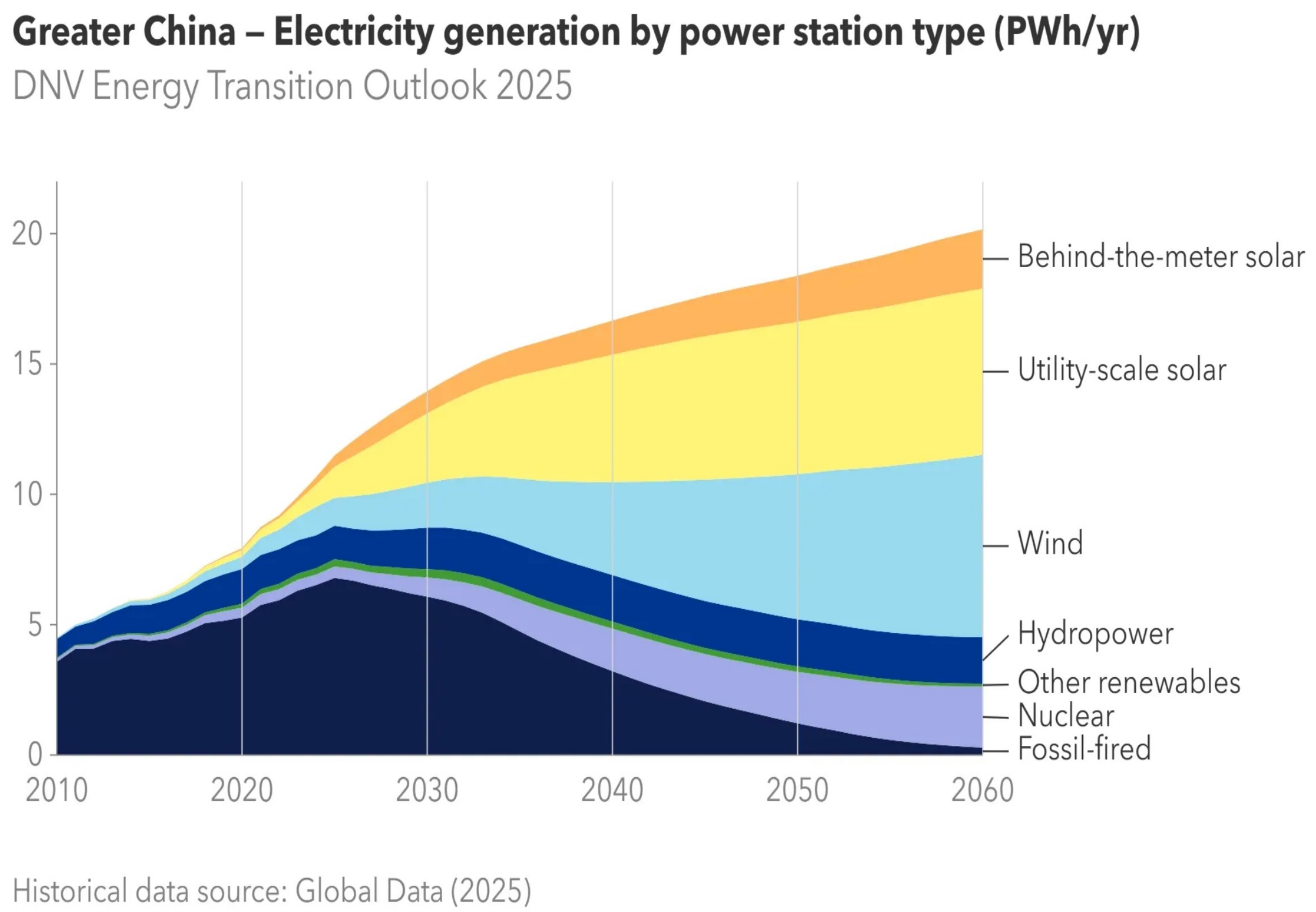
② **Imbalance of power supply–demand causes significant power shortages**



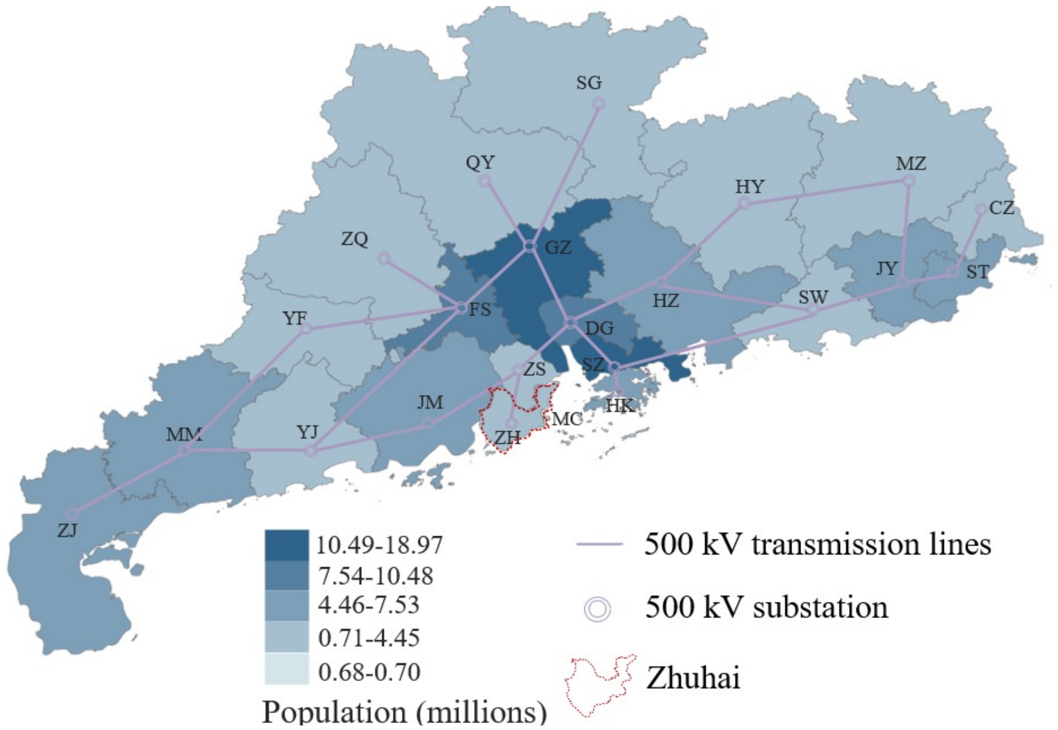
③ **Heatwave-induced outages & cooling interruptions trigger severe health risks**

Decarbonization may intensify urban health risks

- Renewables-dominated power system is more vulnerable to extreme heatwaves



Power Grid of Guangdong Province
(our case study target)



*Energy Transition Outlook 2025, Greater China - A forecast of the energy transition in the region to 2060, based on results from the ETO 2025. https://www.dnv.com/energy-transition-outlook/2025/greater-china/

Decarbonization may intensify urban health risks

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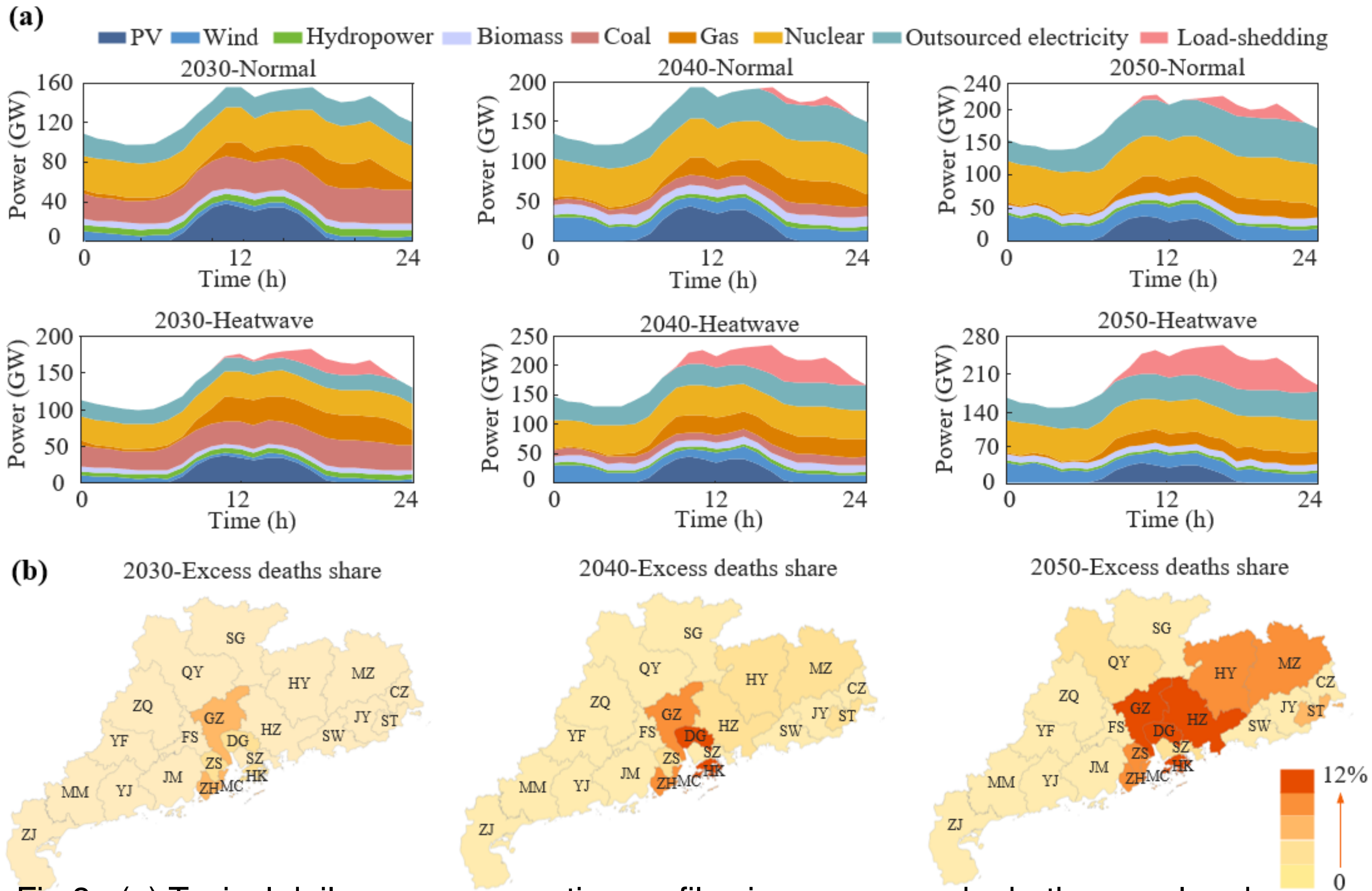


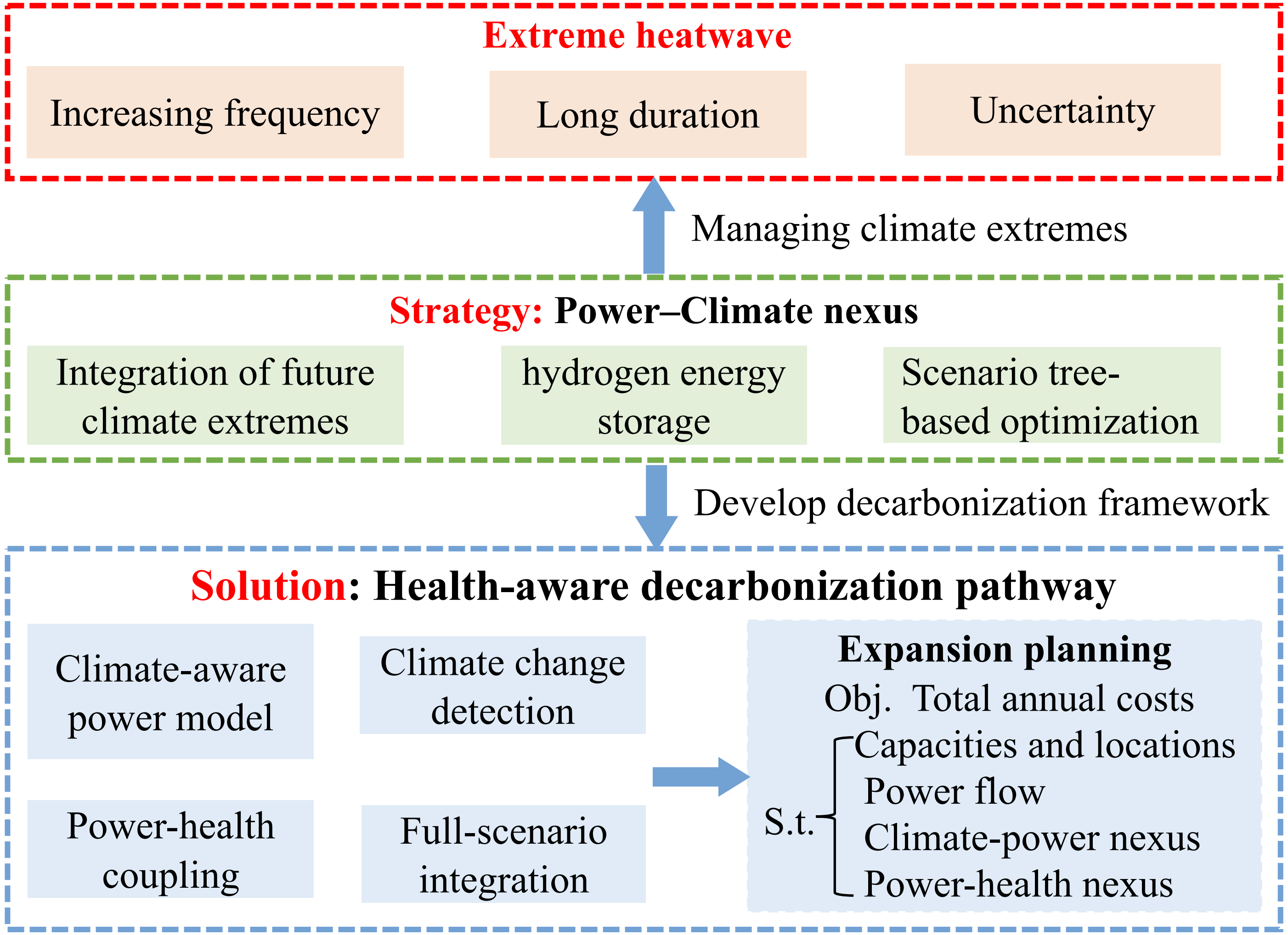
Fig.8: (a) Typical daily power generation profiles in summer under both normal and heatwave scenarios from 2030 to 2050. (b) The share of annual excess deaths in total mortality from 2030 to 2050 under the interval-average health-risk scenarios

- With **decarbonization**, reduced flexible generation and heatwave-driven cooling demand are projected to increase outage risk, **pushing** the **annual load-shedding rate** from **0.52%** in 2030 to **2.48%** by 2050.

- Decarbonization-driven **outage risks** translate into health risks: in the Guangdong–Hong Kong–Macao Greater Bay Area, the average share of **heatwave-related deaths** in total annual mortality **rising from 0.47% in 2030 to 2.78% by 2050**, with cities exceeding 3% excess deaths increasing from 1 to 9.

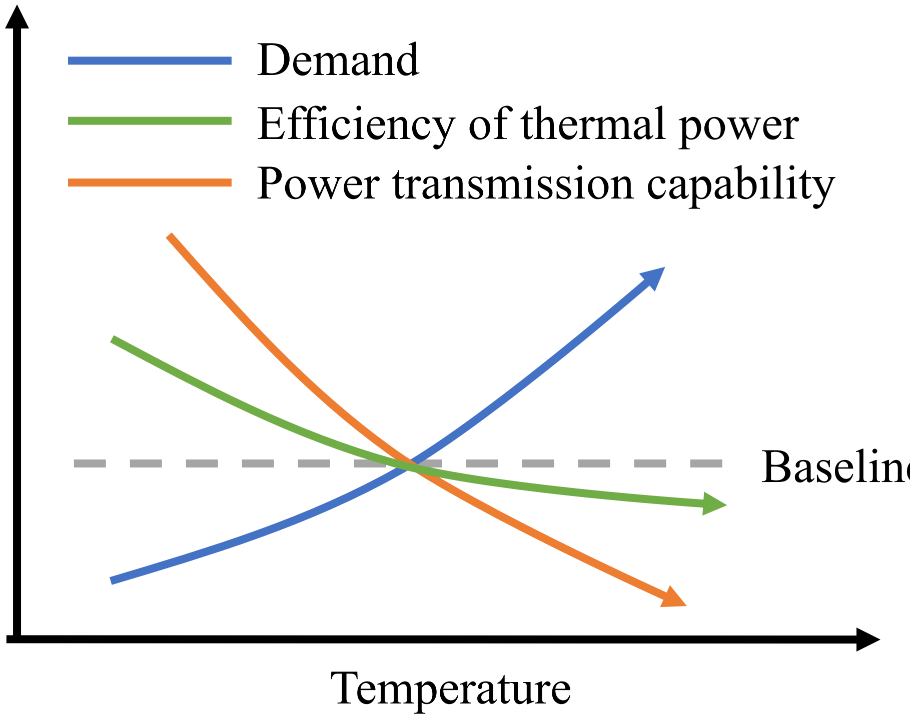
Solution: Health-aware decarbonization

- Health-aware decarbonization
  - **Climate-aware grid modeling**: Explicitly captures heatwave impacts on electricity supply, networks, and demand.
  - **Power outage–health coupling**: Quantifies heatwave-induced excess mortality arising from power outages.
  - **Climate-embedded planning**: Integrates the rising frequency of extreme heatwaves across climate pathways into long-term decarbonization optimization.



Solution: Health-aware decarbonization

- Climate-aware power grid model



Impact of high temperature on power grid

- **Efficiency loss of generator**

$$\eta_{n,t}^{\text{real}} = \eta_n^{\text{rated}} k_{n,t}^{\text{gen}},$$

$$k_{n,t}^{\text{gen}} = \begin{cases} (-\lambda_n^{\text{gen}} T_{s,t}^{\text{tem,hw}} + 100)/100 & T_{s,t}^{\text{tem,hw}} \geqslant 0, \\ 1 & T_{s,t}^{\text{tem,hw}} < 0, \end{cases}$$

- **Reduction in power transmission capability**

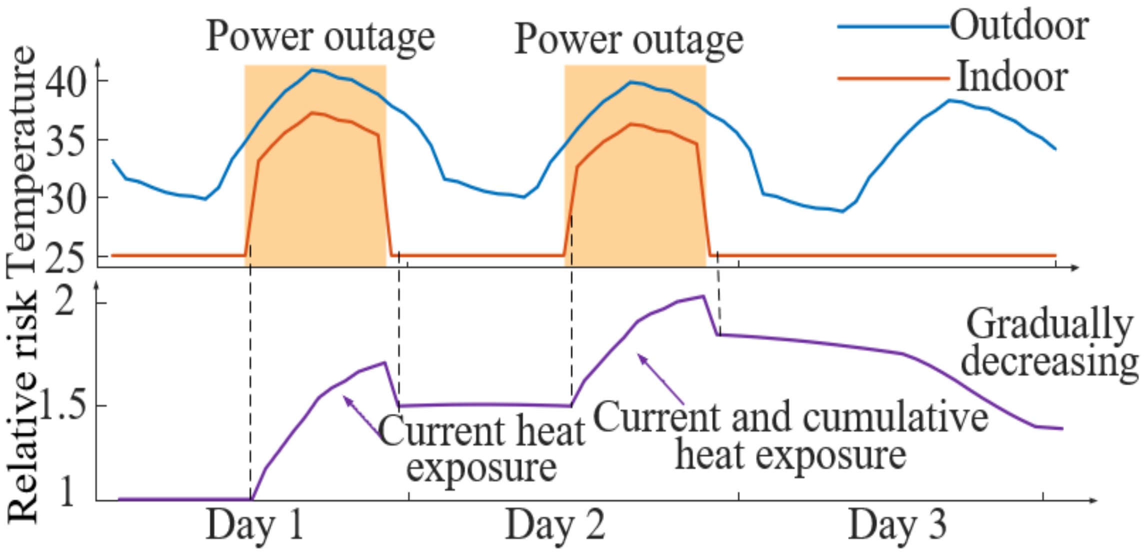
$$Cap_{s,l,t}^{\text{line,hw}} = (1 - K^{\text{tem}}(T_{s,t}^{\text{tem,hw}} - T_t^{\text{tem,ref}}))Cap_l^{\text{line,ref}}$$

- **Electricity demand growth**

$$P_{s,n,t}^{\text{load,hw}} = (1 + (5.33 - 0.067L^{\text{lat}})(T_{s,t}^{\text{tem,hw}} - T_t^{\text{tem,ref}})/100)P_{n,t}^{\text{load,ref}}$$

Solution: Health-aware decarbonization

- Health risk induced by power outage



Dynamic evolution of health risks during power outages

- **Power outage-induced heat exposure**

$$\Delta T_{s,n,t}^{\text{tem}} = \begin{cases} T_{s,n,t}^{\text{tem,indoor}} - T^{\text{tem,opt}} & T_{s,n,t}^{\text{tem,indoor}} \geqslant T^{\text{tem,opt}} \\ 0 & T_{s,n,t}^{\text{tem,indoor}} < T^{\text{tem,opt}} \end{cases}$$

- **Health risks caused by heat exposure**

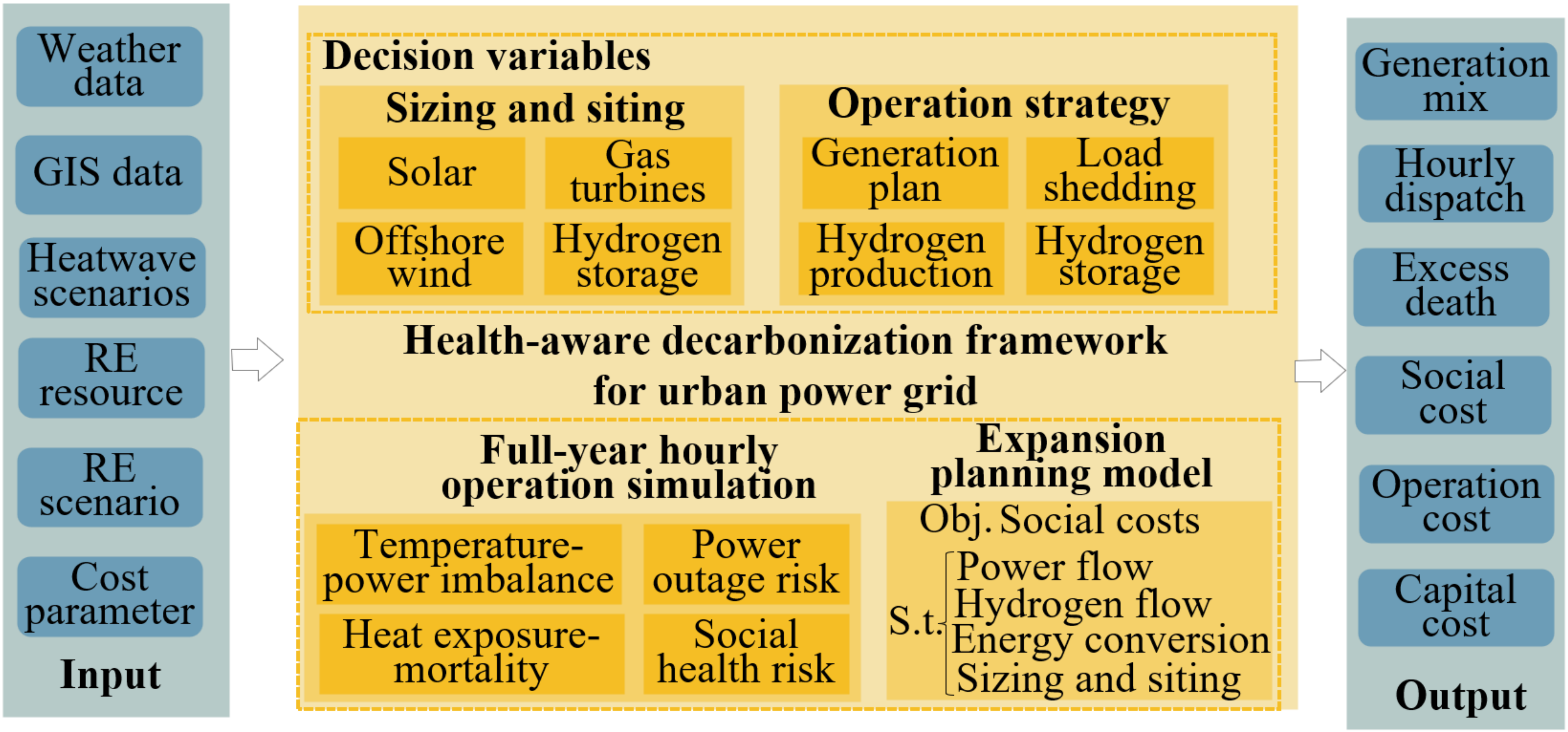
$$R_{s,n,t} = \sum_{q=0}^{Q} a_q (\Delta T_{s,n,t}^{\text{tem}} \Delta t)^q + \sum_{q=0}^{Q} b_q \left(\sum_{t_0=t}^{t-k} \gamma(k) (\Delta T_{s,n,t_0}^{\text{tem}} \Delta t) \right)^q$$

- **Excess deaths resulting from increased health risks**

$$M_{s,n,t}^{\text{mor,hw}} = (1 + R_{s,n,t}) M^{\text{mor,nor}}$$

Solution: Health-aware decarbonization

- Health-aware capacity expansion for urban power grid

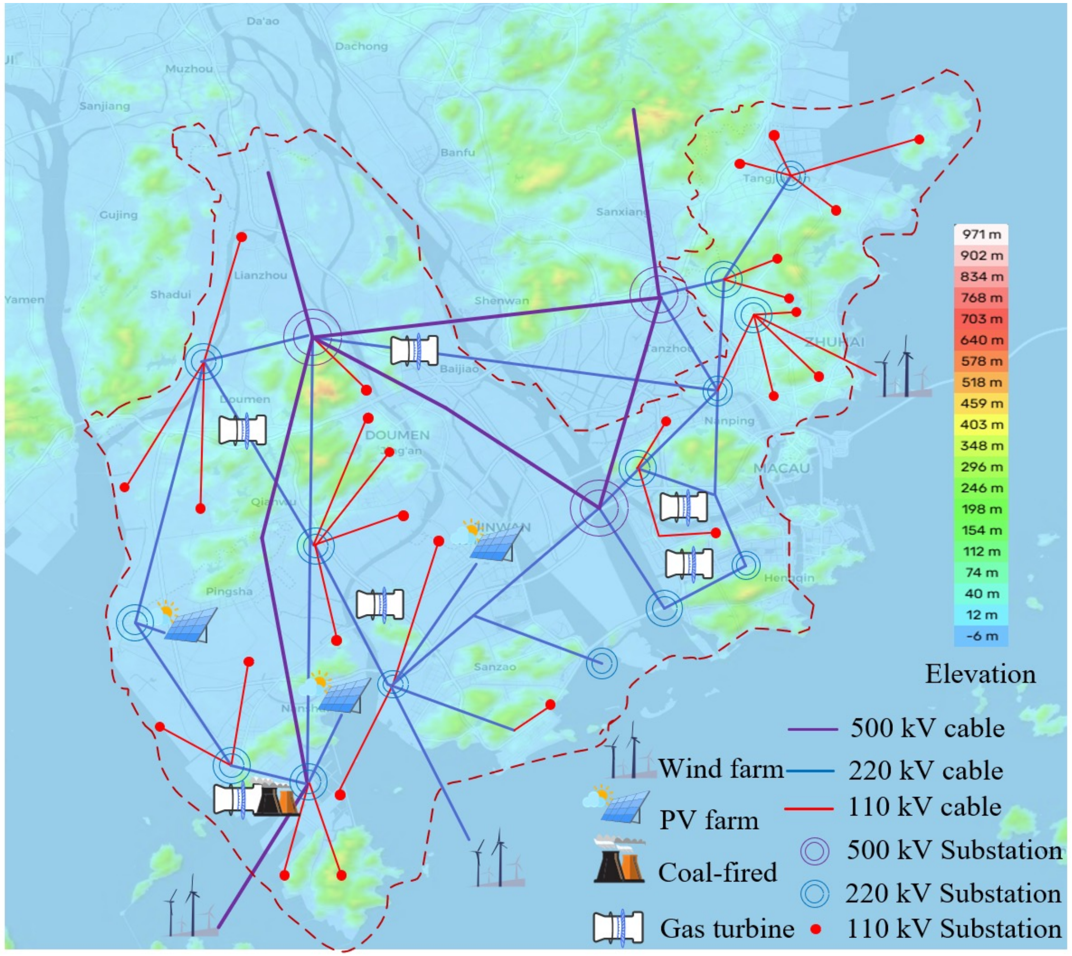


Note: GIS (Geographical Information System) RE (Renewable Energy)

Health-aware decarbonization in Zhuhai City

- Case analysis based on detailed urban power grid in Zhuhai City

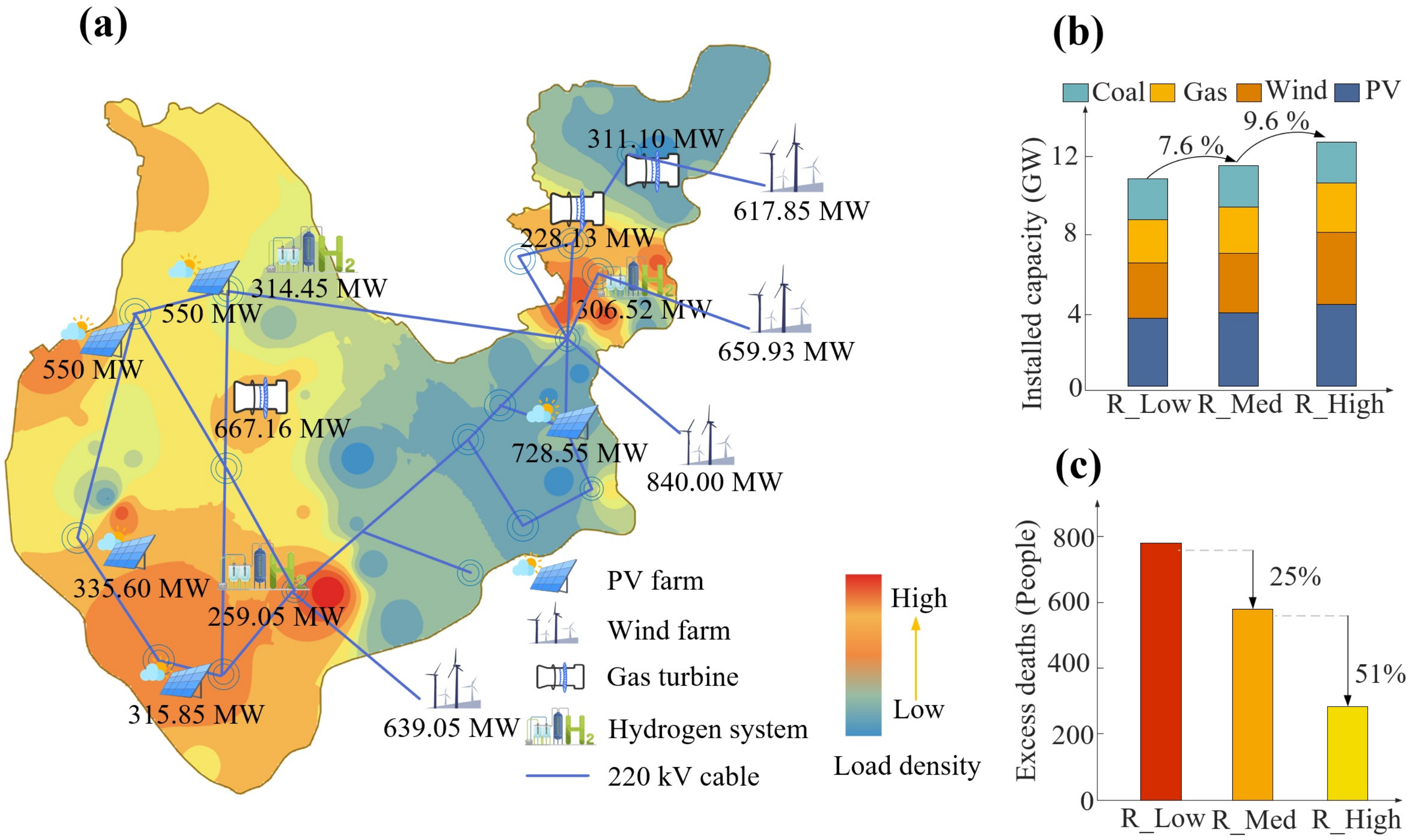
- We designed three distinct decarbonization pathways to analyze the impacts of heatwaves on power grid expansion planning and health risk:
  - **R_Low**: Low resilience, does not account for the impacts of extreme heatwaves
  - **R_Med**: Medium resilience, considers only the effects of extreme heatwaves on power systems
  - **R_High** (Proposed method): High resilience, considers the impacts of heatwaves on power systems and urban health



Current power grid in Zhuhai (110 kV, 220 kV, and 500 kV voltage levels)

Health-aware decarbonization in Zhuhai City: Results

- Investing more generation enhances both power & health resilience in cities



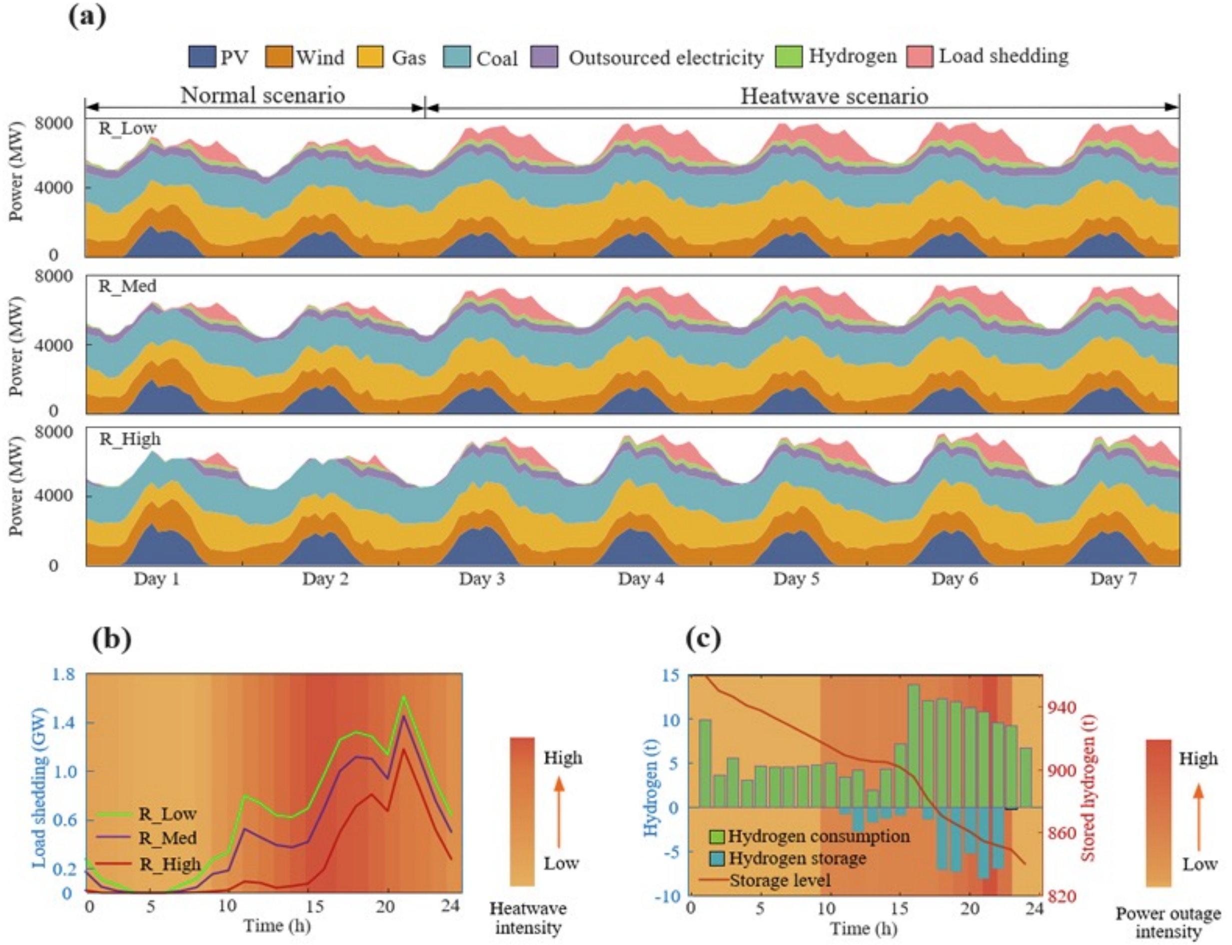
Planning results for the 2030 Zhuhai power grid under different cases.
(a) Distribution of newly deployed generation resources in case R_High.
(b) Total installed generation capacities under different cases.
(c) Excess deaths under different cases.

- Health-aware strategy (that considers extreme heatwaves & associated health risks) increases generation **capacity** by **7.6%** in R_Med and a **further 9.6%** in R_High compared to case R_Low.

- Conservatively **investing in more generation** enhances both urban power & health resilience, **reducing excess deaths** by **63%** in case R_High compared with case R_Low, from 775 to 283.

Health-aware decarbonization in Zhuhai City: Results

- Synergies between solar generation & energy storage reduces excess mortality



Power scheduling results in different cases (R_Low-R_High). (a) Weekly power profiles. (b) Load-shedding profiles on a typical day. (c) Hydrogen storage profiles on a typical day.

Deploying more **solar** and shifting outages to nighttime can remarkably **cut excess mortality**

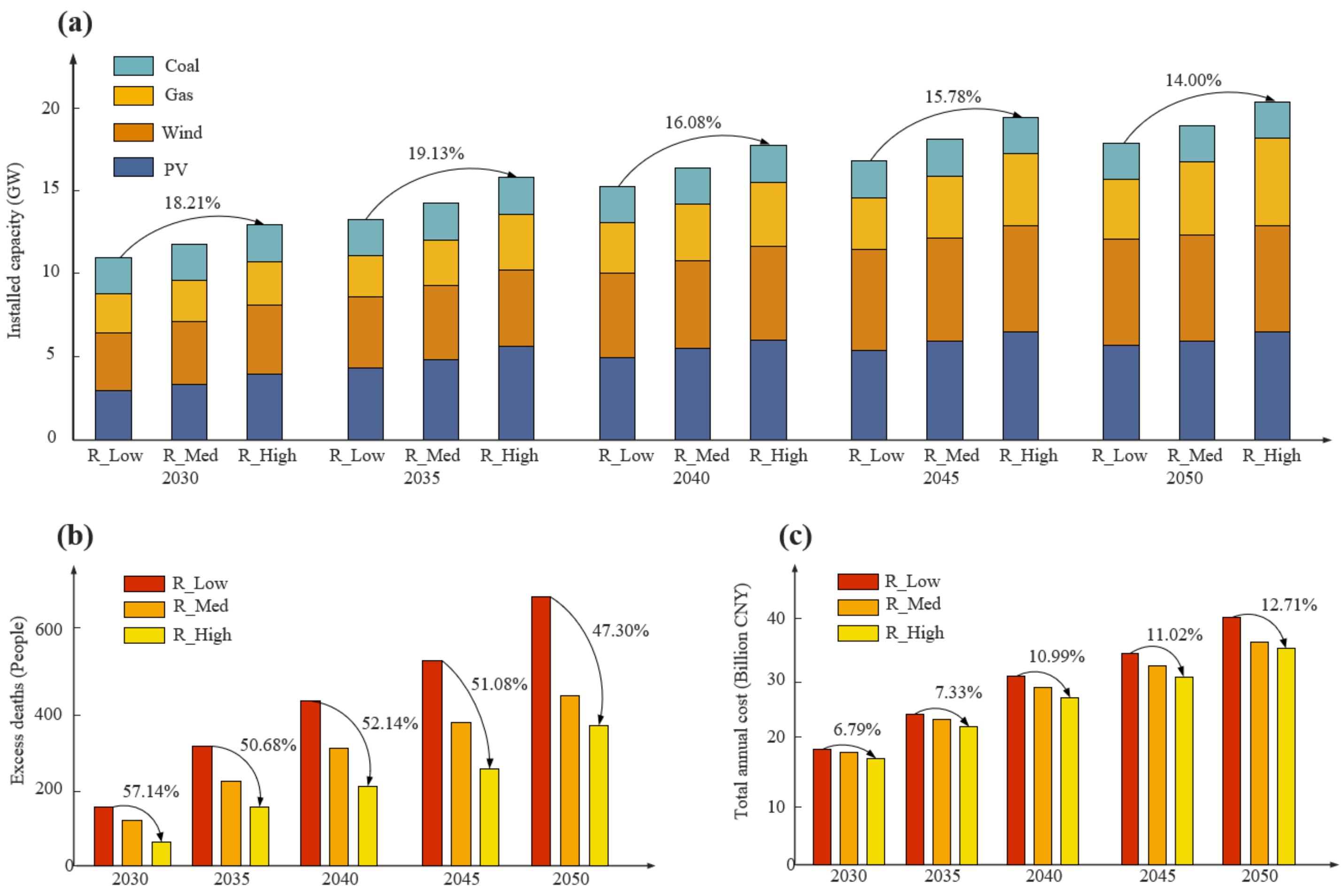
- Health-aware strategy increases solar capacity/share by 35.26%/14.43%, reduces daytime load-shedding by >90%
- Sensitivity analysis shows each **1% solar** increase reduces excess deaths by **~1–3%.**

Adding power-to-hydrogen-to-power **storage** further closes night gap

- **Raising renewable** integration by **10.06%**
- **Cutting daily load-shedding** by **40.93%**
- Investing ~15% of total capex in hydrogen storage consistently reduces load-shedding by 32.8–41.2% across different cases

Health-aware decarbonization in Zhuhai City: Results

- Enhancing climate resilience also brings up economic and health benefits



Economic & health benefits in different cases.
(a) Generations mix. (b) Excess deaths. (c) Total annual costs.

- Optimizing the **generation mix** and expanding installed **capacity** enhance **climate resilience** of urban grid to against extreme heatwaves.

- Under increasing heatwave frequency, the **health-aware decarbonization** pathway delivers progressively larger **cost savings** than the conventional strategy, rising from **8.71%** in 2030 to **13.63%** by 2050.

Summary

- Climate change-induced extreme events are profoundly impacting urban power grid operations and urban health
  - Deep **decarbonization** of urban power grid may **increase health risks** during extreme heatwaves, with the annual share of heatwave-related excess deaths in 11 core cities of the Guangdong–Hong Kong–Macao Greater Bay Area rising from **0.99%** in 2030 to **5.72%** in 2050
  - Investing in more power generation can enhance both urban power & health resilience, while coordinated deployment of **solar** and **long-duration energy storage** optimizes the spatiotemporal distribution of outages, reducing heatwave-related excess mortality by **55%–65%**
  - **Health-aware decarbonization** strategy that co-optimizes power system planning and health resilience reduces total system **costs** by **6.79%–12.71%**, while delivering increasing joint climate, social, and economic benefits over time.

- **Read more:** Z. Yang, **H. Zhang***, H. Li, S. Moura, Y. Song*. Toward a sustainable megalopolis by reconciling power system decarbonization and urban health resilience. Communications Earth & Environment, 2026. DOI: 10.1038/s43247-026-03198-4 (Nature Portfolio Journal)

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