

SMR Cogeneration for Hyperscale Data Centers

A techno-economic boundary analysis of power and cooling

Buxin She | Assistant Professor

Mike Wiegiers Department of Electrical and Computer Engineering, Kansas State University

Joint work with Honglin Li and Jie Zhang



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Dr. Honglin Li

First author

Postdoctoral researcher in my group
Kansas State University

Prof. Jie Zhang

Coauthor and collaborator

The University of Texas at Dallas

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Energy Conversion and Management: first revision submitted

Awaiting the editorial decision. Results in this talk reflect the revised manuscript.

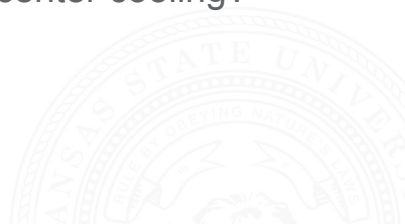
Outline

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- 3 System and Optimization**
Components, constraints and operation

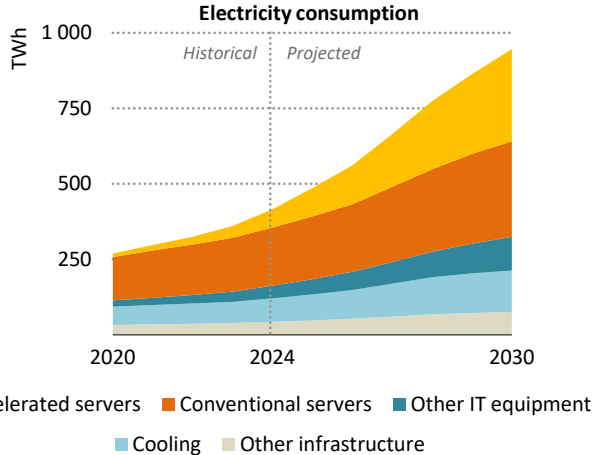
- 4 Data and Scenarios**
Cases, data and sensitivity scenarios
- 5 Results**
Q1 cost, Q2 absorption, Q3 parity
- 6 Conclusions and Future Work**
Findings and deployment learning

Motivation

Why combine nuclear power and data-center cooling?



Growth in Data-Center Electricity Demand

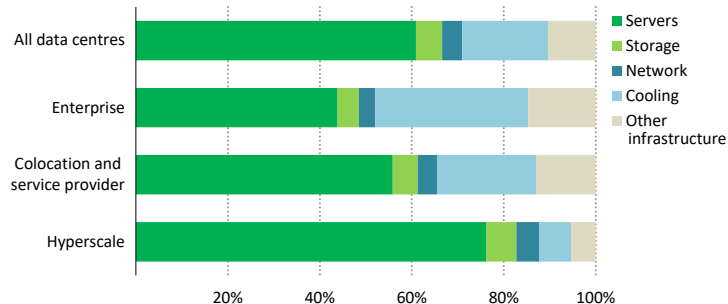


- AI is driving rapid growth in data-center electricity demand.
- Global demand is projected to more than double from 2024 to 2030.

Source: IEA, *Energy and AI* (2025), Fig. 2.11, p. 64.

Data-Center Electricity Breakdown

Share of total facility electricity by equipment and data-center type, 2024

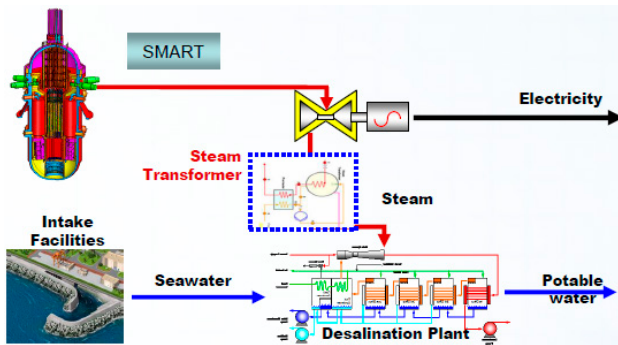


- Servers dominate electricity use, followed by cooling.
- At hyperscale, a small cooling share still represents substantial electricity use because total demand is large.

Data centers are integrated energy systems coupling electricity and cooling.

Source: IEA, *Energy and AI* (2025), Fig. 2.2, p. 53.

SMRs Couple Thermal and Electric Output



SMART: electricity + heat for desalination

- **Small modular reactors (SMRs)**
Fission heat drives the steam cycle.
- **Coupled heat and power**
Electricity and useful heat share the same reactor energy input.
- **Complementary services**
Data centers need electricity and cooling.

SMRs are integrated energy systems with coupled heat and power outputs.

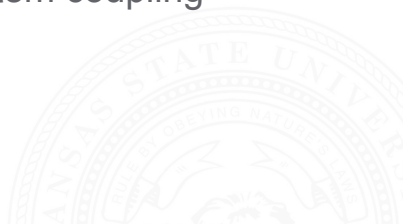
Source: IAEA (2019), Fig. 12, p. 36.

Three Questions We Investigate

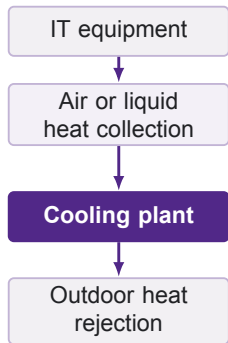
- Q1** Can a colocated SMR supply a data center at lower cost than the grid?
- Q2** Does adding steam-driven cooling reduce total cost compared with electricity-only SMR supply?
- Q3** Under what capital, market, financing and carbon conditions does SMR supply become competitive?

Technical Background

Cooling demand, SMR heat and system coupling



How Do Data Centers Remove Heat?



Evaporative heat rejection consumes water.

- **Collect heat**

Air or liquid removes heat from IT equipment.

- **Move heat**

The facility cooling system carries heat toward an outdoor sink.

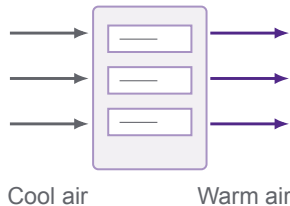
- **Reject heat**

The outdoor system transfers heat to the environment.

Heat collection is one step in the complete heat-removal path.

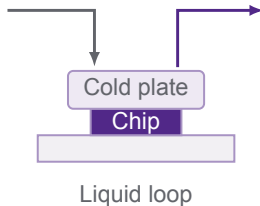
Source: DOE (2024), pp. 14–22.

Heat Collection Methods



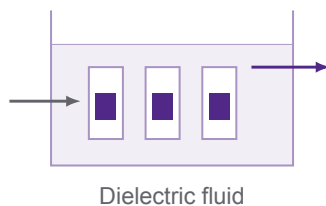
Air cooling

Air carries heat away from IT equipment.



Cold plates

Liquid in cold plates removes heat from chips.



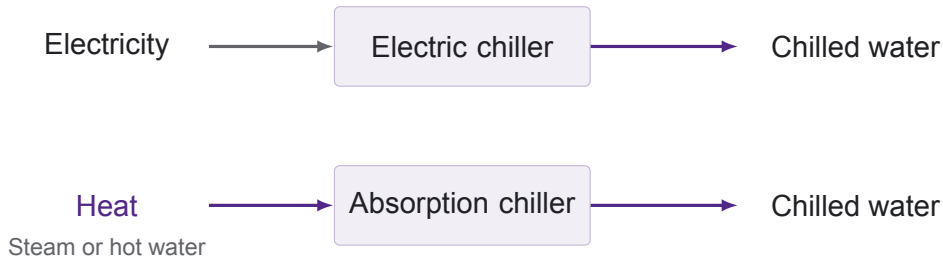
Immersion

Electronics transfer heat to a nonconductive fluid.

All three methods still require heat rejection outdoors.

Source: DOE (2024), pp. 14–15, 20–22.

Two Ways to Produce Chilled Water

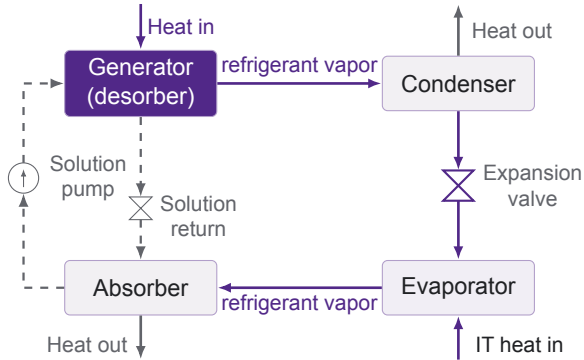


Absorption chillers also use electricity for pumps and auxiliaries.

Both supply chilled water, but use different driving energy.

Source: DOE (2017), pp. 1–2.

Absorption-Chiller Cycle



Single-effect principle. Study model: double-effect LiBr unit.

■ Create cooling

Water refrigerant evaporates at low pressure, cooling the chilled-water loop.

■ Regenerate with heat

Heat releases refrigerant from LiBr solution, replacing compressor work.

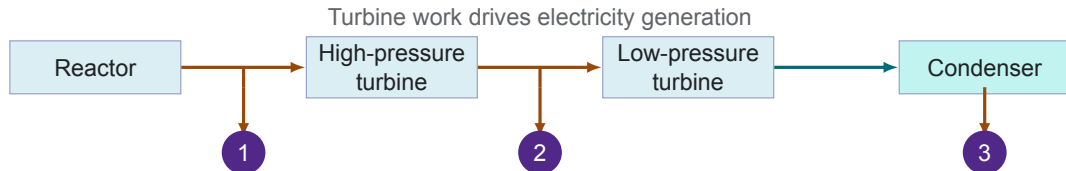
■ Reject heat outdoors

The condenser and absorber release heat while pumps use electricity.

Evaporation produces cooling in a heat-driven cycle.

Source: DOE (2017), Fig. 1, p. 2.

SMR Heat Sources



1 Main steam

Steam before turbine expansion.

2 Intermediate steam

Steam after partial turbine expansion.

3 Low-grade heat

Condenser heat usually needs upgrading for absorption cooling.

Match the heat-source temperature to the cooling technology.

Source: IAEA (2019), pp. 3–4, 25. DOE (2017), Table 1, p. 1.

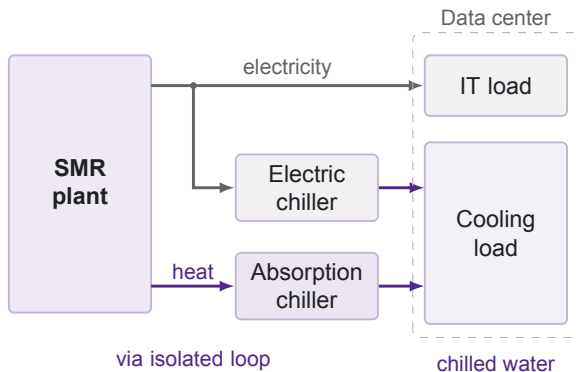
The Heat Source Determines the Tradeoff

Main steam	More forgone generation for comparable heat delivery.
Intermediate steam	Retains upstream turbine work but requires extraction equipment.
Low-grade heat	Heat upgrading can add equipment cost and electricity use.

Cooling savings must cover added equipment, lost power and auxiliary energy.

Source: IAEA (2019), pp. 15–17, 25. DOE (2017), pp. 2–4.

Connecting SMRs and Data Centers



- **Electrical pathway**
Power serves IT and the electric chiller.
- **Thermal pathway**
Selected steam supplies the absorption chiller.
- **Joint operation**
Cooling choices affect both electric output and electricity demand.

Assess thermal coupling by modeling power generation and cooling together.

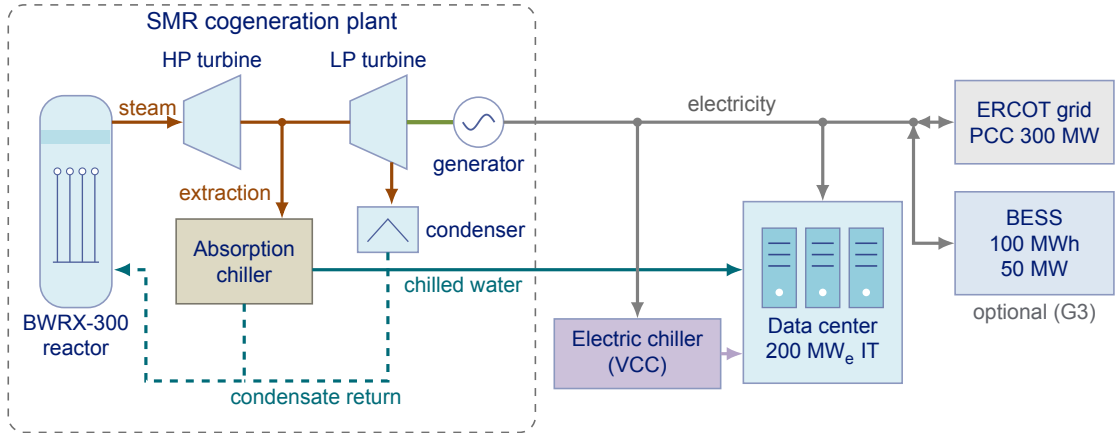
Source: IAEA (2019), pp. 3–4, 18.

System and Optimization

Components and constraints, then least-cost operation



System Layout



The SMR supplies electricity and steam to meet data-center power and cooling loads.

Overall Optimization Formulation

Minimize

$$\min_{\mathbf{u}} \text{TAC} = C_{\text{cap}}^{\text{ann}} + C_{\text{O\&M}} + \Phi_{\text{fuel}} + \Phi_{\text{grid}} + \Phi_{\text{CO}_2} - \Phi_{\text{ptc}}$$

$\mathbf{u}$: dispatch over 8,760 hours. Φ_{ptc} : credit on net nuclear generation.

Constraints

Power balance

$$P_{\text{tn}} + P_{\text{g}}^+ = P_{\text{IT}} + P_{\text{cool}} + P_{\text{g}}^-$$

Cooling balance

$$Q_{\text{a}} + Q_{\text{v}} = Q_{\text{cool}}^{\text{dem}}$$

Operating constraints

Capacity limits, ramping and outages.

Chiller performance and steam extraction losses.

Inputs

Hourly data

IT load, weather, electricity prices and grid carbon intensity.

Equipment and costs

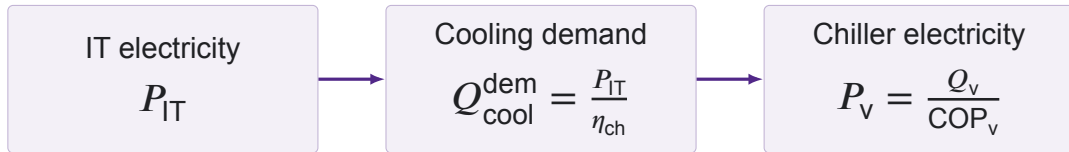
Fixed capacities, capital and fuel costs, O&M and financing.

Policy assumptions

Carbon price and 45Y credit rate.

IT Load and Electric Cooling

Electric-chiller baseline



Cooling demand

$\eta_{ch} = 0.90$: modeled chilled-water delivery efficiency.

Electric-only baseline: $Q_v = Q_{cool}^{dem}$.

Electricity needed

COP (coefficient of performance) = cooling output / electric input.

Design COP: 3.2 at 26 °C wet bulb. Actual COP varies with load and weather.

IT load sets cooling demand, and chiller performance determines the extra electricity.

Reactor Operating Constraints

Thermal output $P_{rx}(t)$, in MW_{th}

$$435 \leq P_{rx}(t) \leq 870 \quad \text{online}$$

$$P_{rx}(t) = 0 \quad \text{maintenance}$$

$$|P_{rx}(t) - P_{rx}(t-1)| \leq 261 \quad \text{ramping}$$

- **Maintenance and refueling**

701 scheduled hours give 92% annual availability.

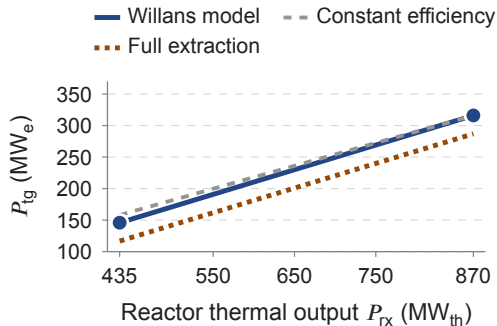
- **Dispatch formulation**

Given maintenance schedule, continuous output when online.

Reactor output follows hourly dispatch within capacity and ramping limits.

Turbine Model

Part-load performance



Electric output (online)

$$P_{tg} = a_w P_{rx} - b_w - \alpha_w Q_{ext}$$

$$P_{tn} = (1 - \xi_{aux}) P_{tg}$$

Steam extraction reduces electric output. Both outputs are zero during outages.

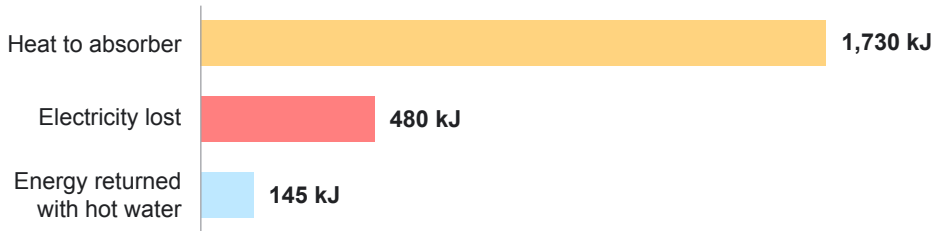
P_{tg} , P_{tn} : gross and net power.

Q_{ext} : heat extracted for cooling.

Steam and electricity share the same reactor heat input.

Steam Extraction Penalty

HEAT BALANCE PER KILOGRAM AT THE 7 BAR / 165 °C CROSSOVER TAP

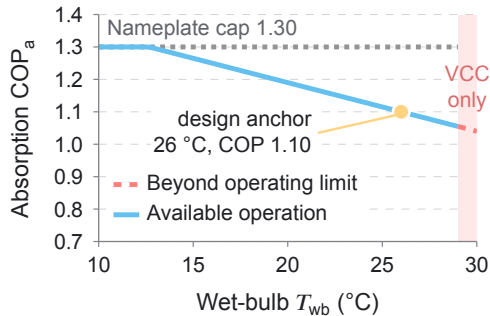


$$\alpha_w \approx \frac{480 - 145}{1730} = 0.19 \rightarrow 0.20 \text{ MW}_e \text{ gross per MW}_{th}$$

Steam used for cooling means less electricity, partly offset by energy in the returning hot water.

Absorption-Chiller Model

Weather-dependent performance



Heat to cooling

COP (coefficient of performance) is cooling output divided by heat input.

$$Q_a = \text{COP}_a(t) a(t) Q_{\text{ext}}$$

$a(t) \in \{0, 1\}$ denotes availability.

At 26 °C wet bulb, COP = 1.10: each MW of heat supplies 1.10 MW of cooling.

Warmer cooling water reduces the cooling obtained from steam.

Absorption-Chiller Constraints

Available cooling and heat

$$0 \leq Q_{\text{ext}}(t) \leq a(t) \bar{Q}_{\text{ext}}$$

$$0 \leq Q_a(t) \leq a(t) \bar{Q}_a$$

$a(t) = 1$ at wet-bulb temperatures up to 29 °C, outside reactor outages and absorber maintenance.

Otherwise $a(t) = 0$.

Auxiliary electricity

$$P_{\text{aux},a} = \beta_a Q_a, \quad \beta_a = 0.035$$

Pumps and cooling-tower fans consume electricity as cooling output rises.

Bars denote installed capacity limits.

Absorption and electric chillers jointly serve the cooling load.

Grid Exchange

Import electricity

$$0 \leq P_g^+(t) \leq \overline{P}_{\text{pcc}} y(t)$$

Grid imports supplement on-site generation.

Export electricity

$$0 \leq P_g^-(t) \leq \overline{P}_{\text{pcc}} [1 - y(t)]$$

Grid exports sell surplus on-site generation.

$y(t) \in \{0, 1\}$ selects the exchange direction. Connection limit: $\overline{P}_{\text{pcc}} = 300$ MW.

| Each hour uses one exchange direction within the connection limit.

Battery Storage Model

Energy carried between hours

$$E_B(t) = (1 - \rho_B)E_B(t-1) + \left[\sqrt{\eta_{rt}}B^+(t) - B^-(t)/\sqrt{\eta_{rt}} \right] \Delta t$$

E_B : stored energy. B^+ , B^- : charge and discharge power. η_{rt} : round-trip efficiency. ρ_B : self-discharge.

Operating limits

Power and state of charge stay within the battery ratings.

Annual energy balance

Final stored energy equals its initial value.

Storage shifts electricity between hours, with charging and discharging losses.

Power and Cooling Balances

Cooling balance

$$Q_a + Q_v = Q_{\text{cool}}^{\text{dem}}$$

Absorption and electric chillers share the cooling demand.

Electricity balance

$$P_{\text{tn}} + P_g^+ + B^- = P_{\text{IT}} + P_v + \beta_a Q_a + P_g^- + B^+$$

Generation, imports and storage supply IT, cooling and exports.

$P_{\text{cool}} = P_v + \beta_a Q_a$. Both balances hold every hour.

These balances connect all component models into one operating system.

Optimization Objective

Minimize total annualized cost

$$\min_{\mathbf{u} \in \mathcal{F}} \text{TAC} = C_{\text{fixed}} + C_{\text{operation}}(\mathbf{u})$$

$\mathbf{u}$: hourly decisions. $\mathcal{F}$: component constraints and energy balances.

Fixed annual cost

- Annualized equipment investment
- Fixed operation and maintenance

Cost of operation

- Fuel and net grid purchases
- Variable O&M and carbon, less credits

The optimization selects the least-cost feasible annual schedule.

Fuel and Electricity Costs

Nuclear fuel

$$\Phi_{\text{fuel}} = \pi_f \sum_t P_{\text{rx}}(t) \Delta t$$

Fuel cost follows the reactor's thermal energy output.

π_f : fuel price. $\pi_g(t)$: hourly electricity price. Sum over the year.

Grid electricity

$$\Phi_{\text{grid}} = \sum_t \pi_g(t) [P_g^+(t) - P_g^-(t)] \Delta t$$

Import payments are offset by export revenue.

The hourly schedule determines annual fuel and electricity costs.

Carbon Cost

Annual charge or credit

$$\Phi_{\text{CO}_2} = \pi_{\text{CO}_2} E_{\text{CO}_2}$$

Annual emissions balance $\times$ scenario carbon price.

Nuclear generation

Apply a lifecycle emissions factor to net generation.

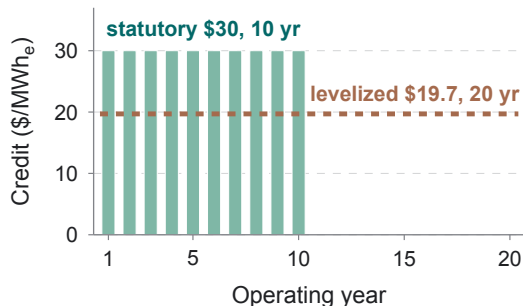
Grid exchange

Imports add emissions. Exports receive a credit at the hourly average grid intensity.

Carbon cost reflects nuclear generation and net grid exchange.

Production Tax Credit

Levelized credit



Credit on net generation

$$\Phi_{\text{ptc}} = c_{45Y} \sum_t P_{\text{tn}}(t) \Delta t$$

The study uses a levelized credit of \$19.7/MWh.

Calendar-2025 policy assumption, levelized over 20 years.

Steam extraction reduces electric output and the associated tax credits.

Optimization Workflow

Annual optimization

- **Set the inputs**

Equipment, hourly load, weather and prices.

- **Solve SMR operation**

Annual MILP over 8,760 hours.

- **Obtain the schedule**

Generation, cooling, grid exchange and storage.

Grid and gas benchmarks use direct cost calculations.

Compare annual costs under matched market and policy assumptions.

Grid-cost margin M

$$M = 1 - \frac{TAC_{\text{case}}}{TAC_{\text{grid}}}$$

Fractional annual cost savings relative to grid supply.

TAC: total annualized cost.

$M > 0$: cheaper than grid supply.

$M = 0$: same cost as grid supply.

$M < 0$: more expensive than grid supply.

Data and Scenarios

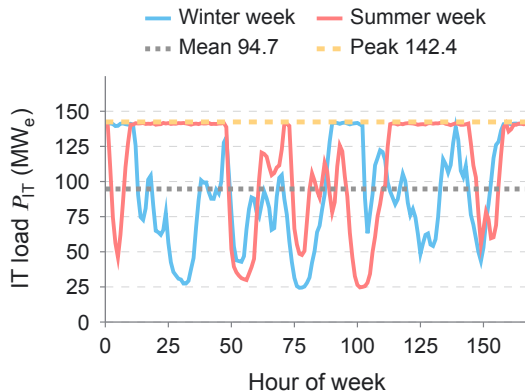
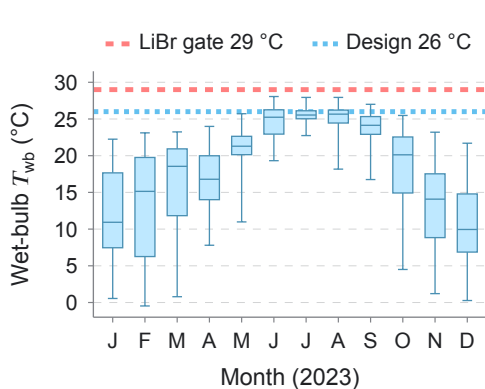
Four configurations, input data and sensitivity scenarios



Study Configurations

Case	Key configuration
■ C0	Grid electricity + electric chiller
■ C1	SMR electricity + electric chiller Grid imports and exports allowed
■ C2	SMR electricity + electric and absorption chillers Grid imports and exports allowed
■ C3	On-site natural gas combined cycle + electric chiller Islanded operation

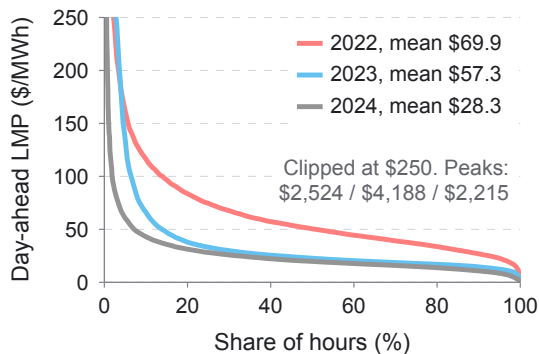
Weather and Load Shape the Cooling Duty



200 MW rated campus. Hourly IT load: 94.7 MW mean, 142.4 MW peak.

The 2023 wet-bulb peak is 28.1 °C, so the 29 °C gate never engages.

Market Inputs



	2022	2023	2024
LMP (\$/MWh)	69.9	57.3	28.3
Gas (\$/MMBtu)	6.53	2.63	2.35

The 2022 and 2024 cases test higher and lower prices around the 2023 baseline.

Reactor Capital Spans a Sixfold Range

Asset	Capital	Fixed O&M	Variable O&M	Recovery
BWRX-300 + turbine	\$7,615/kW _e	\$121/kW _e -yr	\$3.50/MWh _e	40 yr
Absorption chiller	\$450–1,200/kW _c	\$20/kW _c -yr	\$0.40/MWh _c	25 yr
Electric chiller	\$250/kW _c	\$8/kW _c -yr	\$0.50/MWh _c	25 yr
Li-ion battery	\$529/kWh	\$26.5/kW-yr	\$0.50/MWh	15 yr
NGCC, F-class	\$1,330/kW _e	\$29.3/kW _e -yr	\$2.65/MWh _e	30 yr

- Reactor anchors: FOAK \$14,700 (OPG Darlington), ATB-Mid \$7,615 (NLR ATB 2024), NOAK \$2,250 (GE-Hitachi target)
- Absorber baseline \$750/kW_c

Source: NLR ATB 2024. U.S. DOE CHP fact sheet. ASHRAE. OPG. GE-Hitachi.

Scenario Ledger: 109 Entries

Group	Sweep	Levels	Entries
G0	Baseline	2023, PUE 1.35, ATB-Mid capital, WACC 6.7%	4
G1	Full-load PUE	1.10, 1.30, 1.50	6
G2	ERCOT year	2022, 2023, 2024	12
G3	Battery	on, off	8
G4	SMR capital	FOAK, ATB-Mid, NOAK	6
G5	SMR × absorber capital	5 × 5 grid	25
G6	Carbon price	\$0, \$50, \$100/tCO ₂	12
G7	WACC	5, 6.7, 10%	3
G8	Data-center size	0.5–3.0× IT load	24
G9	Capital × market year	NOAK, \$5,000/kW _e × 2022–2024	9

Power usage effectiveness: $PUE = E_{\text{facility}}/E_{\text{IT}}$ over the same period.

G1 varies $1 + 1/(\eta_{\text{ch}} \text{COP}_v)$ at fixed cooling duty. Grid benchmark: PUE 1.35.

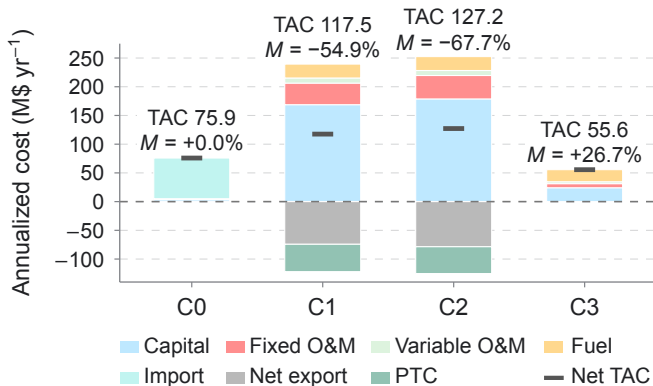
The ledger includes reused dispatch solutions and control rows.

Results

Q1 cost · Q2 absorption value · Q3 conditions for parity



Q1: SMR Supply versus the Grid



- **Both SMRs cost more**

C1: +54.9%. C2: +67.7%
versus grid supply.

- **Capital dominates**

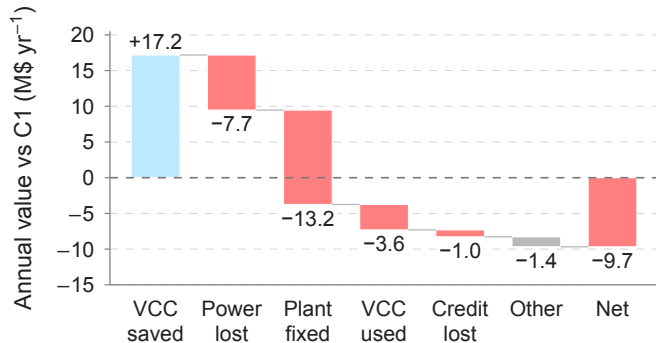
Export revenue and
production credits do not
offset the capital burden.

- **NGCC: natural gas
combined cycle**

Gas turbine + steam turbine;
lowest TAC here at \$55.6M/yr.

2023 prices, reactor capital \$7,615/kW_e, 45Y credit, zero carbon price. Positive *M*: cheaper than the grid.

Q2: Does Steam Cooling Save Money?



- **No net cost saving**

C2 adds \$9.7M/yr relative to power-only C1.

- **Cooling does save electricity**

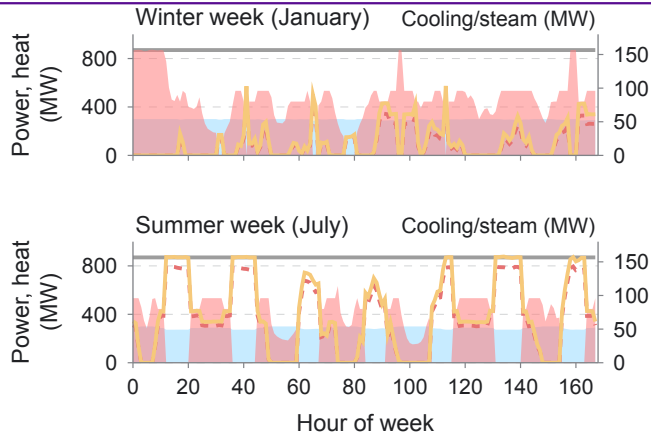
Avoided electric-chiller power is worth \$17.2M/yr.

- **Capital and lost sales dominate**

Absorber: \$13.2M/yr. Lost generation: \$7.7M/yr, plus forgone credits.

2023 baseline, C2 relative to C1. Positive bars are savings; negative bars are added costs.

Electricity Prices and the Cooling Split



- **More absorption in the higher-price week**

Winter: \$21.6/MWh

Absorption supplies 19% of cooling.

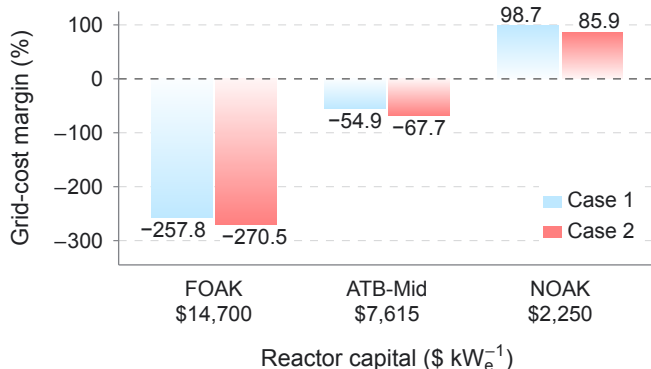
Summer: \$76.6/MWh

Absorption supplies 60% of cooling.

Legend:
Net electricity (light blue area)
Absorption cooling (yellow line)
Reactor heat (grey line)
Electric cooling (pink area)
Steam (dashed red line)

Case C2, 2023. Prices are weekly averages and shares refer to total weekly cooling.

Q3: Can SMR Supply Be Competitive?



- **Yes, at the NOAK target**

Both cases beat the grid under 2023 prices:

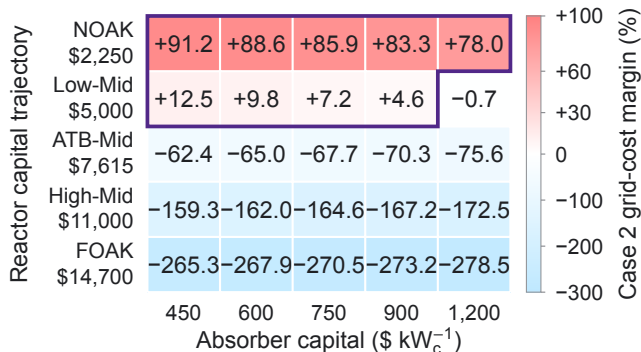
$M = +98.7\%$ for C1 and $+85.9\%$ for C2.

- **A large capital reduction**

\$14,700 to \$2,250/kW_e: about 85% below the FOAK estimate.

FOAK: first-of-a-kind. NOAK: nth-of-a-kind cost target. 2023 prices, 45Y credit and zero carbon price.

Reactor Capital Sets the Parity Boundary



- **Reactor capital must fall**

Approximate parity:
\$5,700/kW_e for C1 and
\$5,250/kW_e for C2.

- **Cheaper absorbers have less leverage**

The full absorber-cost range shifts the C2 margin by only 13.2 percentage points.

2023 prices, 45Y credit, zero carbon price. Cell values are C2 grid-cost margins; outlined cells meet grid parity.

Low Reactor Cost Does Not Guarantee Parity

Wholesale prices fell sharply
Houston Hub day-ahead price (\$/MWh)

\$69.9 → **\$57.3** → **\$28.3**
2022 **2023** **2024**

NOAK, C1	+121.5	+98.7	-0.5
NOAK, C2	+109.9	+85.9	-34.8
\$5,000, C1	+51.3	+20.0	-164.4
\$5,000, C2	+39.8	+7.2	-198.7

- **Cheaper grid power reduces SMR value**

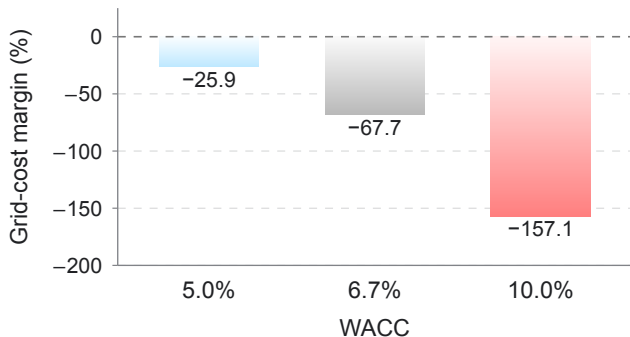
Grid purchases cost less and surplus nuclear electricity earns less.

- **Low capital cost does not ensure parity**

Even a NOAK plant can lose its advantage in a low-price market.

Cell values: grid-cost margin (%). NOAK capital is \$2,250/kW_e; each year has its own grid benchmark.

Cheaper Financing Does Not Close the Gap



- **Lower WACC reduces annual cost**

C2 TAC rises from \$95.6M to \$195.0M/yr as WACC increases from 5% to 10%.

- **Low-cost finance is insufficient**

At 5% WACC, C2 still costs 25.9% more than the grid.

WACC: weighted average cost of capital. 2023 prices, mid-range reactor capital and the study's 45Y credit.

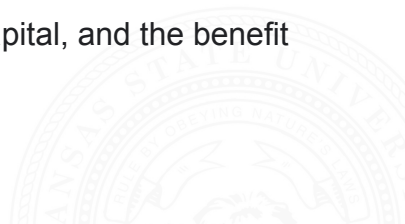
Conclusions and Future Work

Key findings and future research



Conclusions

- Both SMR configurations cost more than grid supply under the baseline assumptions.
- Adding absorption cooling raises total cost because its electricity savings do not cover equipment costs and lost generation.
- Grid parity requires substantially lower reactor capital, and the benefit depends on electricity prices.



Data-Center Demand and SMR Learning

The current study treats reactor capital as an input.

Future work links data-center demand, deployment and cost learning.

- **U.S. demand and learning**

Can U.S. data centers anchor enough SMR deployment to drive learning and lower capital cost?

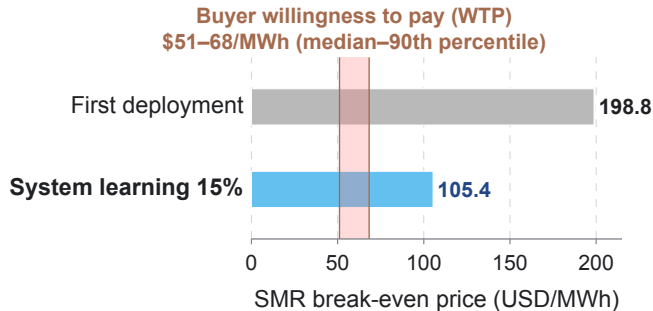
- **Break-even timing**

When can SMR supply costs fall within data centers' willingness to pay?

- **Policy and market conditions**

What policy support is needed, and how do market prices and demand growth affect the outcome?

Learning Lowers Cost, but a Gap Remains



- **Learning reduces the required price**

From \$198.8/MWh for first deployment to \$105.4/MWh in the lowest tested scenario.

- **A gap of about \$37/MWh remains**

The buyer WTP benchmark is \$68.3/MWh at the 90th percentile.

Preliminary IPWR77 deployment study at the assumed 2050 scale; prices include grid delivery.

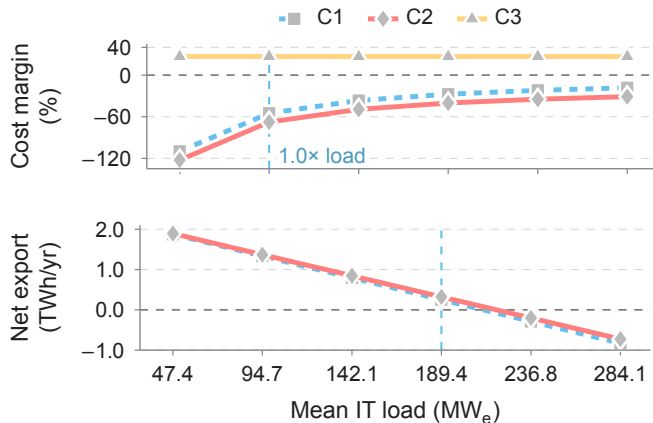
Thank You

Questions and discussion

Buxin She | Kansas State University



Campus Size and the Cost Gap



- **The gap narrows but remains**

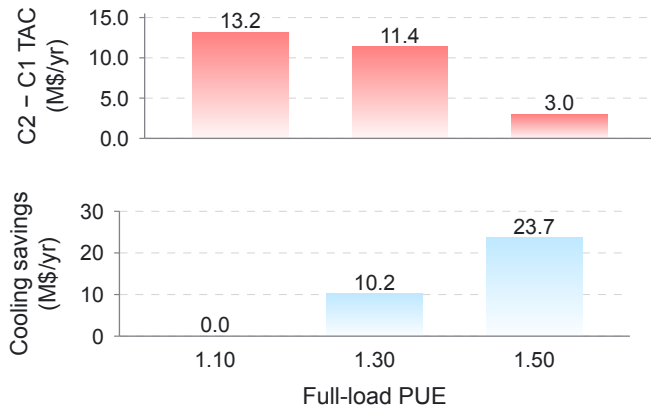
At 3× IT load, C2 still costs 31.1% more than the grid, versus 67.7% at baseline.

- **Self-use replaces exports**

Annual net exports turn into net imports between 2.0× and 2.5× IT load.

Fixed 300 MW_e reactor; IT and cooling scale together. Grid benchmark matched to each campus size.

Cooling Efficiency Changes the Absorber Penalty



- **Inefficient cooling helps**

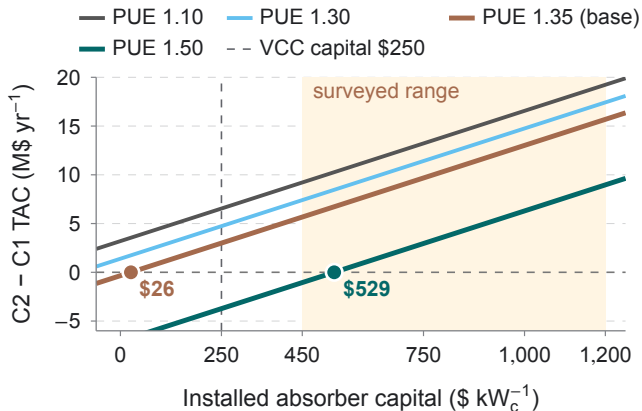
Cooling-electricity savings rise to \$23.7M/yr at PUE 1.50.

- **Still no break-even**

Even at PUE 1.50, C2 costs \$3.0M/yr more than C1 at baseline absorber capital.

PUE is the full-load design label; annual realized PUE varies. Absorber capital fixed at \$750/kW_c.

When Can Absorption Cooling Break Even?



- **Baseline cooling leaves little room**

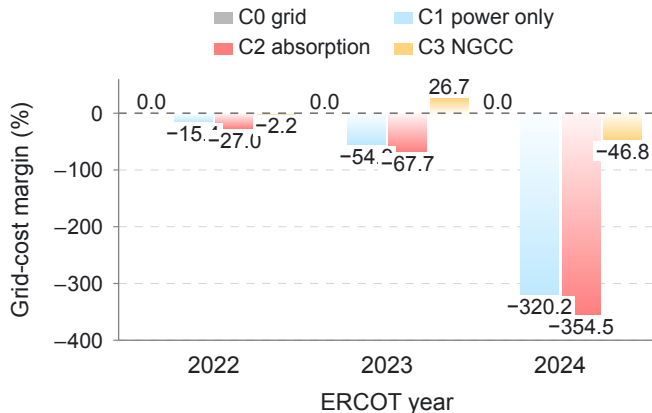
At PUE 1.35, absorber capital must fall to about \$26/kW_c.

- **Legacy cooling creates an opening**

At PUE 1.50, break-even rises to \$529/kW_c, within the lower end of the surveyed range.

Zero on the vertical axis means C2 and C1 have equal annual cost. Surveyed absorber capital: \$450–1,200/kW_c.

Cheap Grid Power Widens the SMR Cost Gap



- **Cheap grid power hurts**

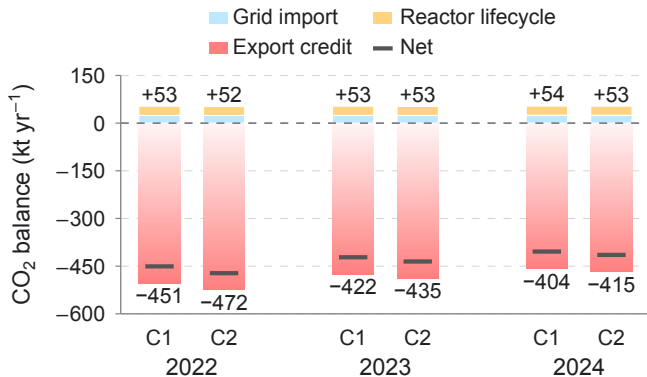
C1 costs 15.4% more than the grid in 2022, versus 320.2% more in 2024.

- **The benchmark also falls**

Grid TAC drops from \$85.1M to \$36.5M/yr, amplifying the percentage gap.

Reactor capital: \$7,615/kW_e. Each year uses its own prices, weather and grid benchmark.

Export Credits Explain Negative Carbon Balances



- **Exports outweigh counted emissions**

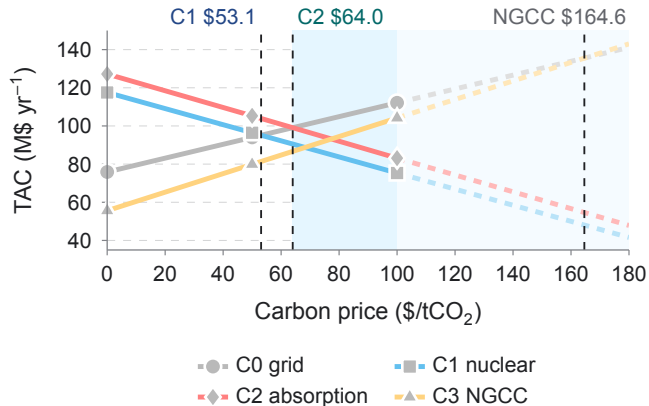
2023 C2: +52.6 kt counted emissions, -488.0 kt export credit, net -435.4 kt CO₂/yr.

- **This is an accounting balance**

Exports receive a credit at hourly average grid intensity; a negative balance does not mean physical CO₂ removal.

Positive bars: import and reactor lifecycle emissions. Negative bars: export credits. Dark ticks: annual net balance.

Carbon Pricing Can Bring SMRs to Grid Parity



- **Parity at \$53 / \$64 per tonne**

C1 reaches grid parity at \$53.1/tCO₂; C2 at \$64.0/tCO₂.

- **The threshold depends on export credits**

Crediting exports lowers the nuclear cost as carbon prices rise; the accounting rule matters.

2023 mid-range capital. Solid lines: solved \$0–100/tCO₂. Dashed lines: extrapolation beyond the solved range.

Operating Assumptions Do Not Reverse the Ranking

Assumption	C1 TAC	C2 TAC
Baseline	117.5	127.2
Two-year refueling	115.8	125.5
60-year recovery	108.4	118.0
80-year recovery	106.0	115.7
Constant IT, same energy	108.7	119.6
PTC over 40 years	127.8	137.2

TAC in M\$/yr. Grid benchmark: \$75.9M/yr; \$67.0M/yr for the constant-IT-load case. PTC: production tax credit.

- **No variant reaches grid parity**

Even with 80-year capital recovery, C2 costs \$115.7M/yr versus \$75.9M/yr for the grid.

- **C2 remains costlier than C1**

The absorption-cooling case has higher annual cost in every paired comparison.