

High-Performance and Climate-Resilient Buildings and Cities

From Annual Efficiency to Hourly Adaptive Resilience

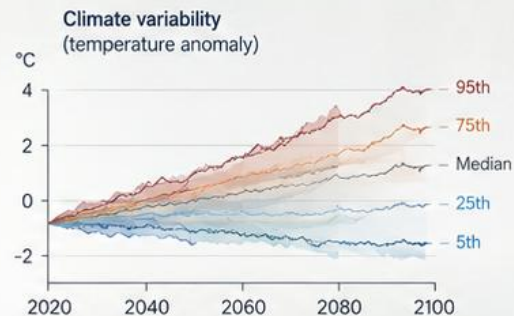
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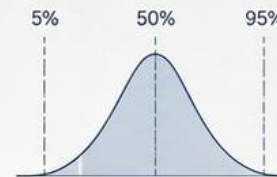


KEY MESSAGE

Buildings are entering an era where efficiency alone is insufficient. Future performance must include adaptability, survivability, flexibility, and climate resilience.



Design for uncertainty (probability distribution)



Adaptive cooling systems



Photovoltaic facades



Thermal storage



Green-blue infrastructure



District energy networks

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01/15

The Great Transition in Building Performance Thinking

PAST PARADIGM



Annual energy metrics



Static climate assumptions



Deterministic simulations



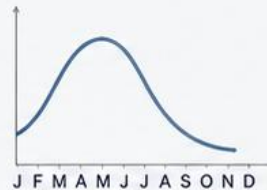
Average occupancy



Energy efficiency focus



Isolated buildings



EMERGING PARADIGM



Hourly resilience metrics



Probabilistic climate futures



Dynamic operation



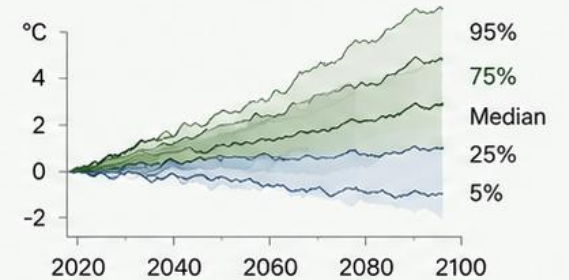
Adaptive occupancy behavior



Survivability and flexibility



District-scale integration



Thermal Storage



Renewable Energy



Grid Interaction



AI-Assisted Operation

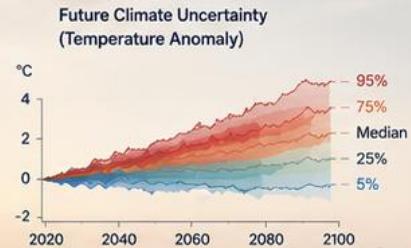


Buildings are still designed deterministically while future climates and infrastructures are fundamentally probabilistic.

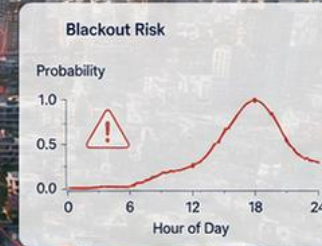
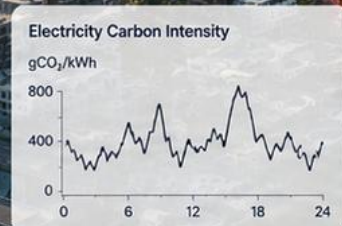
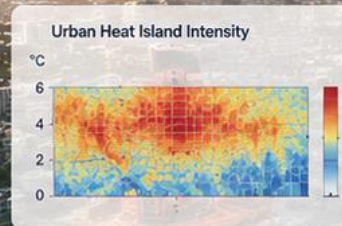
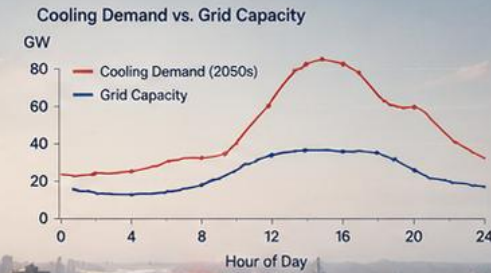
Why Are Traditional Building Metrics Becoming Insufficient?

Key Problems

-  Heat waves exceed design assumptions
-  Cooling demand peaks destabilize grids
-  Urban heat island amplifies overheating
-  Blackout risks increase
-  Dynamic electricity carbon intensity fluctuates hourly
-  Extreme weather creates cascading failures



Heatwave Duration Increasing
+4.2x
by 2100 (median)



Cascading Failure Risk



Core Insight



Annual energy use no longer captures:

- thermal survivability,
- adaptive operation,
- infrastructure stress,
- or resilience capacity.

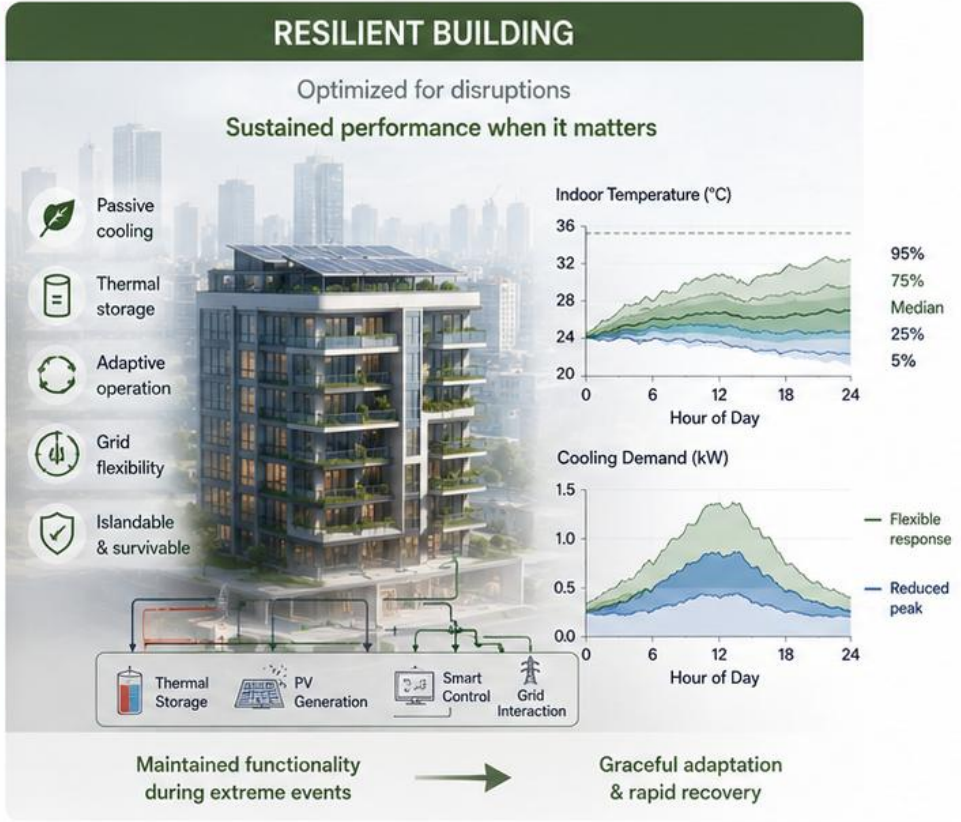
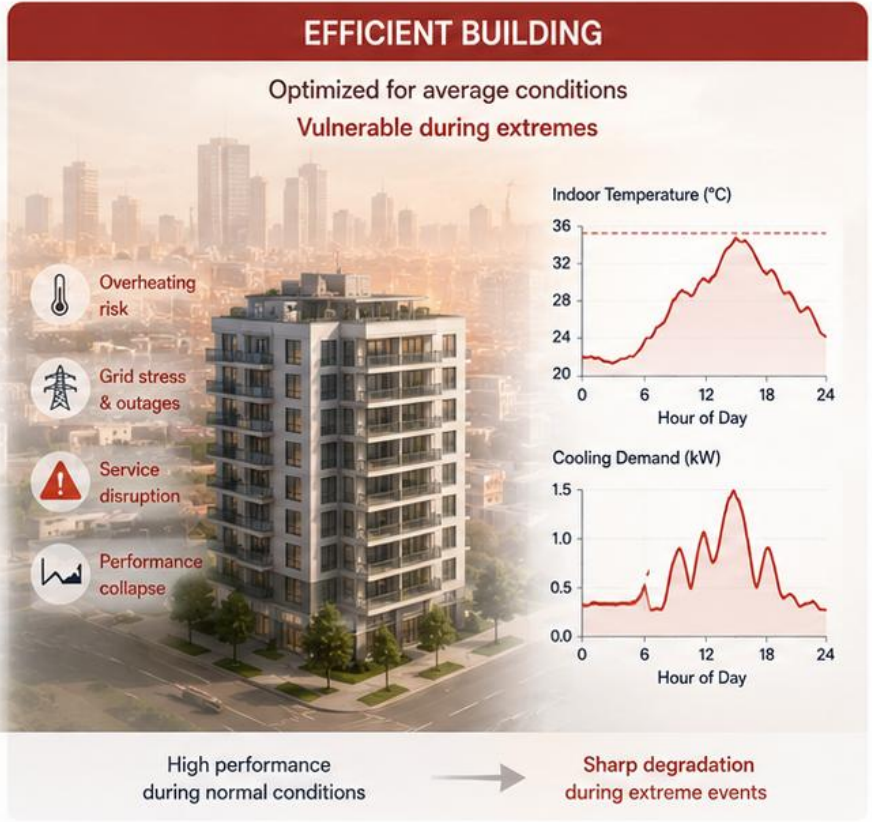


A net-zero building can still fail during a three-day blackout.

RESILIENCE IS NOT EFFICIENCY

Comparative Framework

Efficient Building	vs.	Resilient Building
 Optimized for average conditions		Optimized for disruptions
 Annual metrics		Hourly adaptability
 Low energy demand		Functional continuity
 Static optimization		Dynamic adaptation
 Energy minimization		Survivability



Buildings optimized only for average conditions may fail during extreme events.

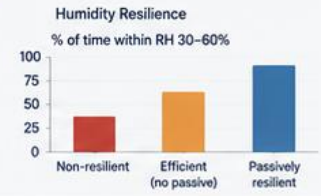
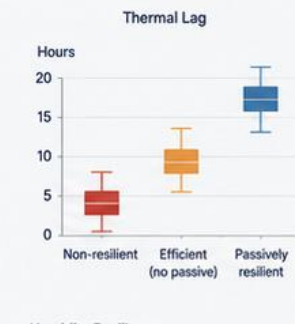
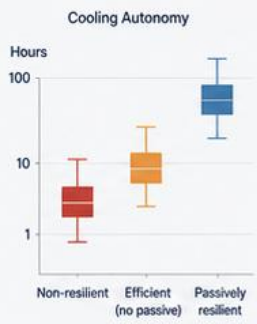
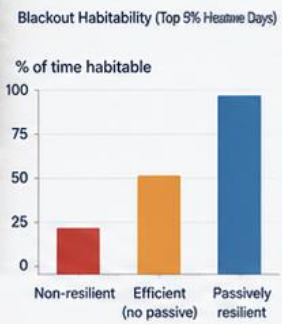
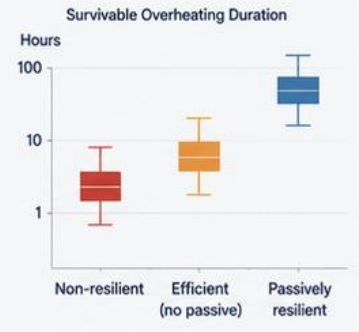
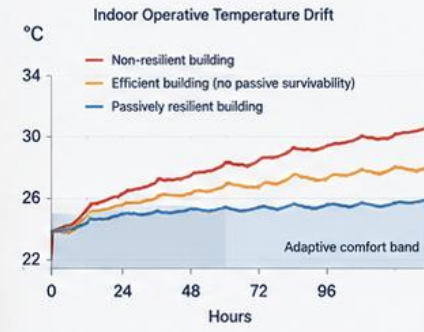
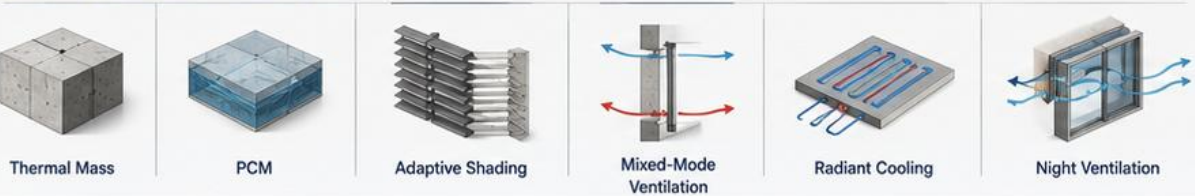
Passive Survivability under Climate Extremes

Metrics

- Indoor operative temperature drift
- Survivable overheating duration
- Blackout habitability
- Cooling autonomy
- Thermal lag
- Humidity resilience



Passive Survivability Technologies



Future buildings must maintain habitable indoor conditions even during infrastructure disruptions.

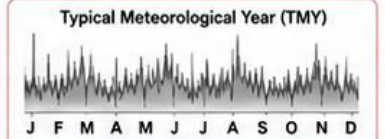
DETERMINISTIC BUILDINGS IN A PROBABILISTIC CLIMATE

CONVENTIONAL DESIGN

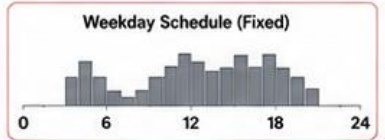
Deterministic, Static, and Average-Based



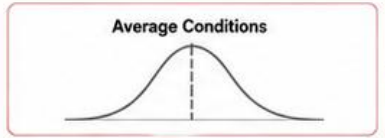
TMY Weather File
Single typical year



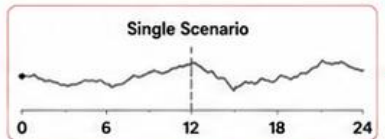
Fixed Occupancy
Constant schedules



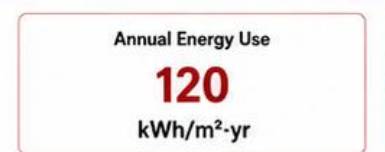
Average Climate
Long-term mean values



Single Operational Scenario
One set of assumptions



Static Energy Model
Deterministic output



VS.

DETERMINISTIC OUTPUT

Single Value
Low Insight into Risk

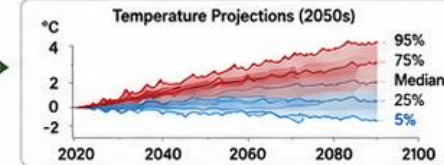


FUTURE ADAPTIVE DESIGN

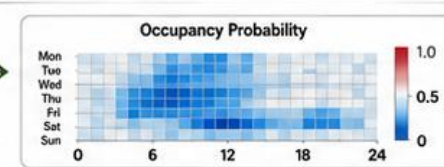
Probabilistic, Dynamic, and Resilience-Oriented



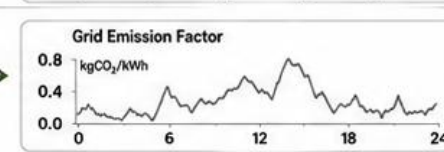
Climate Ensembles
Multiple future climates



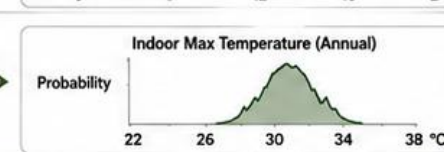
Stochastic Occupancy
Behavioral uncertainty



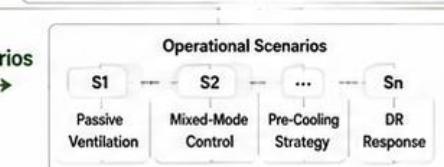
Dynamic Grid Emissions
Hourly carbon intensity



Uncertainty Propagation
Quantify output ranges



Adaptive Operation Scenarios
Multiple strategies



RESILIENCE METRICS

Survivability Probability

Overheating Risk

Outage Tolerance

Grid Impact Distribution



CORE MESSAGE: FUTURE RESILIENCE REQUIRES SCENARIO-BASED AND UNCERTAINTY-AWARE SIMULATION.

PHYSICS VS AI VS HYBRID INTELLIGENCE

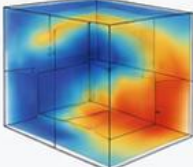
PHYSICS-BASED SIMULATION

First principles • Interpretable • Mechanistic

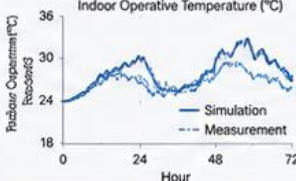


Governing equations
$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (\rho c_p u T) = \nabla \cdot (k \nabla T) + S_T$$
$$\nabla \cdot u = 0$$
$$Q_{zone} = \sum_{hit} \dot{m} c_p (T_i - T_{zone}) + Q_{int}$$

Detailed outputs



Indoor Operative Temperature (°C)



Interpretable

Based on physical laws

Computationally expensive

High fidelity → High cost

Reliable for known systems

Strong extrapolation within physics domain

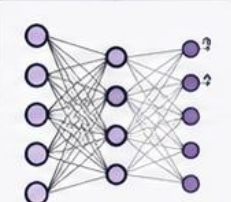
BEST FOR:
Detailed analysis, new systems,
safety-critical design, code compliance

PURE AI (DATA-DRIVEN)

Black-box • Fast • Data-dependent

Inputs

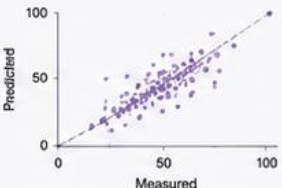
Weather
Occupancy
HVAC
Geometry
Materials
...



Outputs

Energy Use
Temperature
Comfort
Peak Load
...

Black-box prediction



Fast inference



$10^4 - 10^6 \times$
faster than
physics simulations

Fast

Orders of magnitude faster

Weak extrapolation

Fails outside training distribution

Data-dependent

Performance = f(data quality & quantity)

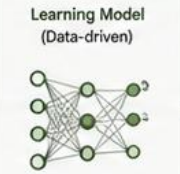
BEST FOR:
Large-scale screening, predictive control,
real-time optimization, pattern recognition

HYBRID INTELLIGENCE

Physics-informed • Data-augmented • Adaptive

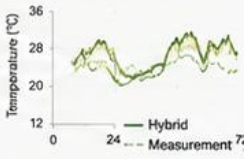
Physics Model (White-box)

$\dot{x} = f(x, u, \theta)$
 $y = g(x, \theta)$



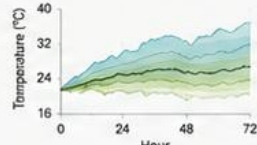
Learning Model (Data-driven)

Hybrid Prediction (Physics-informed)



Residual learning, constraints, conservation laws, uncertainty

Uncertainty-aware



Explainable & physically consistent

Heat balance respected

Mass conservation respected

Causality preserved

Adaptive and grounded

Combines physics reliability and AI flexibility

Physics-informed learning

Better generalization, data efficiency, interpretability

Future frontier

Towards trustworthy, resilient, and adaptive buildings

BEST FOR:
Resilient design, adaptive operation,
uncertainty quantification, future climates

KEY MESSAGE

AI should not replace physics.

The future lies in hybrid physics-informed machine learning.

ML SUPERIORITY DEPENDS ON:

Data richness
Quantity, quality, representativeness

Nonlinearities
Complex dynamics and behaviors

Uncertainty
Noise, variability, unknowns

Feature interactions
High-dimensional couplings

Application context
Objective, risk, and decision needs

➡ THE BOTTOM LINE: Physics gives us **truth**. AI gives us **speed**. Hybrid intelligence gives us **the future**.

SHENZHEN vs BRUSSELS

TWO CLIMATE FUTURES, ONE RESILIENCE CHALLENGE

SHENZHEN, CHINA

Hot-Humid Megacity



CLIMATE FUTURE (2050s)



KEY RESILIENCE RISKS



FOCUS AREAS



ONE SHARED CHALLENGE

Build Resilient Buildings for an Uncertain Future

Survive Extremes
Maintain habitable indoor conditions during heatwaves, cold spells, storms, and outages.

Adapt Dynamically
Respond to uncertain weather, occupancy, and grid conditions in real time.

Reduce System Stress
Lower peak demand, support grid stability, and avoid infrastructure overload.

Enable Long-Term Resilience
Design for flexibility, redundancy, and future climate uncertainty.

Different climates. Different risks.
Same goal: Resilient, adaptable, future-ready buildings.

BRUSSELS, BELGIUM

Temperate Maritime City



CLIMATE FUTURE (2050s)



KEY RESILIENCE RISKS



FOCUS AREAS



TWO CLIMATE FUTURES. ONE RESILIENCE CHALLENGE.

Resilient buildings adapt to their context.
Resilient cities prepare for their future.



BUILDINGS AND CITIES ARE COUPLED

Buildings Cannot Be Simulated Independently from Cities

COUPLED DYNAMICS



UHI ↔
Cooling Demand



Morphology ↔
Ventilation



AC Rejection Heat ↔
Outdoor Temperature



Thermal Stress ↔
Health



Air Pollution ↔
Microclimate

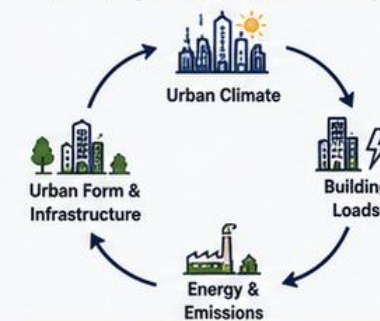


Urban Form ↔
Energy Consumption



KEY INSIGHT

Buildings and urban climate form a dynamic feedback loop.



EXAMPLES OF FEEDBACKS



THE FEEDBACK
LOOP DRIVES:



Higher
Temperatures



Higher
Energy Demand



Worse Air
Quality



Greater Health
Risks



Higher Infrastructure
Stress & Costs



RESILIENT CITIES REQUIRE
COUPLED, SYSTEMS-BASED
DESIGN AND SIMULATION.

ENERGY FLEXIBILITY

Energy Flexibility as a Climate Adaptation Tool

FLEXIBILITY TECHNOLOGIES



THERMAL MASS

- Absorbs excess heat
- Reduces indoor temperature swings



PCM (PHASE CHANGE MATERIALS)

- Stores latent heat
- Stabilizes indoor conditions



BATTERIES

- Stores electricity
- Provides backup and peak shaving



TABS (THERMALLY ACTIVATED BUILDING SYSTEMS)

- Uses building mass for heating/cooling
- High efficiency



PREDICTIVE PRE-COOLING

- Anticipates heatwaves
- Pre-cools when energy is cheap/clean



DEMAND SHIFTING

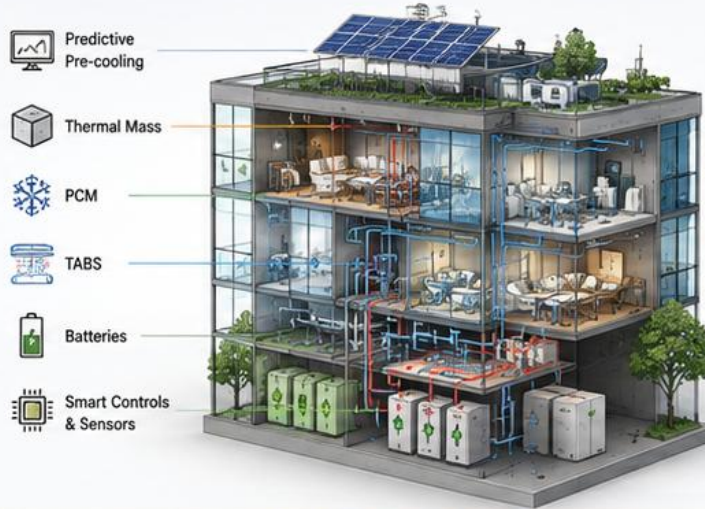
- Moves loads to low-cost /low-carbon periods
- Reduces grid stress



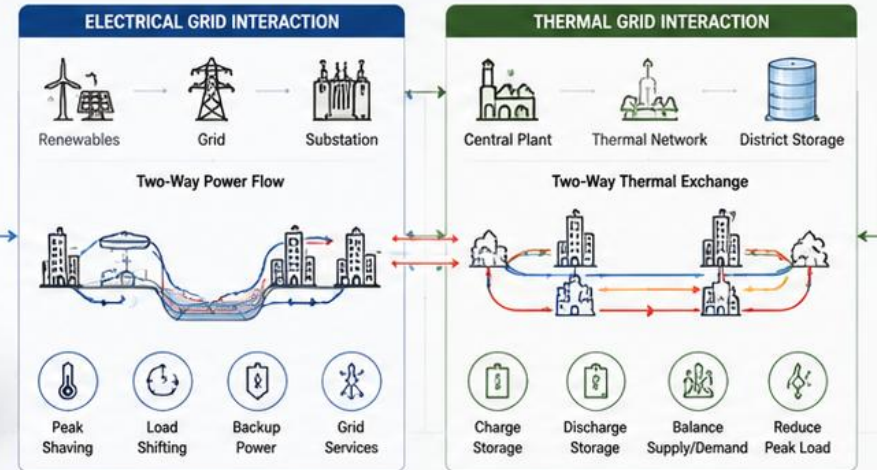
DISTRICT STORAGE

- Shared thermal/electric storage
- Enhances community resilience

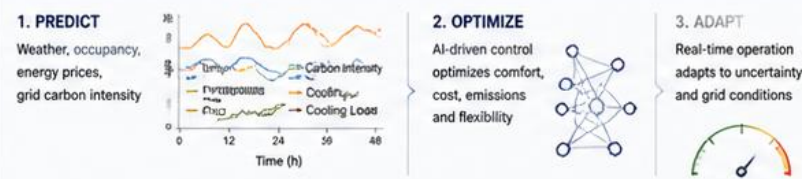
ADAPTIVE BUILDING OPERATION



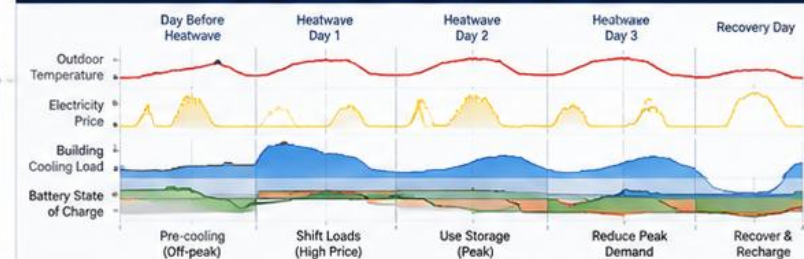
DYNAMIC INTERACTION WITH GRIDS & CLIMATE



PREDICT - OPTIMIZE - ADAPT



FLEXIBLE OPERATION EXAMPLE (SUMMER HEATWAVE)



FLEXIBILITY BENEFITS



ENHANCED RESILIENCE

Maintain comfort and operations during extreme events and outages



LOWER ENERGY COSTS

Use energy when it is cheaper and cleaner



LOWER EMISSIONS

Shift and store energy to maximize renewable use



REDUCED GRID STRESS

Help stabilize the grid and avoid infrastructure overloads



IMPROVED COMFORT & HEALTH

More stable indoor conditions and better air quality



Lower Peak Loads



Lower Energy Costs



Lower Emissions



Higher Resilience



Better Comfort



FUTURE BUILDINGS MUST NOT ONLY CONSUME ENERGY EFFICIENTLY.



THEY MUST DYNAMICALLY INTERACT WITH GRIDS AND CLIMATE CONDITIONS.



STORAGE IS THE CORE OF RESILIENCE

Storage and Scale: The Core of Carbon-Neutral Resilience

STORAGE SYSTEMS



THERMAL STORAGE

- Hot & cold water tanks
- Modular buffer storage
- Load shifting & peak shaving



BATTERIES

- Li-ion / Flow batteries
- Short-duration storage
- Grid services & backup



ATES (AQUIFER TES)

- Seasonal heat storage
- High capacity
- Long-term resilience



BTES (BOREHOLE TES)

- Borehole field storage
- Building & district scale
- Seasonal balancing



HYDROGEN

- Electrolyzer + Storage
- Long-duration storage
- Clean fuel & grid balancing



EV INTEGRATION

- Vehicle-to-Building (V2B)
- Vehicle-to-Grid (V2G)
- Mobile storage assets



DISTRICT THERMAL BALANCING

- Shared thermal networks
- Decentralized storage
- Demand-supply matching



STORAGE AT MULTIPLE TIME SCALES

SHORT DURATION (Seconds – Hours)



Batteries, Building Thermal Mass

DAILY (Hours – Days)



Thermal Tanks, Ice Storage, EVs

SEASONAL (Days – Months)



YEARS TO DECADES (Years – Decades)



District Thermal Storage, Hydrogen

STORAGE ENABLES



Load Shifting



Peak Shaving



Backup Power



Renewable Firming



Energy Arbitrage



Grid Stability



Resilient Communities

CORE INSIGHT

Storage transforms:



INTERMITTENT RENEWABLES

+



FLEXIBLE BUILDINGS

+



RESILIENT DISTRICTS



INTO INTEGRATED ADAPTIVE INFRASTRUCTURE.

KEY BENEFITS



Enhances energy security and system reliability



Reduces peak demand and infrastructure stress



Enables deeper renewable integration



Improves resilience to extreme events and outages



Supports carbon-neutral and sustainable futures



STORE TODAY. ADAPT TOMORROW. RESILIENT FOREVER.



FUTURE ADAPTIVE BUILDINGS

Buildings as Adaptive Energy Organisms

ADAPTIVE CAPABILITIES



ANTICIPATE & PREPARE

Pre-cool before grid stress events



SENSE & SELF-ADJUST

Adaptive ventilation and shading in real time



NEGOTIATE & COORDINATE

Energy and flexibility exchange with districts



PREDICT & PROTECT

Predict occupant discomfort and indoor conditions



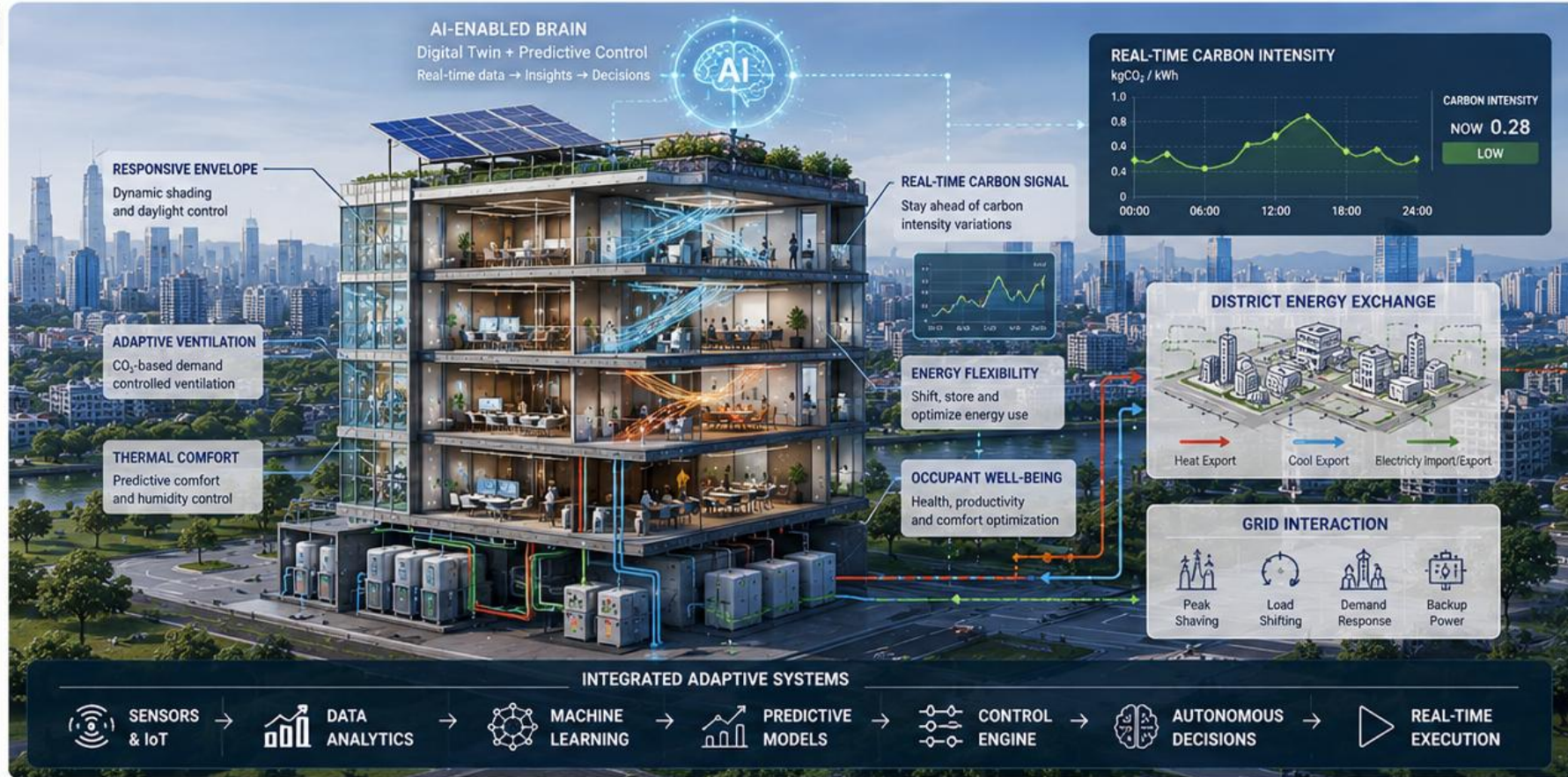
RESPOND TO CARBON

Operate based on real-time carbon intensity



ADAPT & OPTIMIZE

Continuously learn and adapt operation strategies



FUTURE FUNCTIONS



Pre-cool before grid stress



Self-adjust ventilation



Negotiate energy with districts



Predict occupant discomfort



Respond to real-time carbon intensity



Dynamically adapt operation

FINAL MESSAGE

The next generation of buildings will be:
adaptive,
predictive,
flexible,
and **climate-responsive.**



ADAPTIVE

THE NEXT GENERATION OF BUILDINGS WILL BE:

PREDICTIVE

FLEXIBLE

CLIMATE-RESPONSIVE



CONVERGING RESEARCH AGENDAS

Integrated Solutions for Climate Resilient and Carbon-Neutral Built Environments

ULiège SBD Lab – Core Research Agendas



WHOLE-LIFE CARBON

- Life cycle assessment
- Embodied & operational carbon
- Decarbonization pathways



RESILIENT COOLING

- Adaptive cooling strategies
- Thermal comfort & health
- Heat stress mitigation



DISTRICT ENERGY SYSTEMS

- Low-carbon energy networks
- Sector coupling
- Renewable integration



THERMAL STORAGE

- Short & long-term storage
- PCM, BTES, ATEs
- Seasonal balancing



DYNAMIC EMISSIONS

- Real-time carbon intensity
- Dynamic LCA
- Climate impact tracking



AI & DATA-DRIVEN METHODS

- Machine learning
- Digital twins
- Decision intelligence



CROSS-CUTTING ENABLERS



Open Science
& Data Sharing



Interdisciplinary
Collaboration



Capacity Building
& Education



Multi-Scale
Integration



Policy & Market
Alignment



Societal Impact
& Co-Benefits

Partner Institutions – Key Contributions



AI URBAN SIMULATION

- Urban digital twins
- High-resolution modeling
- Scenario exploration



UNCERTAINTY MODELING

- Probabilistic methods
- Sensitivity analysis
- Risk assessment



MPC AND FLEXIBILITY

- Predictive control
- Demand response
- Grid flexibility



URBAN CLIMATE ADAPTATION

- Climate risk assessment
- Adaptation strategies
- Nature-based solutions



EXPLAINABLE ML

- Interpretable models
- Feature importance
- Trustworthy AI



DATA & INFRASTRUCTURE

- Data sharing
- Open platforms
- Scalable computing



CLIMATE RESILIENCE REQUIRES INTEGRATING **BUILDING PHYSICS**, **URBAN CLIMATE SCIENCE**, **UNCERTAINTY MODELING**, AND **INTELLIGENT INFRASTRUCTURE OPERATION**.



FINAL VISION

The Future of Climate-Resilient Cities

The next generation of sustainable buildings will not be defined only by efficiency.

They will be defined by their ability to:



remain **habitable**



adapt dynamically



interact intelligently



and operate **resiliently**

under uncertainty and climate extremes.



Heatwaves



Floods



Storms



Droughts



Sea Level Rise

ADAPTIVE BUILDINGS

Dynamic envelope
Intelligent controls
Predictive operation

DISTRICT ENERGY SYSTEMS

Integrated heating & cooling
Low-carbon networks
Waste heat recovery

THERMAL & ELECTRICAL STORAGE

Short & long-term storage
Flexibility & resilience
Peak shaving & backup

RESILIENT PUBLIC SPACES

Health & well-being
Community & equity
Nature-based solutions

RENEWABLE INTEGRATION

Solar, wind & hydro
Clean electricity
Local generation

GREEN-BLUE INFRASTRUCTURE

Urban forests
Water sensitive design
Cooling & biodiversity

AI & DATA-DRIVEN OPERATIONS

Real-time sensing
Digital twins
Decision intelligence



LOW CARBON
FUTURE



CLIMATE
RESILIENCE



HUMAN
WELL-BEING



ECONOMIC
PROSPERITY



SOCIAL
EQUITY



Climate resilience is no longer only an engineering problem.
It is becoming the **defining infrastructure**
challenge of the 21st century.



ADAPTIVE
SYSTEMS



INTELLIGENT
INFRASTRUCTURE



RESILIENT
COMMUNITIES



SUSTAINABLE
PLANET

TOGETHER FOR A
RESILIENT FUTURE

High-Performance and Climate-Resilient Buildings and Cities

From Annual Efficiency to Hourly Adaptive Resilience

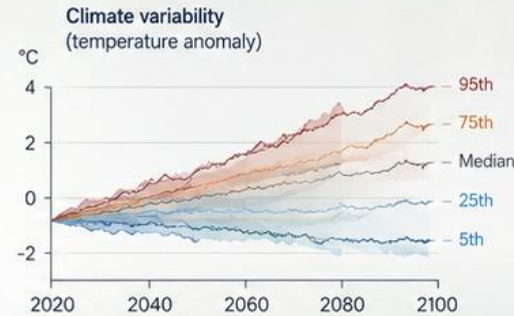
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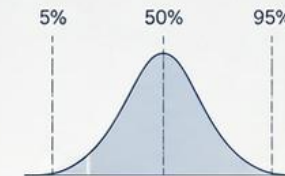


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Design for uncertainty (probability distribution)



Adaptive cooling systems

Photovoltaic facades

Thermal storage

Green-blue infrastructure

District energy networks

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