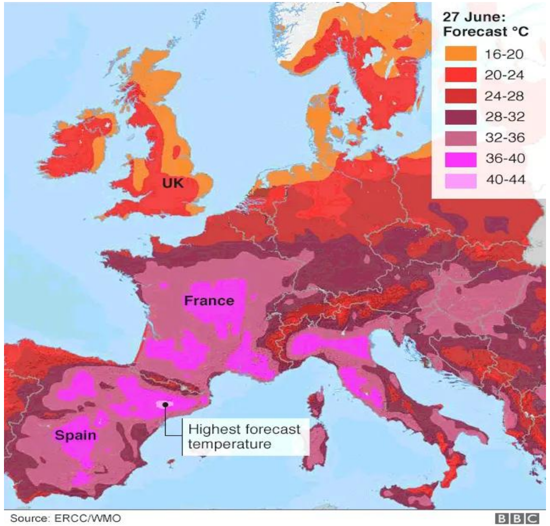
Building Energy Resilience in Cold Climates

Challenges, Framework, Indicators, Techno-Social Perspective

Hassam ur Rehman, PhD.
Senior Scientist & Research Fellow, VTT Technical Research Centre of Finland

VTT – beyond the obvious


27 June:
Forecast °C
16-20
20-24
24-28
28-32
32-36
36-40
40-44
UK
France
Spain
Highest forecast temperature
Source: ERCC/WMO
BBC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Background and rational

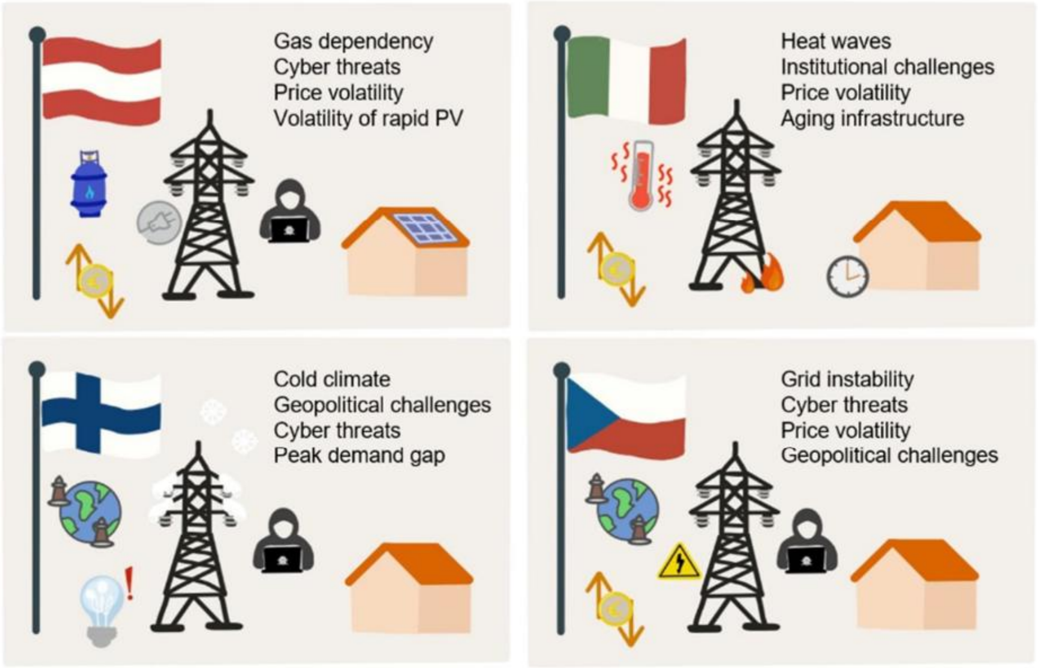
- The future is uncertain and full of various threats
  - Climate crises are becoming more frequent.
  - 399 natural disasters, **86,000 deaths**, **93 million people affected**, and **€192.7B in losses in 2024-25**.
  - **Future crises will be more diverse, interconnected, and unpredictable**
  - **The built environment is central to resilience**
- Thus require capacity to **prepare also for unexpected** and unknown crises
- Paris agreement (2015): **Increase ability to adapt, strengthen resilience and mini risk** to the adverse impacts of climate change.

Resilience in the built environment: Key characteristics for solutions to multiple crises - ScienceDirect

Current challenges

- Ukraine war, 2022
  - Market integration transmitted political price shocks regardless of mix
- Baltic seas incidents, 2022-2024
  - Nordstream, Baltic connector, Eslink 2. Critical energy infrastructure is now an active target → Anchor dragging
- Strait of Hormuz crises, 2026
  - Even a structurally buggered region is exposed through globe price transmissions. Nordic fuel costs rose withing days

Stressors identified (in few countries, 2025)



Finland published guidelines on preparedness for resilience in 2024.

https://www.resped-project.eu/wp-content/uploads/RESPED_Deliverable-1.1_Final.pdf

Stressor categories

Stressor Category	Representative Stressors
Climate & Environmental	Extreme temperatures (heatwaves, cold spells), storms, flooding, snowfall, low renewable generation periods
Market & Economic	Energy price volatility, fuel and component supply chain disruptions, carbon pricing pressures
Infrastructure & Technical	Aging or fragile infrastructure, lack of interoperability, limited monitoring and control systems, shortage of skilled workforce
Geopolitical & Security	Attacks on infrastructure, political tension, conflicts, dependency on imported components
Policy & Governance	Fragmented governance, institutional inertia, lack of emergency planning, stakeholder information asymmetry
Social, Behavioural & Cyber	Low awareness and preparedness, resistance to automation and flexibility, equity and accessibility gaps, cybersecurity vulnerabilities

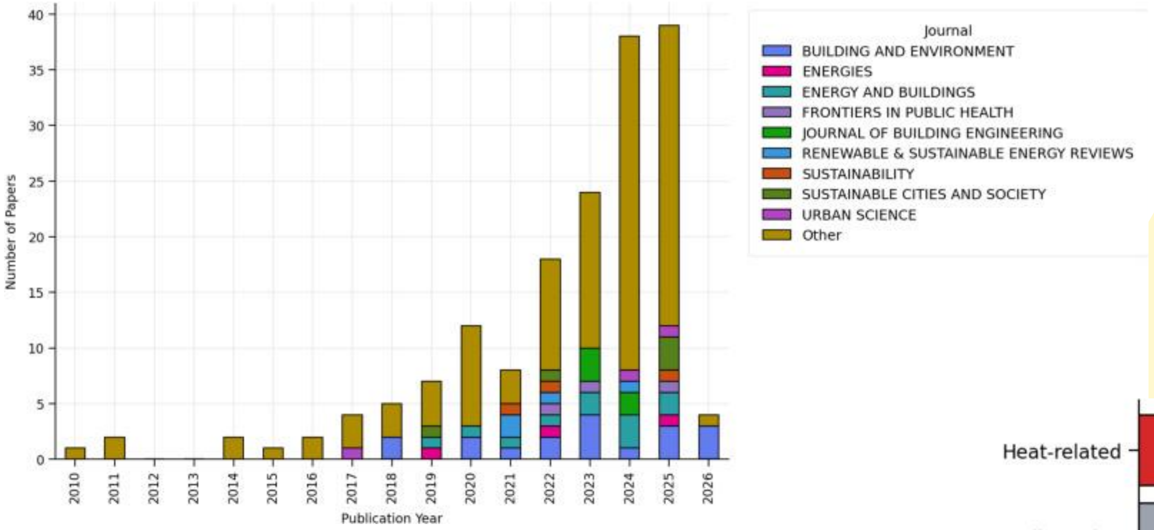
https://www.resped-project.eu/wp-content/uploads/RESPED_Deliverable-1.1_Final.pdf

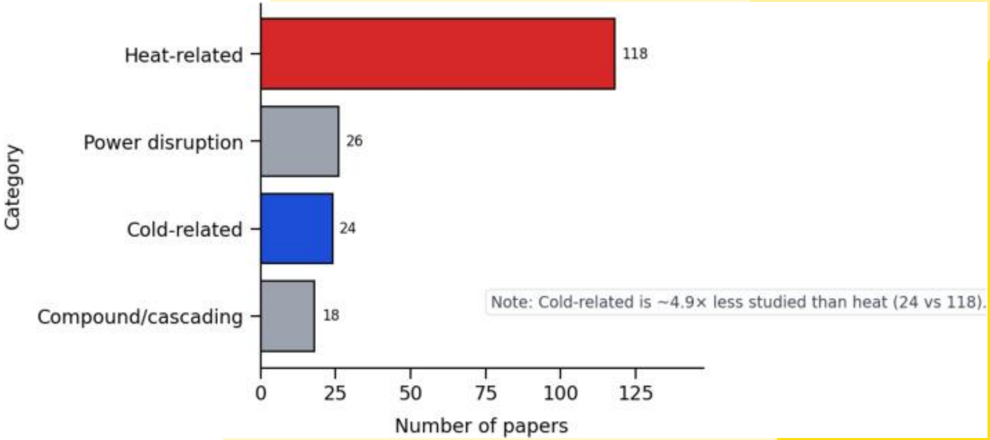
The gap between reputation and reality

- **Built for**
  - Market disruptions
  - Bilateral trust based agreements between established partners
  - Peacetime protocols and weather driven supply interruptions
- **Now facing**
  - Climate change
  - Deliberate hybrid and attack on critical energy infrastructure
  - Geopolitical price transmission across markets regardless of domestic mix
  - Demand transformation: electrification of transport and industry, data centers

State of the art and impact of resilience?

State of the art





https://doi.org/10.1016/j.enbuild.2026.118111

Impact of resilience: Buildings

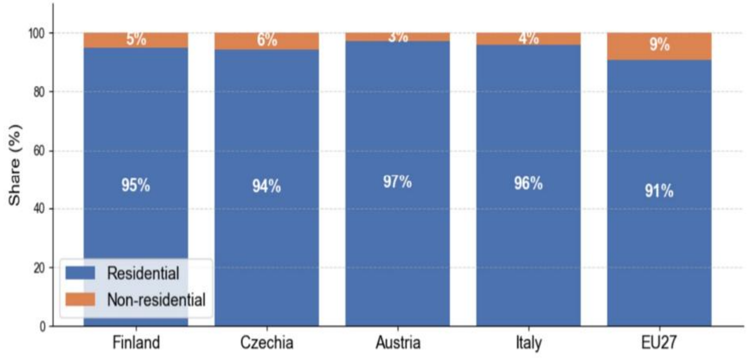


Figure 5: Share of residential and non-residential buildings in the pilot countries vs EU27 (Data from DSO, 2020)

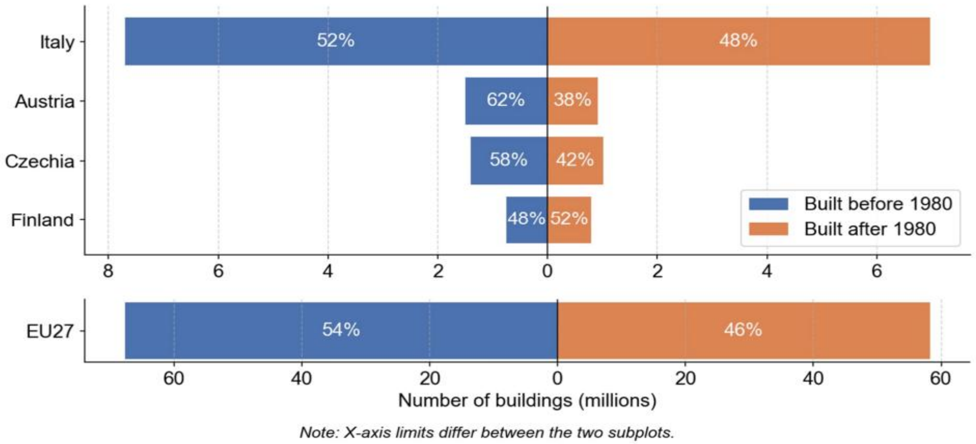


Figure 4: Number of buildings and share of those built before and after 1980 (Year of Data: Finland 2024 (Statistics Finland, 2024), Czechia 2024 (CZCO, 2024), Austria 2021 (Statistics Austria, 2021), Italy 2023 (Estrada Poggio, 2025)

Around 65% are multi dwelling buildings are built before 1980 in Sweden and in Finland it is 50%

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Impact of resilience: Population

Finland

	Count	*Share*
Population (Finland)	**5 603 851**	*100 %*
- 0-3 years	*188 012*	*3 %*
- 0-3 y (one parent)	*188 012*	*3 %*
- 75 + years	*626 643*	*11 %*
Potential evacuation count	**1 002 667**	**18 %**

Sweden

	Count	Share
Population (Sweden)	10 587 694	100 %
- 0-3 years	331 266	3 %
- 0-3 years (one parent)	331 266	3 %
- 75+ years	1 232 087	12 %
Potential impact and evacuatio	1 894 619	18 %

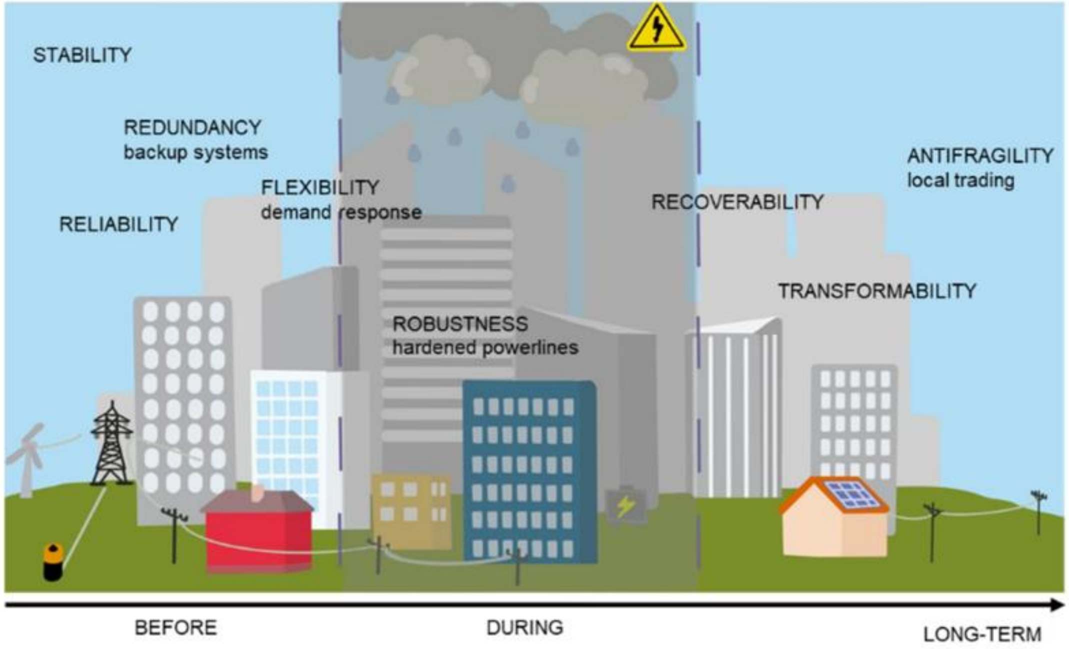
https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0104__BO0104D/BO0104T01/
https://stat.fi/fi/palvelut/tilastodatapalvelut/tilastotietokannat

Research gap

- **Current studies mainly focus on**
  - Energy efficiency, flexibility, grid availability
  - Hot climate and overheating, siloed
  - Regulations are unclear, lack of definition
  - Cost centric approach
- **But fewer studies integrate**
  - Cold and extreme climate resilience
  - Active resilience and survivability
  - User-centric and technical resilience indicators
  - Occupant behavior / social vulnerability
  - Recovery and adaptation capacity
  - Long-duration outage preparedness

Technical concept

Unpacking concepts related to resilience



Stability: Maintains or restores equilibrium.

Reliability: Maintains consistent performance.

Redundancy: Provides backup when systems fail.

Flexibility: Adapts to evolving crises.

Robustness: Prepared before disruptions occur.

Recoverability: Restores performance after disruption.

https://www.resped-project.eu/wp-content/uploads/RESPED_Deliverable-1.1_Final.pdf

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Definition of energy resilient buildings

- Building that can maintain (during power outage):
  - the indoor temperature within the habitability thresholds
  - provide survivability conditions → low level of electrical power for essential services

- The aim:
  - reduce impact on the health of the building's occupants
  - reduce damage to the building's structure.
  - Energy-efficient to conserve heat and energy.

- Finally, improve its long-term resilience for future disruptive event

Definition	City Level	Building Level	Climate/Region Context
Ability to absorb, adapt and absorb to the disruptive event	✓	✗	Mild, hot
Ability to respond to the change and returning to stability	✓	✗	✗
Ability to minimize the interruption caused by the hazardous event	✗	✗	United States of America
Ability to plan for, recover from and adapt to adverse event over time	✓	✗	✗
Ability to tolerate disruptive event and continue to provide affordable service to the end user	✓	✓	United Kingdom
Ability to have a safe energy supply chain that can resist shocks and adapts	✓	✗	European
Ability to predict, absorb, adapt and recover fast from the disruptive event	✓	✗	United Kingdom
Ability to withstand disruptive event with high impact and low probability; recover fast after the event; learn to adapt and prevent impact	✓	✗	Mild, hot
Ability to maintain reliable operation during extreme event	✓	✗	United Kingdom
Ability to meet the desired performance levels during the disruptive event as it is in normal operation	✗	✓	United States, warm
Ability to recover to the normal and secure state after gradual decline under increasing stress and disruption	✓	✗	✗

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Habitability and survivability

- **Habitability**
  - A building's ability to maintain **safe and livable indoor conditions** during a power outage.
- **Passive Habitability (Passive Resilience)**
  - Achieved through **thermal mass, insulation, and airtightness**.
- **Active Habitability (Active Resilience)**
  - Uses **PV panels, batteries, or backup generators**.
- **Survivability**
  - Provides **power for essential services**, enabling occupants to safely remain in the building.

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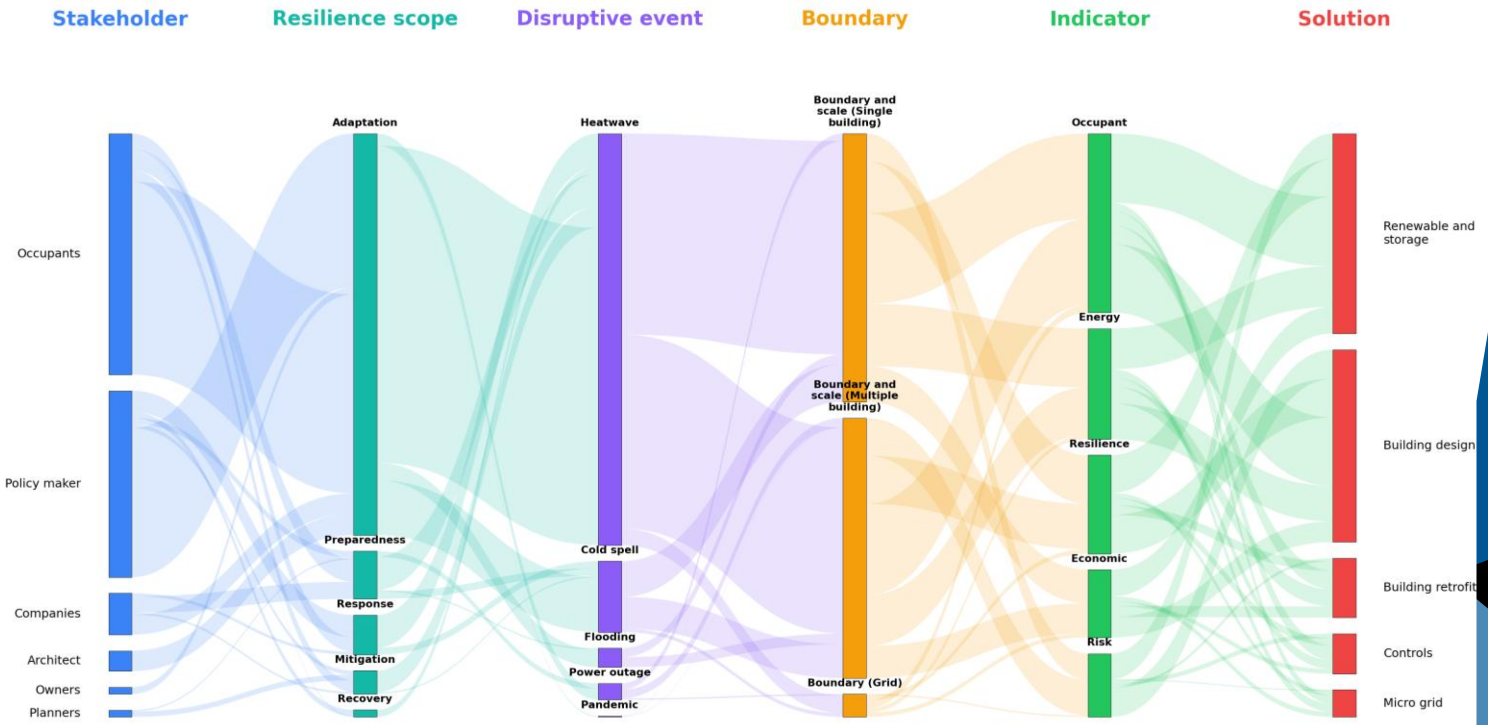
Energy resilience framework



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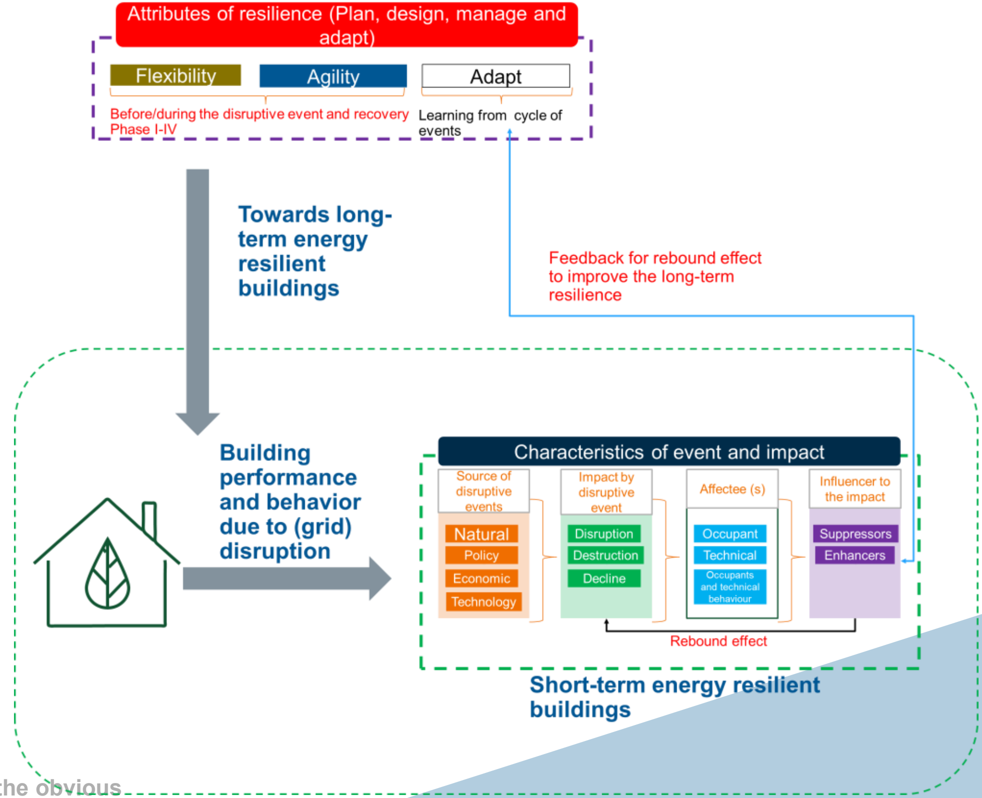
Positioning energy resilient building concept



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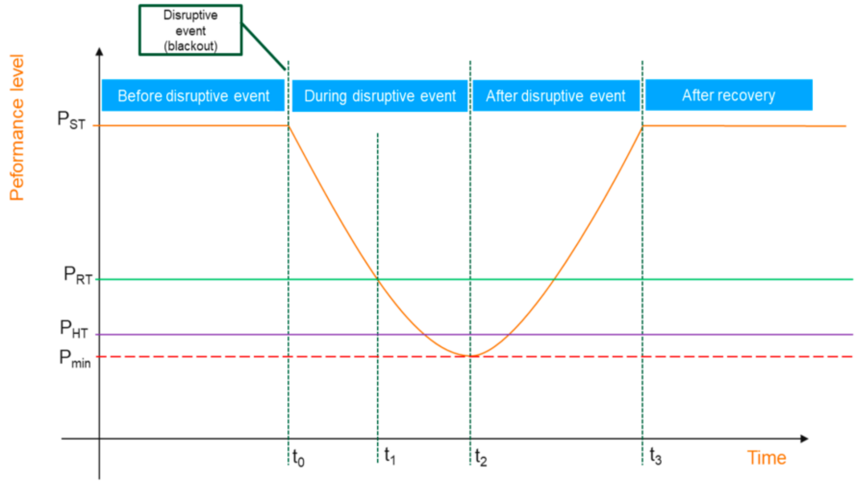
Technical perspective

Multi-disruptive event resilience curve and indicators

- Setpoint temperature
- Robustness threshold and duration
- Habitability threshold and duration
- Thermal autonomy (passive habitability index)
- Collapse speed
- Impact of failure
- Recovery speed and recovery time
- Climate change amplification
- **Indoor underheating/overheating degree:** Heating/cooling risk by considering both the intensity and frequency of the indoor thermal shortfall
- **Ambient coldness/warmness degree**: This factor evaluates the severity of outdoor coldness / warmness
- **Degree of disruption (DoD)**: DoD calculates the severity and impact on the performance of the building during a blackout.



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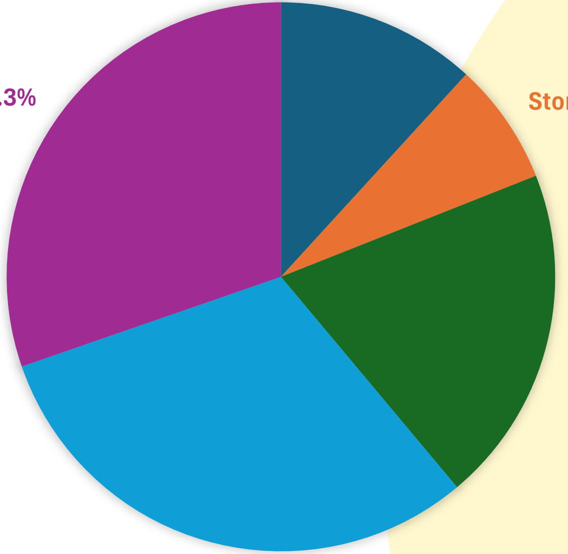
Distribution of resilience enhancement strategies



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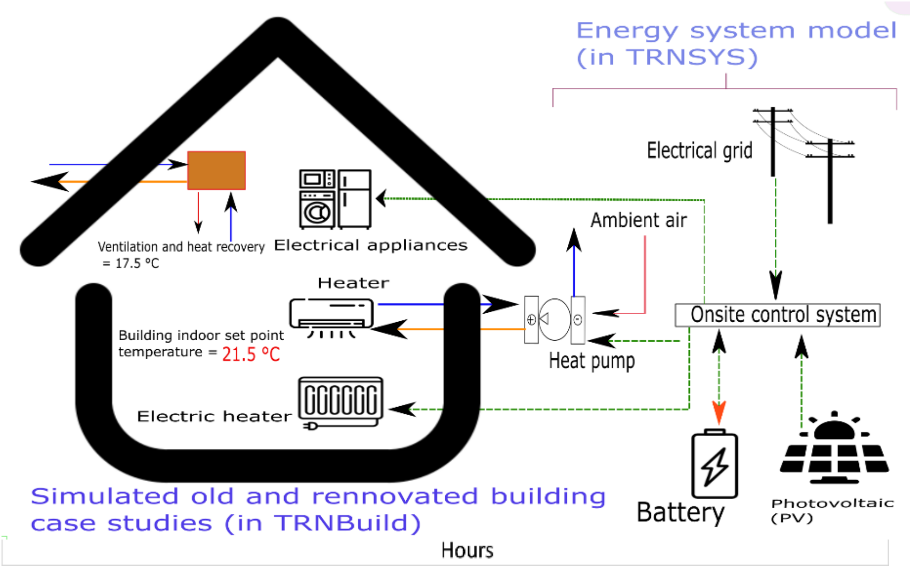
Example case in Finland



- Building data
- Typical old and renovated building
  - Walls, Roof, Floor, Windows (U-values)
  - Airtightness
  - Ventilation rates
- Parametric study

Design variables	Old building	Renovated building
Photovoltaic area (m^2)	0, 50, 75, 100	0, 50, 75, 100
Battery size (kWh)	0, 50, 75	0, 50, 75
Blackout durations (hours)	24, 48, 72	24, 48, 72
Climate data	ECY, TDY, EWY	ECY, TDY, EWY
Heating option	Direct electrical, air source heat pump	Direct electrical, air source heat pump

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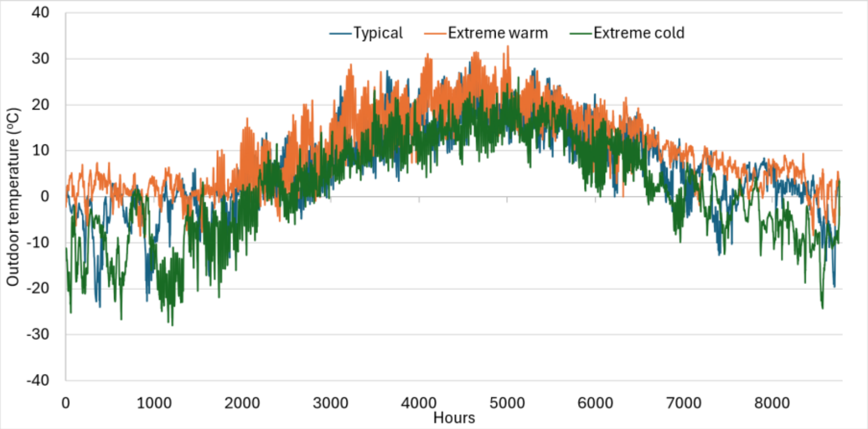
Data and inputs

- Weather data using 30 years of measured climate data
  - Typical representative year
  - Extreme cold and warm year



- Cost data
  - Costs for: Building parameters, PV, battery, heat pump)
  - Initial costs, maintenance cost, replacement cost
  - Life cycle (25 years, 12.5 years)
  - Interest rates

- Buildings heating demand

Building type	Heating demand (ECY weather)	Heating demand (EWY weather)
Old building	199 kWh/m²/yr	124 kWh/m²/yr
Renovated building	86 kWh/m²/yr	46 kWh/m²/yr

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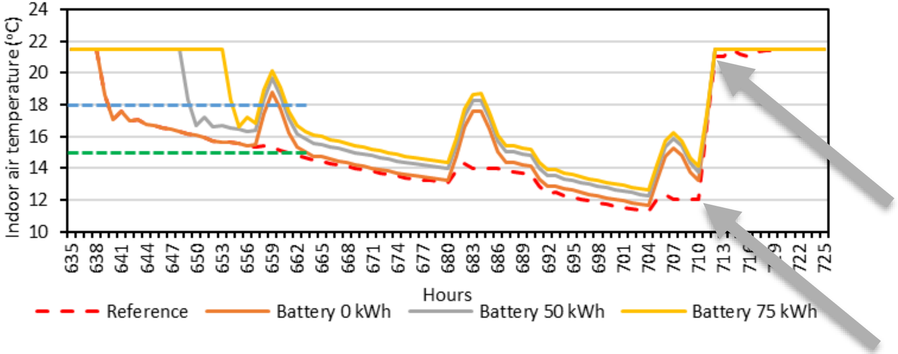
Results: Energy resilience performance of old building for 72 h blackout

- Old building → operating at 21.5°C
- Assumed 72 hours of blackout conditions during winters (-15 °C)
- PV = 100 m^2

2 h to 25 h for 18 °C
23 h to 38 h for 15 °C



- Degree of disruption (DoD) is **0.43** (passive) and with PV and storage DoD is **0.38**

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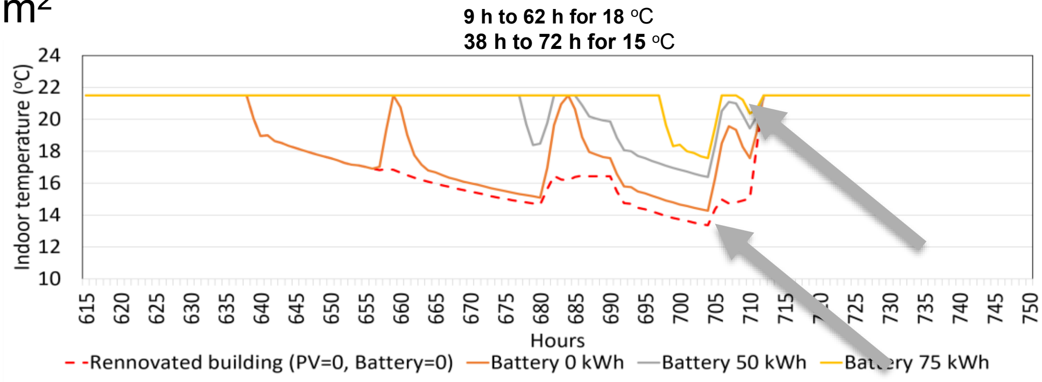
Results: Energy resilience performance of renovated building for 72 h blackout

- Renovated building → operating at 21.5°C
- Assumed 72 hours of blackout conditions during winters (-15 °C)
- PV = 100 m^2



- DoD is **0.35** (passive) and with PV and storage DoD is **0.16**

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Classification and optimization

Old building

PV size, m²	0	50				75				100		
Battery size, kWh	0	0	50	75	100	0	50	75	100	0	50	75
Habitability duration (HT) for 18 °C, hour	2.00	2.00	13.00	16.00	15.00	2.00	13.00	20.00	25.00	3.00	17.00	22.00
Habitability duration (HT) for 15 °C, hour	23.00	25.00	31.00	33.00	32.00	25.00	31.00	35.00	38.00	26.00	31.00	35.00
Minimum temperature, ºC	11.28	11.49	12.09	12.29	12.23	11.58	12.19	12.53	12.80	11.67	12.28	12.62
Impact of failure (IoF), ºC	10.219	10.013	9.406	9.207	9.275	9.919	9.312	8.974	8.698	9.825	9.218	8.880
Collapse speed (CS), ºC/hr	0.155	0.152	0.143	0.139	0.141	0.150	0.141	0.136	0.132	0.149	0.140	0.135
Recovery speed (RS), ºC/hr	0.786	0.770	0.724	0.708	0.713	0.763	0.716	0.690	0.669	0.756	0.709	0.683

Renovated building

PV size, m²	0	50				75				100		
Battery size, kWh	0	0	50	75	100	0	50	75	100	0	50	75
Habitability duration (HT) for 18 °C, hour	9.00	9.00	56.00	57.00	56.00	9.00	55.00	62.00	75.00	9.00	55.00	63.00
Habitability duration (HT) for 15 °C, hour	38.00	41.00	75.00	75.00	75.00	42.00	75.00	75.00	75.00	60.00	75.00	75.00
Minimum temperature, ºC	13.35	13.84	16.43	16.69	16.61	14.06	16.37	17.31	20.87	14.26	16.38	17.57
Impact of failure (IoF), ºC	8.147	7.659	5.071	4.812	4.891	7.437	5.127	4.190	0.629	7.239	5.124	3.935
Collapse speed (CS), ºC/hr	0.123	0.116	0.077	0.073	0.074	0.113	0.078	0.063	0.009	0.110	0.078	0.060
Recovery speed (RS), ºC/hr	0.815	0.766	0.507	0.481	0.489	0.744	0.513	0.419	0.157	0.804	0.641	0.492

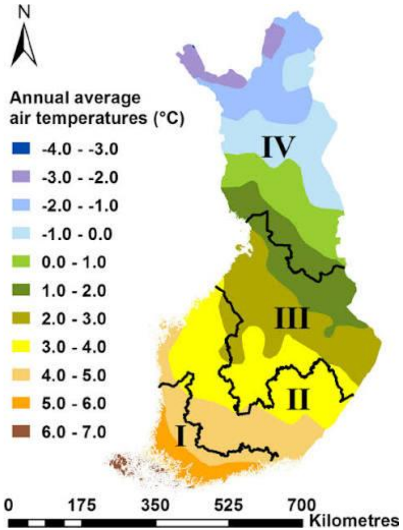
Optimization

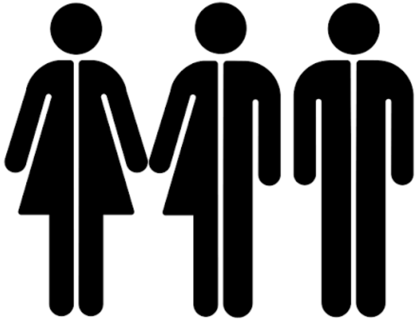
PV size, m²	0	100	75	75
Battery size, kWh	0	100	100	100
Case	*Case 1de, Old building (reference)*	*Case 1de, Old building (no HP)*	*Case 2de, Renovated building (no HP)*	*Case 2hp, Renovated building (with HP)*
Habitability duration (HT) for 18 °C, hour	2.00	27.00	32.00	72.00
Habitability duration (HT) for 15 °C, hour	23.00	39.00	72.00	72.00
Degree of disruption (DoD)	0.43	0.365	0.27	0
Physiological cold stress (18 Centigrade)	3.95	1.86	0.44	0
Physiological cold stress (15 Centigrade)	1.30	0.288	0	0
Survivability factor (for appliance)	0.0	26.2	35.6	97.3
Total cost (€)	8188.0	110884.4	113637.4	118682.2

https://doi.org/10.1016/j.enbuild.2025.116633

How about human and social impact?

Resilience is not just technology





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Method: Social survey

- ⚡ Focus: Energy resilience, habitability & survivability during disruptions

- 📍 Participants: Finland (Climate Zones I–IV)

- 🏢 VTT-led pilot study (January–February 2024), Online survey (Microsoft Forms) distributed via Viva Engage, email, and QR codes

- 👥 378 respondents from 2,386 (15.8% response rate).

https://drive.google.com/file/d/1M9UPVtUsxu7E6Wu4DJ46FPQjeo-w-ip0/view

https://doi.org/10.1016/j.enbuild.2025.116633

Energy Resilience in Buildings in Extreme Cold Weather Conditions of Finland

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Survey questions and awareness

- Background on demography
- Impact of location
- Impact of building type
- Awareness on the energy crises
- Prioritization of the loads
- Habitability needs

Characteristics	Classification & Percentage (in number)
Concern and awareness of the energy crisis	Yes, 50% (189)
Change in behavior and impact on energy prices on daily use	Yes, 70% (262)

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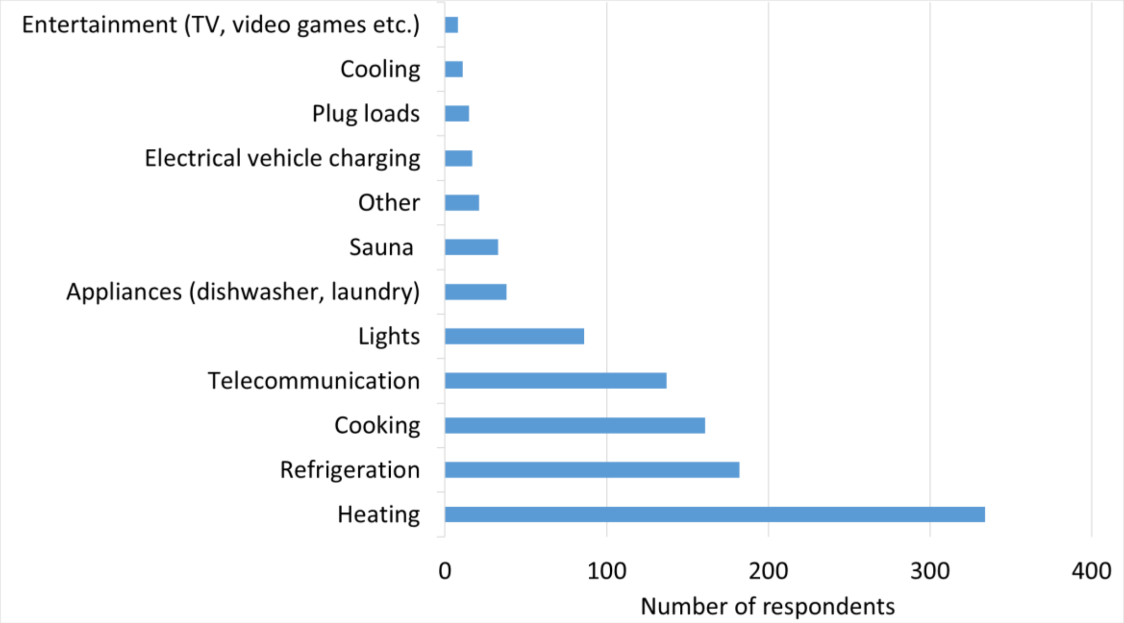
Social survey

- Priority



For electrical loads metrics:

- Survivability factor
- Islanded Autonomy Time (IAT)
- Unserved Energy (UE)
- Critical Load Coverage (CLC)

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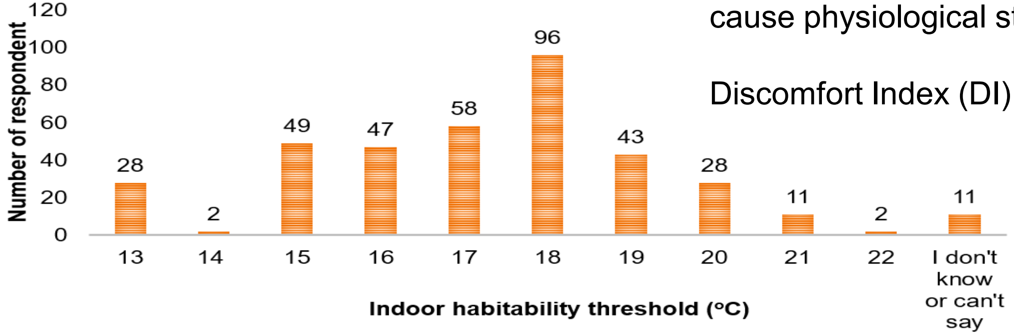
Social survey

- Temperature needs



Physiological cold stress (PCS): Cold stress describes the exposure to low indoor temperatures during a blackout that may cause physiological strain on occupants

Discomfort Index (DI)

- Temperature needs based on gender and age

Habitability threshold (Min. indoor temperature)	*Male*	*Female*
13 centigrade		
14 centigrade		
15 centigrade		
16 centigrade		
17 centigrade		
18 centigrade		
19 centigrade		
20 centigrade		
21 centigrade		
22 centigrade		

- Temperature needs based on location?

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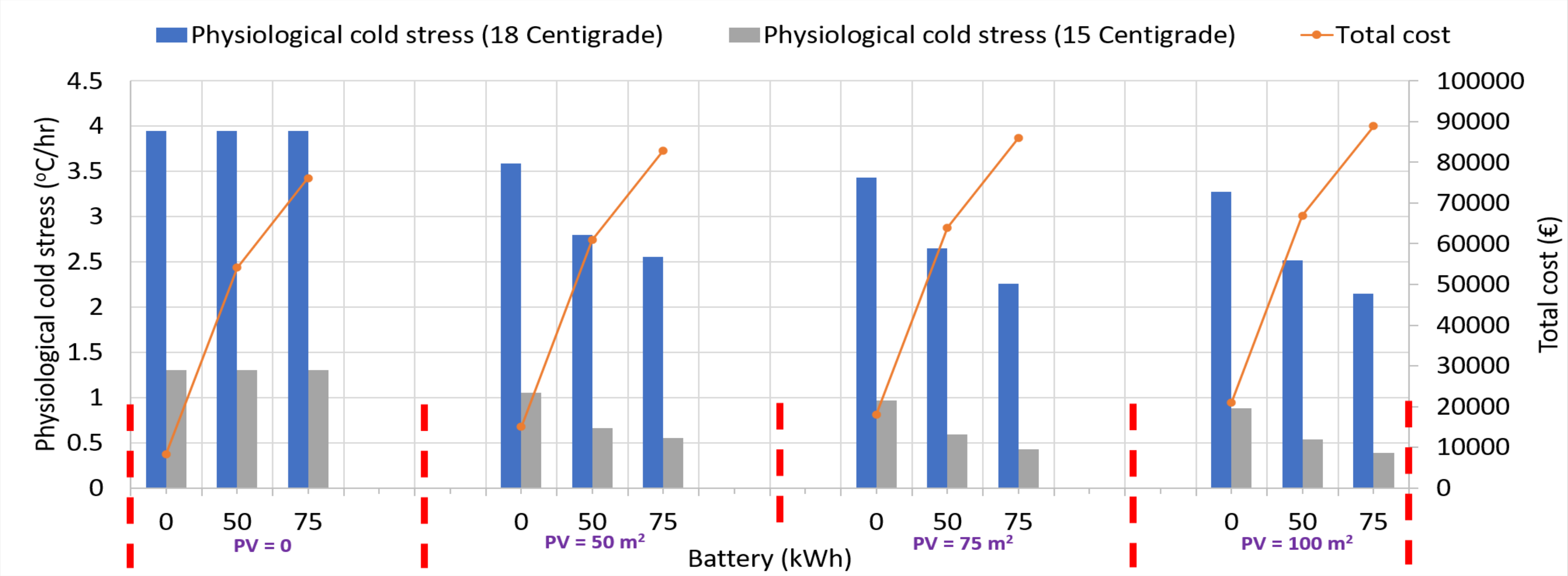
Results: Human and cost impact

- Physiological stress based on needs for old building with 18 ^{o}C and 15 ^{o}C thresholds



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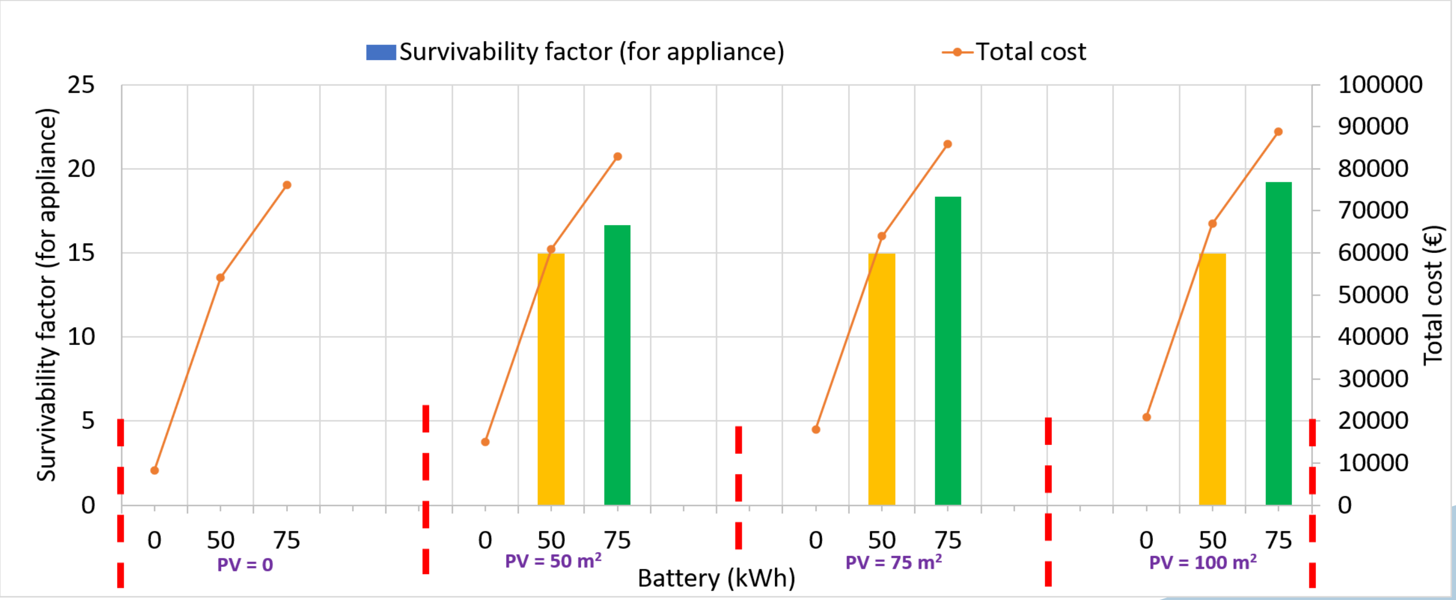
Results: Electrical (critical) loads and cost impact

- Survivability factors after meeting the heating demand for old building



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Impact and benefits

- Improved **regulations and guidelines**
- Building **retrofitting**
- **Cost savings** in normal operation
- **Increased comfort and psychological safety**
- Improved day-ahead **preparedness** and awareness
- Better **resource planning** for rescue operations
- **Reduced cascading events** and minimized extra rescue costs
- Increased **energy flexibility** of buildings
- Enhanced sustainability

Key takeaways

- Efficiency alone is no longer sufficient
- Energy resilience requires integrated technical and social solutions
- Future buildings must become adaptive, intelligent, and resilient
- *"The building of the future is not merely energy efficient—it is energy resilient."*

"Should resilience become a mandatory design criterion alongside efficiency?"

The next generation of buildings will not be judged solely by how little energy they consume, **but**

by how well they protect people, maintain critical services, and recover from disruptions.

Energy resilience is becoming the next frontier of sustainable building design

Hassam ur Rehman, (D.Sc.) Tech.
Research Fellow
Energy Resilient Buildings and Districts
VTT Technical Research Centre of Finland
Tel: +358 40 621 5917
Email: hassam.rehman@vtt.fi

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beyond
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