Towards the energy resilience of buildings in the Nordics

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Aim

Discuss broadly about the concept of energy resilience and review examples

Introduction

Climate change (& high temperatures)→ Emissions caused by fossil fuel use

→ Energy production → Building consumption

Buildings account for 30%-40% of final energy consumption and nearly 40% of the CO_2 emissions in Europe

https://doi.org/10.2833/9937

https://www.ny-engineers.com/blog/how-buildings-produce-carbon-emissions-and-how-to-stop-them

Address the issue

To address this issue,

Paris agreement (2015): Limit global warming to 2-1.5° C above pre-industrial levels.

- ***Ability to adapt and minimize risk*** *to the adverse impacts of climate change.*

The future is uncertain and full of various threats

- Climate crises are becoming more frequent.
- In 2023→ 399 natural disasters, 86k deaths, 93M affected, €192.7B in losses.
- Build environment: Central role in resilience (due to large share of wealth, urbanization, interconnections and complexity).

Finland published guidelines on preparedness for resilience in 2024.

https://www.suomi.fi/guides/preparedness

Why Energy Resilient Buildings/districts are needed? In current situation

Challenges that exist and are forthcoming are:

- Climate change and environment (natural)
- *Political changes and wars (human-induced)*
- *Supply chain disruptions*
- *Cyber threats*
- *Accidents, damage, repair of infrastructure (technical*
- *Older and vulnerable population*

Energy security, crises, and shortage

European Energy Crisis Deepens as Power Prices Reach Records

- French electricity for next year tops 600 euros for first time
- Avoiding blackouts requires 'a lot of preparatory work': CEER

Bloomberg

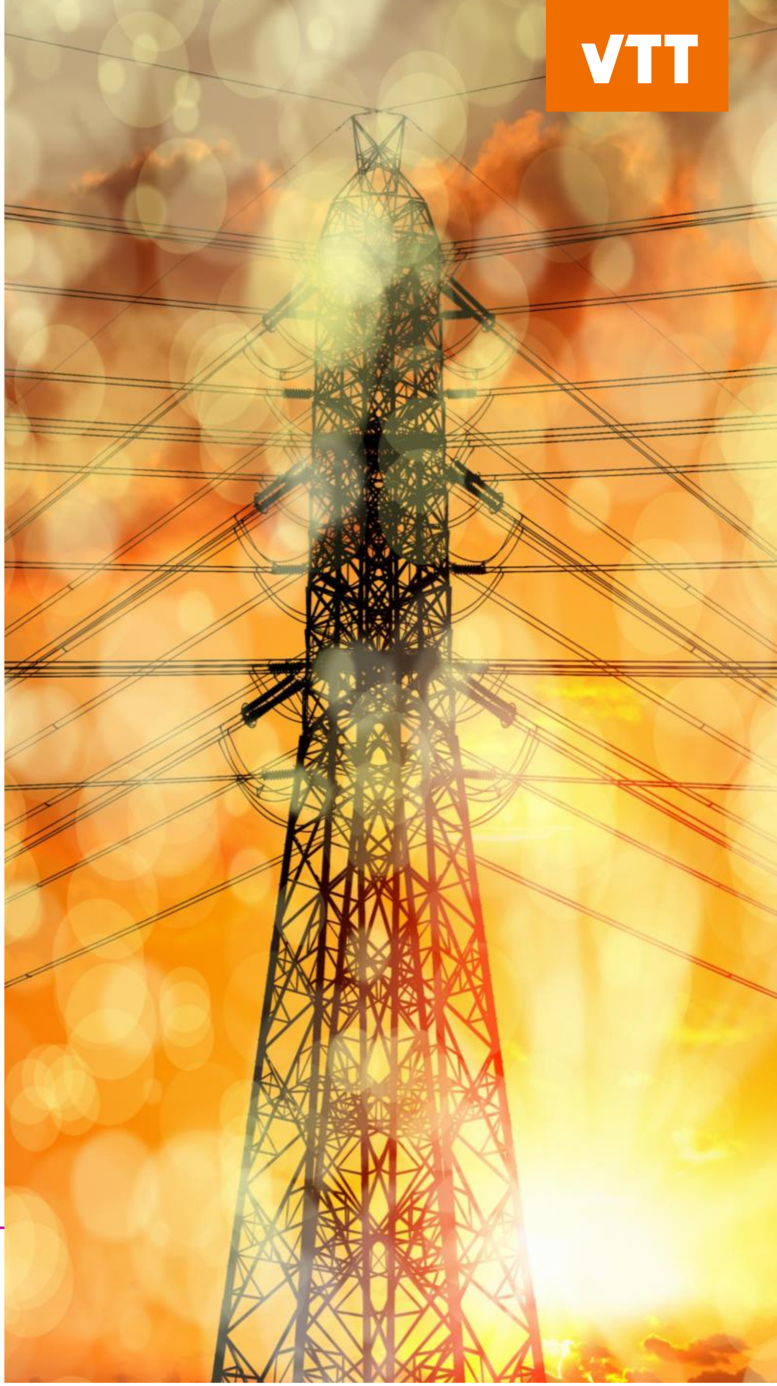
Economic stability and safety

Finland may face 2-hour power outages this winter

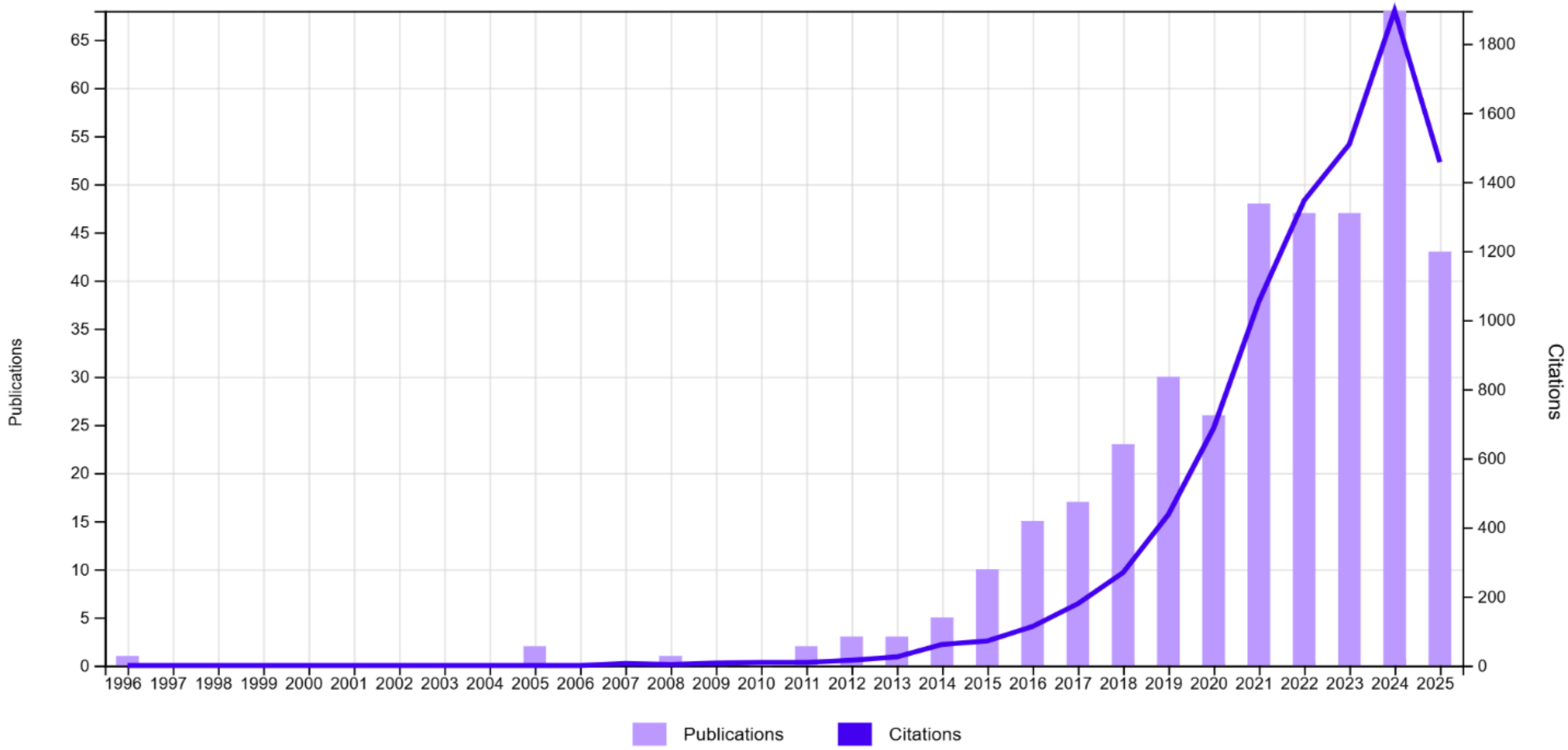
Escalation of negative and costly cascading events in society

Research questions and themes

- **Definition:** How to define energy resilience during crises?
- **Building Classification:** How to classify buildings for resilience?
- **Human Thresholds:** What are the key human vulnerability indicators based on demographics?
- **Integration:** How to combine methods to boost resilience long-term?
- **Optimization:** How to optimize techno-social resilience and cost-effectiveness?

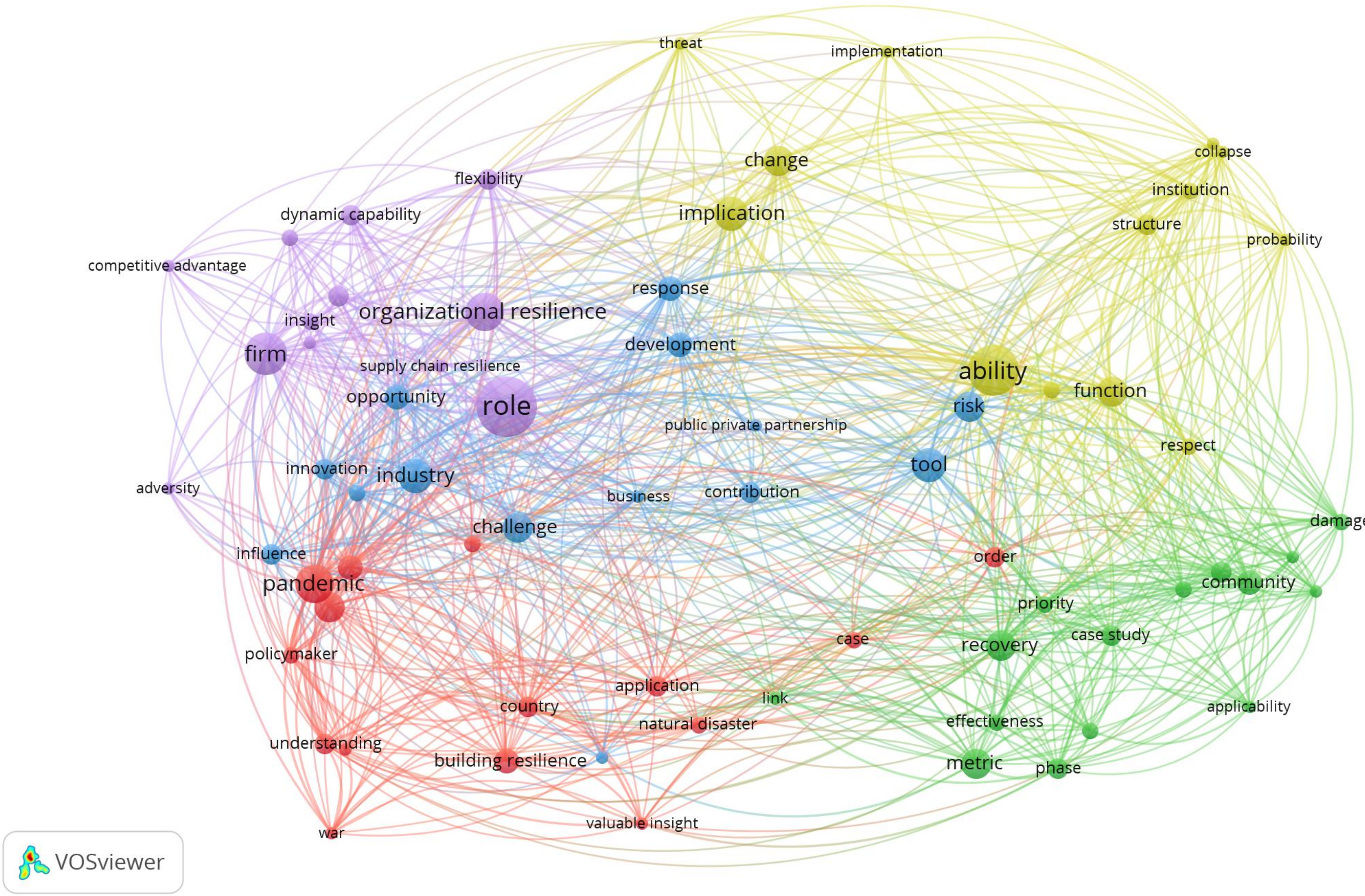


Research questions and themes



Web of Science

Research questions and themes



’Energy Resilience’ term

- Addresses the unpredictable factor, complex and uncertain events
- Addresses low probability and high impact scenario
- Addresses the transient behavior and estimate the capability of the building to withstand and recover from various disruptions

Stability

- Capability to maintain the state of equilibrium
- Considers predictable event
- Capability to return to the state of equilibrium after know deviation from normal state

Reliability

- Addresses the high probability and low impact scenario
- Considers predictable event
- Addresses service interruption
- Focus on the know threats and disruptive events

Robustness

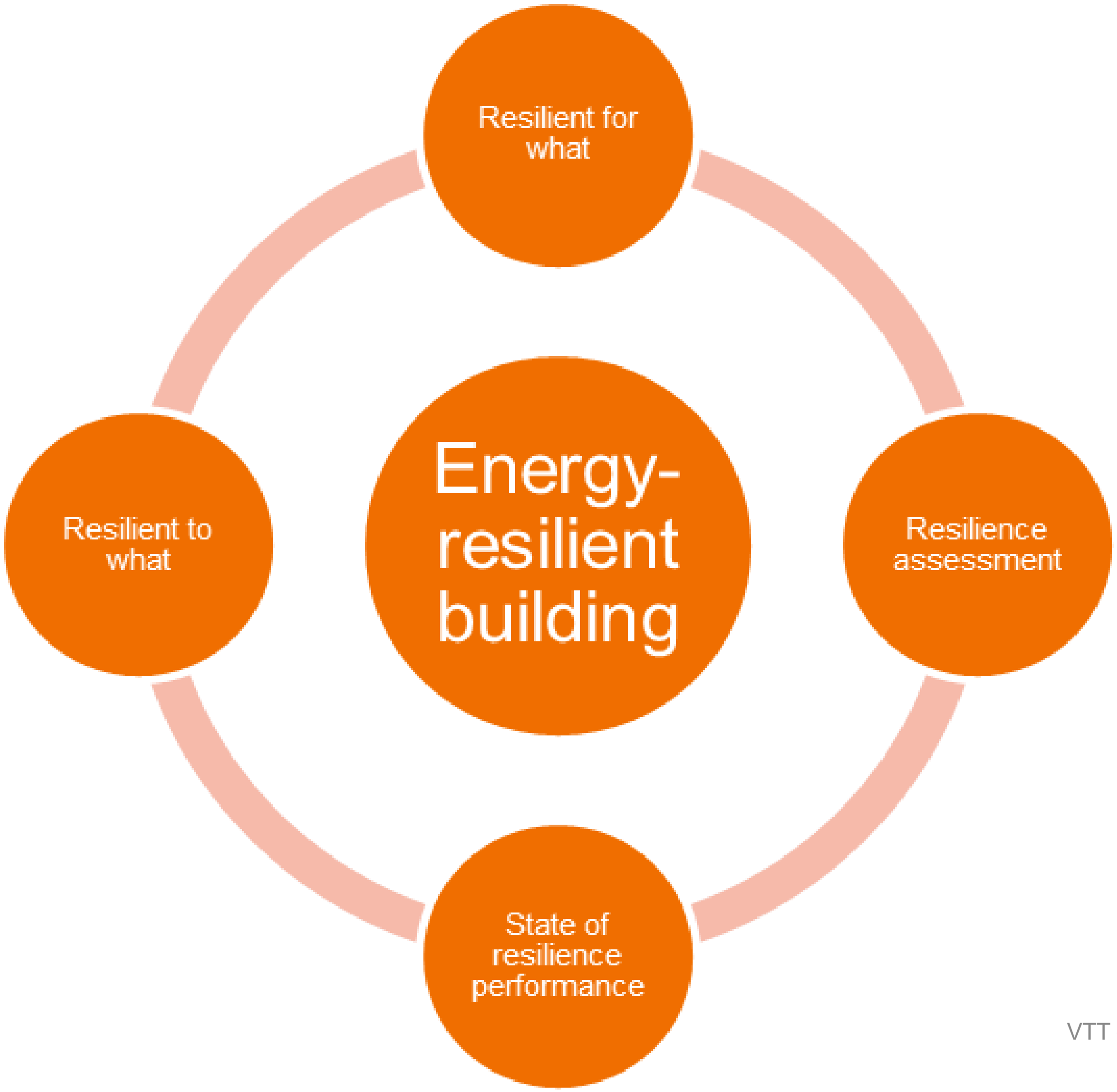
- Considers predictable disruptive event (technical, economic, policy, natural etc.)
- Resistance to change against the disruptive event
- Addresses low probability and high impact scenario

Flexibility

- Addresses high probability and low impact scenario
- Capability to change generation/demand based on the disruptive event
- Withstand the external disruption with less impact on the performance of the building

https://www.mdpi.com/2075-5309/14/5/1453

’Energy Resilience’ term



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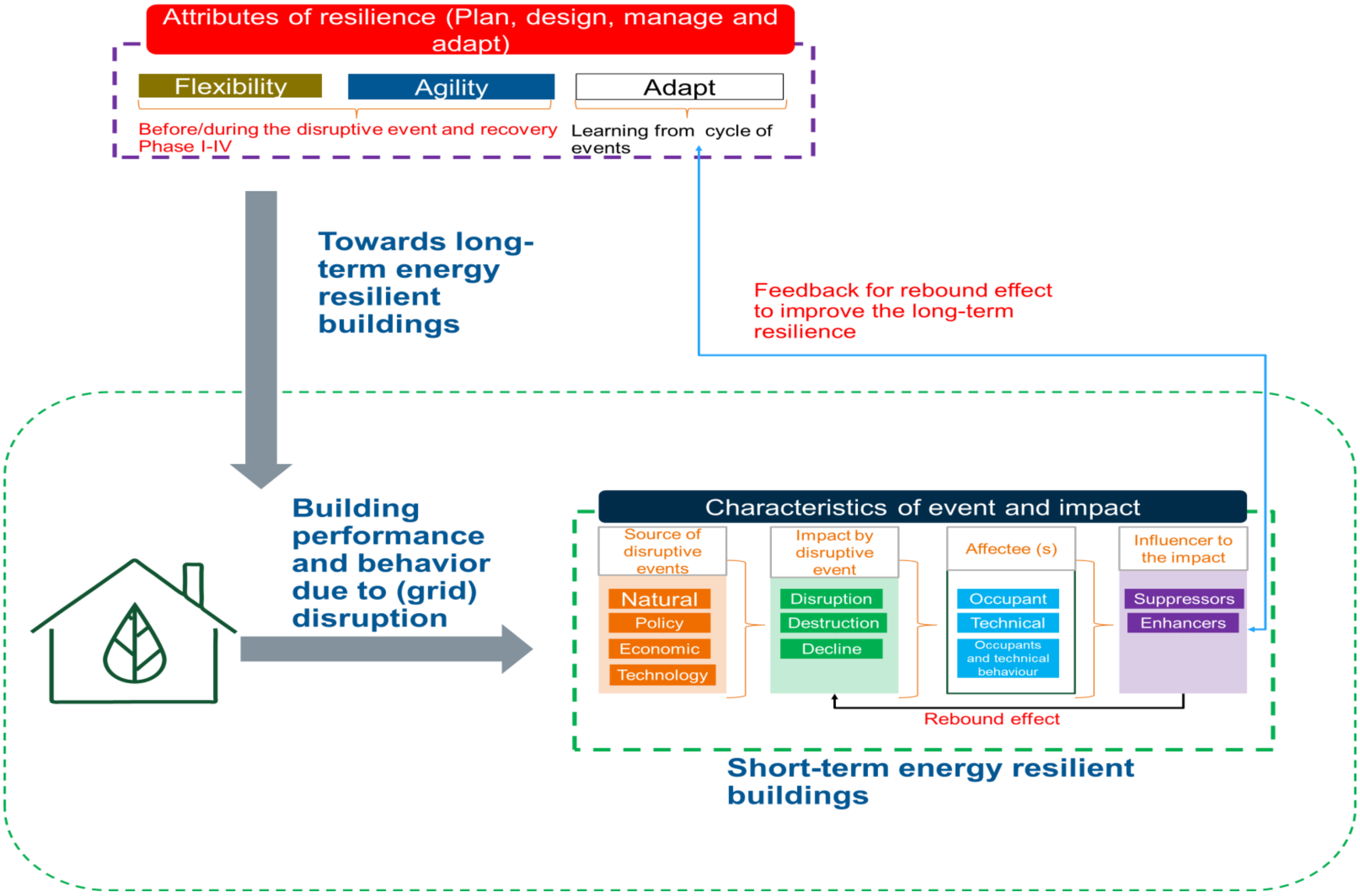
Energy-Resilient Building: Main Components

VTT



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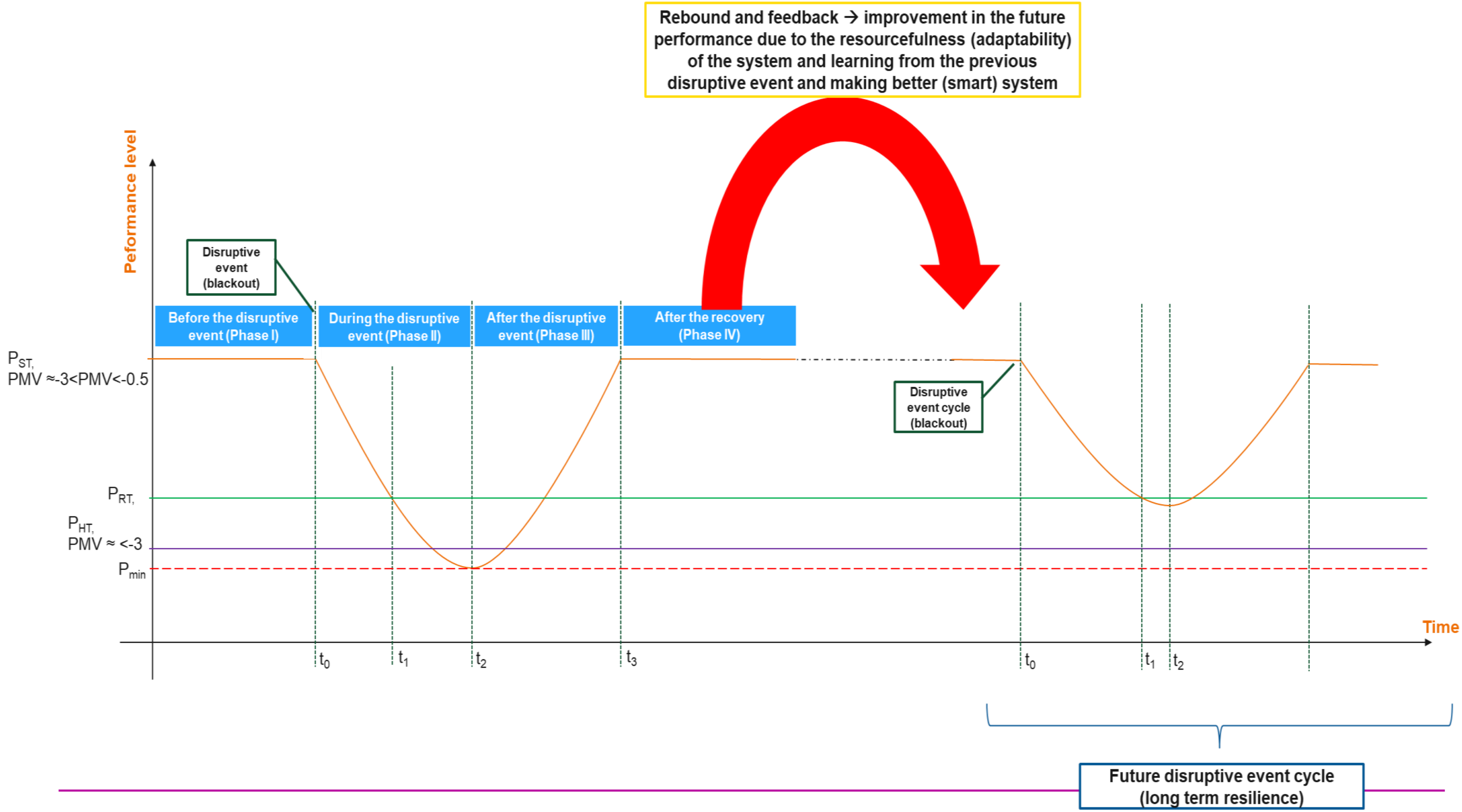
Multi-Disruptive Event Resilience Curve and Key Performance Indicators



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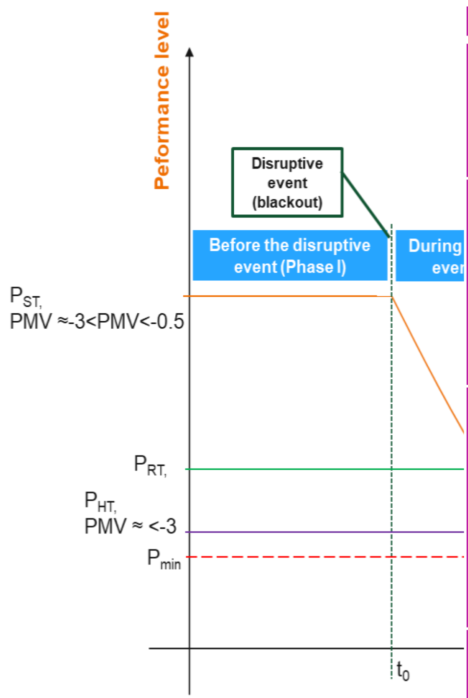

Metric	Name	Definition	Equation
DoR	Duration of robustness	It defines the duration the building can maintain the defined resilience performance after facing the disruptive event (power outage).	t_1-t_0
SoC	Speed of collapse	It defines how quickly the performance of the building deteriorate from the set point. Lower the speed is better is, better is the performance of the building in absorbing the impact.	$(P_{ST}-P_{RT})+(P_{RT}-P_{min})/(t_2-t_0)$
IoE	Impact of event	It provides the impact of the disruptive event and the minimum performance of the building that will be experienced during the disruptive event. Smaller the value is better is the building in terms of resilience performance.	$(P_{ST}-P_{RT})+(P_{RT}-P_{min})$
SoR	Speed of recovery	It defines the speed at which the building can recover after the disruptive event and reaches the target set point.	$(P_{ST}-P_{RT})+(P_{RT}-P_{min})/(t_3-t_2)$

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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
  - smart design learned from rebound.

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Energy Resilience Framework

Define the performance components for the energy resilient building

↓

Climate model and uncertainities

↓

Develop performance indicator

↓

Building energy system and energy model

↓

Resilience assessment

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Passive resilience

“Habitability” refers to a building's ability to maintain at least a low habitable temperature during a blackout.

If the building relies on passive methods such as thermal mass, insulation, and airtightness to achieve it, this is referred to as "passive habitability or resilience."

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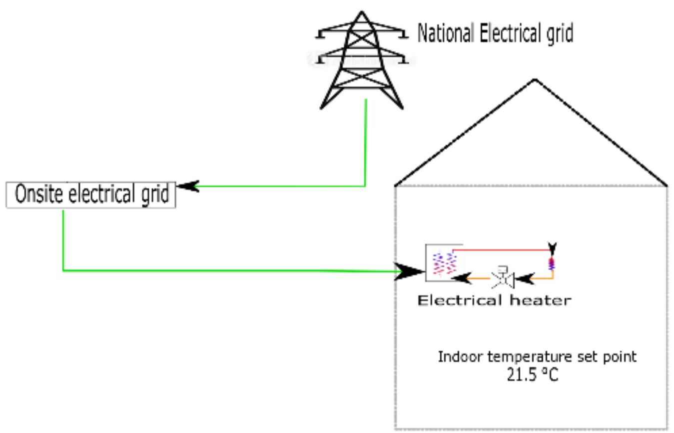
Case studies



Old and new building and energy system

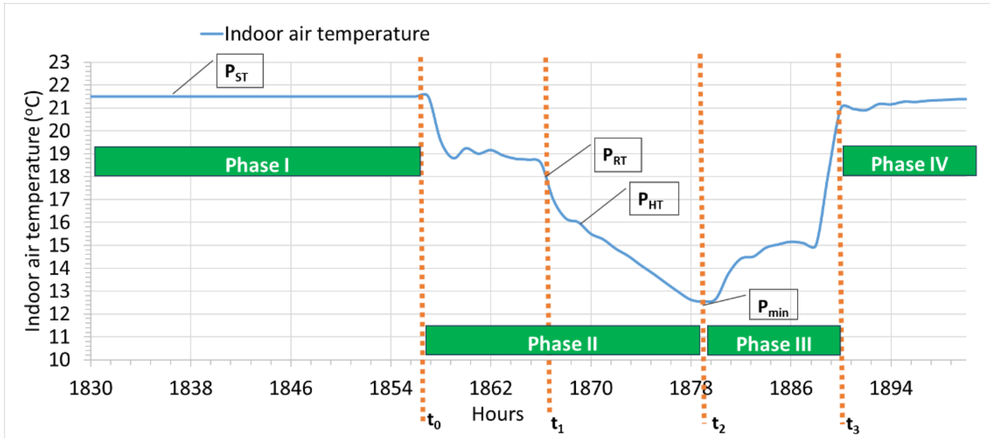
Building type	Ventilation air flow ($m^3/h\ m^2$)	U-value ($W/m^2\ K$)			
		Ext. Walls	Roof	Windows	Floor
Old building	6	0.5	0.27	2.5	0.38
New building	2	0.17	0.09	1	0.16

- Old building (OB)-1980s
- New building (NB)- 2021

Only heating energy is analyzed, direct electricity is used for heating

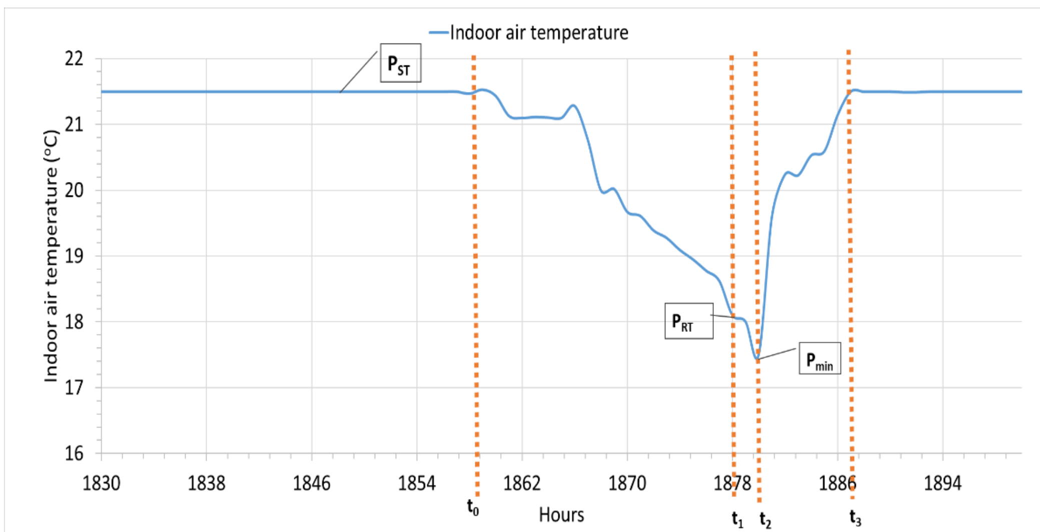
https://www.mdpi.com/1996-1073/16/14/5506

Case studies: Results



Old building resilience

Metrics	Old Building	New Building
P_{RT}	18 °C	18 °C
P_{HT} or MAHT	16 °C	16 °C
P_{min}	12.54 °C	17.5 °C (higher is better)
Degree of disruption (DoD)	0.300	0.138 (lower is better)
Speed of collapse (SoC)	3.75 °C/h	3.2 °C/h (lower is better)
IoE	8.9 °C	4 °C (lower is better)
SoR	0.64 °C/h	0.80 °C/h (higher is better)



New building resilience

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Active resilience

In cold conditions, “habitability” refers to a building's ability to maintain at least a low habitable temperature during a blackout.

When active components, like photovoltaic panels, generators, or batteries, are used, it is called "active habitability or resilience“

Impact of extreme weather: Climate change

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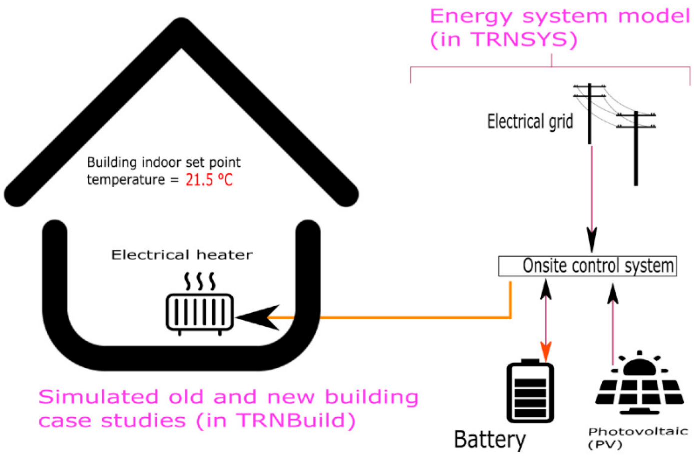
Case studies



- Buildings design data

Building type	Ventilation rate (1/h)	Air tightness ($m^3/h\ m^2$)	U-value (W/m^2 K)			
			Ext. Walls	Roof	Windows	Floor
Old building	0.55	6	0.5	0.27	2.5	0.38
New building	0.55	2	0.17	0.09	1	0.16

- Buildings heating demand

Building type	Heating demand (ECY weather)	Heating demand (EWY weather)
Old building	199 $kWh/m^2/yr$	124 $kWh/m^2/yr$
New building	86 $kWh/m^2/yr$	46 $kWh/m^2/yr$

- Old building (OB)-1980s
- New building (NB)- 2021
- Only heating energy is analyzed, direct electricity is used for heating
- Passive measures and active methods (PV and battery) are used

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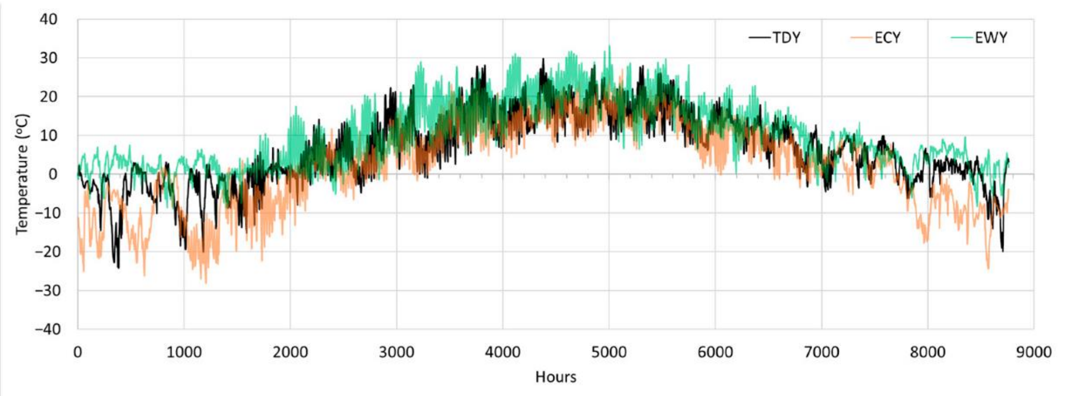
Case studies

- Weather data
  - ECY: Extreme cold year
  - EWY: Extreme warm year



- Parametric study data

Design variables	Option 1	Option 2
Weather	ECY, EWY	ECY, EWY
Building type	Old building	New building
Photovoltaic area (PV), m^2	0, 50, 100	0, 50, 100
Battery capacity, kWh	0, 44, 89	0, 44, 89

- Cost data

Cost type	PV	Battery
Initial cost	124 €/m^2	600 €/kWh
Maintenance cost	1.5% (initial cost)	1.5% (initial cost)
Life cycle	25 years	12.5 years
Replacement cost	Included in the maintenance cost	200 €/kWh

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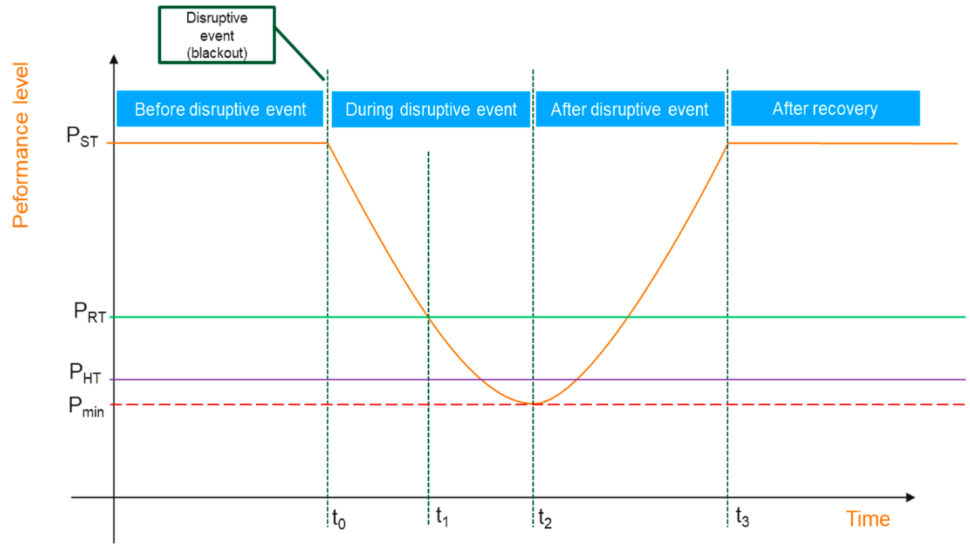
Energy resilience indicators and concept

- Setpoint temperature (ST): 21.5 ºC
- Robustness threshold (RT): 18 ºC
- Robustness period (RP)
- Habitability threshold (HT): 15 ºC
- Collapse speed (CS)
- Impact of failure (IoF)
- Recovery speed (RS)
- Degree of disruption (DoD): DoD calculates the severity and impact on the performance of the building during a blackout.



$$\mathrm{DoD} = \frac{Parameter_{disruption} - Parameter_{reference}}{Parameter_{reference}} \times \frac{Time_{disruption}}{Time_{reference}}$$

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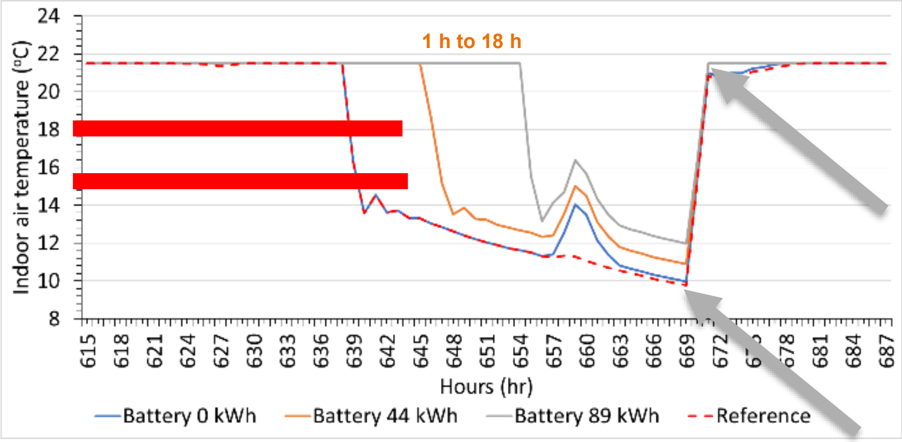
Results: Energy resilience performance of old building

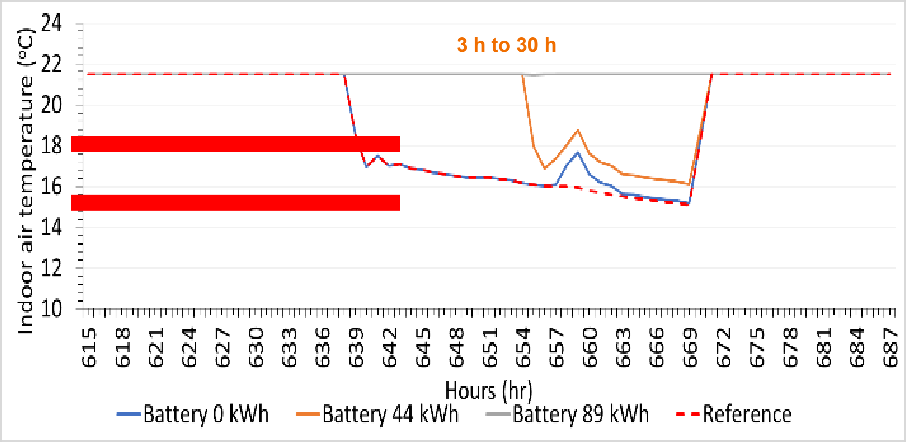
- Old building → operating at 21.5°C (in ECY and EWY)
- Assumed 30 hours of blackout conditions during winters
- PV = 100 m^2

Extreme cold year



DoD is **0.545** (passive) and with PV and storage DoD is **0.44**

Extreme warm year



DoD is **0.299** (passive) and **0** (with PV and battery)

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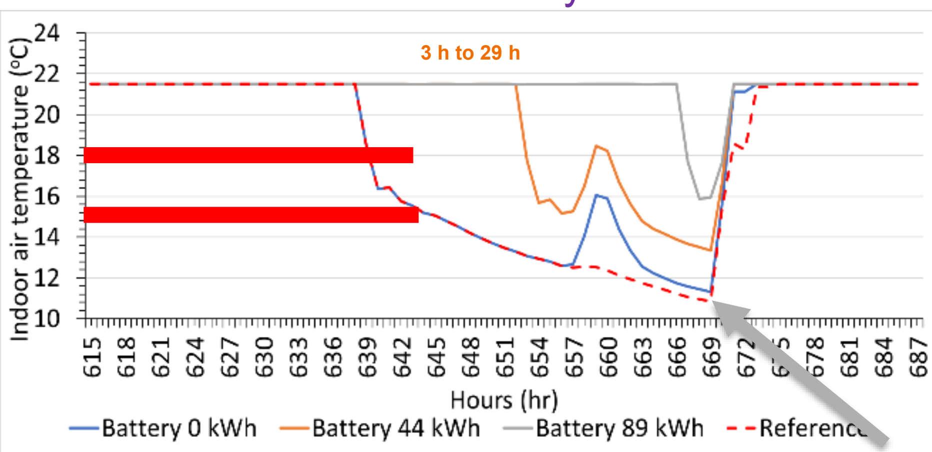
Results: Energy resilience performance of new building

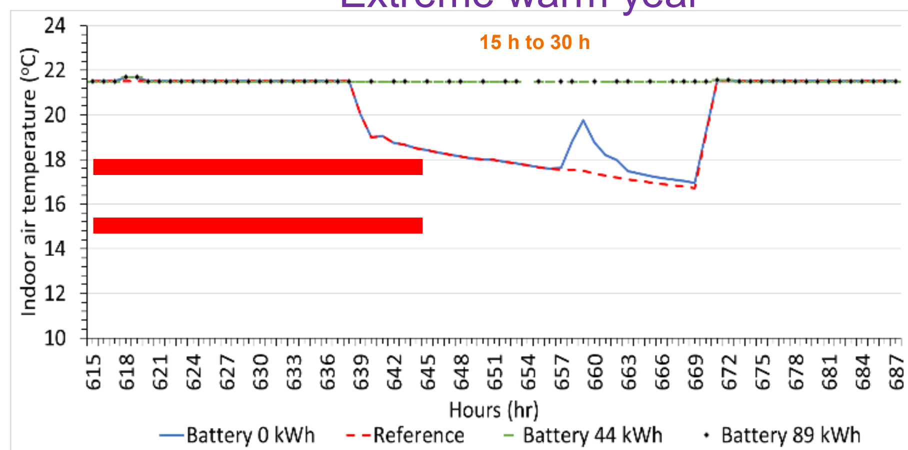
- New building → operating at 21.5°C (in ECY and EWY)
- Assumed 30 hours of blackout conditions during winters
- PV = 100 m^2

Extreme cold year



DoD is **0.49** and with PV and storage DoD is **0.25**

Extreme warm year



DoD is **0.2** (reference) and **0** (with PV and battery)

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Results: Classification using KPIs

- Old building and new building comparison in ECY weather conditions

Table A5. Parametric study, energy resilience performance analysis, and costs for case 1c in ECY (winter) climate scenario with varying PV and battery capacity.

PV Area, m^2	**0**				**50**				**75**				**100**			
Battery Capacity, kWh	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**
Robustness duration (RT), hour	1.00	1.00	1.00	1.00	1.00	8.00	17.00	17.00	1.00	9.00	17.00	24.00	1.00	10.00	18.00	26.00
Impact of failure (IoF), °C	11.723	11.723	11.723	11.723	11.618	10.706	9.624	9.624	11.570	10.650	9.576	8.739	11.523	10.608	9.528	8.553
Collapse speed (CS), °C/h	0.378	0.378	0.378	0.378	0.375	0.345	0.310	0.310	0.373	0.344	0.309	0.282	0.372	0.342	0.307	0.276
Recovery speed (RS), °C/h	0.977	0.977	0.977	0.977	1.056	5.353	4.812	4.812	1.157	5.325	4.788	4.370	1.152	5.304	4.764	4.277
Degree of disruption (DoD)	0.545	0.545	0.545	0.545	0.540	0.498	0.448	0.448	0.538	0.495	0.445	0.406	0.536	0.493	0.443	0.398
PV cost (€)	0	0	0	0	6838	6838	6838	6838	9851	9851	9851	9851	12,864	12,864	12,864	12,864
Battery cost (€)	0	39,377	79,649	119,027	0	39,377	79,649	119,027	0	39,377	79,649	119,027	0	39,377	79,649	119,027

Colors grading variations: Red is the 'worst' performing and green is the 'best' performing cases.

Table A11. Parametric study, energy resilience performance analysis, and costs for case 2c in ECY (winter) climate scenario with varying PV and battery capacity.

PV Area, m^2	**0**				**50**				**75**				**100**			
Battery Capacity, kWh	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**
Robustness duration (RT), hour	3.00	3.00	3.00	3.00	3.00	14.00	29.00	30.00	3.00	15.00	29.00	31.00	3.00	15.00	29.00	31.00
Impact of failure (IoF), °C	10.660	10.660	10.660	10.660	10.418	8.375	5.636	5.654	10.307	8.265	5.636	0.021	10.197	8.155	5.636	0.021
Collapse speed (CS), °C/h	0.344	0.344	0.344	0.344	0.336	0.270	0.188	0.188	0.332	0.267	0.188	0.001	0.340	0.263	0.188	0.001
Recovery speed (RS), °C/h	1.777	1.777	1.777	1.777	1.736	2.094	2.818	2.827	2.577	2.755	2.818	0.010	2.039	2.718	2.818	0.010
Degree of disruption (DoD)	0.496	0.496	0.496	0.496	0.485	0.390	0.254	0.254	0.479	0.384	0.254	0.001	0.459	0.379	0.254	0.001
PV cost (€)	0	0	0	0	6838	6838	6838	6838	9851	9851	9851	9851	12,864	12,864	12,864	12,864
Battery cost (€)	0	39,377	79,649	119,027	0	39,377	79,649	119,027	0	39,377	79,649	119,027	0	39,377	79,649	119,027

Colors grading variations: Red is the 'worst' performing and green is the 'best' performing cases.

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Results: Optimal analysis

- New building and old building comparison in ECY and EWY weather conditions

Table 7. Energy resilience performance analysis for case 1a and case 2a in TDY (winter) climate scenario with and without PV and battery.

PV Area, m^2	0				50				75				100			
Battery Capacity, kWh	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**	**0**	**44**	**89**	**133**
Case 1a (TDY) winters: Degree of disruption (DoD)	0.357	0.357	0.357	0.357	0.351	0.308	0.289	0.289	0.348	0.305	0.274	0.114	0.334	0.293	0.274	0.114
Case 2a (TDY) winters: Degree of disruption (DoD)	0.271	0.271	0.271	0.271	0.257	0.099	0.000	0.000	0.251	0.099	0.000	0.000	0.248	0.099	0.000	0.000

Colors grading variations: Red is the ‘worst’ performing and green is the ‘best’ performing cases.

Table 8. Optimal points in terms of energy resilience performance for cases 1a, 1b, and 1c and cases 2a, 2b, and 2c in TDY, EWY, and ECY for winter and spring climate scenarios and the corresponding total costs.

	Old Building						New Building					
PV Area, m^2	**75**	**50**	**50**	**50**	**100**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
Battery Capacity, kWh	**133**	**89**	**89**	**44**	**133**	**133**	**44**	**44**	**44**	**44**	**89**	**44**
Case	1a TDY, Winter	1a TDY, Spring	1b EWY, Winter	1b EWY, Spring	1c ECY, Winter	1c ECY, Spring	2a TDY, Winter	2a TDY, Spring	2b EWY, Winter	2b EWY, Spring	2c ECY, Winter	2c ECY, Spring
Degree of disruption (DoD)	0.114	0	0.172	0.153	0.398	0.141	0.099	0	0	0	0.254	0
PV cost (€)	9851	6838	6838	6838	12,864	6838	6838	6838	6838	6838	6838	6838
Battery cost (€)	119,027	79,649	79,649	39,377	119,027	119,027	39,377	39,377	39,377	39,377	79,649	39,377

Colors grading variations: Red is the ‘worst’ performing and green is the ‘best’ performing cases.

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How about human and social impact?

"habitability" should be based on human needs?

How about electrical loads and needs?

"Survivability" refers to a building's ability to maintain indoor air temperature within habitable ranges while also providing power for essential services

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Method: Social survey

- Survey and data collected from 400 people at an organization (Survey distributed across 2400 individuals)

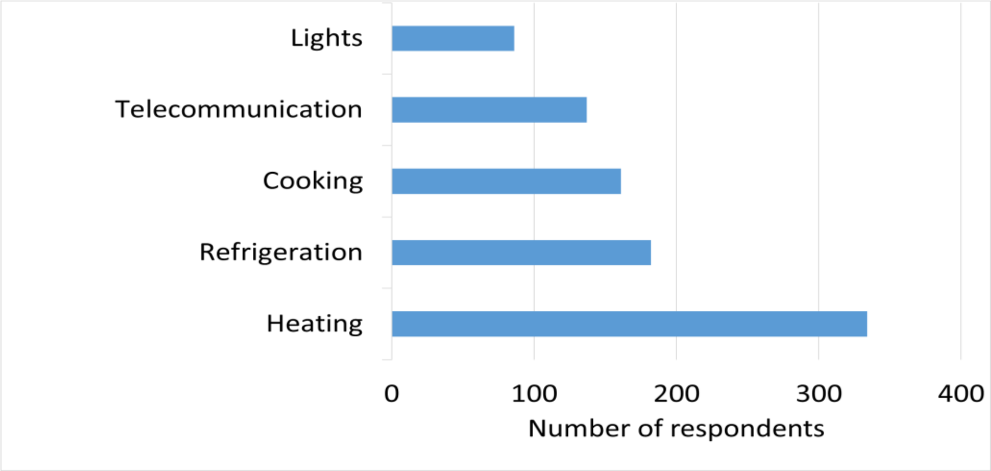
Energy Resilience in Buildings in Extreme Cold Weather Conditions of Finland

Characteristics	Classification
Age	Below 20
	20-30
	31-40
	41-50
	51-60
	Above 61
Gender	Male
	Female
	Non-binary and prefer not to say
Location	Helsinki, Espoo
	Oulu
	Tampere
	Kuopio
	Kajaani
	Jyväskylä
	Other
Building type	Apartment
	Single-family and semi-detached houses

Social survey

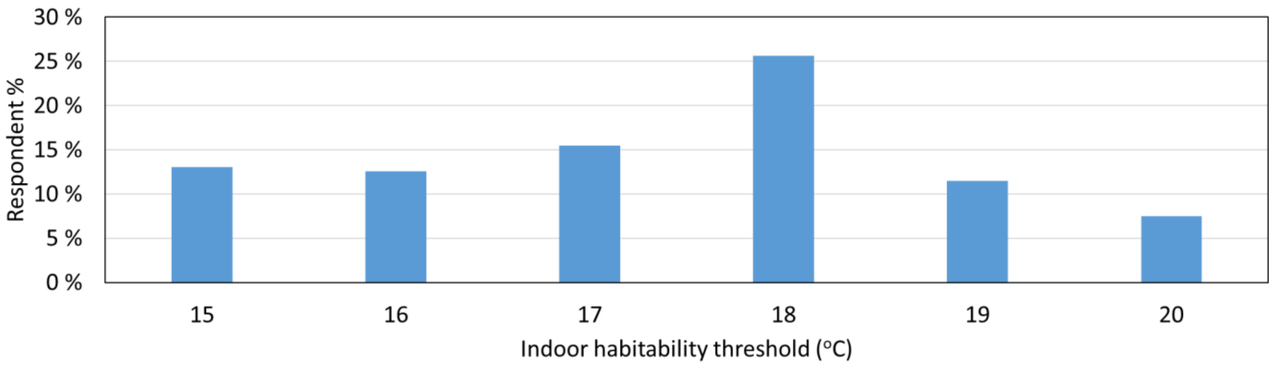
- Survey and data collected from 400 people (Survey distributed across Finland)

- Overall needs priority



Survivability factor $\sum_{t0}^{t4} \frac{(Energy\ available\ in\ battery\ after\ heating)}{Electrical\ appliance\ demand}$

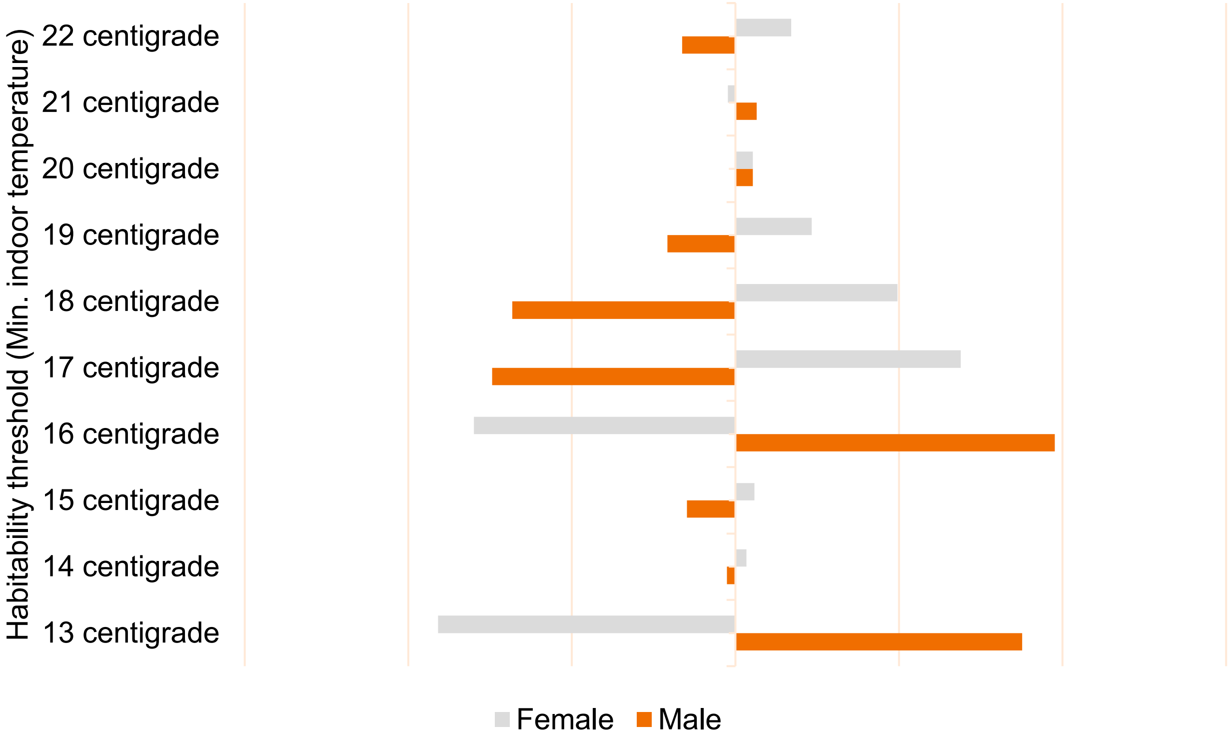
- Temperature needs



Social survey

- Survey and data collected from 400 people (Survey distributed across Finland)

- Temperature needs based on gender…age?

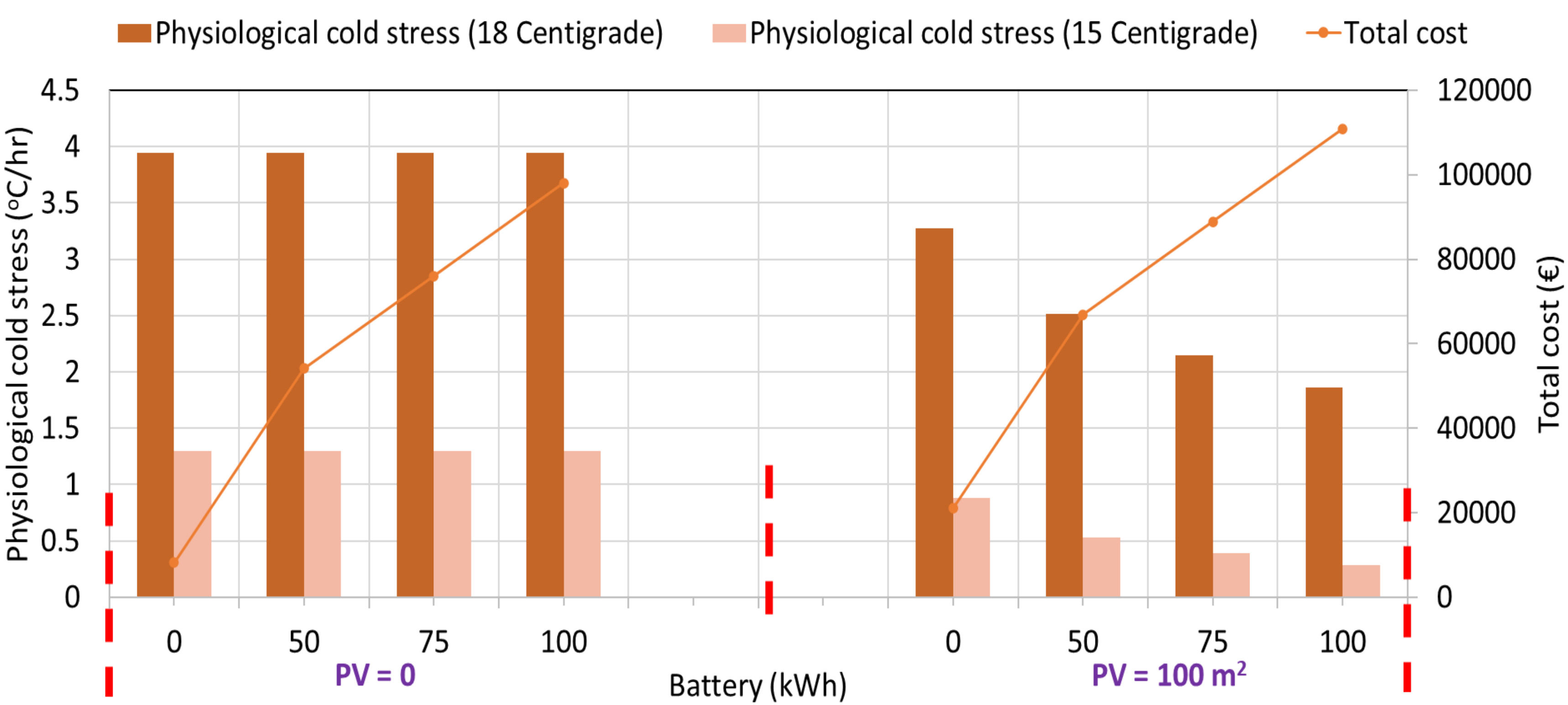


Physiological cold stress (PCS) $\sum_{t1}^{t3} \frac{(L_{HT} - L_{temperature\ below\ habitability})}{t_4 - t_0}$

Results: Technical resilience performance, human and cost impact using indicators

- Energy resilience performance of old building during winters in 72 h power outage

- Physiological stress based on needs



- Survivability factors (after meeting the heating demand) is around 0 to 25 %

Benefits

- Cost savings in normal operation
- Increased comfort & psychological safety for occupants, homeowners based on demography
- 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

Summary

- Challenges and need for energy resilience
- Definitions and framework
- Building simulation models
- Integration of renewables and storage
- Climate impact
- Cost
- Engagement with the end users

References

- Energy Resilience in Buildings in Extreme Cold Weather Conditions in Finland-FinERB (2022-2025) (https://cris.vtt.fi/en/projects/energy-resilience-in-buildings-in-extreme-cold-weather-conditions)

- Addressing the challenges of achieving energy resilience in buildings during power outages in Finland: A human centric approach integrating social, economic and technical dimensions (ongoing 2025-2029) (https://research.fi/en/results/funding/83044)

- IEA EBC - Annex 93 - Energy Resilience of the Buildings in Remote Cold Regions (ongoing 2025-2028) (https://annex93.iea-ebc.org/)

- Driving Urban Transitions (DUT)– Sustainable future for cities and European Union project: RESPED – Enabling Energy Resilience through new energy flexible and affordable Positive Energy District (PED) concepts (https://cris.vtt.fi/en/projects/enabling-energy-resilience-through-new-energy-flexible-and-afford)

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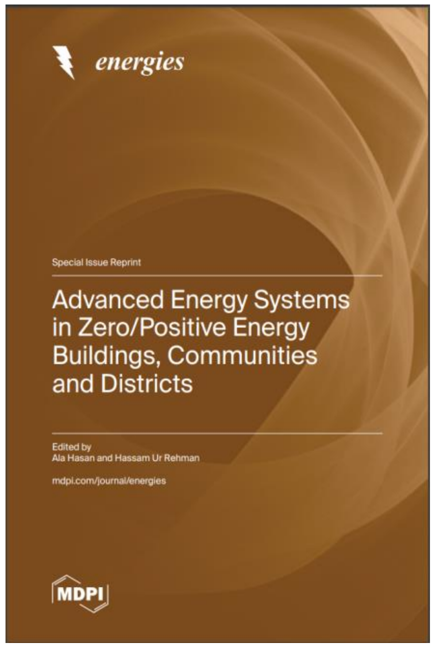

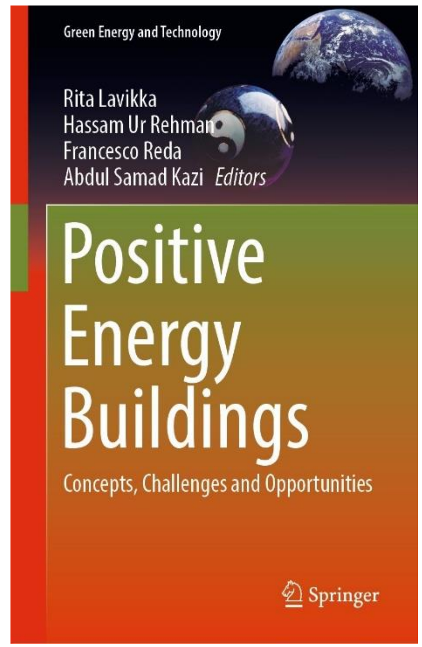

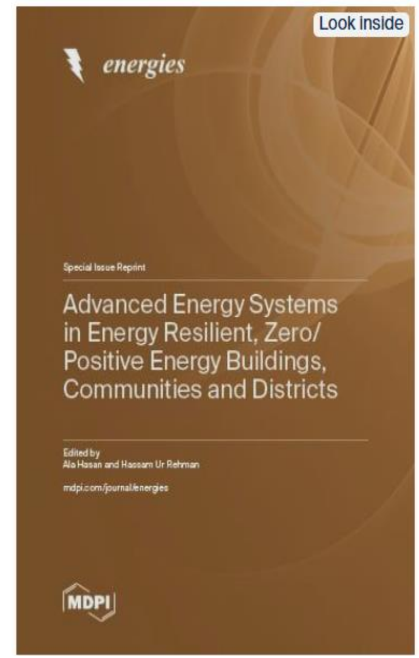

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ANNEX 93

EBC
Energy in Building and Communities Programme

Project (FinERB) [Grant number: 348060]
Project (REBUILD-Fin) [Grant number: 367935]