Joint meeting

# IEA EBC Annex 93 and Annex 94

Hassam ur Rehman
Alexander Zhivov

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

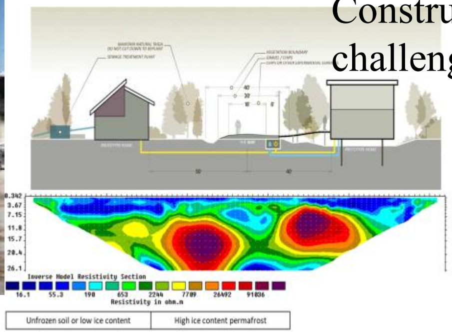
- Intergovernmental Panel on Climate Change (IPCC) report
  - Emissions of greenhouse gases from human activities are largely responsible for approximately 1.1°C of warming
- Due to climate change in cold regions
  - Natural disasters such as extreme temperature, storm and heavy precipitation etc. → **resulting in electrical grid loss, blackout and brownout**
- Moreover the arctic regions are warming faster than global average resulting in frequent natural disasters → **grid loss and overheating**
- Energy security, crises, and shortage
  - Political changes and wars (human-induced)
  - Supply chain disruptions (congestion of the grid)
- Economic stability and safety
- **Escalation** of negative and costly **cascading events** in society

# Challenges in cold, very cold regions

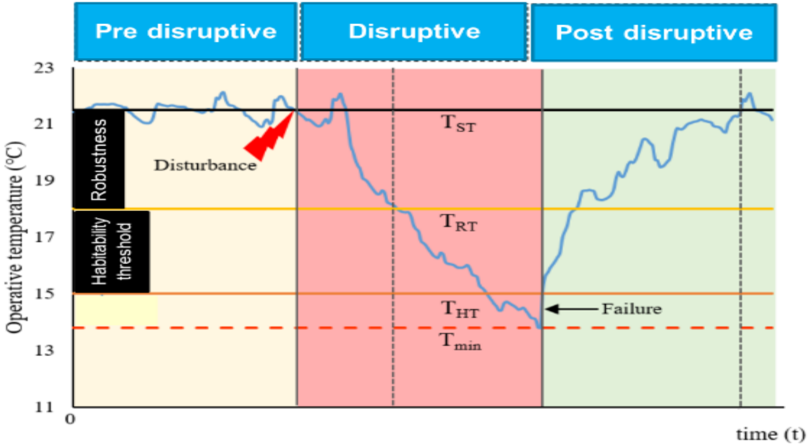
Remoteness, lack of resources (e.g. fuel)

Cold wave

Construction challenges




Lack of parts and maintenance, high costs, accessibility, delivery issues → Research is needed



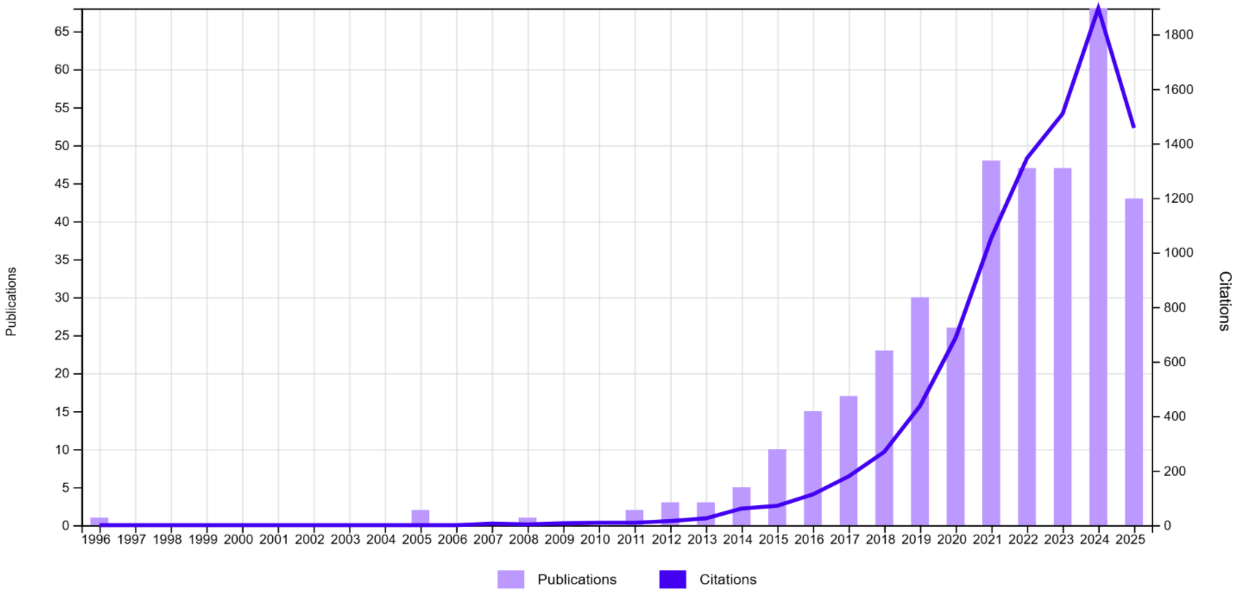

Energy security -> risk to health with the loss of power, heat

-Habitability, low humidity -> human health

-building infrastructure, mold, piping etc.

https://annex73.iea-ebc.org/

# Research history




Web of Science

# ’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

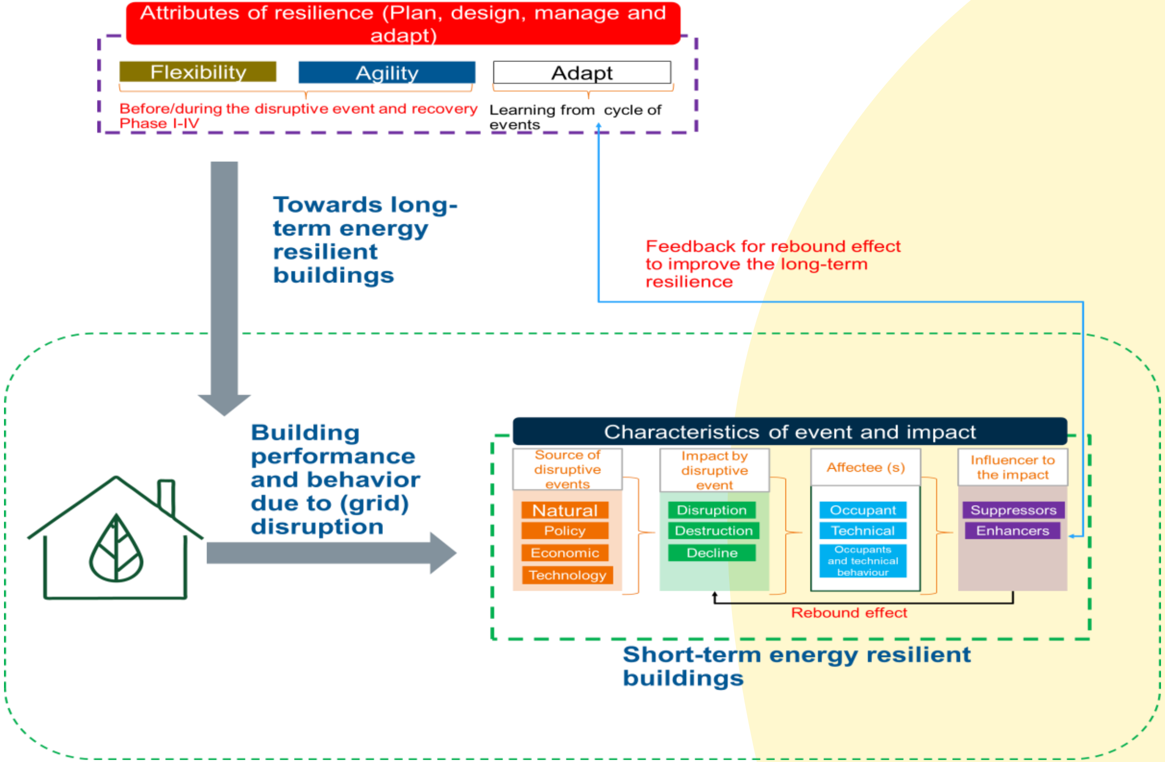
**Robustness**

- 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

# Energy-Resilient Building: Main Components



# Energy Resilience

# 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.

# Summary and Background

## **IEA EBC - Annex (93):** Energy Resilience of the Buildings in Remote Cold Regions

This Annex is developing technical, economic, environmental, policy, and societal frameworks that will result in the development of Guidelines for improving the resilience of the buildings and building communities located in cold and very cold climates.

Cold-climate buildings must stay warm in normal use and habitable in crises. Design factors include extreme cold, low humidity, wind, freezing rain, snow loads, and drifting. Permafrost is critical in subarctic/arctic zones, and warming is causing damage as it thaws. **Resilient buildings, systems, and energy supplies are essential.**

**https://annex93.iea-ebc.org/**

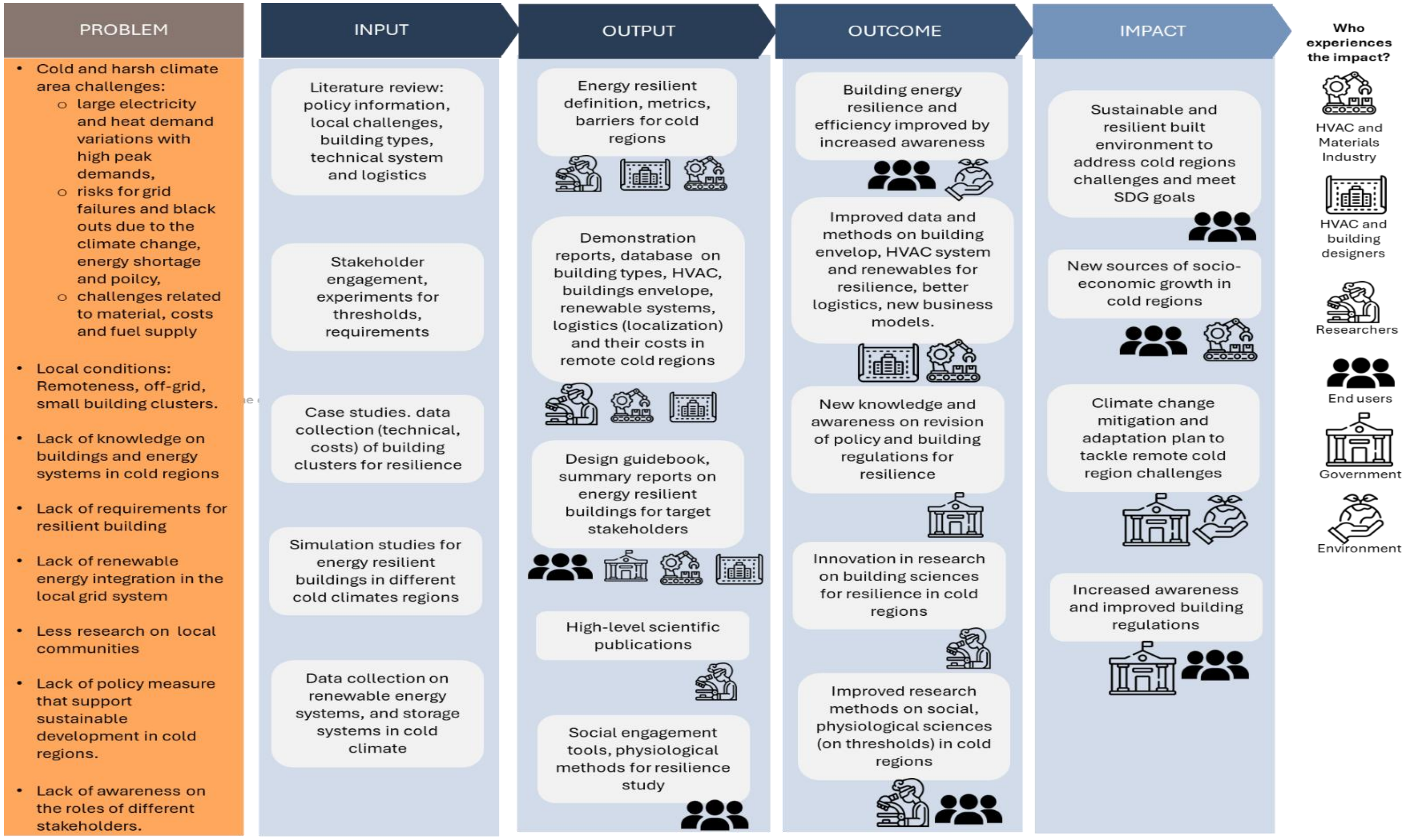
**The keys aims of this project were / are to:**

- Objective 1: Identify cold-region threats to buildings and energy systems; define resilience metrics and requirements for habitability, survivability, IAQ, and sustainability.
- Objective 2: Document case studies of resilient buildings and communities that reduce health and infrastructure risks.
- Objective 3: Assess (nearly) net-zero buildings for performance; develop scalable, local guidelines for resilient solutions.
- Objective 4: Share best practices through publications, presentations, and training.

**The key stakeholders for this work were / are:**

- Decision makers, energy planners, architects, engineers, building physicists, construction companies, facilities managers, and academia.

# **Theory of Change:** Energy Resilience of the Buildings in Remote Cold Regions



# Subtasks

**Subtask 1:** Establishing energy resilience definition, threshold and challenges for the building clusters in cold climate

**Subtask 2:** Investigate specifics of buildings and their construction in remote cold regions

**Subtask 3:** Investigate resilient building and building clusters' energy systems, renewable energy sources, and systems integration

***Subtask 4:*** Develop guidelines and disseminate knowledge

# Guidelines book

| Milestone |
| --- |
| Chapter 1: Introduction to climate conditions<br>Chapter 2: Requirements for indoor climate for resilience<br>Chapter 3: Building and Energy Systems Resilience |
| Chapter 4: **Building envelope design**<br>Chapter 5: Foundation and construction<br>Chapter 6: Mechanical systems in cold regions |
| Chapter 7: Energy supply (electricity, heating, cooling) and storage<br>Chapter 8: **Case studies (Greenland, Japan, Sweden, Canada, Iceland, Denmark, Norway, Japan, China)**<br>Chapter 9: Lighting in cold regions |
| Project Completion and Closure |

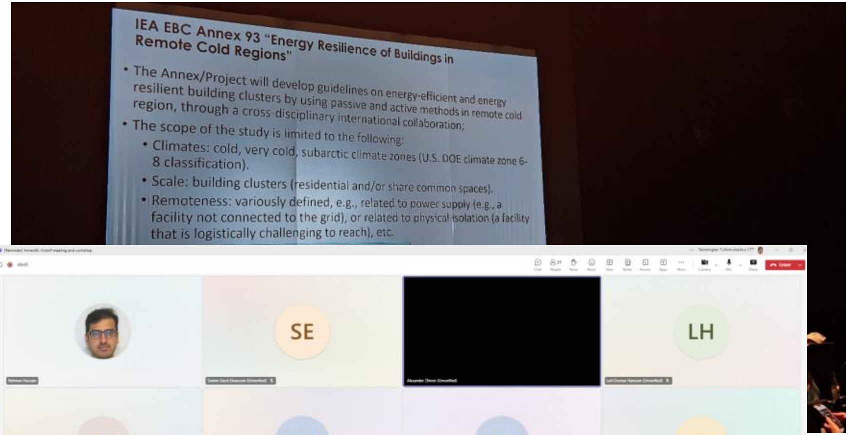
# Key questions

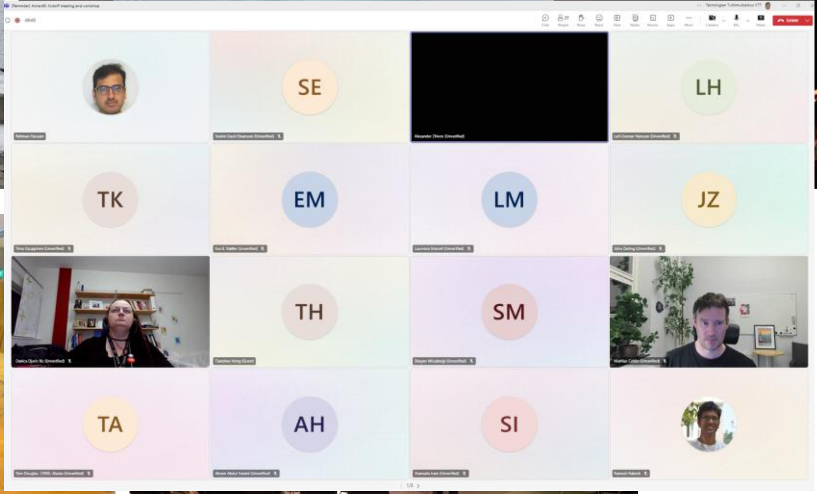
- Building and its design systems can **meaningfully enhance energy resilience** in cold climates

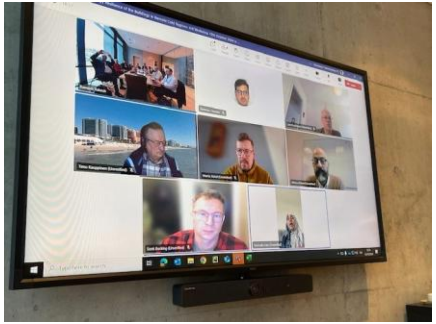
- **Key research priorities**
  - Performance assessment under **extreme climate events**
  - Advanced control and dispatch for passive and active technolgies
  - Long-term monitoring of buildings in cold regions
  - Integration of solar with storage and flexible demand
  - System-level design is critical for handling variability and extremes

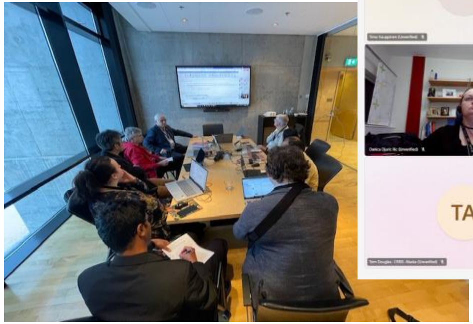
# Workshops

- Akureyri, Iceland







# Workshops

- Narvik, Norway

# Case study, Narvik

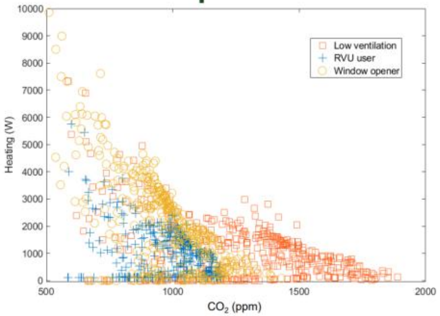
## INDOOR CLIMATE AND MOLD PROBLEMS IN BUILDINGS


## Case buildings and the renovation measures

- Constructed in1968 and 1973
- Renovation in 2015

## Results

### Air Quality and Ventilation Performance with Different Ventilation Practices



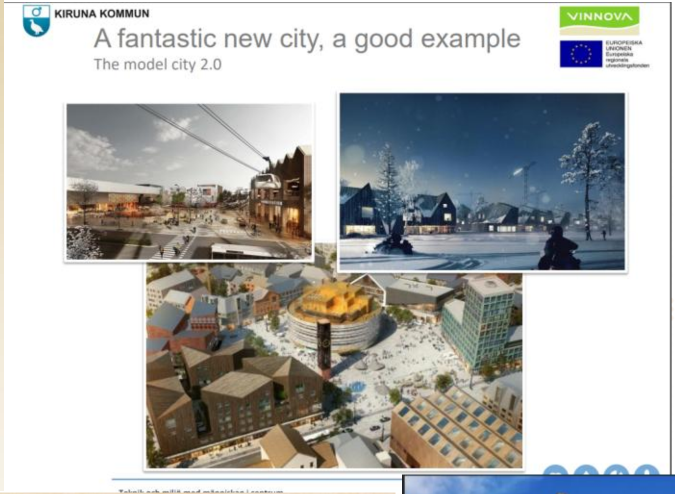

- 3650 occupied hours (22:00-08:00)
- 48 bedrooms across 12 floors

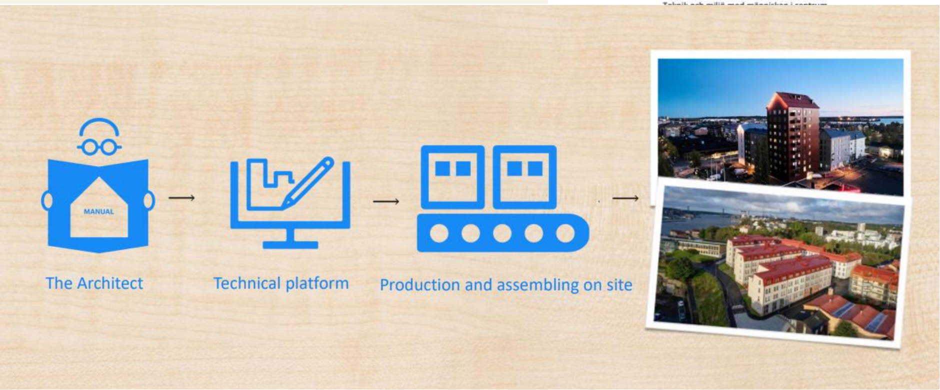
**Fig.** Distribution of $CO_2$ concentration and heating load in master bedrooms with three ventilation operations.

# Case study, Kiruna

## Our task

- ✓ Create space for 3000–4000 housing
- ✓ Plan for new commercial centre, offices and healthcare.
- ✓ Plan and build new infrastructure in the new city center.
- ✓ Plan and build new public buildings like cultural centre, swimming hall, upper secondary school, sportshall.




# Deliverables

| # | Official Deliverable | Timing |
|---|---|---|
| D1 | **Biannual Annex Status Report** according to Annex Status Report template including material to be used in the EBC Annual Report; progress, main results, and events organized and completion of final report | Every 6 months |
| D2 | **Newsletters** for Annex | Monthly |
| D3 | **Summary** on the project outcome, guideline and best practices dedicated for target audience | At the end of the project |
| D4 | Project final report and **guideline** book | At the end of the project |
| D5 | A collection of **scientific publications** in high-level journals. | Throughout the project when individual results are available |

**Website**

**Workshops/webinar with relevant stakeholders and TCPs**

**International conferences/workshops**

**Blogs, book publishing etc**

**Summer school**

**Social media**

# Publication, website and outreach

- Follow the website : [https://annex93.iea-ebc.org/](https://annex93.iea-ebc.org/)
- LinkedIn: [https://www.linkedin.com/company/iea-ebc-annex-93/?viewAsMember=true](https://www.linkedin.com/company/iea-ebc-annex-93/?viewAsMember=true)

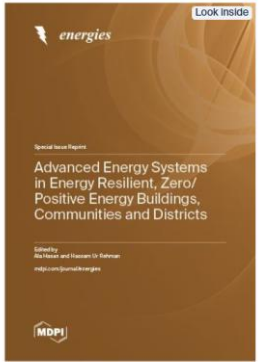
**Annex 93 Publications**

Keyword..

Sort By Publication Date

**Energy Resilience of the Buildings in Remote Cold Regions** (PDF 0.71MB)
*Factsheet*
November 2024

**EPCDescriptor: A Multi-Attribute Visual Network Modeling of Housing Energy Performance** (PDF 1.53MB)
August 2025
Author(s): Hafiz Muhammad Shakeel, Shamaila Iram, Hafiz Muhammad Athar Farid, Richard Hill, Hassam ur Rehman
Publisher: MDPI buildings
Conventional methods of studying houses' Energy Performance Certificates (EPCs) typically fail to investigate the impact of interrelated contextual elements instead fixating exclusively on the specific attributes of individual houses. This study presents a new method that combines network graph analytics (NGA) with interactive visual analytics to investigate hidden linkages at the individual house level. Our proposed platform collects and analyses data related to housing attributes, creates a network based on the links between these attributes, and employs sophisticated graph algorithms to provide visual representations. Users have the ability to dynamically choose postcodes, metrics, and attributes, which, in turn, generate layouts of networks that provide valuable insights. The visualisation utilises colour gradients and node metrics to improve the comprehensibility of energy performance areas. The platform enables homeowners and stakeholders to comprehend the interrelationships between aspects such as neighbouring housing features, and house infrastructure. The results prove the efficacy of the strategy by giving a collection of case studies that encompass various Energy Performance Certificates (EPCs) ranging from A to G. Each case study demonstrates the evolution of network architectures and visual assessments, showcasing the energy performance linked to certain EPC ratings. The platform offers a user-friendly interface for stakeholders to investigate and understand attribute relationships.



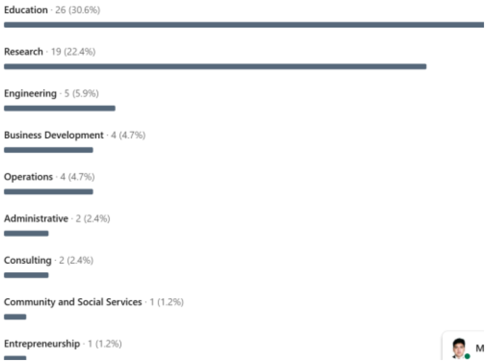

**March 2025**

Main discussion and outcomes

1. Kiruna, Sweden city plan 1
2. Kiruna, Sweden city plan 2
3. Tiny village concept
4. Indoor environment in the Arctic zone
5. Narvik building renovation use case
6. Narvik housing company use case

**Follower highlights**

85
Total followers



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

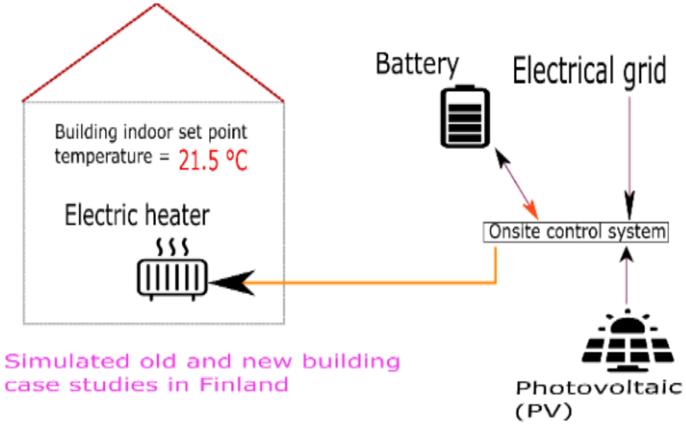
SUOMEN AKATEMIA
FINLANDS AKADEMI
ACADEMY OF FINLAND

ANNEX 93

EBC
Energy in Building and
Communities Programme

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

# Energy resilience of building with and without PV in varying weather conditions



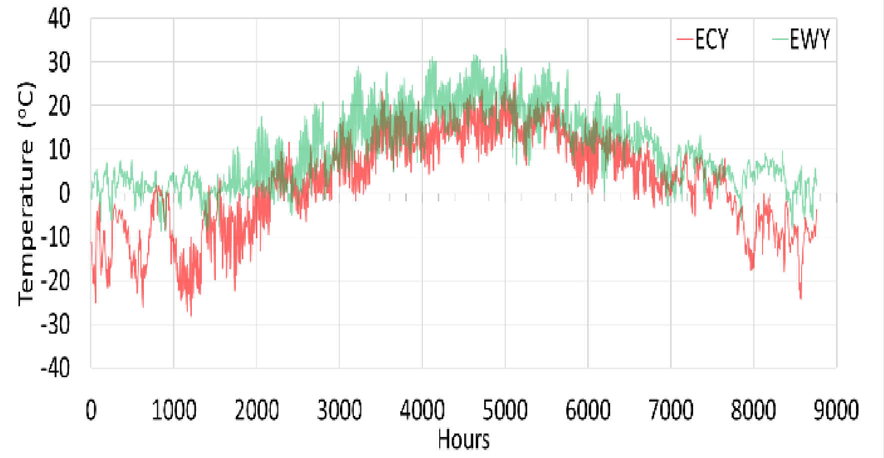

- Buildings design data

| 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 |

- 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

# Weather in cold region

- 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 |

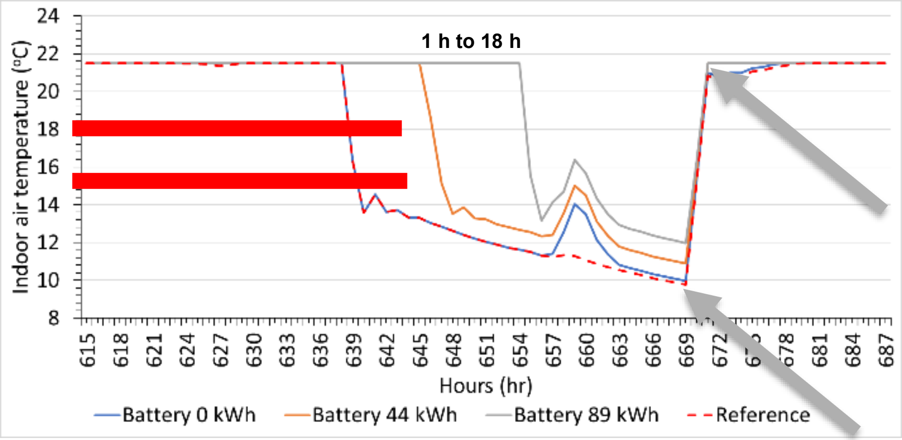
- Buildings heating demand

| 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 $kWh/m^2/yr$ |

# Energy resilience performance of old building

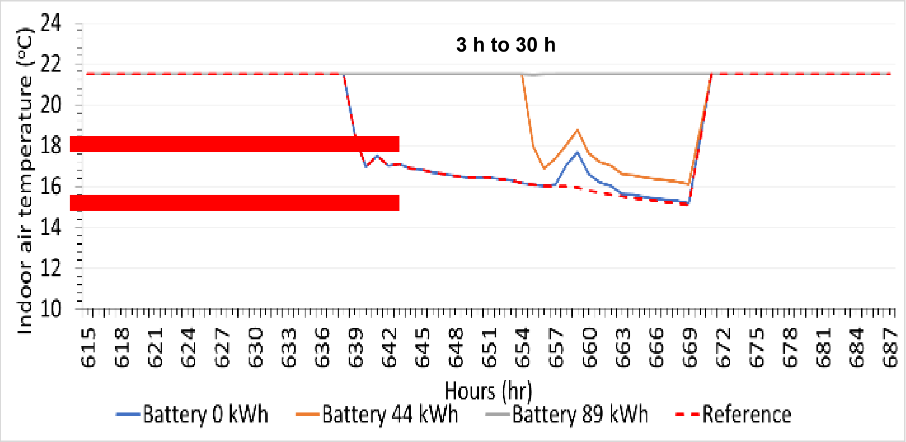
- Old building → operating at 21.5°C (in ECY and EWY)
- Assumed 30 hours of blackout conditions during winters (-15 °C)
- PV = 100 $m^2$

Extreme cold year




**The impact of failure is 12 ºC (passive)**; with PV and storage it is 9.5 ºC
The collapse speed is 0.38 ºC/hr, recovery speed is 1 ºC/hr
DoD is **0.545** (passive) and with PV and storage DoD is **0.44**

Extreme warm year

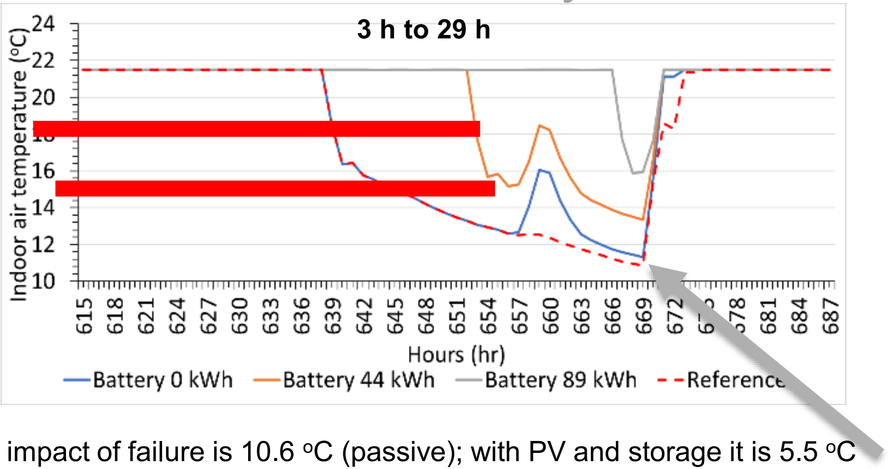



DoD is **0.299** (passive) and **0** (with PV and battery)

# 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 (-5 °C)
- PV = 100 m$^2$

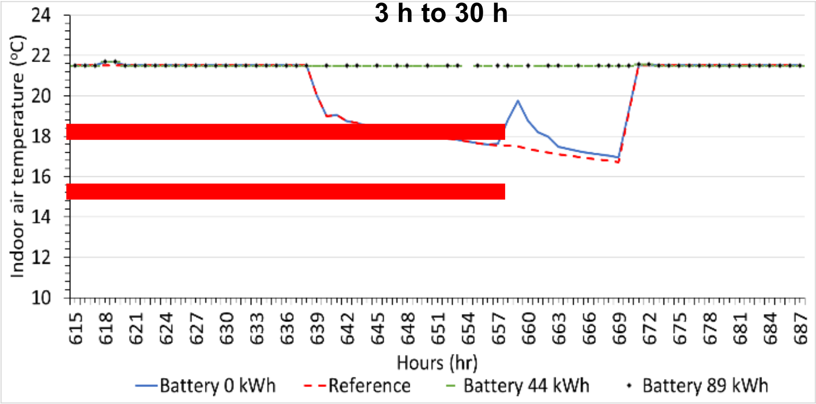
Extreme cold year




The impact of failure is 10.6 $^{o}$C (passive); with PV and storage it is 5.5 $^{o}$C

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

Extreme warm year




The impact of failure is 0 $^{o}$C (with PV and battery)

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

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

| PV size, $m^2$ | 0 | | | 50 | | | 100 | | |
|---|---|---|---|---|---|---|---|---|---|
| Battery size, kWh | 0 | 44 | 89 | 0 | 44 | 89 | 0 | 44 | 89 |
| Robustness period (RP), hour | 1.00 | 1.00 | 1.00 | 1.00 | 8.00 | 17.00 | 1.00 | 10.00 | 18.00 |
| Impact of failure (IoF), °C | 11.723 | 11.723 | 11.723 | 11.618 | 10.706 | 9.624 | 11.523 | 10.608 | 9.528 |
| Collapse speed (CS), °C/hr | 0.378 | 0.378 | 0.378 | 0.375 | 0.345 | 0.310 | 0.372 | 0.342 | 0.307 |
| Recovery speed (RS), °C/hr | 0.977 | 0.977 | 0.977 | 1.056 | 5.353 | 4.812 | 1.152 | 5.304 | 4.764 |
| Degree of disruption (DoD) | 0.545 | 0.545 | 0.545 | 0.540 | 0.498 | 0.448 | 0.536 | 0.493 | 0.443 |
| PV cost (€) | 0 | 0 | 0 | 6838 | 6838 | 6838 | 12864 | 12864 | 12864 |
| Battery cost (€) | 0 | 39377 | 79649 | 0 | 39377 | 79649 | 0 | 39377 | 79649 |
| Total cost (€) | 0 | 39377 | 79649 | 6838 | 46215 | 86487 | 12864 | 52241 | 92513 |

| PV size, $m^2$ | 0 | | | 50 | | | 100 | | |
|---|---|---|---|---|---|---|---|---|---|
| Battery size, kWh | 0 | 44 | 89 | 0 | 44 | 89 | 0 | 44 | 89 |
| Robustness period (RP), hour | 3.00 | 3.00 | 3.00 | 3.00 | 14.00 | 29.00 | 3.00 | 15.00 | 29.00 |
| Impact of failure (IoF), °C | 10.660 | 10.660 | 10.660 | 10.418 | 8.375 | 5.636 | 10.197 | 8.155 | 5.636 |
| Collapse speed (CS), °C/hr | 0.344 | 0.344 | 0.344 | 0.336 | 0.270 | 0.188 | 0.340 | 0.263 | 0.188 |
| Recovery speed (RS), °C/hr | 1.777 | 1.777 | 1.777 | 1.736 | 2.094 | 2.818 | 2.039 | 2.718 | 2.818 |
| Degree of disruption (DoD) | 0.496 | 0.496 | 0.496 | 0.485 | 0.390 | 0.254 | 0.459 | 0.379 | 0.254 |
| PV cost (€) | 0 | 0 | 0 | 6838 | 6838 | 6838 | 12864 | 12864 | 12864 |
| Battery cost (€) | 0 | 39377 | 79649 | 0 | 39377 | 79649 | 0 | 39377 | 79649 |
| Total cost (€) | 0 | 39377 | 79649 | 6838 | 46215 | 86487 | 12864 | 52241 | 92513 |

| Building type | Old building | | New building | |
|---|---|---|---|---|
| **Weather type** | **ECY** | **EWY** | **ECY** | **EWY** |
| **PV size, $m^2$** | **100** | **50** | **50** | **50** |
| **Battery size, kWh** | **89** | **89** | **89** | **44** |
| Robustness period (RP), h | 18 | 30 | 29 | 31 |
| Impact of failure (IoF), °C | 9.528 | 3.704 | 5.636 | 0.002 |
| Collapse speed (CS), °C/hr | 0.307 | 0.119 | 0.188 | 0 |
| Recovery speed (RS), °C/hr | 4.764 | 1.852 | 2.818 | 0.001 |
| **Degree of disruption (DoD)** | **0.443** | **0.172** | **0.254** | **0** |
| *PV cost (€)* | *12864* | *6838* | *6838* | *6838* |
| *Battery cost (€)* | *79649* | *79649* | *79649* | *39377* |

# Findings and Implications

## IEA EBC - Annex (93): Energy Resilience of the Buildings in Remote Cold Regions

**Developing**:

- Climate specifications in cold regions are different
- Challenges to the constructions are different
- Building regulations are being compared
- Indicators and assessment methods are identified
- Develop an impact on health, due to COVID and, guidelines related to the indoor environment
- Permafrost challenges
- Energy system design and challenges → to analyze the impact on resilience
- Compare and define case studies in cold regions

**This has led to several key developments in this area including (expected):**

- Development of local understanding for resilience in cold
- Best practices in building envelope design
- Best practices in developing energy systems, storage, and alternative fuels guidance

**The impact of this work has been:**

- Resilience framework and good practices in terms of building design
- Adaptation to climate change and disruptions
- Guide on developing energy system in cold regions

**The implications of these finding for policy are:**

- Guidelines and good practices for resilience in cold region

# Solar Energy Systems in Cold Climates

- **Solar PV and Thermal Technologies**
  - Solar photovoltaic and thermal systems have great potential to enhance energy resiliencein cold, high-latitude areas.
- **Seasonal Variability Challenges**
  - Cold regions face seasonal variability and limited winter sunlight, requiring specialized system designs for reliability.
- **System Integration and improved Resilience**
  - Integrating solar systems into decentralized energy infrastructures improves resilience and system-level performance in harsh climates.

# Characteristics of Cold and High-Latitude Environments

- **Seasonal Solar Variability**
  - Cold regions experience extreme seasonal changes in solar irradiance, with long summer days and very limited winter daylight.
- **Extreme Winter Conditions**
  - Low temperatures, heavy snowfall, wind, and ice impose mechanical and thermal stress on energy systems in these environments.
- **Climate Change Impacts**
  - Changing snow cover and cloud patterns due to climate change affect solar energy availability in high-latitude areas.
- **Importance of Event-Based Assessment**
  - Evaluating system performance during extreme events is vital for resilience beyond average annual performance metrics.

# Role of Solar PV in Cold-Climate Power Systems

- Solar PV increases **energy resilience** by:
  - Decentralizing electricity generation
  - Diversifying energy sources
  - Reducing reliance on **diesel fuel**, especially in remote communities

- Distributed PV systems:
  - Reduce risk of **large-scale blackouts**
  - Avoid **single-point failures** during extreme events (Sotomayor, n.d.)

- PV integration options:
  - Rooftop systems
  - Building-integrated façades
  - Grid export during overproduction periods (Luthander et al., 2015)

# Enclosed Concentrated Solar Thermal System

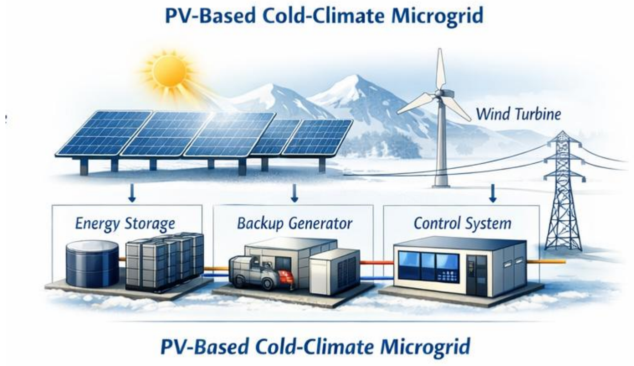
- **SolarSteam Prototype – CanmetENERGY Ottawa**
  - Tested by **CanmetENERGY Ottawa (Natural Resources Canada)**
  - Developed by **SolarSteam Inc. (Alberta, Canada)**

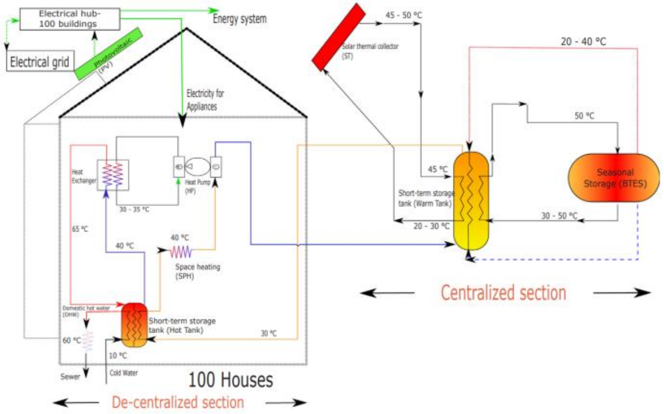
- Key features:
  - Parabolic trough collector with **evacuated tube absorber**
  - Fully **enclosed transparent thermal module**

- The enclosure:
  - Protects against **wind, snow, hail, and rain**
  - Enables **passive solar heating** of internal air
  - Eliminates forced air flow over the collector
  - Reduces convective heat losses to **natural convection only**

# Resilient PV-Based Microgrids

- Key design requirements:
  - **Energy storage systems**
  - Backup generation
  - Advanced **control and dispatch strategies**
- Intelligent coordination between:
  - Generation
  - Storage
  - Flexible demand
- Enables:
  - Higher shares of solar PV
  - Stable operation during **extreme cold events**
- Especially critical in cold regions where **prolonged outages pose severe risks** (Hosseini et al., 2025)



# Building and design variable

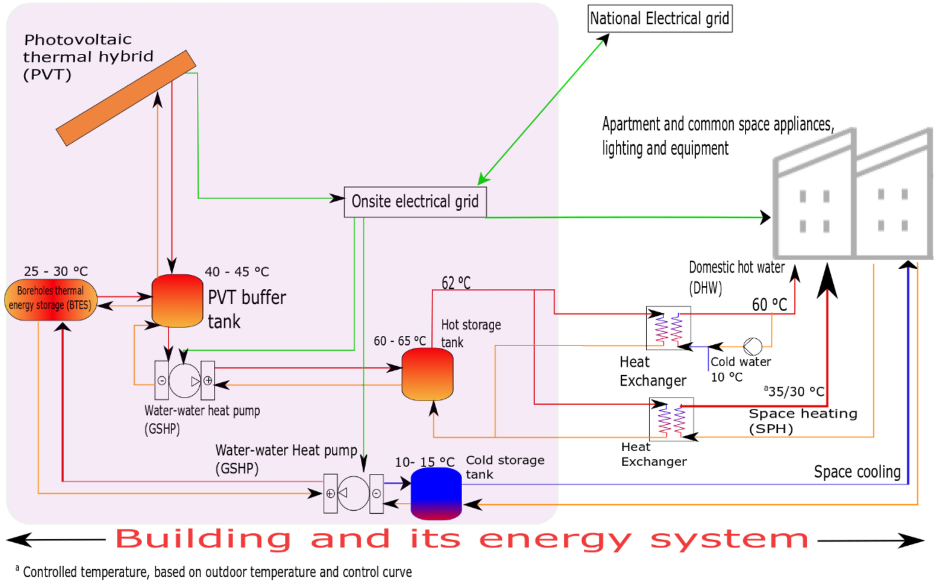
- IDA-ICE simulation
  - Heating load is 15.4 kWh/m$^2$/yr,
  - Domestic hot water load is 42.1 kWh/m$^2$/yr
  - Cooling load is 2.36 kWh/m$^2$/yr
  - Plug loads is 36.9 kWh/m$^2$/yr

| Parameters | Value |
|---|---|
| Floor area | 4000 m$^2$ |
| Walls (U value) | 0.15 W/m$^2$ K |
| Roof (U value) | 0.09 W/m$^2$ K |
| Floor (U value) | 0.16 W/m$^2$ K |
| Windows (U value) | 0.6 W/m$^2$ K |
| Heat recovery efficiency | 75 % |
| Ventilation air flow | 0.5 dm$^3$/sm$^2$ |

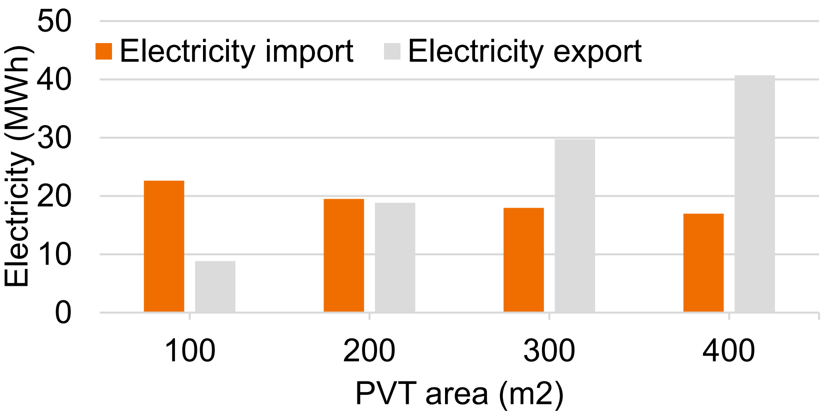
# Energy system and design variables

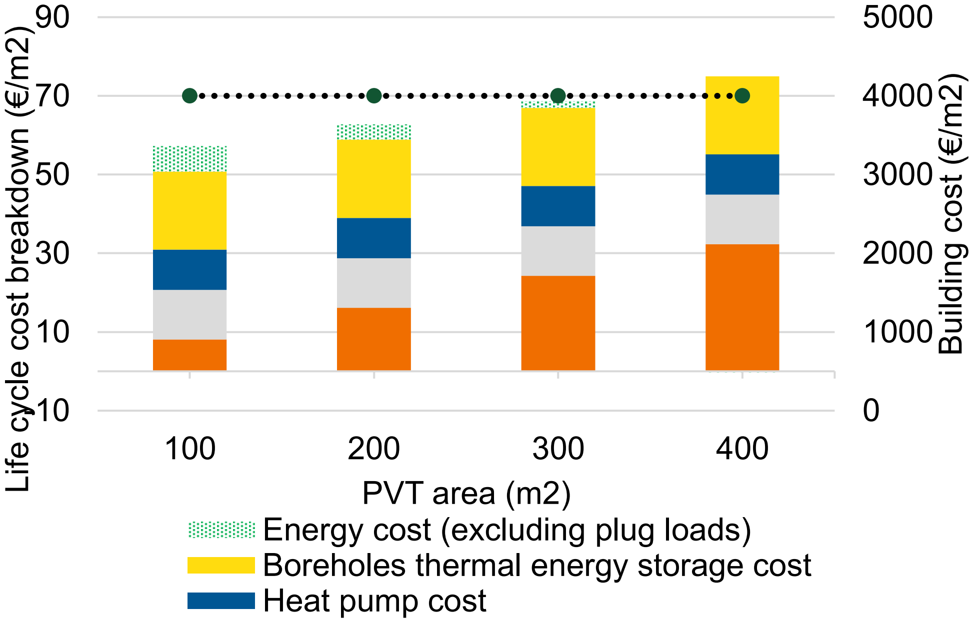
- TRNSYS simulation
  - Design variables used for parametric study
    - Including the plug loads
    - Excluding the plug loads

| Component | Parametric values |
| --- | --- |
| Photovoltaic-thermal collector ($m^2$) | 100, 200, 300, 400 |
| PVT Buffer tank ($m^3$) | 10, 20, 30, 40, 50 |
| Deep borehole height ratio | 1, 3, 5 |
| Deep borehole density (BH(s)/$m^2$ BH area) | 0.05, 0.10, 0.15 |



# Performance Analysis



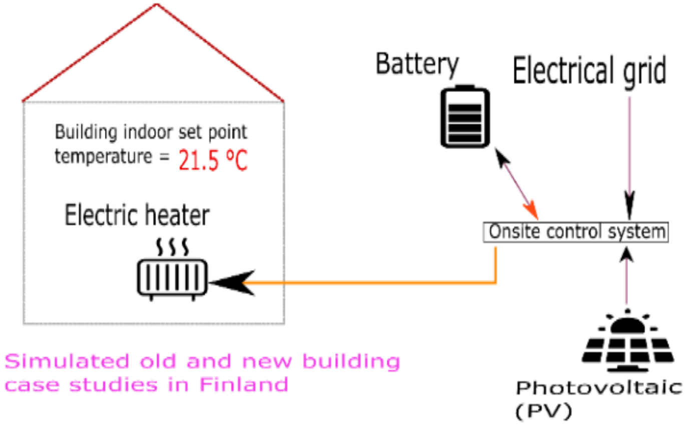




Life cycle cost breakdown and the building cost for different PVT areas

The energy cost is -0.3 €/m$^2$ when the PVT area is 400 m$^2$

# Energy resilience of building with and without PV in varying weather conditions






Simulated old and new building case studies in Finland

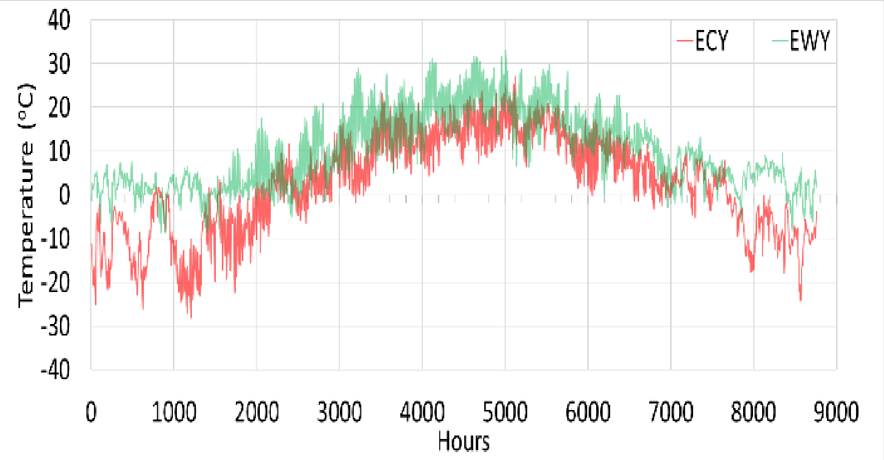
- Buildings design data

| 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 |

- 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

# Weather in cold region

- 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 |

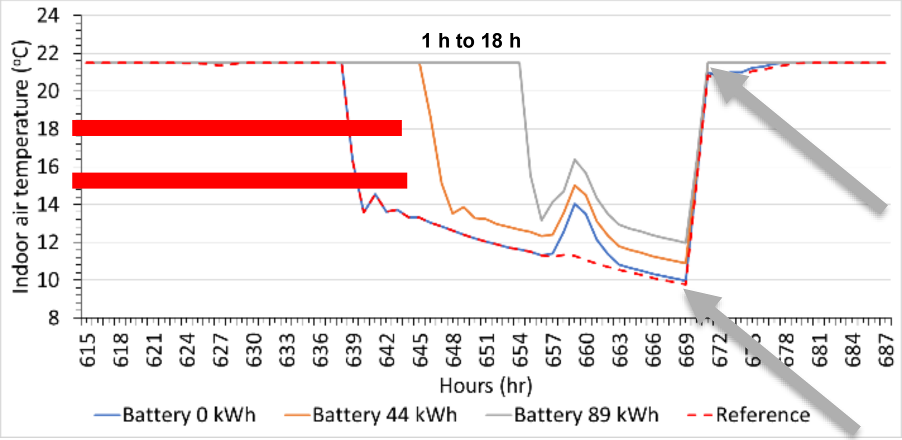
- Buildings heating demand

| 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 $kWh/m^2/yr$ |

# Energy performance of building and PV

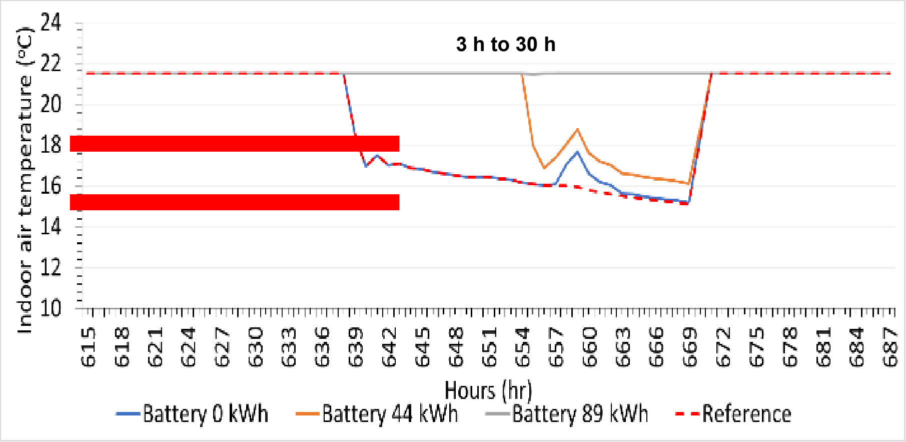
- Old building → operating at 21.5°C (in ECY and EWY)
- Assumed 30 hours of blackout conditions during winters (-15 °C)
- PV = 100 m²

Extreme cold year




**The impact of failure is 12 °C (passive)**; with PV and storage it is 9.5 °C
The collapse speed is 0.38 °C/hr, recovery speed is 1 °C/hr
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)

# Impact on Diesel Reduction and Energy Security

- PV systems supplying **20–30%** of community electricity demand can:
  - Reduce diesel fuel consumption by **50–70%**

- Demonstrated in **Canada's Arctic communities** (De Witt et al., 2021; McDowall, 2018)

- Outcomes:
  - Improved local energy resilience
  - Reduced exposure to volatile fuel supply chains
- Further research needed on:
  - High-PV microgrid operation
  - Advanced dispatch methodologies

# Challenges of High PV Penetration in Remote Communities

- Intermittency of solar PV can challenge:
  - Grid stability
  - Frequency and voltage control

- In remote Canadian communities:
  - Non-dispatchable renewables are typically limited to **20–30%** of electricity supply
  - Higher shares require significant investment in **grid-forming resources** (De Witt et al., 2021; McDowall, 2018)

- Resilience limitation is **system management**

# PV Durability in Cold Climates

- Manufacturer-rated PV module lifetime:
  - **20–30 years** (Jordan et al., 2022)
- Degradation strongly influenced by climate:
  - Hot and humid / dry climates: **0.75–1.2% per year**
  - Continental, subarctic, and tundra climates: **~ –0.45% per year** (Tonita et al., 2025)
- Cooler operating temperatures:
  - Improve long-term PV reliability
  - Offset impacts of snow, ice, and freeze–thaw cycles
- **Data gaps remain** due to limited long-term monitoring in Arctic and subarctic regions
- Continued monitoring needed to fully quantify **PV resilience in cold climates**