ANNEX **80**

EBC

Energy in Building and Communities Programme

International Energy Agency

Resilient Cooling of Buildings Project Summary Report (Annex 80)

Energy in Buildings and Communities Technology Collaboration Programme

May 2024

Technology Collaboration Programme by iea

ANNEX 80

EBC

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International Energy Agency

Resilient Cooling of Buildings Project Summary Report (Annex 80)

Energy in Buildings and Communities Technology Collaboration Programme

May 2024

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Published by Institute of Building Research & Innovation ZT GmbH, Wipplingerstraße 23/3, 1010 Vienna Austria.

DOI: 10.52776/KKGB4933

Participating countries in the EBC TCP: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits.
– improvement of planning, construction, and management processes to reduce the performance gap between design stage assessments and real-world operation.
– the creation of 'low tech', robust and affordable technologies.
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible.
– the creation of holistic solution sets for district level systems considering energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA).
– benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures.
– improving smart control of building services technical installations, including occupant and operator interfaces.
– addressing data issues in buildings, including non-intrusive and secure data collection.
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)

Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behaviour in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalized Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy efficient Heating, Cooling and IAQ Control in Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Summary

This report summarizes the structure and the outcomes of Annex 80 – Resilient Cooling of Buildings, which was conducted as a five-year international research project within the IEA Technical Collaboration Programme EBC – Energy in Buildings and Communities.

Annex 80 has been started against the background of a worldwide rapidly growing need for cooling. It aimed to develop, evaluate, and communicate solutions for resilient cooling and resilient overheating protection.

Annex 80 covered the spectrum of the following four technology groups:

(1) Reducing heat gains to the indoor environment and people environments
(2) Removing sensible heat from the indoor environment
(3) Increasing personal comfort apart from space cooling
(4) Removing latent heat from indoor environment

Annex 80 was joined by 33 research teams from 18 countries. It has been structured in four subtasks and another five task groups.

Its outcomes are published in seven official Annex Deliverables. These are:

1. State of the Art Review (SOTAR)
2. Midterm Report
3. Technology Profiles Report
4. Resilient Cooling Design Guidelines, published in collaboration with REHVA
5. Resilient Cooling Field Studies Report
6. Policy Recommendations
7. Project Summary Report

All reports can be found at: https://www.building-research.at/annex_80/.

In addition, partial results of Annex 80 have been published in numerous scientific journals.
A list of the most important journal articles is presented at: https://annex80.iea-ebc.org/publications.

Table of content

Abbreviations

Abbreviations	Meaning
CORDEX	Coordinated Regional Climate Downscaling Experiment
KPIs	Key Performance Indicators
NRIs	National Research Items
SOTAR	State of the Art Review
TMY	Typical Meteorological Year

1. Introduction

The technical temperature control of buildings for cooling purposes is increasing rapidly world-wide. This is due to various factors, such as urbanization and densification, climate change and higher comfort requirements. Another decisive factor is the increasing economic growth in the hot and densely populated regions of the world. The trend towards ever-increasing use of room cooling seems inevitable, so it is imperative to steer this development towards sustainable solutions.

In view of these circumstances, the aim of Annex 80 Resilient Cooling of Buildings was to develop, evaluate and communicate solutions for resilient cooling and resilient overheating protection.
The term "resilient cooling" refers to energy efficient, low emission and financially affordable cooling concepts that increase resilience to thermal and other influences of climate change on a global and local level and also prevent them.

Annex 80 contributed to overcoming this challenge. Annex 80 comprises a systematic evaluation of existing cooling technologies, their potentials, limitations, and qualities of resilience. Furthermore, cooling technologies were further developed and improved in terms of robustness, efficiency, CO_2 neutrality and affordability. The actual performance of cooling technologies was evaluated to identify performance gaps and develop solutions to systematically overcome them. Regulatory measures that can support the broad application of resilient cooling technologies were also identified and communicated.

Annex 80 covers the spectrum of the following four technology groups:

(1) Reducing heat gains to the indoor environment and people environments
(2) Removing sensible heat from the indoor environment
(3) Increasing personal comfort apart from space cooling
(4) Removing latent heat from indoor environment

Methodologically, the research activity was organized into four subtasks and a further five overarching task groups. The results of Annex 80 are documented in seven deliverables and in numerous scientific publications and are freely available.

Annex 80 has made significant contributions to the professionalization and application support of resilient cooling of buildings and has expanded the possibilities for its application in a wide range of climate zones and building types. However, the work on passive cooling strategies has also shown the limits of purely building-related measures: The outdoor conditions of buildings, the thermal interactions of built structures and also the cross-sectoral energy and heat flows in urban settlement areas must definitely be included in the design of climate change-resilient and decarbonized living spaces.

Against this background, a further annex is currently being prepared as part of the IEA EBC and Cities programs, with an extended focus on resilient and sustainable cooling of and in cities.

2. Initial Situation

The technical temperature control of buildings for cooling purposes is increasing rapidly world-wide. This is due to various factors, such as urbanization and densification, climate change and higher comfort requirements. Another decisive factor is the increasing economic growth in the hot and densely populated regions of the world. The trend towards the ever-increasing use of room cooling seems inevitable, so it is imperative to steer this development towards sustainable solutions.

Foreseeable impacts of climate change include longer and more frequent extreme events such as heatwaves, power outages and the lack or inadequate design of cooling technologies and strategies to cope with future climate conditions and reduce the risk of power outages. Such events also have an impact on the construction sector, creating new challenges for building cooling systems and putting them under unprecedented pressure. Today's widely used cooling technologies, which are mainly dependent on fossil fuels (so called active systems with electricity/fuel requirements), will not be able to withstand extreme events in the long term. In contrast, there are technologies that reduce or eliminate fuel/energy requirements through so called passive systems, which reduce the cooling requirements of buildings or dissipate excess heat efficiently and with minimal energy input, preferably using renewable energy sources (active systems).

In view of these circumstances, the aim of Annex 80, Resilient Cooling of Buildings, was to develop, evaluate and communicate solutions for resilient cooling and resilient overheating protection. The term "resilient cooling of buildings" refers to energy efficient, low emission and financially affordable cooling concepts that increase resilience to and prevent thermal and other climate change impacts at global and local level.

There is already a wide range of cooling technologies and solutions. Nevertheless, far reaching initiatives are needed to steer the general development of room cooling towards sustainability and resilience. Annex 80 contributed to overcoming this challenge.

Not only the development, but also the broad application of resilient cooling is effectively supported by:

- Systematic evaluation of existing cooling technologies, their potential, limitations, and qualities of resilience.
- Development and improvement of cooling technologies in terms of robustness, efficiency, CO_2 neutrality and affordability.
- Evaluate the real-world performance of cooling technologies to identify performance gaps and develop solutions to systematically overcome them.
- Identification and communication of regulatory measures that can support the broad application of resilient cooling technologies.

Several IEA Annexes have already dealt with aspects of energy efficient and low emission room cooling. These have focused on specific technologies. Annex 80 builds on the results of these projects and integrates them into its broader approach:

Annex 28	Low Energy Cooling Systems
Annex 35	Hybrid Ventilation
Annex 37	Low Exergy Systems for Heating and Cooling
Annex 48	Heat Pumping and Reversible Air Conditioning
Annex 49	Low Exergy Systems for High Performance Buildings and Communities
Annex 59	High Temperature Cooling and Low Temperature Heating in Buildings
Annex 62	Ventilative Cooling
Annex 67	Energy Flexible Buildings
Annex 69	Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Annex 80 covers the evaluation, research and development of active and passive as well as hybrid cooling technologies and systems, categorized into the following four groups:

- Reducing heat gains to the indoor environment and people environments
- Removing sensible heat from the indoor environment
- Increasing personal comfort apart from space cooling
- Removing latent heat from indoor environment

The main objective of Annex 80 was to support a rapid shift towards an environment in which energy efficient and low emission cooling systems are the most important and preferred solutions to cooling and overheating problems in buildings. The focus of this Annex was on residential and office buildings.

At the beginning of the project, the state of the art was analyzed and published in report form, Annex 80 Deliverable 1: Resilient Cooling of Buildings - *State of the Art Review*. This deliverable contains an inventory of current cooling technologies for buildings. The primary objective was to provide a comprehensive and systematic description of the available cooling solutions, including an examination of their underlying physical principles, the advantages and limitations associated with each, their current technological state of development, their practical availability, and their applicability in various settings. The assessments are based on extensive and systematic literature research as well as on the scientific and practical expertise of the authors. In this way, *the State of the Art Review* (SOTAR) forms the basis for the work in the Annex 80 project. The document is the result of collaborative work by participants in IEA EBC Annex 80.

The scope of the Annex is limited to measures within the building itself. The area of the urban microclimate is not included in the analysis. However, the variety of possible external climatic conditions (temperature, humidity, air quality, noise) is taken into account. Annex 80 also sets itself apart from research into indoor comfort. However, indoor comfort is included as an important boundary condition.

3. Project Structure

3.1 Subtasks

3.1.1 Subtask A – Fundamentals

Subtask A defines resilience in relation to building cooling by assessing a broad range of disciplines, their disaster risk management strategies and resilience measures to heat waves and/or power outages.

As part of Subtask A, suitable key performance indicators (KPIs) were developed to assess the resilience of cooling technologies and systems using a holistic approach. The KPIs were related to thermal comfort, heat load and CO_2 emissions.

Subtask A consists of several closely interlinked activities. A key aspect is the compilation of the current knowledge and evidence base as well as the intensive cooperation and exchange of information between the participating institutions and countries. Subtask A is divided into the following research activities:

Activity A.1. This activity involves the assessment of a wide range of sectors, their disaster risk management strategies and resilience measures in order to formulate a definition of resilience in relation to the cooling of buildings.

Activity A.2. This activity focuses on the development of multi-criteria methods for evaluating technologies that lead to standardized and measurable KPIs in terms of thermal comfort, heat load and CO_2 emissions.

Activity A.3. This activity involves the identification and further development of methods to predict the performance of the full range of possible resilient cooling technologies to reduce cooling demand and overheating risks. The findings on suitable methods from this research activity will be integrated into the Technology Profile Sheets produced in Activity B.1.

Subtask A is also significantly involved in the Resilience Definition, Thermal Conditions and Key Performance Indicators task groups. The task groups are described in detail after the subtasks.

3.1.2 Subtask B – Solutions

Subtask B systematically assesses the benefits, limitations and performance indicators of resilient cooling solutions. Both barriers and favorable conditions for implementation are identified. This subtask provides guidelines for the integration of resilient cooling systems into existing and new calculation methods for determining energy requirements and predicting room comfort (Dynamic Simulation Guideline, Resilient Cooling Guideline).

Subtask B also deals with specific research work with regard to new developments and improvements in resilient cooling and overheating protection. The possibilities of existing energy efficient and low emission cooling solutions were expanded and new solutions, combinations of technologies and applications were developed.

Subtask B is organized within the framework of specific national research projects of the project partners (National Research Items (NRIs)). It applies methodological approaches such as numerical modelling and measurements on a laboratory and prototype scale. As the participating partners have specific climatic and other contextual interests of the respective countries, Subtask B covers research topics that are both internationally relevant and nationally specific. Subtask B coordinated more than 40 such national research projects.
The results were published in scientific journals, for example in the special issue of Energy and Buildings entitled "Building Cooling for Sustainable Societies" and in the *State of the Art Review* (SOTAR) [1].
The subtask is divided into the following research activities:

Activity B.1. This activity involves a systematic assessment of the potential benefits, limitations and performance indicators of resilient cooling solutions under a variety of application scenarios and constraints. Technology Profile Sheets for resilient cooling technologies were created to clearly summarize the operational characteristics and benefits of each technology. Recommendations for efficient implementation, commissioning and operation were formulated. In addition, obstacles to application and further research opportunities were identified.

Activity B.2. This activity includes specific national research projects to develop new solutions and combinations of technologies and applications. In addition, this activity includes research projects to extend the scope of existing technologies and systems for resilient cooling (e.g. with regard to building type, climate zones or occupancy characteristics)

3.1.3 Subtask C – Field Studies

Subtask C demonstrates the potential and benefits of resilient cooling by analyzing and evaluating well-documented applications of energy efficient and low emission resilient cooling solutions.
The field studies analyzed and observed specific technologies and solutions rather than specific buildings. The performance deficits of existing cooling applications and their actual performance in use were analyzed, with particular attention paid to socio-technical interaction and control strategies.
The results of Subtask C complement the Technology Profile Sheets developed in Subtask B. The subtask is divided into the following research activities:

Activity C.1. This activity provides a methodological framework for conducting field studies and analyzing the data sets collected.

Activity C.2. This activity consists of assessing the performance and analyzing the performance shortcomings of resilient cooling solutions, design methods and tools, with particular attention to socio-technological interaction and control strategies, using the criteria and methods defined in Activity C.1.

Activity C.3. As part of this activity, experience has been gathered, and recommendations developed for the design and operation of resilient cooling solutions. Obstacles to application and operation were also identified. All findings were published in the *Field Studies Report* (Deliverable D4).

Subtask C was also heavily involved in the task group on key performance indicators. Subtask C also facilitated the coordination of 13 case studies on the monitoring of resilient cooling systems.

3.1.4 Subtask D – Policy Action

Subtask D focused on strategic efforts to promote energy efficiency and resilient cooling at the regulatory level. This subtask analyzed product labelling, energy efficiency standards, building regulations, standards, guidelines and recommendations in order to identify international best practice examples and potential obstacles.

The aim was to develop recommendations for future regulatory measures to support the implementation and enforcement of resilient cooling systems at national, European and international level. In this context, Subtask D aimed to provide a link to international programmes such as KIGALI - Cooling Efficiency Programme, Mission Innovation Challenge #7 and the IEA Technology Collaborating Programmes.
The subtask was divided into the following research activities:

Activity D.1. This activity analyzed and compared national and international product labelling, energy efficiency standards, sustainability aspects in building regulations and standards with regard to resilient cooling at international level (Policy Recommendation Sheets).

Activity D.2. This activity involved collaboration with international programmes to support and incorporate resilient cooling systems.

3.2 Task Groups

3.2.1 Resilience Definition Task Group

The Resilience Definition Task Group, which strongly supported Subtask A, was set up to create a definition of resilience in the context of the Annex, which also were used as the starting point for all considerations in the further course of the project.

3.2.2 Thermal Conditions Task Group

The Thermal Conditions Task Group had the following objectives:

- Coordination with all task groups.
- Definition of standardized thermal boundary conditions for the evaluation of different cooling technologies, based on the definition of resilience from Subtask A.
- Definition of standardized comparative values.

The results of this task group formed the basis for the other task groups and subtasks.

3.2.3 Weather Data Task Group

Future meteorological boundary conditions are crucial for a conclusive assessment of resilient cooling technologies. This task group developed proposals for a coordinated methodology for creating prospective climate data sets, in particular for visualizing and predicting the effects of climate change and heatwaves.
One aim was to create weather data sets for characteristic climate zones and representative cities. This includes:

- A typical meteorological year (TMY) (in hourly resolution, for the periods 2001-2021, 2041-2061 and 2081-2101).
- Illustration of characteristic heat waves (in hourly resolution, for the periods 2001-2021, 2041-2061 and 2081-2101).
- Design conditions for cooling.

A further aim was to describe the methodology, the sources, and the definition of minimum requirements for the quality of the individual weather data sets.
ASHRAE Climate zones are used as a basis to select representative cities for each climate region. A total of 15 cities were analyzed. When selecting the representative cities, preference was given to cities with a high population density and high growth. The weather data was created based on CORDEX data (Coordinated Regional Climate Downscaling Experiment) using the EN ISO 15927-4:2005 standard for the worst-case scenario RCP8.5 of the 5th IPCC assessment report from 2014 [2]. Historical observation data (20 years of continuous hourly data), which is necessary to reduce long term distortions in connection with climate model data, was also used. CORDEX data were generated using different models, taking into account the relevant scientific literature on which model is most reliable for each climate zone. Heatwaves were modelled using the model developed by Ouzeau et al [3] in the CORDEX data. This methodology for generating the weather data sets made it possible to use the same data source and time periods for different cities and climate zones and to recognize future extreme events such as heatwaves. This was not possible with other weather data generators, such as METEONORM.

3.2.4 KPI Task Group (Working Group on Performance Indicators)

Within the Key Performance Indicators Task Group, a structured basic catalogue of key performance indicators (KPIs) relevant to resilient cooling technologies was created. The KPIs were described within the Annex, including definition, unit, source, information value and areas of application. They include metrics for indoor air quality, energy consumption, heating, ventilation, cooling, and the power grid. Special focus was placed on the identification of resilience associated KPIs. The KPIs were subsequently applied in the individual deliverables of the Annex.

3.2.5 Simulation Task Group (Thermal Simulations Working Group)

The Simulation Task Group was set up to evaluate the cooling technologies and create technology profiles. The input for the simulations came from the Weather Data Task Group, the KPI Task Group and the Thermal Conditions Task Group. The framework conditions were set out in a simulation guideline (Dynamic Simulation Guideline).

4. Official Annex Deliverables

The results of Annex 80 are available in the form of seven publications (deliverables). They form an integral part of this final report and are available online.

Further information can be found at:
https://www.building-research.at/annex_80/

1. State of the Art Review (SOTAR)
2. Midterm Report
3. Technology Profiles Report
4. Resilient Cooling Design Guidelines, published in collaboration with REHVA
5. Resilient Cooling Field Studies Report
6. Policy Recommendations
7. Project Summary Report

In addition, partial results of Annex 80 have been published in numerous scientific journals.
A list of the most important journal articles is compiled at:
https://annex80.iea-ebc.org/publications

4.1 Deliverable 1: State of the Art Review (SOTAR)

Deliverable 1: State of the Art Review [1] is the result of collaborative work by the Annex participants and summarizes the current status of cooling technologies that can be classified as resilient in four chapters.

The main objective was to systematically describe the available cooling technologies, their physical principles, their advantages and limitations, their technological progress and their practical availability and applicability. The assessment of the *State of the Art Review is* based on an extensive and systematic literature research as well as on the scientific and practical experience of the authors.

The first chapter contains relevant technologies and strategies that contribute to the reduction of externally induced heat gains to the indoor environment and people environments. These technologies and strategies include Window and Glazing Technologies, Shading Technologies, Cool Envelope Materials, Evaporative Surfaces, Ventilated Façades, Heat Storage and Heat Release.

In the second chapter, cooling strategies and technologies responsible for the removal of sensible heat from indoor spaces were evaluated: Ventilation Cooling, Evaporative Cooling, Compression Cooling, Desiccant Cooling Systems, Ground Source Cooling, Night Sky Radiative Cooling and Radiant Cooling.

The third chapter analyzed different types of cooling strategies and technologies that can be used to improve personal comfort apart from space cooling. This group includes ceiling and wall fans. In addition, small desktop-scale fans or stand fans, fans integrated into furniture, devices that combine fans with misting/evaporative cooling, cooled chairs with convective/conductive cooled heat absorbing surfaces, cooled desktop surfaces, workstation micro-air-conditioning units and radiantly cooled panels.

The fourth chapter analyzed technologies and strategies for removing latent heat from indoor environments. Dehumidification with desiccants, dehumidification through cooling, dehumidification through ventilation and thermoelectric dehumidification were analyzed.

The study on the state of the art confirmed the initial hypothesis of the Annex. There is a large number of cooling technologies for different building types and climate zones, but their resilience has not yet been adequately described.

The *State of the Art Review* formed the basis for the further work of Annex 80. Extracts from this deliverable are shown and described below. The full report can be found on the Annex 80 publication list (https://annex80.iea-ebc.org/publications) and was published under DOI 10.52776/COXK4763.

2.3 Evaporative Envelope Surfaces

Technology Group A.3a

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2.3.1 Physical Principles

Water retention on external envelopes is a passive cooling solution. This passive technique is mainly used through vegetated surfaces like green roofs and green façades [1–3], or water surfaces like roof ponds and water spray façades [4]. Figure 2-2 shows the thermal flux for the main typologies of evaporative surfaces. The primary difference between façades (green or watered) and roofs (green roof or roof pond) is linked to the vertical water runoff, which amplifies the water effect in the thermal balance due to gravity. However, the retention of runoff depends on the seasonal variation in rainfall. Storm water events with heavy rainfall are managed by partial retention on green roofs or roof ponds. Evaporative techniques for façades require continuous water spray or water supply to permanently irrigate the upper part.

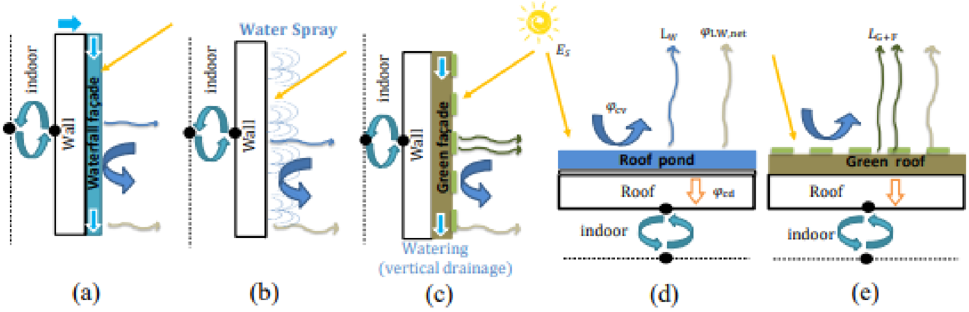


Figure 2-2 Heat transfer in evaporative envelope surfaces, including (a) a waterfall façade, (b) a spraying system, (c) a green façade, (d) a roof pond, and (e) a green roof.

All these systems have a water retention or watering technique supplied by regular rainfall or controlled watering devices. On the external envelope, the evaporative process absorbs the sensible heat fluxes that are derived mainly from solar irradiance (ES), conducted heat flux (φcd), and convective heat flux (φcv) with outdoor air. Thus, the cooling effect on the outside is mainly due to the latent heat flux (LW) resulting from surface water evaporation, or from growing medium (LG) and foliage (LF) evapotranspiration, and longwave radiation to the sky (φLW,net). The evaporative process is amplified by direct solar gains for open wet surfaces (e.g., roof ponds), compared to vegetated surfaces (Figure 2-2 a, b, d). The external evaporative system limits the transferred and stored heat in the wall and the roof, reducing the indoor surface temperature.

Figure 1: *SOTAR* extract 1 - Physical principle of evaporative surfaces in buildings.

The physical principles behind how the technology works are explained at the beginning of each technology chapter. The example shows various options for evaporative surfaces on a building and their heat flow behavior. The text also refers to important influencing factors.

2.3.4 Performance

2.3.4.1 Key Performance Indicators for Evaporative Envelope Surfaces

The performance of evaporative surfaces can be assessed in terms of a decrease in surface temperature (external or internal), or by reduction in the temperature of the indoor environment. Indoor cooling performance depends on the indoor air temperature (T_i) or operative temperature (Top) or the cooling energy consumption of the building. The main physical parameters for the calculation of key performance indicators (KPIs) are represented in Figure 2-3, which illustrates heat transfer for evaporative envelope surfaces compared generally with either a reference bare roof (ref 1) or a galvanized iron roof (ref 2). The latter is the worst case, with a maximum ceiling temperature ($T_{c,max}$) equal to the sol-air temperature (T_{sa}).

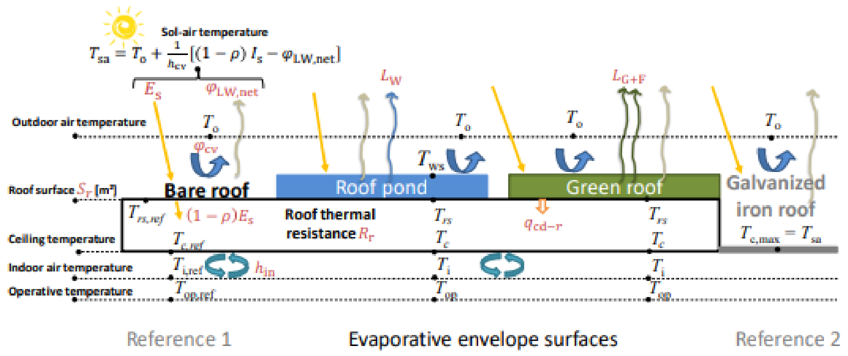


Figure 2-3 Heat flux and temperature of a reference bare roof and evaporative envelopes

A first KPI can be defined as the temperature reduction of the roof (Trs) or the ceiling (Tc). A comparison of the daily extrema of both internal and external surfaces was defined as the decrement factor $DF_s = (T_{c,max} - T_{c,min})/(T_{rs,max} - T_{rs,min})$ by Barrios et al. [24], where Tc,min is the ceiling temperature limit for thermal comfort. The smaller the decrement factor, the better the thermal performance. Another KPI, the thermal performance index TPI (%), is also used for evaporative techniques by Barrios et al., and Kabre [24,25].

Figure 2: *SOTAR* extract 2 - Performance indicators of evaporative surfaces on buildings.

This figure shows the beginning of the chapter on the performance of evaporative surfaces on buildings. This chapter focuses on how the performance of the technology is achieved and how it is calculated. Relevant performance indicators are also explained.

3.6.2.2 Classifications and design parameters

The classification of BHEs for comfort cooling in buildings falls into two main categories: direct-ground cooling (passive method) and ground-source heat pumps (active method), Figure 3-4. In a direct-ground cooling system, cooling is provided by supplying the cold water from the borehole system directly to the building cooling system. The direct-ground cooling system utilizes ground as the only source for cooling the working fluid without any mechanical refrigeration. In a ground-source heat pump system, the cooling is provided through a mechanical refrigeration system using the ground as a sink for dissipating the heat [135].

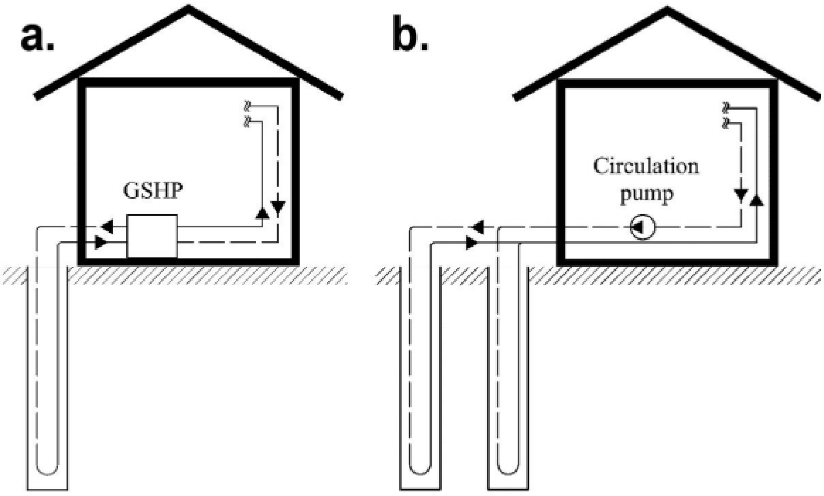


Figure 3-4 Schematic diagram of a A) ground-source heat pump GSHP and B) direct-ground cooling system

Sizing and dimensioning of is one of the principal tasks of designing a ground-source cooling system. BHEs are generally the most expensive part of a ground-source cooling system, and their appropriate dimensioning can help reduce drilling and installation costs, while simultaneously improving the thermal performance of the overall system. The key design parameters of BHEs include undisturbed ground temperature, ground thermal conductivity, borehole thermal resistance, ground heat transfer rates, and pumping rate of the working fluid [136,137]. Each of these parameters not only has its design requirements but each parameter also influences the choice of the other parameters.

Figure 3: *SOTAR* extract 3 - Design parameters of ground cooling.

This figure shows the beginning of the subchapter on design parameters for ground cooling. This subchapter deals with the classification of the corresponding technologies.

4.2 Deliverable 2: Midterm Report

The *Midterm Report* [4] is the second official Annex 80 Deliverable.

It should be emphasized that this report does not primarily present substantive progress or newly acquired findings, but rather is designed as a management report. Its main function is to report in detail on the progress of the project to date, particularly with regard to its organizational and administrative aspects.

The *Midterm Report* therefore fulfils an instrumental role as a tool for monitoring and documenting project management, while its content dimension takes a subordinate position.

The publication can be found on the official Annex 80 publication list (https://annex80.iea-ebc.org/publications), at https://www.building-research.at/annex_80/ and was published under DOI: 10.52776/MLGU9719.

4.3 Deliverable 3: Technology Profiles Report

Deliverable 3, the *Technology Profiles Report* [5] presents a collection of 16 technologies that are suitable as part of solutions for resilient cooling of buildings. It is intended as a source of information for all those who need to make decisions on the design and development of buildings and their technical systems, both for refurbishment and construction.
The 16 technologies are grouped into one of the following four categories for categorizing resilient cooling technologies:

- Reducing heat gains to the indoor environment and people environments
- Removing sensible heat from the indoor environment
- Increasing personal comfort apart from space cooling
- Removing latent heat from indoor environment

Each technology is described briefly and concisely and always includes the following chapters:

In the "Description" chapter, the reader will find information on the physical principles, function, and characteristic applications of the respective cooling technology. Relevant subtypes are listed. This chapter is somewhat an abstract of the full Technology Profile. The next figure shows an excerpt from one of these chapters for the technology Cool Envelope Materials.

2.4 Cool Envelope Materials

Ronnen Levinson, Lawrence Berkeley National Laboratory, USA.
Sang Hoon Lee, Lawrence Berkeley National Laboratory, USA.

2.4.1 Description

A cool envelope material (CEM) is a roof or exterior wall product whose elevated solar reflectance and high thermal emittance keep it cooler in the sun than a conventional roof or wall.[1] Common examples include white roofing membranes, "cool-colored" roofing tiles, and light or cool-colored exterior wall paints, but cool options are available for virtually all types of roof and exterior wall materials.

Cool roofs and walls reduce radiative heat gain at the building's opaque envelope to decrease heat flow into the conditioned space, saving energy in an air-conditioned space or lowering the temperature inside a free-running building. (They can also increase the need for heating energy in cold weather, but in hot-summer climates the annual cooling energy savings typically exceed the annual heating energy penalty.) Annual heating, ventilation, and air conditioning (HVAC) energy savings are greatest for older buildings in climates with hot summers and mild-to-warm winters. As a passive cooling strategy, cool envelope materials boost resilience to extreme heat events in all climates, especially when heat waves coincide with power outages.

Cool roofs and walls also mitigate the urban heat island effect, slow the temperature-dependent formation of smog, and provide global cooling ("negative radiative forcing") by reflecting sunlight out of the Earth system.

Figure 4: *Technology Profiles Report* extract 1 - Chapter Description.

In the "Key Technical Properties" chapter technical properties of the specific technology are presented and briefly explained. Readers find System Design Indicators and properties of the technology which are relevant when designing/purchasing the system. Where appropriate, a differentiation between Internal and External System Design Indicators is made. The earlier relevant to the technology itself, the latter relevant to the bordering conditions of the technology. The next figure shows an excerpt from one of these chapters for Natural Cooling.

3.7.2 Key Technical Properties

3.7.2.1 Earth-coupled heat exchangers

System Design Indicators

Thermal conductivity of the heat sink [W/(m·K)]. This value indicates the quality of the heat sink's ability to absorb heat, with a higher value indicating quicker absorption of discarded heat. Soil thermal conductivity values typically fluctuate between approximately 0.1 and 3 W/(m K) depending on the soil type [84].

The **specific [W/m]** and **installed [kW] cooling capacity** are determined via a thermal response test [85]–[87]. For example, the specific cooling capacity per metre of borehole length can range from 22 – 63 W for areas in Cyprus, Germany and Japan [88]. For horizontal earth brine heat exchangers, the specific cooling capacity per metre of pipe length ranges from about 17 to 35 W [89].

Maximum allowed return temperature [°C] of the cooling medium. This is subject to legislation to ensure the ecological integrity as well as chemical stability of the used heat sink. Earth air heat exchangers in moderate climates display a specific peak cooling capacity of about 45 W per m^2 of ground coupling area at an outdoor temperature of 32 °C [90].

Nominal power of auxiliary equipment [kW]. This gives the electricity consumption of the cooling system supplied by a natural heat sink.

The cooling power of ground source heat exchangers is thus determined by the soil temperature, specific heat capacity and conductivity, as well as the pipe diameter and length, heat transfer medium velocity and, for open-loop earth air heat exchangers, air inlet temperature. To increase the cooling capacity, the area of the heat exchanger can be shaded, wetted or painted in a light colour to decrease the soil temperature.

3.7.2.2 Water-coupled heat exchangers

System Design Indicators

Water-coupled closed-loop heat exchangers provide a cooling capacity of between 35 and 117 **W per metre of pipe** length [89].

For open-loop systems, another important parameter is the **water productivity of the aquifer [m^3/day]**, as well as regulations concerning the **maximum allowed water withdrawal rate [m^3/day].** For example, an open-loop cooling system in London using groundwater at a

Figure 5: *Technology Profiles Report* extract 2 - Chapter Important technical features.

The chapter "Performance and Application" deals with aspects of performance and the correct application of the respective technology. It contains information on how the technology contributes to the overall performance of the building. Where available, exemplary simulation results are also presented to illustrate the benefits of the technology during heatwaves. In addition, recommendations for efficient application and possible limitations of the technology in different climate zones are given. Finally, this chapter contains information on the compatibility and incompatibility with other technologies as well as on the availability, the current state of development and the expected future development of the technology.

The next figure shows an excerpt from one of these chapters for Ventilative Cooling.

3.1.3 Performance and Application

3.1.3.1 Building performance

Ventilative cooling can make a significant contribution to reducing the cooling energy demand of a building and improving indoor thermal comfort. The extent of these contributions depend on outside climate, building properties, internal heat gains and, finally, the achievable airflow rates and user behaviour. Occupants' behaviour is identified as a major factor influencing the performance of ventilative cooling. The impact becomes more critical in passive low energy buildings. Table 4 shows performance data for this technology.

Table 4. Key Performance Indicators (KPIs) of HVAC-related energy usage and heat stress for a single-family home in Los Angeles, California, U.S. for CORDEX 2050 weather conditions and changes in KPIs from the application of natural ventilation

KPI	Baseline	Reduction from window opening 5%[f]	Reduction from window opening 10%[f]	Reduction from window opening 25%[f]	Reduction from window opening 50%[f]
Daily heat stress[a] [°C·h]	19	26%	31%	36%	36%
Annual HVAC electricity need intensity[b] [kWh/m²]	40	18%	27%	34%	37%
Annual HVAC heating need intensity[c] [kWh/m²]	27	0%	0%	0%	-1%
Annual HVAC primary energy intensity[d] [kWh/m²]	113	13%	20%	25%	27%
Annual HVAC carbon emission intensity[e] [kgCO_2e/m²]	17,1	12%	17%	22%	24%

[a] Daily degree hours of exceedance against a standard effective temperature (SET) of 30 °C during a heatwave without AC

[b] Annual electricity need per conditioned floor area related to HVAC usage

[c] Annual gas need per conditioned floor area related to HVAC usage

[d] Annual primary energy usage per conditioned floor area related to HVAC energy need with primary energy factor for electricity: 2.05 and gas: 1.09 based on 2021 eGRID California State average [21]

[e] Annual carbon emission per conditioned floor area related to HVAC energy need with CO_2 emission factor for electricity: 272 g/kWh and gas: 225 g/kWh based on 2021 eGRID California State average [21]

[f] Windows are open only when the outside air temperature is above the heating setpoint and below the cooling setpoint

3.1.3.2 Resilience

In the event of heat waves, even with parallel power outage, ventilative cooling offers good possibilities for manually controlled emergency operation of buildings. A distinction must be made between the different ventilative cooling techniques. Natural nighttime ventilation requires no energy input and can therefore be described as a resilient cooling strategy.

Figure 6: *Technology Profiles Report* extract 3 - Chapter Performance and Application.

Finally, a "Further Reading" chapter at the end offers a pathway to a deep-dive both in other Annex 80 publications and external literature.

The *Technology Profiles Report* can be found on the Annex 80 publication list (https://annex80.iea-ebc.org/publications) and at https://www.building-research.at/annex_80/. It was published under DOI: 10.52776/HFTR4661.

4.4 Deliverable 4: Field Studies Report

This report [6] presents 13 field studies on applications of resilient cooling that were carried out in 7 different countries. Each field study includes a description of the cooling system, simulation, and

performance. Numerous cooling solutions in different buildings and climate zones are summarized and compared in this report.
The field studies are presented in the form of brochures in a standardized format. Each brochure contains general information such as building characteristics, component dimensions, design criteria, simulations in the design phase, control strategies and other information. The brochures consist of three sections:

- A summary describing the project and the cooling technology. This section also contains details of the chosen control strategy and the design process.
- Performance evaluation using key performance indicators and other metrics.
- Discussion and conclusions from the design, construction and operation phases of the project.

Extracts from this deliverable are shown below.

ANNEX 80 Resilient Cooling

WOHNPROJEKT WIEN

Introduction & Climate

EBC Energy in Buildings and Communities Programme

1. Introduction & Climate

1.1 Introduction

Completed in 2013, the building provides space for apartments, events and retail. It was built according to the most stringent energy standard in Austria and has won several awards as a result. In addition, special attention was paid to the use of HFC- and PVC-free materials for installations, windows and doors, as well as solar shading. The building has a gross floor area of around 6,000 m², the majority of which is occupied by the 39 apartments. Residents have access to a green roof terrace. In terms of mobility, the building is designed so that residents can walk, cycle or use public transport for as many journeys as possible.

Fig.1 Exterior view, west view, Residential project Vienna

Table.1 Key information about the building

Location	Vienna, Austria
Building Type	Residential property with commercial space
Retrofit (Y/N)	N
Surroundings (Urban/Rural)	Urban
Year of Completion	2013
Floor Area (m²)	6,071
Building Volume (m³)	19,014
Shape factor (m)	3.19
Openable Area to Floor Area Ratio (%)	21.5 %
Window to Wall Ratio (%)	44.2%
Climate Zone	Temperate (4A)
No. of Days with Te max > 25	55
Cooling Season Humidity	68%
Heating Degree days 12/20 (Kd)	3,446

1.2 Local Climate

Location: The building is located in a high-density urban area. One side of the building borders is adjacent to a public park.

Climate Zone: The building is located in a temperate climate zone (4A). This zone is characterized by a warm to cool temperate climate.

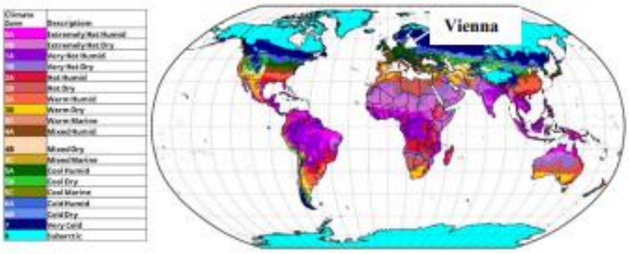


Fig.2 Climate map (Koppen-Geiger Map World future.svg)

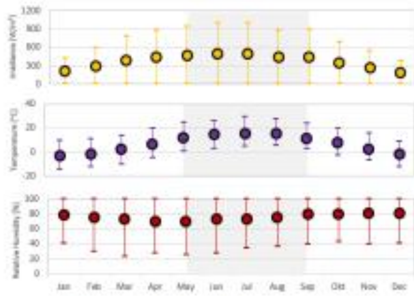


Fig.3 Mean, maximum and minimum external conditions in Vienna, using TMY3 from Meteonorm 7

Figure 7: *Field Studies Report* extract 1 - Chapter Introduction and Climate.

ANNEX 80
Resilient Cooling

WOHNPROJEKT WIEN

Resilient Cooling

EBC
Energy in Buildings and Communities Programme

3. Resilient Cooling

3.1 Principles

In principle, the rooms are cooled by introducing conditioned supply air into the room. There is a cooling coil in the ventilation system. The cooling coil is responsible for cooling the air in the supply air. It is supplied with well water.
The building ventilation is used for controlled ventilation of the rooms. To increase efficiency, a heat recovery system and a geothermal heat exchanger have been installed. To promote the use of thermal mass, the building consists of a horizontal concrete structure.

Supply and exhaust air characteristics:
- Residential: 5,700/5,700 m³/h
- Commercial: 3,800/3,000 m³/h

Table.4 STRUCTURE OF THE SYSTEM

1. Reducing Heat Loads to People and Indoor Environments	
1.1. Solar Shading Technologies	
1.2. Cool Envelope Materials	
1.3. Glazing Technologies	
1.4. Ventilated Façades	
1.5. Green Roofs and Green Façades	
2. Reducing Heat Loads to People and Indoor Environments (Production, Emission and combined)	
2.1. Ventilative cooling	
2.2. Thermal Mass Utilization	
2.3. Evaporative Cooling	
2.4. Sky Radiative Cooling	
2.5. Compression Refrigeration	
2.6. Adsorption Chiller	
2.7. Natural Heat Sinks	
2.8. Radiant Cooling	
3. Increasing Personal Comfort Apart from Space Cooling	
3.1. Comfort Ventilation and Elevated Air Movement	
3.2. Micro-cooling and Personal Comfort Control	
4. Removing Latent Heat from Indoor Environments	
4.1. Dehumidification	

3.2 Structure of resilient cooling technology

II REMOVING HEAT FROM INDOOR ENVIRONMENT
Ventilation System
- Fans: The fan is responsible for introducing the cooled air into the room. It absorbs the fresh air and brings it to the room as supply air through all components in the supply air duct. In the extract air duct, the fan is responsible for extracting the return air from the room and exhausting it to the outside.
- Cooling coil: The cooling coil is responsible for lowering the temperature of the supply air. It is fed by the cold medium from the well cooling.
- Heat recovery: Heat recovery increases the efficiency of the system. It uses the heat or cold of the extract air to heat the fresh air in winter and to cool it in summer.

Well cooling:
With well cooling, cold groundwater is used for cooling. The groundwater is drawn in via an abstraction well and fed into the cooling circuit. It is then fed back into the groundwater system through the injection well.

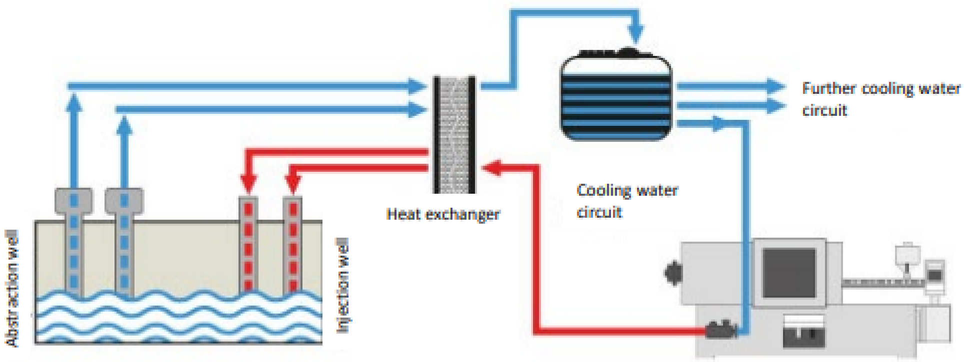
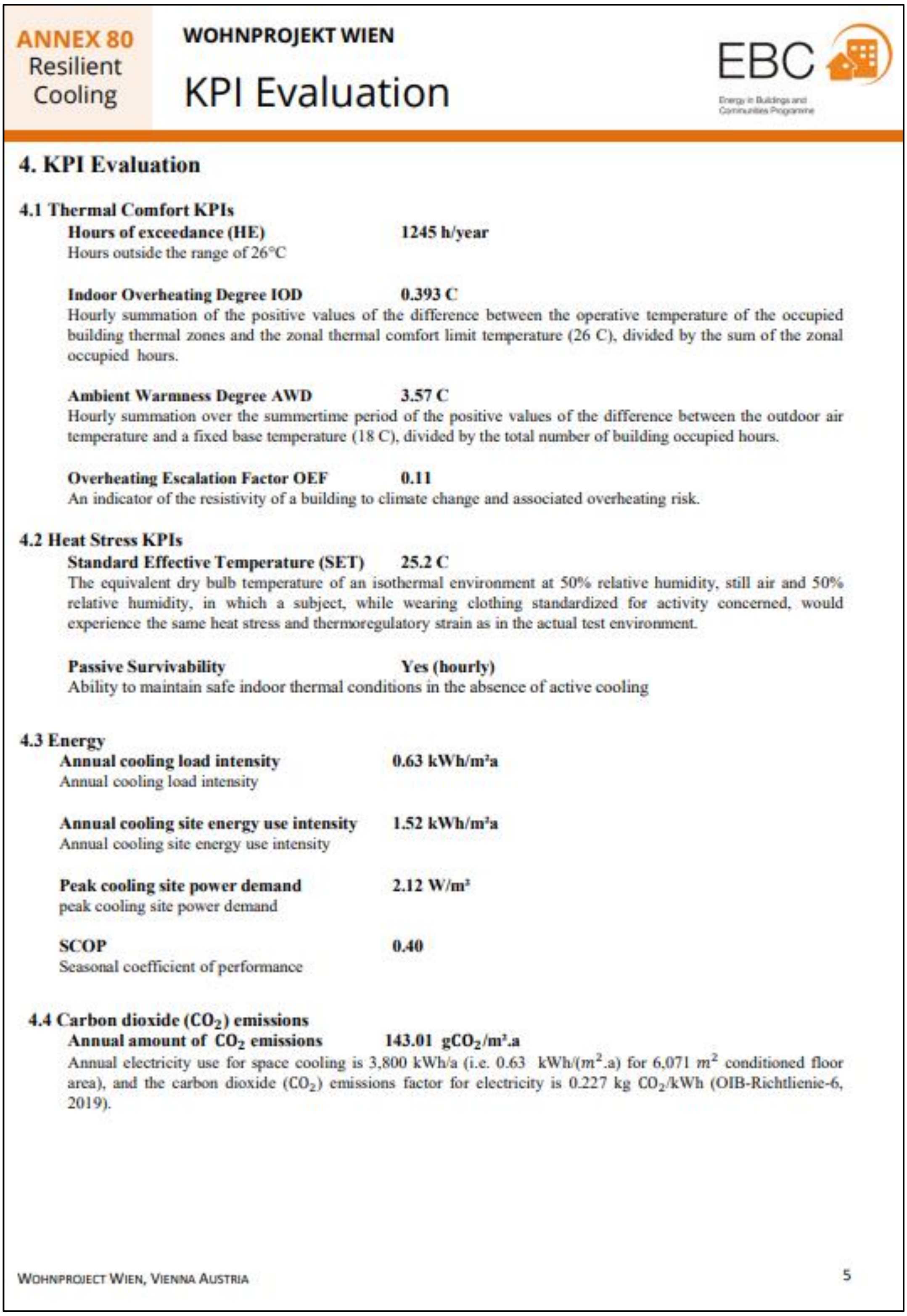


Fig.6 SCHEMATIC OF A WELL COOLING SYSTEM (HTTPS://WWW.IKS-KUEHLUNG.DE/)

WOHNPROJECT WIEN, VIENNA AUSTRIA 4

Figure 8: *Field Studies Report* extract 2 - Resilient cooling chapter.



ANNEX 80 Resilient Cooling

WOHNPROJEKT WIEN

KPI Evaluation

EBC Energy in Buildings and Communities Programme

4. KPI Evaluation

4.1 Thermal Comfort KPIs

Hours of exceedance (HE) **1245 h/year**
Hours outside the range of 26°C

Indoor Overheating Degree IOD **0.393 C**
Hourly summation of the positive values of the difference between the operative temperature of the occupied building thermal zones and the zonal thermal comfort limit temperature (26 C), divided by the sum of the zonal occupied hours.

Ambient Warmness Degree AWD **3.57 C**
Hourly summation over the summertime period of the positive values of the difference between the outdoor air temperature and a fixed base temperature (18 C), divided by the total number of building occupied hours.

Overheating Escalation Factor OEF **0.11**
An indicator of the resistivity of a building to climate change and associated overheating risk.

4.2 Heat Stress KPIs

Standard Effective Temperature (SET) **25.2 C**
The equivalent dry bulb temperature of an isothermal environment at 50% relative humidity, still air and 50% relative humidity, in which a subject, while wearing clothing standardized for activity concerned, would experience the same heat stress and thermoregulatory strain as in the actual test environment.

Passive Survivability **Yes (hourly)**
Ability to maintain safe indoor thermal conditions in the absence of active cooling

4.3 Energy

Annual cooling load intensity **0.63 kWh/m²a**
Annual cooling load intensity

Annual cooling site energy use intensity **1.52 kWh/m²a**
Annual cooling site energy use intensity

Peak cooling site power demand **2.12 W/m²**
peak cooling site power demand

SCOP **0.40**
Seasonal coefficient of performance

4.4 Carbon dioxide (CO_2) emissions

Annual amount of CO_2 emissions **143.01 $gCO_2/m^2.a$**
Annual electricity use for space cooling is 3,800 kWh/a (i.e. 0.63 kWh/(m^2.a) for 6,071 m^2 conditioned floor area), and the carbon dioxide (CO_2) emissions factor for electricity is 0.227 kg CO_2/kWh (OIB-Richtlienie-6, 2019).

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Figure 9: *Field Studies Report* extract 3 - Key Performance Indicators.

The publication can be found on the official Annex 80 publication list (https://annex80.iea-ebc.org/publications) and at https://www.building-research.at/annex_80/. It was published under DOI: 10.52776/JIIT7246.

4.5 Deliverable 5: Resilient Cooling Design Guidelines

Deliverable 5: *Resilient Cooling Design Guideline* [7] is aimed at planners and users. It describes the design process, the principles for checking building resilience to heat waves and power outages and the available software tools.

The last two chapters of [7] show an exemplary application of the *Resilient Cooling Design Guidelines* using two implemented case studies.

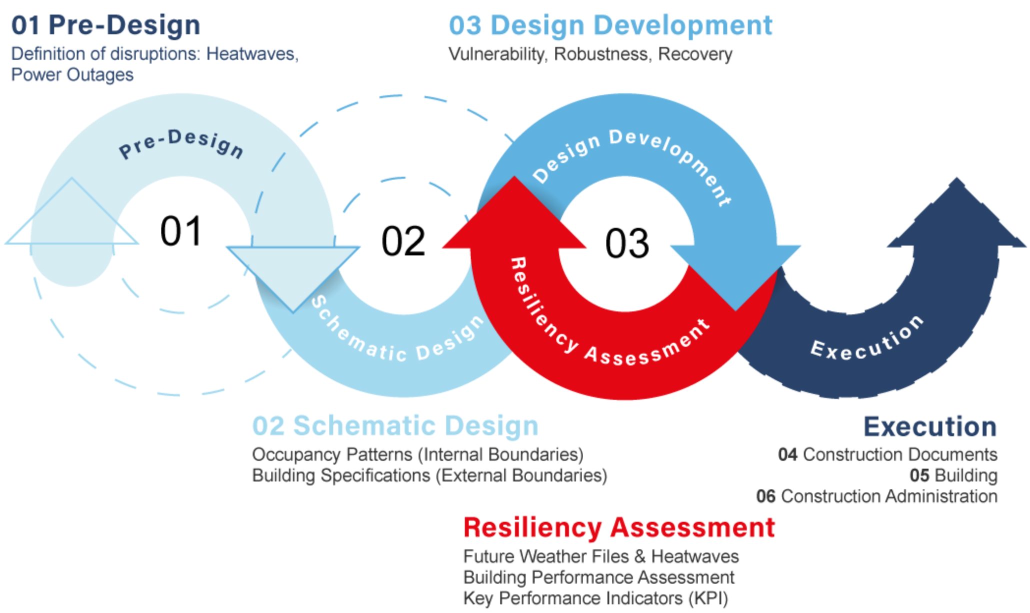

Figure 10: Conceptual diagram of a resilient design process (Source: IBR&I).

This deliverable is published in co-operation with the *Federation of European Heating, Ventilation and Air Conditioning Associations* (REHVA) and distributed internationally as part of the REHVA Guidebooks.
A link to the publication can be found on the official Annex 80 publication list (https://annex80.iea-ebc.org/publications) and at https://www.building-research.at/annex_80/.

4.6 Deliverable 6: Policy Recommendations

Subtask D developed in Deliverable 6: *Policy Recommendations* [8] methods for recording and evaluating existing regulatory measures, analyzed them in detail and identified gaps and opportunities for improvement. It then developed 37 regulatory recommendations to promote resilient cooling in buildings.

The recommendations promote passive or energy efficient cooling technologies for buildings. They do not address the resilience of the power grid, ways to supplement the grid power supply or other ways to respond to extreme heat. Each recommendation serves as a starting point for the development of a comprehensive solution. That is, it represents the beginning rather than the end of the process of creating and implementing a policy. A qualitative assessment of the implementation costs was also carried out. Each of the 37 recommendations contains the following information:

- Policy number: A serial number (1-37) identifying the policy.
- Category: Either the cooling technology addressed by the policy recommendation, or “whole building” if the recommendation applies to design, construction, or operation of the entire building.
- Author(s): The working group member(s) who wrote the policy recommendation.
- Summary: A summary of the policy recommendation.
- Policy mechanism(s): The mechanism(s)—regulation, information, incentives, R&D, or standards—through which the policy recommendation could be applied.
- Technology target: Whether the policy recommendation targets a specific technology, or is agnostic (technology independent).
- Disruption(s) mitigated: The type of disruption - heatwave and/or power outage - against which the recommendation would increase resilience.
- What: What the policy recommendation is to accomplish.
- Why: Why the policy recommendation should be developed and applied.
- How: How the policy recommendation is to be developed and applied.
- Who: Who will create, implement, and/or execute the policy recommendation.
- Where: Where the policy recommendation could apply.
- Implementation timeline: Whether the time to implement the policy recommendation would be short (typically less than 1 year), medium (1 to 5 years), or long (greater than 5 years).
- Cost: Costs to create, implement, and/or execute the policy recommendation.
- Potential significant undesirable side effects of executing the policy: What could go wrong.
- Policy model to follow: An existing policy that could inform the creation, implementation, and execution of the policy recommendation.

A complete recommendation from this deliverable is shown below.

3.19 Establish minimum energy performance standards (MEPS) for chillers and air conditioners

Policy number: 19

Category: B3 (Compression refrigeration)

Author(s): Peter Holzer

Summary: Establish regulations on minimum energy performance of chillers and air conditioners.

POLICY MECHANISM(S)

Regulation	Information	Incentives	R&D	Standards
✓				✓

TECHNOLOGY TARGET

Specific	Agnostic
✓	

DISRUPTION(S) MITIGATED

Heatwave	Power Outage
✓	

What: Adopt a binding rule on the minimum energy performance standard (MEPS) for chillers and air conditioners.

Why: For reasons of cost, appliances are often marketed with an energy efficiency that is significantly below the technical possibilities. The binding definition of a Minimum Energy Performance Standard (MEPS) can solve this.

How: Pass a binding regulation that defines Minimum Energy Performance Standards (MEPS) for chillers and air conditioners. This measure should be applied by either very big countries or by a union of more than one nation.

Who: This policy has to be created by governments. The policy shall be executed by governmental bodies.

Where: The policy can be applied world-wide. It should be applied by either very big countries or by a union of more than one nation.

Implementation timeline: Short (less than 1 year).

Cost: The implementation costs are low. The policy may raise product cost.

Potential significant undesirable side effects of executing the policy: None.

Policy model to follow: Good examples include the regulations on the implementation of the European Community's eco design directive 2009/125/EC which is a framework for the setting of ecodesign requirements for energy-related products, amongst them chillers and air conditioners. See here and here.

Figure 11: *Policy Recommendations* Excerpt from Recommendation 19.

The publication is on the official Annex 80 publication list (https://annex80.iea-ebc.org/publications) and at https://www.building-research.at/annex_80/.It was published under DOI 10.20357/B7288C.

4.7 Deliverable 7: Project Summary Report

This is the publication in hands [9]. It is the seventh and final official Annex 80 Deliverable.

This report is characterized by the consolidation and content summary of all previously published deliverables, publications and papers. A central function of this report is to provide a comprehensive overview of the entire range of work carried out within the framework of Annex 80.

A precise reference structure to the individual relevant documents is used to enable efficient navigation and targeted accessibility for the reader. The *Project Summary Report* thus acts as the keystone of the research process and helps to present the overall results of the Annex 80 project in a coherent and easily accessible form.

The publication can be found on the official Annex 80 publication list (https://annex80.iea-ebc.org/publications) and at https://www.building-research.at/annex_80/. It was published under DOI:10.52776/KKGB4933.

5. Scientific Publications

In addition to the official Annex Deliverables, numerous scientific publications were developed as part of the Annex. All publications can be found on the website: https://annex80.iea-ebc.org/publications.
A selection is presented below.

5.1 Resilient Cooling Definition

The definition of the term "Resilient Cooling" was summarized in the paper "Resilient Cooling of Buildings to Protect Against Heat Waves and Power Outages: Key Concepts and Definition" [10] which was published in *Energy and Buildings* and in the synthesis of the paper "Conceptualising a Resilient Cooling System: A Socio-Technical Approach" [11] which was published in *City and Environment Interactions*.

The first paper analyses most of the existing definitions of resilience and the various approaches to possible resilient buildings. A total of 90 documents were analyzed. It concludes by proposing a definition and a set of criteria - vulnerability, resilience, robustness and recoverability - that can help to develop performance-related indicators and functions of passive and active cooling solutions in buildings. These should be particularly geared towards heatwaves and power outages.

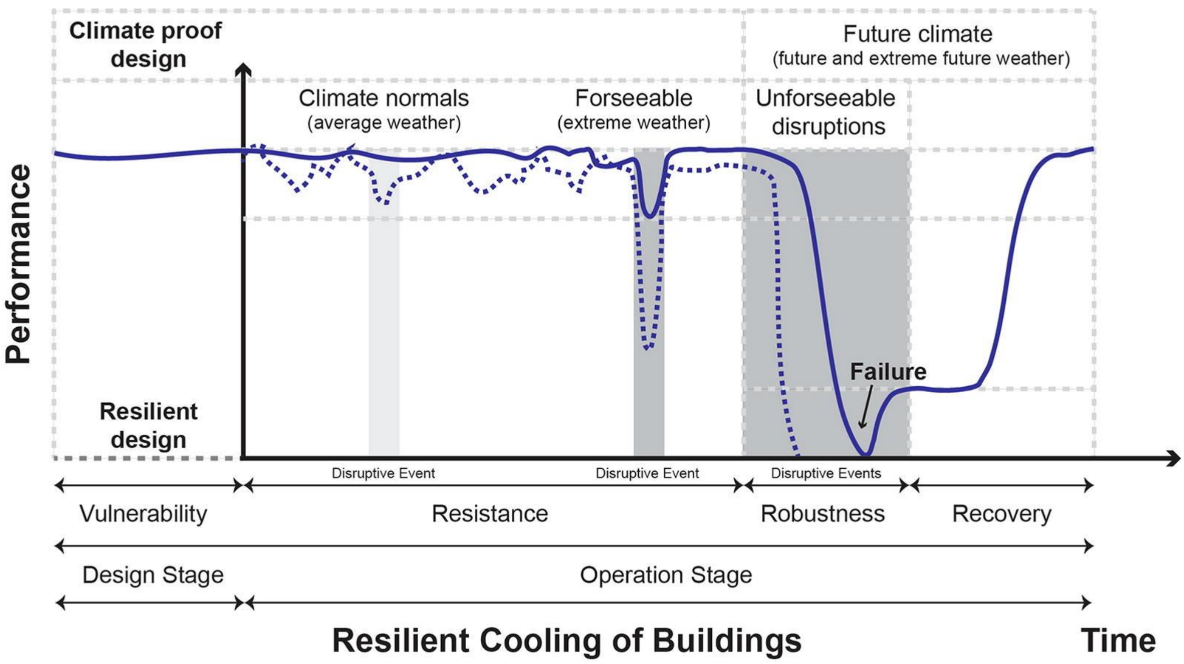

Figure 12: Components of the resilience definition from Attia et al. [10].

The second paper presents a conceptual model of a resilient cooling system centered on people, the socio-cultural-technical contexts shaped by people and the risks posed by overheating. An integrative literature review was conducted to provide a critical and comprehensive assessment of published research and grey literature, with the aim of making the model clearer and more detailed. This paper provides a more detailed description of the functional characteristics of a resilient cooling technology and the key elements of the four subsystems - people, buildings, cooling technologies and energy infrastructure. Six key messages are derived from this analysis, which provide a point of reference for future work in policy and practice and are incorporated into the definition of resilience in the Annex.

5.2 Weather Data Files

The results of the *Weather Data* Task Group were submitted to the research journal *Nature* - Data Descriptor under the title "Typical and Extreme Weather Datasets for Studying the Resilience of Buildings to Climate Change and Heatwaves". The paper was accepted and published by the journal *Scientific Data*. The created weather datasets are available for download on the official Annex 80 website at: https://annex80.iea-ebc.org/weather-data.

5.3 Dynamic Simulation Guidelines

The title of the simulation guideline created is "IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies" by Zhang et al. (2021). In 2023, an updated simulation guideline was published under the title "IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies: Version 2" by Zhang et al. [12].

5.4 Thermal Conditions Report

The results of the *Thermal Conditions* Task Group are summarized in "Framework to Evaluate the Resilience of Different Cooling Technologies" by Attia et al. [13].

5.5 KPI Report

The KPI report includes a list and glossary of Key Performance Indicators (KPIs) that are relevant to Annex 80. It contains detailed definitions and units of measurement of various indicators focusing on topics such as energy, CO_2 emissions, thermal comfort and heat stress. The KPIs are divided into categories such as "Thermal Comfort KPIs" and "Heat Stress KPIs", with specific indicators such as "Hours of Exceedance" and "Thermal Autonomy".
The KPI report is available on https://www.building-research.at/annex_80/ and the official Annex 80 publication list (https://annex80.iea-ebc.org/publications). It was published under DOI: 10.52776/RHET5776.

5.6 More

"Resilient Cooling Strategies - A Critical Review and Qualitative Assessment" by Zhang et al. [14] was published in the journal *Energy and Buildings, Special issue: Building Cooling*. In this paper, the state of the art of various cooling technologies was critically analyzed with a particular focus on their performance during heat waves and power outages. A definition of the term "Resilient Cooling" was proposed and four criteria for resilience were described - absorption capacity, adaptability, regeneration capacity and regeneration speed - which were used to qualitatively assess the resilience of the individual strategies.

"Resilient Cooling in Buildings - A Review of Definitions and Evaluation Methodologies" by Attia et al. [15] focuses on the review of most existing definitions of resilient cooling and the different approaches for possible resilience evaluation methodologies.

6. Conclusions

The conclusions of the IEA-EBC Annex 80 project on resilient cooling of buildings can be divided into four main areas, each of which highlights findings and developments in the world of building technology:

6.1 Lessons Learnt

- **Research under extreme conditions**: One of the most significant achievements of the project was the first-ever investigation of building cooling under extreme events as part of an IEA co-operation. This approach was characterized by its strong basic research character and led to new developments in building technology., particularly with regard to the adaptability and resilience of cooling systems under extreme climatic conditions.
- **New conceptualization of resilience:** A major step forward was the development of a new definition of "resilience" in the context of building technology. As there were no existing definitions specifically for this area, the project team orientated itself on concepts from other specialist areas, such as "disaster management". This new development made it possible to look at resilience in building cooling from a broader and more in-depth perspective.
- **Technology assessment and development:** Fundamental work had to be carried out to test the cooling technologies. This included the identification of disruptive events that could affect building cooling, such as power outages and heat waves. In addition, a discussion was held on thermal comfort conditions during extreme events, based on research into heat stress. At this point, particular reference was made to the work of the *National Research Council Canada*. The need to define framework conditions for a technology assessment using dynamic computer simulations was also recognized.
- **Development of methods for future weather data sets:** One challenge was the lack of weather datasets for long term, future conditions. The team therefore developed a method for creating such datasets to ensure that the planning and development of cooling systems also takes into account future climate scenarios and the expected increase in extreme weather events.
- **Key performance indicators for resilience:** Specific Key Performance Indicators (KPIs) for resilience have been developed to objectively assess the performance and adaptability of cooling systems. These indicators make it possible to systematically compare different cooling technologies and assess their efficiency in terms of resilience.
- **Analyzing use cases (field studies):** Carrying out field studies was another important aspect of the project. These analyses provided important insights into the operational optimization of cooling systems and made it possible to draw well-founded conclusions about the effectiveness of building simulations and user behavior. Such practical findings are crucial for linking theory with reality and ensuring that the cooling strategies developed are both technically feasible and user-friendly.

6.2 Utilization of the Results

- ***State of the Art Review* and Weather Data Publication:** The publications in the field of scientific research were important, in particular the *State of the Art Review* and the publication on weather data in the *Nature Data Descriptor*. These papers attracted a lot of attention in the scientific community and beyond, which emphasizes the relevance and influence of the project's research results.
- **Expectations for future publications**: With the imminent publication of further results and deliverables from the project, this trend is expected to continue and possibly even intensify. Statistics from the online portal *Research Gate* also show that the previous work will be used as a basis for future publications and will further increase the attention already achieved.
- **Cooperation with research institutes**: Cooperation with international research institutes played a key role. These collaborations were not only important for the exchange of knowledge and experience, but also led to joint project applications at European level. Such collaborations broaden the field of research and enable a more comprehensive approach to solving global challenges.
- **Development of follow-up projects**: The project team took a leading role in the design and development of follow-up projects. These projects, including the TCP (Technology Collaboration Programme) Energy in Buildings and Communities (EBC) and the TCP Cities, demonstrate the ambition to further advance research in the field of resilient cooling and to test and validate the applicability and transferability of the results in different contexts.
- **Invitations and participation**: The quality and relevance of the Annex 80 project's research results were reflected in invitations to various scientific conferences and events. These platforms offered the project team the opportunity to present their findings to a wider audience, receive valuable feedback and establish new collaborations.
- **Further scientific contributions**: Participation in these events and the general response to the publications resulted in further opportunities for scientific contributions. These contributions strengthen the influence of the project in the scientific community and contribute to the further dissemination of the research results.

6.3 Legal Hurdles

- **International standards and legislation:** A core component was the analysis of international standards, directives and legislation relating to resilient cooling technologies. This comprehensive research aimed to develop a deep understanding of the legal framework to facilitate the introduction of the technologies.
- **Identification of room for maneuver:** It was important to identify legal barriers and opportunities. The analysis helped to identify challenges that could hinder the implementation of new technologies, as well as opportunities arising from existing or potential legal frameworks.
- **Policy recommendations**: Specific policy recommendations were developed based on this analysis. These are intended to help to adapt the legal framework in such a way that they promote the use and dissemination of resilient cooling technologies.

6.4 Exploitation and Dissemination Activities

- **Cooperation with specialist organizations**: Cooperation with organizations such as *AIVC*, *INIVE* and *Venticool* was crucial in order to disseminate the knowledge gained across the industry and obtain feedback from building cooling professionals.
- **Dialogue with practitioners**: Through regular meetings with experts in the field of building cooling, practical perspectives and challenges were discussed and incorporated into the legal recommendations.
- **Educational initiatives and information dissemination**: Webinars and newsletter articles were used to provide information on legal aspects and disseminate policy recommendations in order to create a broader understanding and awareness of the topic.
- **Active participation in conferences**: Presentations and discussions at conferences raised awareness of the legal challenges and provided a forum for dialogue with experts.
- **International dissemination of recommendations**: The dissemination of policy recommendations through international channels supported the global reach and application of the research findings.

6.5 Summarized Conclusion

Overall, these conclusions illustrate the scope and depth of the progress made as part of the IEA-EBC Annex 80 project. The insights gained have implications for the project team and beyond. They are not only important for scientists and engineers, but also relevant for policy makers, legislators and end users. The project team plans to build on these findings by integrating the results into ongoing and future projects to further develop and disseminate resilient cooling technologies. The aim is to deploy these technologies in a variety of applications and contexts, from urban to rural areas, taking into account different climatic conditions.

The project's findings and developments are of particular interest to architects, civil engineers, urban planners, energy consultants and political decision makers. These stakeholders can use the data and recommendations obtained to design and realize more resilient and energy efficient buildings. In addition, the results provide valuable insights for the development of guidelines and standards in the field of building cooling.

Legal hurdles, particularly in the context of implementing new technologies and standards, were identified and analyzed in the project. These challenges include the integration of new technologies into existing legal and regulatory frameworks. The project team has formulated recommendations aimed at overcoming these hurdles and paving the way for the implementation of efficient and environmentally friendly cooling technologies.

The project's exploitation and dissemination activities were extensive and targeted. Through collaboration with organizations such as *AIVC, INIVE* and *Venticool*, as well as active participation in conferences and webinars (An overview of related webinars can be found in [16]), the project was able to reach a wide audience. The results were disseminated through various channels, including specialized publications, newsletters and presentations. These activities have raised awareness of the importance of resilient cooling technologies and created the basis for their further dissemination and application.

The potential for market and dissemination success of the project is considerable. The technologies and strategies developed have the potential to fundamentally change the way buildings are cooled and offer solutions that are both environmentally friendly and economically efficient. Given the increasing awareness of climate change and energy efficiency, it is expected that the demand for such technologies will continue to grow in the coming years.

To summarize, the IEA-EBC Annex 80 project has not only made important scientific and technical progress, but has also made a significant contribution to the development of strategies and measures needed to address the challenges of climate change and promote sustainable building technologies. The results of the project provide a solid foundation for future research and development in this area and have the potential to develop a lasting impact on the practice of building cooling worldwide.

7. Outlook and Recommendations

The work on passive cooling strategies in particular has also shown the limits of purely building-related measures: The outdoor conditions of buildings, the thermal interactions of built structures and also the cross-sectoral energy and heat flows in urban settlement areas must definitely be included in the design of climate change resilient and decarbonized living spaces. Against this background, a further annex is currently being prepared as part of the IEA Energy in Buildings and Communities (EBC) and Cities programmes, with an extended focus on resilient and sustainable cooling of cities and in cities. This concept provides for the following research questions to be addressed:

Identification, impact analysis and optimization of heat and climate change adaptation measures in urban outdoor spaces.

- Water and plants in cities (blue and green infrastructures).
- Cooling by reflection of short-wave solar radiation and by emission of long-wave terrestrial thermal radiation.

Further development of hybrid building-related cooling strategies, especially for existing buildings.

- Efficient hybrid cooling strategies in relation to limited parts of the residential units and in relation to limited operating times of the technical cooling.
- Coupling measures for cooling buildings with measures for climate-effective outdoor space design.

Research and strategic optimization of heat dissipation from cities.

- Creation of meaningful and robust thermodynamic models of cities.
- Use of these models to identify and optimize technologies for heat removal from cities on a climate-relevant scale, for example through heat harvesting with seasonal storage or through cooling networks with heat transfer to environmental heat sinks outside the city or with waste heat utilization in industrial processes.

The EBC Executive Committee has passed a resolution instructing the current Austrian programme management of Annex 80 to prepare a subsequent annex entitled "Resilient and Sustainable Cooling in Cities". This work is already underway at the time of this report.

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