ANNEX 88

EBC
Energy in Building and Communities Programme

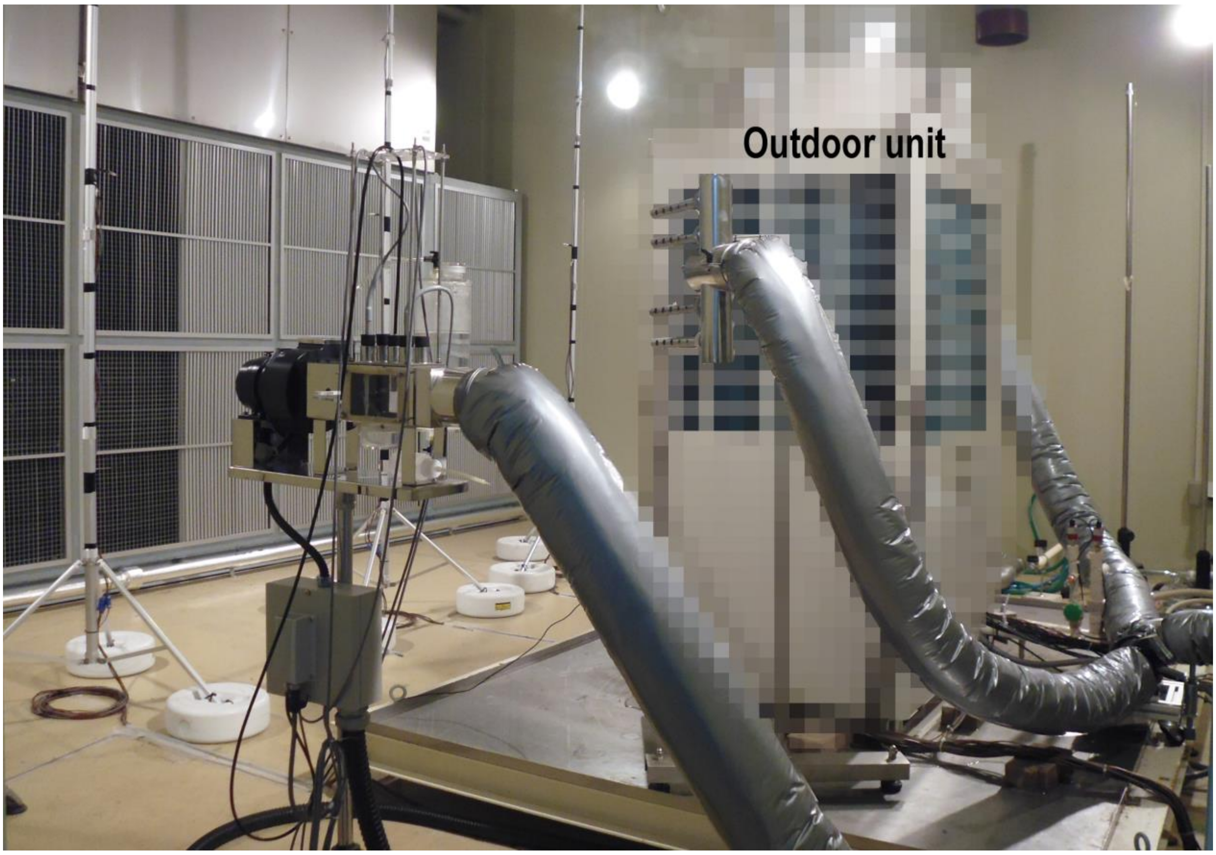
International Energy Agency

Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings (Annex 88)

State of the Art (Subtask A Report)

Energy in Buildings and Communities Technology Collaboration Programme

October 2024



Technology Collaboration Programme
by iea

ANNEX **88**

EBC

Energy in Building and Communities Programme

International Energy Agency

Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings (Annex 88)

State of the Art (Subtask A Report)

Energy in Buildings and Communities Technology Collaboration Programme

October 2024

Editors

Alberto Hernandez Neto, University of São Paulo, Brazil, (ahneto@usp.br)
Lu Aye, The University of Melbourne, Australia, (lua@unimelb.edu.au)
Takao Sawachi, Building Research Institute - National Research and Development Agency, Japan, (tsawachi@kenken.go.jp)

Main Authors

Akinori Hosoi, Japan Women's University, Japan, (hosoia@fc.jwu.ac.jp)
Alberto Hernandez Neto, University of São Paulo, Brazil, (ahneto@usp.br)
Alireza Afshari, Aalborg University, Denmark (aaf@build.aau.dk)
André Wachau, Federal Institute for Materials Research and Testing BAM, Germany, (andre.wachau@bam.de)
Baolong Wang, Tsinghua University, China, (wangbl@tsinghua.edu.cn)
Bruce Harley, Bruce Harley Energy Consulting LLC, United States, (bruce@bruceharleyenergy.com)
Christian Vering, RWTH Aachen University, Germany, (cvering@eonerc.rwth-aachen.de)
Dirk Müller, RWTH Aachen University, Germany, (dmueller@eonerc.rwth-aachen.de)
Jaap Hogeling, EPB Center, Netherlands, (jaap.hogeling@epb.center)
Jeremy Sager, Natural Resources Canada, Canada, (jeremy.sager@nrcan-rncan.gc.ca)

Kiyoshi Saito, Waseda University, Japan, (saito@waseda.jp)
Koji Kurotori, Tsukuba Building Research and Testing Laboratory, Center for Better Living, Japan, (kurotori@tbtl.org)
Laurent Socal, Independent expert, Italy, (socal@iol.it)
Lu Aye, The University of Melbourne, Australia, (lua@unimelb.edu.au)
Napoleon Enteria, Mindanao State University, Philippines, (napoleon.enteria@g.msuiit.edu.ph)
Niccolo Giannetti, The University of Electro-Communications, Japan, (giannetti.n@gmail.com)
Shigeki Kametani, Osaka Metropolitan University, Japan, (kametani@omu.ac.jp)
Stephan Göbel, RWTH Aachen University, Germany, (stephan.goebel@eonerc.rwth-aachen.de)
Takao Sawachi, Building Research Institute - National Research and Development Agency, Japan, (tsawachi@kenken.go.jp)
Tetsutoshi Kan, Tsukuba Building Research and Testing Laboratory, Center for Better Living, Japan, (kan@tbtl.org)

Reviewers

Michele Zinzi, ENEA-TERIN-SEN, Italy
Søren Østergaard Jensen, Danish Energy Agency, Denmark

Published by Building Research Institute - National Research and Development Agency, Japan, 1 Tachihara Tsukuba City, Ibaraki, Japan, 305-0802 as its Building Research Paper No. 152.

ISSN 0453-4972 (Building Research Paper, Building Research Institute – National Research and Development Agency, Japan)

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.

Additional copies of this report may be obtained from: EBC Executive Committee Support Services Unit (ESSU), C/o AECOM Ltd, The Colmore Building, Colmore Circus Queensway, Birmingham B4 6AT, United Kingdom
www.iea-ebc.org
essu@iea-ebc.org

About IEA and Energy in Buildings and Communities Programme

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 31 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 R&D strategy of the EBC TCP for the five-year period from 2024 to 2029 was derived from the IEA Future Building Forum Think Tank Workshop convened jointly with the other buildings-related IEA TCPs, as the members of the IEA Buildings Co-ordination Group and held in October 2022 in Gatineau, Canada, as well as the strategic planning workshop held at the EBC Executive Committee meeting in Istanbul, Türkiye in November 2022. To this end, four main themes form the basis of the EBC Strategic Plan 2024-2029, which are as follows:

- Collaboration with other related IEA TCPs
- Refreshing the priority research topics
- Achieving impact from EBC research activities
- Developing EBC governance

A series of actions have been agreed for each, as shown below.

Collaboration with Other Related IEA TCPs

- Introduce a process for evaluating, and if appropriate, proposing collaboration with other IEA TCPs as part of the review of proposals at the project concept stage to ensure early communication with other TCPs.
- Introduce a process by which Executive Committee members from the EBC TCP can work with Executive Committee members from other TCPs to propose fully collaborative projects.
- Introduce a process to scrutinise project concepts put forward to the Executive Committee to decide if they are more relevant to another TCP and should be directed accordingly.

Refreshing the Priority Research Topics

- The overall objective should follow the IEA 'Net Zero by 2050 – A Roadmap for the Global Energy Sector', with a demand-led approach that focuses on reduction in energy use and energy demand.
- Members countries should be asked to actively propose topics for research based on their priorities.
- In developed countries the overriding objective must be to address the retrofit of the existing building stock. Whilst in emerging economies more emphasis should be placed on delivering net-zero new buildings.
- Recognising the need to deliver energy security, avoid unnecessary infrastructure reinforcement, and alongside energy efficiency pay equal attention to demand management and flexibility to fully utilise fluctuating renewable energy supplies.
- Achieving performance in practice by closing the performance gap will be vital to delivering net zero greenhouse gas emissions by 2050.
- Ensuring that energy efficiency / decarbonisation measures in buildings are future-proof and ready for our 2050 climate.

Achieving impact from EBC research activities

- The main responsibility for delivering impact rests with each EBC project ('Annex').
- Encourage Annexes to engage early with stakeholders that facilitate the introduction of the developed technologies and processes to practising engineers, architects, designers and the market.

- During project planning, apply criteria for evaluating legal 'Annex Texts' that scrutinise their anticipated pathways to impact.
- Use ‘theory of change’ to identify relevant actors and their information needs for Annex outputs.
- Tailor outputs to the information needs and literacy of the relevant stakeholders, for example policy briefings should follow best practice guidance.
- Work with established channels for dissemination.

Developing EBC Governance

- Modernise the EBC Implementing Agreement (the overarching legal agreement), including introducing ‘limited sponsors’ with their benefits and obligations to be defined.
- Develop EBC policy on equality, diversity and inclusion.
- Reduce the number of running Annexes.
- Nominated Executive Committee members will review new project proposals and will be selective.
- Create platform for EBC Operating Agents (project managers for the Annexes) to share experience.
- Consider cost-shared proposals for funding Executive Committee agreed activities.

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 (RAP-RETRO) (*)
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 Behavior 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 Personalised 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

Annex 93: Energy Resilience of the Buildings in Remote Cold Regions

Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques

Annex 95: Human-centric Building Design and Operation for a Changing Climate

Annex 96: Grid Integrated Control of 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

Preface

This report has two objectives. One is to share the recognition of the state-of-the-art of current practices for heat pump systems among participating experts in the IEA EBC Annex 88 project 'Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings', of which main activity will continue until June 2027. Another objective is to share the state-of-the-art with international, national, and industrial policymakers regarding the decarbonisation of buildings.

As many know, the heat pump is one of the most promising technologies for reducing energy use for space heating/cooling and domestic hot water and efficiently utilising renewable energies. However, inappropriate design and the installation of heat pumps (e.g., capacity determined without sizing procedure, inappropriate operating temperatures, etc.) might negatively affect the energy consumption of this technology and the system payback period might become longer than its lifetime.

Transparent technological information on the heat pump should be exchanged between HVAC designers/building owners and heat pump manufacturers. However, different viewpoints and technical approaches have resulted in inconsistencies that represent an unresolved gap in product and building performance analyses that has limited the potential of the heat pump technology as an integrated part of efficient buildings. It can be said the problem may not be purely technological but a sort of blind spot in existing standards and regulations. Heat pump performance depends highly on the several parameters that define operating conditions. It is difficult to identify and foresee their influences with simple tests and calculation methods. For example, energy efficiency of heat pumps under low partial load conditions (i.e., heat pumps operated inevitably much below their maximum capacity) is not appropriately represented by existing testing standards and calculation methods for building energy codes.

The IEA EBC[1] Annex 88 is a five-year R&D project between July 2022 and June 2027, and comprises the following five subtasks:

- State-of-the-art for testing methods, monitoring methods and database, energy calculation methods and design guidelines
- Testing methods for heat pump products
- Monitoring methods and database
- Calculation methods of energy use by heat pump systems
- Design guidelines for HVAC system designers

[1] IEA EBC is the abbreviation of the International Energy Agency, Energy in Buildings and Communities Program. See https://iea-ebc.org/.

Executive Summary

1. Findings in the State-of-the-art

Chapter 1: testing methodologies and performance rating standards for heat pump systems

- In currently used testing methodologies (referred to in this report as Category A standards), heat pumps are tested in steady state conditions that are obtained by deactivating the built-in control of the tested unit and fixing the compressor speed with proprietary test modes at defined load conditions. The impacts of decreased performance during part-load operation (equipment on/off cycling) as well as defrost cycles are not directly accounted for in such test procedures. This can lead to seasonal performance values that do not fully account for the drop in performance experienced during these non-steady-state operating modes.
- It has been increasingly recognised that energy performance at lower partial load conditions cannot be neglected when estimating the actual energy performance of heat pumps in buildings and test conditions should cover such operating modes (particularly because the actual part-load ratio can be much smaller in practice than that expected by the developers of such testing standards). In fact, HVAC designers who are engaged in sizing heat pumps may often use a "safety margin" and over-size equipment to avoid a risk of complaints from their customers due to the perceived risk of shortage of capacity.
- In response to the need to compensate for the above shortfall of current testing standards, there are ongoing projects to develop load-based testing standards (referred to in Category B standards). In the load-based testing standards, the actual operation of variable-speed heat pumps and air conditioning units are tested with the same control as operated in buildings (i.e., "native controls"). Four projects that have developed such load-based test standards are reviewed in this report: three for air-to-air heat pumps (Waseda University, Canadian Standard Association and BRI/Better Living) and one for air-to-water heat pumps (BAM/RWTH).
- These newly developed load-based test methodologies and standards aim to replace current fixed-speed test standards. They may also help to inform building-level simulation and policy objectives by providing more representative data for energy calculation methodologies, equipment sizing, and design guidelines, internationally or nationally. Indeed, the extent to which these newly developed load-based test methodologies may support the needs of building-level simulation is a subject of the next phase of work in this Annex.
- The repeatability, reproducibility, and representativeness (3Rs) of the results of these newly developed load-based test methodologies and standards must be assured through ongoing R&D projects (this work is underway and will be evaluated during the next phase of work in this Annex).
- A project to develop the new ISO 21280 standard by adopting a load-based testing methodology for air-to-air products has already been launched within ISO/TC86/SC6/WG15, with the engagement of Annex 88 experts. Similarly, for hydronic heat pumps, CEN/TC113/WG8 has worked on a load-based test with Annex 88 experts involved.

Chapter 2: monitoring methods and database for actual energy efficiency of heat pump systems

- By overcoming obstacles to installing sensors in occupied buildings, the most realistic phenomena for heat pump systems can be monitored. Plenty of informative monitoring results already confirm the non-steady state condition of heat pumps, how low the partial load ratio is, the discrepancy between efficiency values based on current testing standards and actual energy efficiency, etc.
- Methods for monitoring are grouped into those for air conditioners (e.g., VRF, room air conditioner) and hydronic heat pump systems transporting heat by water. For air conditioners, 1) indoor side air enthalpy difference methods, 2) outdoor side air enthalpy methods, and 3) refrigerant specific enthalpy

difference methods exist. For hydronic heat pump systems, the water side method is available when the water side is accessible besides 2) and 3) as for air conditioners.

- Standards for the monitoring method exist, such as T/CAS 305-208 and ASHRAE Standard 221-2020. An ISO project is also developing a new standard to prescribe a monitoring method.
- Eight monitoring projects are reviewed in this report.

Chapter 3: energy use calculation methods for heat pump systems

- Building energy policies emerged in the 1970s, triggered by the 1973 oil crisis, and evolved in the 1980s. In the 1990s, they integrated the energy efficiency of building technical systems (e.g., heating systems, lighting, etc.), and they continued evolving in each nation, reflecting local traditions of relevant industries. A variety of methods flourished, especially for technical systems and their calculation of energy consumption. This variety of methods is even more evident for new technologies like heat pumps, and there is an urgent and obvious need for reliable heat pump energy calculation methods.
- Current challenges for energy calculation methods are 1) reasonable accuracy, 2) comprehensiveness (i.e., coverage of all major types), 3) availability of input data based on product testing standards, 4) easily understood by practitioners, 5) objectivity and unbiasedness, and 6) proof of energy calculation methods.
- Specific challenges for calculating heat pump energy consumption include the sensitive dependency of energy efficiency on operating conditions (e.g., part load ratio, outdoor temperature, supply hot water temperature), and control options. Adequate information (i.e. test data) is required to be the input to reliable energy calculation methods.
- Existing energy calculation methods for heat pumps are reviewed in Chapter 3. They are 1) European standards based on EN 15316-4-2 and EN 16798-13, 2) EnergyPlus, 3) NECB (National Energy Code of Canada for buildings), 4) Building Energy Conservation Standard of Japan, 5) UNI-TS 11300-4 of Italy, 6) DIN V 18955 of Germany, 7) SBEM (for non-residential buildings) of UK, and 8) SAP (for residential buildings) of UK.

Chapter 4: design guidelines for heat pump systems in buildings

- Existing installation and design guidelines for heat pump systems that are reviewed in Chapter 4 included:

   1. European standard EN 15450 is being revised. It is a design standard for hydronic (water based) heating systems with heat pumps for residential buildings. The ongoing revision will introduce a comprehensive approach to all design issues of a heat pump system, focusing specially on renovation, also extended to cooling and non-residential buildings. Reference is made to EN 15316-4-2, revised in parallel, to determine the resulting seasonal efficiency and evaluate the design choices. Several influence factors are considered, and various design techniques and computations are proposed to limit the cyclic operation during part load conditions and achieve appropriate operating conditions. Several sizing techniques are suggested to prevent oversizing, making use of historical energy consumption data when available. Guidance is included on the sizing of the volume of hot water storage, on the design of hydraulic circuits, and the way to estimate costs. A German standard as guidelines for heating systems with heat pumps in single and multi-family houses and Danish guidelines are also reviewed as examples of European guidelines for heat pumps.
   2. The ASHP (Air Source Heat Pump) Sizing and Selection Toolkit has been developed by NRCan (Natural Resources Canada). The Toolkit It is intended for use by mechanical system designers and renovation contractors and provides a step-by-step sizing and selection procedure and an Excel-based and online tool. CSA (Canadian Standards Association) published an ‘HVAC guide for Part 9 homes’ as CSA SPE-17:23, in which technical information on various HVAC systems, not only for heat pumps systems, is provided for housing and small buildings defined in Part 9 of National Building Code of Canada. In the US, ACCA (the Air Conditioning Contractors of America), which is an HVAC industry association, has published several relevant design manuals, ANSI/ACCA 3 Manual S (2014) - Residential Equipment Selection and ANSI/ACCA 1 Manual D

(2016) – Residential Duct Systems. NEEP (the Northeast Energy Efficiency Partnership) has produced two guides for sizing, selecting and installing ASHP for residential buildings in cold climates with support from the US DOE, including an online sizing tool.
3. ISO 13153:2013 Framework of the design process for energy-saving single-family residential and small commercial buildings prescribes how to integrate quantitative information on energy use reduction by applying technologies, including heat pumps, and their specifications, such as the rated energy efficiency of heat sources. According to the ISO, the Building Research Institute has published design guidelines.

- The design guidelines to be developed by Annex 88 should be focused on 1) the sizing procedure of heat pumps, 2) countermeasures to avoid operation under low partial load conditions and to improve energy efficiency under the low partial load condition by selecting products (referring to the load-based test methods and provided performance indices), 3) emphasising the critical role of controlling the systems together with a transparent specification of the control logics, 4) quantitative information on the energy use by different specifications and product selections in coordination with energy use calculation methods to be tackled in Subtask C (Subtask for energy calculation). Examples of monitoring results in fields shall be introduced based on the deliverable from Subtask B2 (Subtask for monitoring). Limiting the scope to a few major types of heat pump systems (e.g., air-to-air system and air-to-water hydronic system) is also necessary.

2. Message to policy makers related to heat pump products' evaluation and to building energy codes and performance certification schemes

- Policymakers already know the importance and potential of promoting the heat pump market. It is absolutely a correct judgment. However, one-sided promotion is not enough, and it is indispensable to support the provision of transparent technical information to practitioners by reorganising and strengthening industrial standards and guidelines so that the potential of heat pumps is fully achieved.
- Good players (e.g., the manufacturing industry of heat pumps) already exist. Still, without good referees and rules, they are not good enough to fully use the potential of heat pumps to save much energy use. There is a recognition that industries take care of themselves for product standardisation and producing practical guidelines for their business, even though it seems almost impossible to depend on different players to make rules, or it will take much time to see the ideal situation.
- The connection between product data and energy performance calculations is not yet well established, making it difficult to produce reliable and easy-to-use energy performance calculations.
- Policy makers are requested to refer to the situation of existing testing standards for heat pumps (Chapter 1), information on their actual energy efficiency (Chapter 2), how relevant engineers engaged in international and national energy use calculation are struggling (Chapter 3), and the present situation of guidelines for practitioners (Chapter 4).

3. Prioritised R&D targets for the working phase of IEA EBC Annex 88

- Validation of proposals for the load-based test methods for heat pump systems.
- Exploration of ways in which load-based test methods could be leveraged to inform building energy simulation needs and inform building-level policy (e.g., generating performance map data using load-based testing).
- Preparation of standard proposals for monitoring methods and collecting monitoring results to be published in a deliverable.
- Development of more reliable energy calculation methods for heat pump systems with examples.
- Development of a design guideline for heat pump systems with quantitative information on energy saving by different designs and specifications.

Table of content

Preface ... 10

Executive Summary ... 11

Acronyms and Abbreviations ... 17

Explanations of technical terms ... 18

1. State of the art of testing methodologies and performance rating standards for evaluating the actual energy efficiency of heat pumps and air conditioners ... 23

1.1 Categories of testing standards and their backgrounds ... 23

1.2 Current testing methodologies and performance rating standards for heat pump systems (Category A Standards) ... 25
- 1.2.1 Targeted heat pump systems and scope ... 25
- 1.2.2 Test methods ... 26
- 1.2.3 Control of test specimens during tests ... 26
- 1.2.4 Performance indices and requirements for part load tests ... 26
- 1.2.5 Tolerance of measurement uncertainty ... 27
- 1.2.6 Other issues ... 27

1.3 New type testing standards for heat pump systems (Category B Standards) ... 27
- 1.3.1 Overview of load-based testing methodologies ... 27
- 1.3.2 Emulator-type load-based testing methodology for air conditioners by Waseda University .. 32
- 1.3.3 CSA SPE-07:23 Load-based and climate-specific testing and rating procedures for heat pumps and air conditioners ... 36
- 1.3.4 Load-based test to obtain relationships between partial load ratio and energy efficiency of VRF systems by Better Living ... 40
- 1.3.5 Load-based testing of hydronic heat pumps - load-based method (by BAM) and hardware-in-the-loop testing (by RWTH) ... 46

1.4 Perspectives of load-based test standards and R&D plans in Annex 88 ... 51
- 1.4.1 Perspective of load-based tests and considerations on methods of utilization of the results 51
- 1.4.2 Perspective within Subtask B1 of Annex 88 Perspective of load-based tests and considerations on methods of utilization of the results ... 54

1.5 References for testing methods ... 55

2. State of the art for field monitoring methods and database for actual energy efficiency of heat pump systems ... 58

2.1 Background ... 58

2.2 Current field monitoring methods ... 59
- 2.2.1 Air-air heat pump systems ... 59
- 2.2.2 Air-water (hydronic) heat pumps ... 64

2.3 Existing standards and protocols for monitoring methods for heat pump systems ... 65

2.3.1 China's specifications and standards ... 65
2.3.2 Canada's specifications ... 67
2.3.3 US's specifications ... 68
2.3.4 Europe's specifications ... 69

2.4 Existing data on monitored energy efficiency of heat pump systems and comparison with laboratory test results ... 70
2.4.1 Case 1 (VRF) ... 70
2.4.2 Case 2 (VRF) ... 72
2.4.3 Case 3 (RAC) ... 74
2.4.4 Case 4 (Water-water HP) ... 76
2.4.5 Case 5 (Water-water HP) ... 79
2.4.6 Case 6 monitoring projects for air-to-water heat pumps by Fraunhofer ISE ... 80
2.4.7 Case 7 monitoring projects for air-to-water heat pumps by Eastern Swiss University of Applied Sciences ... 81
2.4.8 Case 8 IEA Heat Pumping Technologies TCP projects and SEPEMO-Build ... 81

2.5 Perspectives of monitoring of actual energy efficiency of heat pump systems and R&D plans in Annex 88 ... 82

2.6 References for monitoring methods and database ... 83

3. State of the art for energy use calculation methods for heat pump systems ... 86

3.1 Introduction (context of energy performance calculation methods and standards) ... 86
3.1.1 Context/Background ... 86
3.1.2 Challenges ... 88

3.2 Heat pump energy performance basics ... 91
3.2.1 Definition of energy performance indicators and common parameters ... 91
3.2.2 Influence factors ... 94
3.2.3 Connection with the overall building energy performance calculation ... 99

3.3 Current methods ... 99
3.3.1 EN standards ... 99
3.3.2 EnergyPlus ... 114
3.3.3 National energy code of Canada for buildings ... 118
3.3.4 Japanese standard, BECS ... 120
3.3.5 Italy UNI-TS 11300-4 ... 127
3.3.6 UK SAP 10.2 ... 130
3.3.7 Germany DIN V 18599 ... 132
3.3.8 France RE 2020 ... 134
3.3.9 UK SBEM for non-residential buildings ... 137

3.4 Discussion ... 139

3.5 Perspectives of the future development of energy calculation methods for heat pump systems and harmonization with their testing methods ... 143

3.6 References ... 144

4. State of the art on design guidelines for heat pump systems in buildings ... 147

4.1 Background ... 147

4.2 Existing guidelines for designers and installers of heat pump systems in buildings ... 148
4.2.1 European guidelines ... 148

4.2.2 Canadian codes and practices 160
4.2.3 US 166
4.2.4 ISO 13153:2012 and Japanese design guidelines for low energy housing with validated effectiveness 171
4.3 Perspectives of developing design guidelines for heat pump systems in Annex 88 177
4.4 References 181

Acronyms

Acronyms	Meaning
AA, A/A	Air to air
AE	Air specific enthalpy
APF	Annual performance factor
ASHP	Air source heat pump
AW, A/W	Air to water
BES	Building Energy Systems
CEC	Compressor energy conservation
COP	Coefficient of performance
CSEC	Compressor set energy conservation
CT	Cooling tower
CVE	Compressor volumetric efficiency
DBT	Dry-bulb temperature
EER	Energy efficiency ratio
EPBD	Energy Performance of buildings directive
GSHP	Ground source heat pump
HiL	Hardware-in-the-Loop
HP	Heat pump
HX	Heat exchanger
IC	Indoor conditions
KPI	Key performance indicator
MPC	Model predictive controller
MQTT	Message Queuing Telemetry Transport
nZEB	Nearly zero-energy building
OC	Outdoor conditions
PLR	Partial load ratio
PV	Photovoltaic
RAC	Room air conditioner
RE	Refrigerant specific enthalpy
RH	Relative humidity
RRT	Round robin tests
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
TC	Technical Committee (e.g., ISO TC163, CEN TC371)
TES	Thermal energy storages
VRF	Variable refrigerant flow
VRV	Variable refrigerant volume
WA, W/A	Water to air
WBT	Wet-bulb temperature
WW, W/W	Water to water
3Rs	Repeatability, reproducibility, and representativeness

Abbreviations

Abbreviations	Meaning
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air conditioning Engineers
CEN	Comité Européen de Normalisation
CSA	Canadian Standards Association
EN	Europäische Norm (European Norm)
ISO	International Organization for Standardization
JIS	Japanese Industrial Standards
NEEP	Northeast Energy Efficiency Partnership
NT VVS	Nordtest Värme, Ventilation, och Sanitet (Heating, Ventilation, and Sanitation)
T/CAS	China Association for Standardization
T/CECS	China Association for Engineering Construction Standardization
UNI	Ente Italiano di Normazione (Italian Standardization Body)
VDI	Verein Deutscher Ingenieure (Association of German Engineers)

Explanations of technical terms

The following explanations of key technical terms, which appear in this report, are intended to provide reference information for broader experts, practitioners and policy makers to understand the state-of-the-art (problems and possible solutions) for heat pump systems in buildings. More detailed and accurate definitions should be found in relevant standards for terminology, and the definitions of new technical terms and concepts shall be determined in the working/reporting phase of Annex 88 during 2024 and 2027.

Adiabatic compression: an ideal thermodynamic process where the pressure of a gas/vapour increases without any heat transfer to or from the system.

Air specific enthalpy (AE) method: methods to obtain cooling or heating capacity of heat pumps by measuring air volume and air enthalpy difference of the air flowing through indoor unit or outdoor unit.

Air-to-air (air-air) heat pumps: heat pumps with outdoor air as heat source and indoor air as heat sink.

Air-to-water (air-water) heat pumps: heat pumps with outdoor air as heat source and water as heat sink.

Annual average efficiency: average energy efficiency throughout whole year.

Auxiliaries: components attached to the main part of heat pump systems.

Back-up generator (heater): electric heater or boiler, which compensates for the shortage of the capacity of heat pumps, especially when outdoor temperature is very low.

BIN method: a simplified calculation method of heating need, cooling need and energy use for heating and cooling by using numbers of hours in each range of outdoor temperature for each month for a location.

Bivalent operation: simultaneous operation of heat pump and back-up heater to compensate for the shortage of the heat pump capacity at outdoor temperature lower than a set-point outdoor temperature.

Bivalent temperature: a temperature, below which a back-up heater is needed.

Buffer storage: hot or cold water storage to be prepared for thermal need larger than heat or cold production by heat generators (heat pumps).

Built-in control: control built-in to the heat pump equipment at the time of factory shipment.

Capacity: amount of output by heat pump systems.

Category A standards: current test standards for heat pumps, which apply proprietary control in order to maintain the steady state of the heat pumps and their continuous operation.

Category B standards: load-base test standards, which apply built-in (native) control of heat pumps. During the test, according to Category B standards, heat pumps may operate intermittently.

Carnot efficiency: theoretical maximum efficiency that a heat engine can achieve when operating between two temperatures: a hot reservoir (source) and a cold reservoir (sink). It is defined as the ratio of the work output of the engine to the heat input from the hot reservoir. The Carnot efficiency depends solely on the temperatures of these two reservoirs.

Compressor: device for increasing the pressure of a gas/vapour by mechanically decreasing its volume.

Continuous operation: operation of heat pumps at constant input and output.

Cooling need (cooling load, energy need for cooling): heat to be extracted from a thermally conditioned space to maintain the intended space temperature and humidity conditions during a period.

Defrost operation: operation of heat pumps to remove frost on coils of outdoor units. During the defrost operation, compressed refrigerant is supplied to the coils of the outdoor units to be heated.

Degradation coefficient (C_D): reduction rate of energy efficiency to apply to estimate energy efficiency under intermittent operation of heat pumps.

Emulator: a control method of temperature of return air (or water) to indoor unit (or to heat pump) in order to consider the influence of the thermal inertia of the buildings and the heat transport systems on the temperature.

EN (CEN) Standards: European standards developed by Technical Committees of the European Committee for Standardisation.

EN-EPB standards: a set of EN standards and accompanying technical reports to support EPBD.

Energy calculation method: a method to calculate energy use (consumption) of a building or a component of the building such as its HVAC system, its domestic hot water system. National building energy codes and standards have their own energy calculation methods to quantify the energy performance of buildings.

Energy Efficiency Ratio (EER): energy efficiency of heat pumps when they operate for space cooling. However, in some countries and regions, EER is not used, and COP is used for both space heating and cooling.

Energy use (energy consumption): energy input to systems (e.g., heating, cooling and domestic hot water systems).

EPBD (Energy Performance of Buildings Directive): An EU directive is a legal act adopted by the EU institutions addressed to the EU Member States. It sets out an objective to be achieved but leaves it to individual countries to implement it in their own way. EPBD is the EU directive aims to achieve a fully decarbonized building stock by 2050.

Equipment sizing: an important process of the design of building services, in which the capacity of equipment is decided.

Expansion Valve: valve reducing the pressure of the liquid refrigerant to allow expansion or change of state from a liquid to a vapor in the evaporator.

Fixed-compressor speed test: performance test of heat pumps by fixing the rotation speed of the compressor to maintain stable condition.

Hardware-in-the-loop testing: test method for heat sources (e.g., heat pumps) connected with the hardware comprising secondary water circuit and thermal load simulator where the loads are based on simulations.

Heat need: amount of heat to be provided or extracted by space heating system or space cooling system, respectively, to maintain indoor thermal condition. It can be the amount of heat to be provided to supply hot water at a certain temperature and amount.

Heat pump: a device to move heat from air or liquid of lower temperature to that of higher temperature. It is used for space heating and cooling as well as for domestic hot water in buildings as a promising energy saving measure.

Heat sink, sink: substance, to which heat is dissipated by heat pump systems (e.g., indoor air or hot water for heating operation of heat pumps)

Heat source, source: substance, from which heat is extracted by heat pump systems (e.g., outdoor air or groundwater for heating operation of heat pumps).

Heating need (heating load, energy need for heating): heat to be delivered to a thermally conditioned space to maintain the intended space temperature conditions during a period.

Hydronic heat pumps: heat pumps with water circuits to provide space heating or cooling as well as domestic hot water.

Input (energy input): energy supplied to equipment such as electricity supplied to a heat pump.

Intermittent operation: operation of heat pumps cyclically raising and reducing their input and output.

Inverter (inverter technology): a power electronic device or circuitry to convert DC to AC electricity.

ISO Standards: International Standards developed by Technical Committees of the International Organization for Standardization.

Legionella disease: a form of atypical pneumonia (severe lung inflammation) caused by any species of Legionella bacteria. The bacteria can contaminate hot water in tanks and pipes.

Load-based test: test method imposing thermal load on heat sources (e.g., heat pumps) without using proprietary control for the heat sources.

Multi-split system: air conditioning system with at least one outdoor unit and multiple indoor units.

Native control: the same as built-in control.

nZEB (Nearly Zero Energy Building): buildings with a high energy performance and very low-energy needs, covered largely by onsite and nearby renewable energy sources.

On-board control: the same as built-in control.

On-off cycling: operation of heat pumps cyclically changing their status (switched on and off) to adjust output to heating or cooling need.

Output (energy output): energy generated by equipment such as thermal energy generated by a heat pump.

Part load: heating or cooling load, which is less than the maximum heating or cooling capacity of the heat pump systems dealing with the load.

Part load condition: condition in which heat pumps are operated at capacity lower than maximum.

Part load ratio, Partial load ratio: the ratio of the actual capacity of a heat source to its rated capacity.

Part load factor (LR): the ratio of the actual required power output in the calculation interval to the maximum power output in the given operating conditions for source and sink temperature.

Performance curves: curves (functions) representing the influence of heat source and sink temperatures on full capacity of heat pumps and the influence of part load operation on COP and EER.

Performance map: data set representing the influence of heat source and sink temperatures on the capacity of heat pumps and the influence of part load operation on COP and EER.

Performance mapping (performance map): multiple dimensional table(s) containing performance data of heat pumps. The values represent performance of heat pumps at different operating conditions such as for source temperature, sink temperature and part load ratio.

Performance monitoring: collection of data for status of targeted equipment or system.

Performance rating method (performance rating methodology): a method to calculate a single or only a few indices, which represent energy performance of heat pumps, based on parameters obtained through test methods.

Primary circuit: a hot or cold water circuit between heat generators (heat pumps) and tanks or headers.

Product data: data describing performance of a product. For heat pump products, rated capacity, COP, EER, SCOP, SEER, HSPF, APF, etc.

Proprietary control (proprietary mode): control, which is implemented only for test and of which algorithm is different from that of the built-in control.

Psychometric chamber: chamber, of which dry-bulb temperature and humidity can be controlled by its own air conditioning system.

Reconditioning equipment: equipment for conditioning air from the unit under test at set point dry-bulb temperature and humidity.

Refrigerant specific enthalpy (RE) method: methods to obtain cooling or heating capacity of heat pumps by quantifying the refrigerant mass flow rate and by calculating the enthalpy difference between the refrigerant at inlet and outlet of the indoor heat exchanger.

Room air conditioner (RAC): relatively small capacity air conditioner, which comprises a refrigerator and fans.

Seasonal average efficiency: energy efficiency of heat pumps is affected by outdoor climate conditions, such as dry-bulb temperature, and the specific heating demand they handle at any given time. Seasonal average efficiency of heat pumps is average of energy efficiency during heating season or cooling season, which is calculated taking outdoor climatic conditions and heat need throughout each season.

Seasonal Coefficient of Performance (SCOP): average of energy efficiency of heat pumps for heating season.

Seasonal Energy Efficiency Ratio (SEER): average of energy efficiency of heat pumps for cooling season.

Sink temperature: temperature of a sink, to which a heat pump transfers heat extracted from a source. The sink is at a higher temperature than the source.

Source temperature: temperature of a source, from which a heat pump extracts heat and transfer it to a sink. The source is at a lower temperature than the sink.

Testing method (testing methodology): a method to measure the capacity and the energy consumption of heat pumps at conditions for temperatures of heat source and heat sink.

Tolerance: allowable errors of mean values or individual readings from specified test conditions.

Uncertainty (of measurement): an estimate characterising the range of the values within which the true value of the measurement lies based on a specific confidence interval.

Variable Refrigerant Flow (VRF) system, Variable Refrigerant Volume (VRV) system: heat pump system using refrigerant, of which flow rate is variable according to thermal load, to transport heat or cold between outdoor unit and indoor unit.

Variable speed system: system which can change rotational speed of the electric motor driving the compressor.