Final report

1.1 Project details

Project title	Naturlig køling med udeluft (IEA ECBCS Annex 62)
Project identification (program abbrev. and file)	64013-0160
Name of the programme which has funded the project	EUDP, Energy Efficiency
Project managing company/institution (name and address)	Aalborg University, Department of Civil Engineering Thomas Manns Vej 23, 9220 Aalborg Ø
Project partners	VELUX A/S, Ådalsvej 99, 2970 Hørsholm (CVR 30003519) Institut for Byggeri og Anlæg, DTU, Nils Koppels Allé, Bygning 402, Lyngby (CVR. Nr. 30060946) WindowMaster A/S, Skelstedet 13, 2950 Vedbæk (CVR. Nr. 13827532)
CVR (central business register)	29102384 (AAU)
Date for submission	March 10, 2018

1.2 Short description of project objective and results

The development in building energy efficiency towards nearly-zero energy buildings lead to increased need for cooling and in most post-occupancy studies of high performance buildings elevated temperature levels are the most frequently reported problem. The objectives and achievements of the annex have been:

- Analysis, development and evaluation of design methods and tools for prediction of cooling need, ventilative cooling performance and overheating risk.
- New key performance indicators for ventilative cooling have been developed, tested and evaluated.
- Guidelines has been developed for integration of ventilative cooling in energy performance calculation methods and regulations.
- New flexible and reliable ventilative cooling solutions have been further developed and optimized
- Performance of ventilative cooling has been demonstrated through analysis and evaluation of well-documented case studies.

De seneste års udvikling i kravene til bygningers energieffektivitet og fokus på reduktion af varmeforbruget har medført et større kølebehov i byggeriet.

Erfaringerne fra lavenergibyggeri i praksis har vist, at de stort set alle har udfordringer med overophedning. Projektets formål og resultater har været:

- Analyse, udvikling og evaluering af design metoder og værktøjer til estimering af kølebehov, effekt af køling med udeluft og risiko for overophedning.
- Nye "key performance indicators" for køling med udeluft er blevet udviklet, afprøvet og evalueret.
- Guidelines er udviklet for implementering af køling med udeluft i energiberegningsmetoder og i bygningsreglementer
- Nye fleksible og pålidelige løsninger for køling med udeluft er blevet udviklet og optimeret
- Effekt af køling med udeluft er demonstreret gennem analyse og evaluering af vel-dokumenterede case studier

1.3 Executive summary

The current development in building energy efficiency towards nearly-zero energy buildings lead to increased need for cooling and in most post-occupancy studies of high performance buildings elevated temperature levels are the most frequently reported problem.

We are presently facing this situation in high performance residential buildings because the design process is too simplified and to a very large extent based on experiences and rules of thumb. To reach a low energy need for heating designers typically apply guidelines for passive solar buildings developed in the past, where insulation and airtightness levels were far from the levels of today, and they underestimate the need for cooling or might not even take it into account. For offices and other commercial buildings, the challenges are different and mainly related to the development of new approaches towards reduction of the existing energy use for cooling to meet high performance requirements. In high performance buildings the cooling demands depend less on the outdoor temperature, and more on solar radiation and internal heat gains. This naturally gives better potential for the use of ventilative cooling, because the cooling need is not only in the summertime, but actually all year round.

At the start of the project the development status of ventilative cooling for residential buildings was low. There was limited awareness among users and designers on how to cool in an efficient and energy optimal way. The development status for office and commercial buildings with full mechanical ventilation was high although the increased use of electricity for fans did limit the advantage. The estimated TRL range on ventilative cooling solutions in the different countries was widespread, but typically it was about 1-4 for residential buildings and 6-9 for offices and other commercial buildings.

In most countries prediction tools developed as part of the national mandatory energy rating system are typically used for residences and small office buildings and are capable of computing basic estimates of cooling loads and some of them also the risk of overheating. In the design of larger office buildings and other commer-

cial buildings more detailed thermal building calculation tools are used for evaluating the cooling need and overheating risk. The estimated TRL range on calculation methods in the different countries was estimated to be 3-6 with a majority in the lower end.

The Annex proved that ventilative cooling can have considerable impact on the risk of overheating in all climates. In cold and moderate climate the risk of overheating can be eliminated completely, while in warm and hot climates supplementary cooling solutions will be needed to ensure acceptable comfort levels. In cold climate (e.g. Oslo) daytime ventilative cooling is sufficient to remove the heating loads, while in most other climates it is essential to apply night cooling strategies to efficiently remove excess heat loads. In warm and hot climates daytime ventilative cooling strategies have very limited effect, while night cooling strategies are more efficient.

The Annex has developed new Key Performance Indicators to represent the performance of ventilation cooling. These include among others: The Cooling Requirement Reduction (CRR), which is defined as the percentage of cooling requirements saved in a ventilative cooling scenario compared to the reference scenario; The Seasonal Energy Efficiency Ratio (SEER), which is defined as the cooling requirement saving divided by the electrical consumption of the ventilation system; and the Ventilative Cooling Advantage (ADV_{VC}), which is defined as the benefit of the ventilative cooling, i.e. the cooling energy difference divided by the energy for ventilation.

The Annex has developed a ventilative cooling potential tool (VC tool) able to assess the potential effectiveness of ventilative cooling strategies by taking into account both building envelope thermal properties, occupancy patterns, internal gains, ventilation needs and the outdoor climate. The tool is useful in the conceptual design phase where decisions about application of ventilative cooling in buildings is made.

The Annex has based on a review on the existing conditions investigated, developed and reported future recommendations for adequate implementation of ventilative cooling in standards, legislation and compliance tools with main focus on natural ventilative cooling parameters. The work includes recommendations in relation to both EN standards, ISO standards and national standards, as well as national/regional legislation. Annex participants has developed new work items (NWI's) relevant to ventilative cooling applications that recently have been approved in the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO).

The Annex has developed an international ventilative cooling application database that contains 91 buildings located in Europe. The building-datasheets offer illustrative descriptions of buildings of different usages, sizes and locations, using ventilative cooling as a mean of indoor comfort improvement.

Well documented case studies using ventilative cooling from across the world were collected. For these case studies, rich information was available about their design, construction and operational performance that is presented in specific case study brochures. From the case studies a number of key lessons learned are reported. A number of these relate to that the design of a building incorporating ventilative cooling can be challenging and may require a lot of detailed building information.

1.4 Project objectives

Introduction and Motivation

The current development in building energy efficiency towards nearly-zero energy buildings (nZEB) represents a number of new challenges to design and construction. One of the major new challenges is the increased need for cooling arising in these highly insulated and airtight buildings. The cooling demand depends less on the outdoor temperature, and more on solar radiation and internal heat gains. This naturally gives better potential for the use of ventilative cooling technologies, because the cooling need is not only in summer, but actually all year round.

In most post-occupancy studies of high performance buildings, elevated temperatures are the most frequently reported problem. Also, conventional buildings can experience high temperatures resulting in a high need for cooling (e.g. commercial buildings with too high internal gains). There is a number of different reasons to why we presently are facing this situation in high performance buildings.

For **residential buildings**, the design process is much more simplified than for commercial buildings and is to a very large extent based on experiences and rules of thumb. To reach a low energy need for heating designers typically apply guidelines for passive solar buildings developed in the past, where insulation and airtightness levels were far from the levels of today, and they underestimate the need for cooling or might not even take it into account.

Prediction of energy use in residential buildings is often based on simplified monthly methods and it is estimated for the residence as a whole. Averaging the need for cooling in both time and space underestimates the total cooling demand. Excess heat in spaces exposed to solar radiation is considered to be distributed fully to other spaces and excess solar radiation during daytime is partly distributed to night-time. Due to these simplifications, the real need for cooling to ensure acceptable temperature levels in all spaces will be higher than the predicted one. Cooling and overheating in residences have so far not been considered a design challenge, especially in colder climates. Therefore, the developed solutions to address cooling issues available for residential application are very limited, often too simplified and might not be well adapted for practical application. In the few cases, where the cooling challenge is addressed by a “one-of-a-kind” design, the solutions were expensive and needed careful commissioning to function.

Finally, especially to owners of high performance buildings in cold climate countries, cooling might be an unknown challenge that they have not experienced before. They do not know how to effectively reduce the overheating in their building and their behaviour might instead actually increase the problem. If technologies such as solar shading and ventilative cooling are applied, it is critical to use an appropriate control and operation strategy, taking into account occupant behaviour, to make sure that they operate successfully.

For **offices and other non-residential buildings**, the challenges are different and mainly related to the development of new approaches towards reduction of the existing energy use for cooling. Sometimes the cooling potential of outdoor air is already utilised in mechanical ventilation systems. However, due to thermal comfort issues and the risk of draught limited temperature differences between supply air and room can be utilized making heat recovery or air preheating necessary. The result of this is a cooling capacity reduction and an increased airflow rate - sometimes with a factor of more than five. In mechanical ventilation systems, this leads to an increase in energy use for air distribution and an increased investment in equipment. As a results, the energy and cost advantage of utilising the free cooling potential of the outdoor air in a mechanical ventilation system compared to a mechanical cooling solution might become very limited.

These limitations do not apply to the same extent when the outdoor air cooling potential is applied to a free-running building (naturally ventilated building) and thus the appropriate use of ventilative cooling in connection with natural ventilation in non-residential buildings could contribute significantly to a reduction of the energy consumption. Secondly, as the buildings are heavily insulated and airtight, the variations in excess heat load will significantly vary between occupied and unoccupied hours and between cloudy and sunny days. The dynamic thermal characteristics will have a relatively higher influence on energy use and exploitation of building thermal mass as heat storage for reduction of cooling demand in combination with night cooling will become more important for energy optimization.

Objectives

The objectives of the annex have been:

- To analyse, develop and evaluate suitable design methods and tools for prediction of cooling need, ventilative cooling performance and risk of overheating in buildings.
- To give guidelines for integration of ventilative cooling in energy performance calculation methods and regulations including specification and verification of key performance indicators.
- To extend the boundaries of existing ventilation solutions and their control strategies and to develop recommendations for flexible and reliable ventilative cooling solutions that can create comfortable conditions under a wide range of climatic conditions.
- To demonstrate the performance of ventilative cooling solutions through analysis and evaluation of well-documented case studies.

Work plan

The annex addressed both residential and non-residential buildings, however, these two sectors was treated separately because the issues, challenges and possible solutions are very distinct. The Annex addressed both new constructions and renovation of buildings.

The research and development work in the Annex was be divided in three subtasks, which was further divided in a number of research activities.

Subtask A: Tools and Guidelines.
This subtask analysed, developed and evaluated suitable design methods and tools for prediction of cooling need, ventilative cooling performance and risk of overheating in buildings. The subtask also gave guidelines for integration of ventilative cooling in energy performance calculation methods and regulation including specification and verification of key performance indicators.

Activity A.1. Development of key performance indicators for ventilative cooling solutions including verification methods to be used in energy performance calculations.

Activity A.2. Identification of existing methods and tools for prediction of cooling needs, ventilative cooling capacity and risk of overheating. Development of new design methodologies including guidelines for their use.

Activity A.3. Development of recommendations for integration of ventilative cooling in legislation, standards, design briefs as well as on energy performance calculation and verification methods.

Subtask B: Solutions
This subtask investigated the cooling performance of existing mechanical, natural and hybrid ventilation systems and technologies and typical comfort control solutions as a starting point for extending the boundaries for their use. Based upon these investigations the subtask will also develop recommendations for new kinds of flexible and reliable ventilative cooling solutions that can create comfort under a wide range of climatic conditions.

Activity B.1. Analysis of the performance of existing ventilation systems and technologies

Activity B.2. Extention of the ability of existing ventilation system solutions to prevent overheating while lowering the energy use.

Activity B.3. Development of recommendations for new ventilative cooling solutions and control strategies.

Subtask C: Case studies
The subtask demonstrated the performance of ventilative cooling through analysis and evaluation of well-documented case studies.

Activity C.1. Definition of criteria for selection and evaluation of case studies. Development of guidelines for investigation.

Activity C.2. Analysis and evaluation of performance of ventilative cooling solutions in case studies

Activity C.3. Identification of perceived barriers for implementation and functioning of ventilative cooling solutions.

Activity C.4. Development of guidelines for practical application, operation and control of ventilative cooling solutions

The project was carried out as planned and also reached the goals and milestones expected. The Danish team participated in all subtask and research activities. Denmark (Per Heiselberg, AAU) was coordinator of the project and also Denmark (Theofanis Psomas, AAU) was also Co-leader of Subtask B.

The main research contribution from Denmark was carried out in the two projects PSO (Journal nr 345-061): Natural Cooling and Ventilation through Diffuse Ceiling supply and thermally activated building constructions and EUDP II (Journal nr 64013-0544): Ventilative Cooling in Energy Renovated Residences. The outcome of these two projects has been reported separately. The PSO project received ELFORSK prisen 2017.

Denmark was also heavily involved in the preparation of final Annex reports:

- Per Heiselberg, AAU: Editor of State-of-the-art Report and Ventilative Cooling Design Guidelines
- Theofanis Psomas, AAU: Editor of Ventilative Cooling Source Book and International Ventilative Cooling Application Database
- Christoffer Plesner and Karsten Duer, VELUX: Editor of Recommendations on Ventilative Cooling for Standrards and Regulation.

1.5 Project results and dissemination of results

The results presented in this chapter illustrates the main achievement of the Annex. The focus is on the achievements obtained in cooperation between the participating countries. Individual research projects contributing with knowledge and background information used to reach the results of the Annex is not presented.

Definition and Principles

The annex worked on the development of a definition of ventilative cooling and came to the following conclusion:

- Ventilative Cooling (VC) is defined as the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment.
- Ventilative Cooling utilizes the cooling and thermal perception potential of cool outdoor air and the air driving force can be either natural, mechanical or a combination of the two. The most common technique is the use of increased daytime ventilation airflow rates and/or nighttime ventilation.

The Annex also developed appropriate ventilative cooling principles for different outdoor climatic conditions and building ventilation systems. These are summarized in Table 1.

Table 1. Overview of typical ventilative cooling strategies applied depending on outdoor climatic conditions and type of ventilation system [1]

Temperature Difference[1]	Ventilative Cooling	Supplementary cooling options
Cold (ΔT more than 10°C)	Minimize air flow rate - draught free air supply	-
Temperate (2-10°C lower than comfort zone)	Increasing air flow rate from minimum to maximum	Strategies for enhancement of natural driving forces to increase air flow rates Natural cooling strategies like evaporative cooling, earth to air heat exchange to reduce air intake temperature during daytime
Hot and dry (ΔT between -2°C and +2°C)	Minimum air flow rate during daytime Maximum air flow rate during night time	Natural cooling strategies like evaporative cooling, earth to air heat exchange, thermal mass and PCM storage to reduce air intake temperature during daytime. Mechanical cooling strategies like ground source heat pump, mechanical cooling
Hot and humid	Natural or mechanical ventilation should provide minimum outdoor air supply	Mechanical cooling/ dehumidification

[1] Temperature difference between indoor comfort temperature and mean outdoor air temperature.

Ventilative cooling potental and rationale

Ventilative cooling can be an attractive and energy efficient natural cooling solution to reduce cooling loads and to avoid overheating in buildings. Ventilation is already present in most buildings through mechanical and/or natural systems and by adapting them for cooling purposes, cooling can be provided in a cost-effective way (the prospect of lower investment and operation costs). Ventilative cooling can both remove excess heat gains as well as increase air velocities and thereby widen the thermal comfort range.

As cooling becomes a need not only in the summer period, the possibilities of utilizing the cooling potential of low temperature outdoor air increases considerably. However, it is most effective to address the cooling challenge through a combination of measures including utilization of the potential of other passive measures like solar shading and thermal mass activation.

Naturally, expectations of ventilative cooling performance will vary between different countries because of climate variations, energy prices and other factors. In countries with cold climate, ventilative cooling can avoid the trend to use air conditioning in new buildings, which has occurred in response to the heavily insulated and air tight building designs, higher occupant expectations and the requirements of building regulations, codes and standards. In countries with warm climate, it can reduce the reliance on air conditioning and reduce the cost, the energy penalty and the consequential environmental effects of full year-round air conditioning.

In the Annex it was decided that to illustrate potential expectations for ventilative cooling performance in different climates, by predictions of expected thermal comfort and cooling requirements reduction by utilization of ventilative cooling for the same building configuration located in different climates.

Figure 1 shows the impact of ventilative cooling in the form of cooling requirement reduction and expected reduction in overheating hours in different climates. Ventilative cooling can have considerable impact on the risk of overheating in all climates. In cold and moderate climates the risk of overheating can be eliminated completely, while in warm and hot climates supplementary cooling solutions will be needed to ensure acceptable comfort levels. In cold climate (e.g. Oslo) daytime ventilative cooling is sufficient to remove the heating loads, while in most other climates it is essential to apply night cooling strategies to efficiently remove excess heat loads. In warm and hot climates daytime ventilative cooling strategies have very limited effect, while night cooling strategies are more efficient.

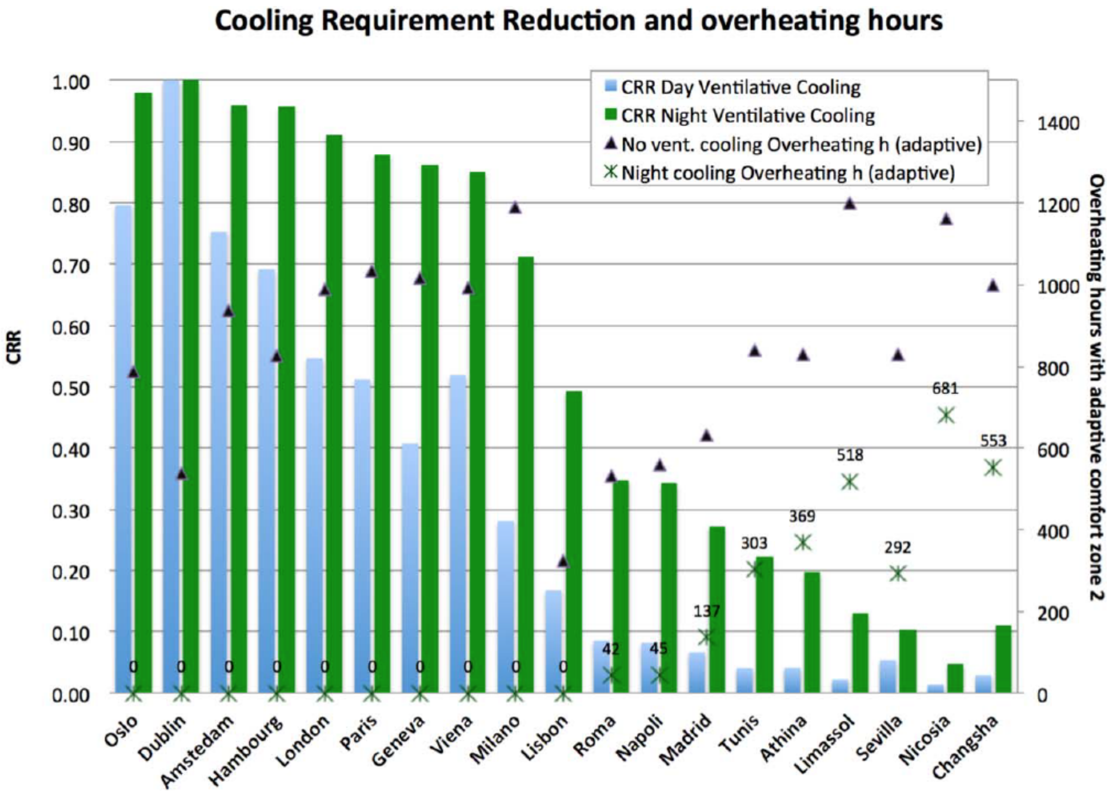

Figure 1. Expected cooling requirement reduction for day and night ventilative cooling strategy and overheating hours according to class 2 adaptive comfort indicator for a standard scenario without ventilative cooling and a scenario with night cooling [1].

Key Performance Indicators

A qualitative survey conducted among the participating countries revealed that in many countries energy performance calculations do not explicitly consider ventilative cooling as a cooling option for achieving energy performance. Therefore, the appropriate treatment of ventilation requirements for ventilative cooling and its effect on cooling energy demand reduction is unclear and available tools used for such calculations might not be well suited to model its impact.

Secondly, no specific key performance indicators focused on ventilative cooling performance was available. This is also a major barrier for application and further development of the technology as it makes it difficult to evaluate and compare the ventilative cooling performance and other technologies for cooling and ventilation.

The Annex discussed and developed Key Performance Indicators to represent the performance of ventilation cooling within four different categories:

- SYSTEM INDICATORS: 'system' refers to all the components which together allow the functioning of the ventilative cooling strategy. Therefore, system indicators reflect building performance in both energy and thermal comfort terms;

- COMPONENT INDICATORS: component indicators represent the performance of each component of the ventilative cooling system (i.e. opening efficiency, ventilation unit, SPF of cooling system, etc.). Component indicators are complimentary indicators to be used for component design and selection, compliance verification and in Statement-of-Requirements for a building;

- BOUNDARY CONDITIONS INDICATORS: boundary conditions indicators represent the assumptions on input data or building operating conditions (i.e. level of internal gains, solar gains, thermal mass, window surface area, solar transmission, airflow - natural or mechanical, ventilation and occupation schedules, weather data) under which the system indicators are calculated. Boundary condition indicators aim at easing the control of assumptions on input data and the identifying tricky projects or errors;

- SENSITIVITY INDICATORS: sensitivity indicators communicate the uncertainty on predicted/expected performance (design phase) due to assumptions and boundary conditions. They also indicate the risk of divergence of real performance to the predicted one (compliance phase) due to building use, occupant behaviour, weather condition as well as in relation to the varying capacity of passive solutions.

Examples of system indicators that was developed and tested in the project are:

- The Cooling Requirement Reduction (CRR), which is defined as the percentage of cooling requirements saved in a ventilative cooling scenario compared to the reference scenario

- The Seasonal Energy Efficiency Ratio (SEER), which is defined as the cooling requirement saving divided by the electrical consumption of the ventilation system.

- Ventilative Cooling Advantage (ADV_{VC}), which is defined as the benefit of the ventilative cooling, i.e. the cooling energy difference divided by the energy for ventilation.

- Percentage outside the Range (*POR*), which is defined as the number or the percentage of hours of occupation (*Oh*) when the — actual or simulated — indoor operative temperature are outside a specified comfort range.

- *Degree-hours Criterion* (*DhC*), which is defined as time during which the actual operative temperature exceeds the specified comfort range during occupied hours weighted by a factor that depends on the difference between actual or calculated operative temperature, θ_{op}, at a certain hour, and the lower or upper limit, $\theta_{op,limit}$, of a specified comfort range.

Design Proces

Ventilative cooling of indoor spaces has the best chance of success, when the design process is carried out in a logical, sequential manner with increasing detail richness towards the final design and in the framework of a design procedure.

Depending on possibilities and limitations in the actual case, the ventilative cooling system may come out as mechanical, hybrid or pure natural ventilation and may also be supplemented by other natural cooling technologies like ground cooling, earth-to-air heat exchangers or evaporative cooling.

The design procedure developed and adapted to ventilative cooling design is shown in Figure 2. Phases for construction, commissioning and operation are also included to achieve a holistic approach. The design procedure for ventilative cooling ensures a thermal environment where every important issue is considered, that the process is efficient and that the final design is allowed to evolve in a logical way from idea to construction. The procedure is aiming for a good thermal indoor environment at a low energy use and integration of the ventilative cooling solution with the building design and the environment. The tight integration results in many parameters to consider in an organized way, especially at an early stage.

A ventilation design procedure consists of different phases: conceptual design phase, basic design phase, detailed design phase and design evaluation. The conceptual design phase for ventilative cooling sets off by an analysis of the ventilative cooling potential of the site taking into account both the climate and the surroundings as well as overall building characteristics and targets for indoor environment, energy use and cost. If applicable the ventilative cooling principle to be used is decided together with any supplementary passive and natural cooling solutions as needed.

In the basic design phase the building heat, sun and contaminant loads are estimated on room level and the ventilative cooling system layout designed. The necessary air flow rates as well as expected temperature levels are calculated. A coarse yearly energy consumption is calculated together with the necessary peak power demands. If the results do not meet the targets, the building and its systems will have to be redesigned and/or other supplementary passive or natural cooling solutions to be considered before entering the next phase.

In the detailed design phase, thermal loads are re-evaluated and source control options are considered and/or optimized. The type and location of ventilative cooling system components are selected as well as the control strategy and sensor location. If needed other natural cooling solutions are designed and their operation integrated with the ventilative cooling solution.

Based on hour by hour calculations through a design year the whole system (building and technical systems) is optimized with regard to indoor environment, energy use and costs. Finally, in the design evaluation phase detailed predictions of thermal comfort can be performed to ensure that the design fulfils the targets of the project.

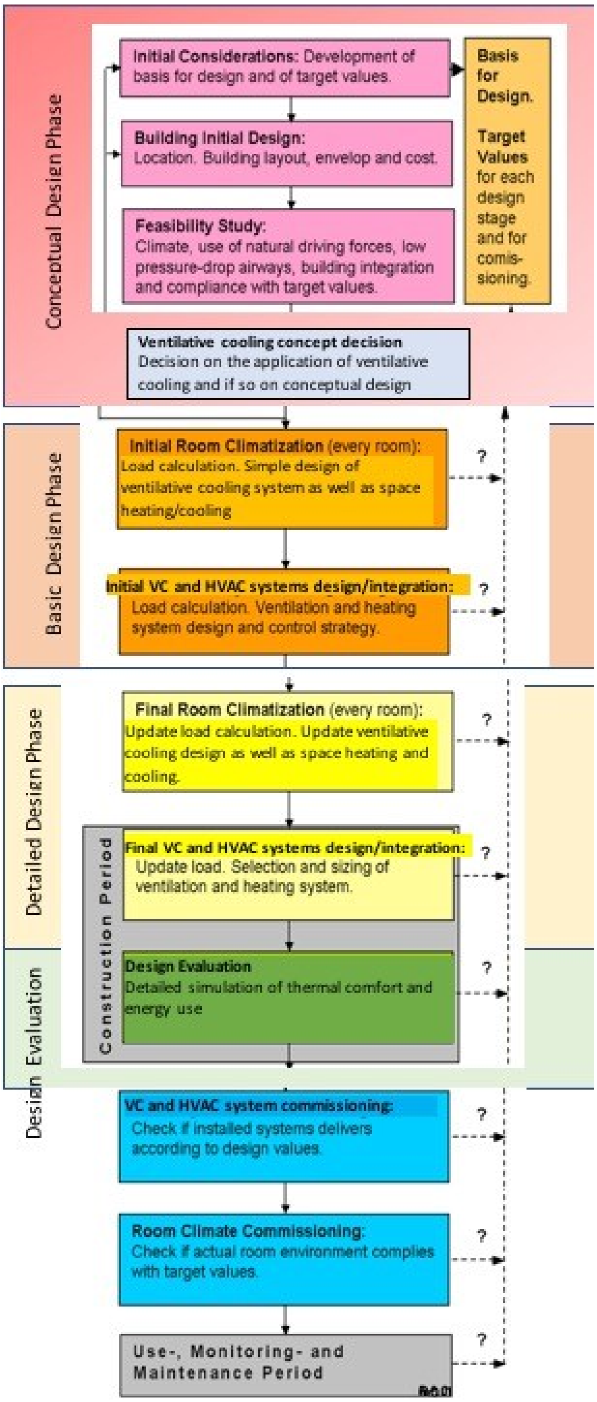

Figure 2. Design procedure for ventilation and ventilative cooling.

Cooling Potential

Decisions about application of ventilative cooling in buildings is made in the conceptual design phase and it is important to be able to assess the ventilative cooling potential without the need for rigorous analysis.

Ventilative cooling is dependent on the availability of suitable external conditions to provide cooling and buildings with different use patterns, envelope characteristics and internal loads level will react differently to the external climate conditions. Therefore, the ventilative cooling potential analysis must include both climate considerations and building characteristics and use.

In the Annex a ventilative cooling potential tool (VC tool) able to assess the potential effectiveness of ventilative cooling strategies by taking into account both building envelope thermal properties, occupancy patterns, internal gains, ventilation needs and the outdoor climate.
The tool is freely accessible on the IEA-EBC website including the user guide and examples to guide users through its use. Figure 3 illustrates the tool GUI with input and outputs visualization.

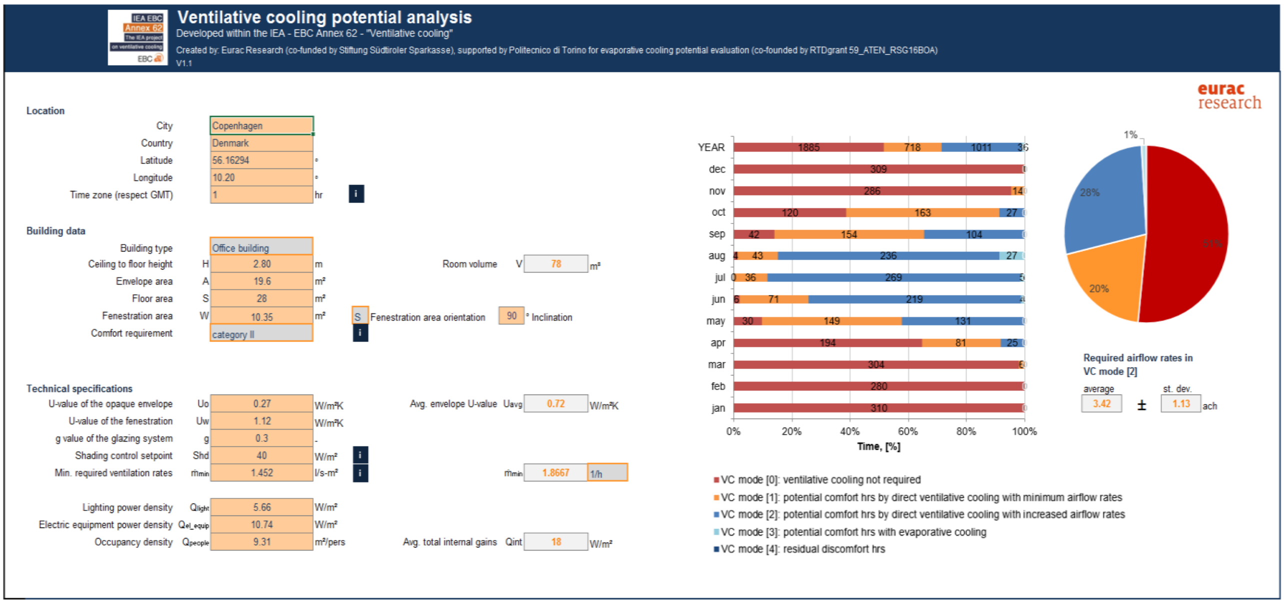

Figure 3. Tool GUI with input data and output visualization [1].

The VC Tool analysis is based on a single-zone thermal model applied to user-input climatic data on hourly basis. For each hour of the annual climatic record of the given location, an algorithm splits the total number of hours when the building is occupied into the following groups:

Ventilative Cooling mode [0]: when the outdoor temperature is below the heating balance point temperature no ventilative cooling is required since heating is needed;

Ventilative Cooling mode [1]: Direct ventilation with airflow rate maintained at the minimum required for indoor air quality can potentially ensure comfort

Ventilative Cooling mode [2]: Direct ventilative cooling with increased airflow rate can potentially ensure comfort. The tool calculates the airflow rate required to maintain the indoor air temperature within the comfort temperature ranges.

Ventilative Cooling mode [3]: direct evaporative cooling (DEC) can potentially ensure comfort even if direct ventilation alone is not useful

Ventilative Cooling mode [4]: Direct ventilative cooling is not useful

Figure 4 shows the ventilative cooling potential of the Annex case studies divided into the different ventilative cooling modes. Results look different even for buildings within the same climate because of their different use characteristics.

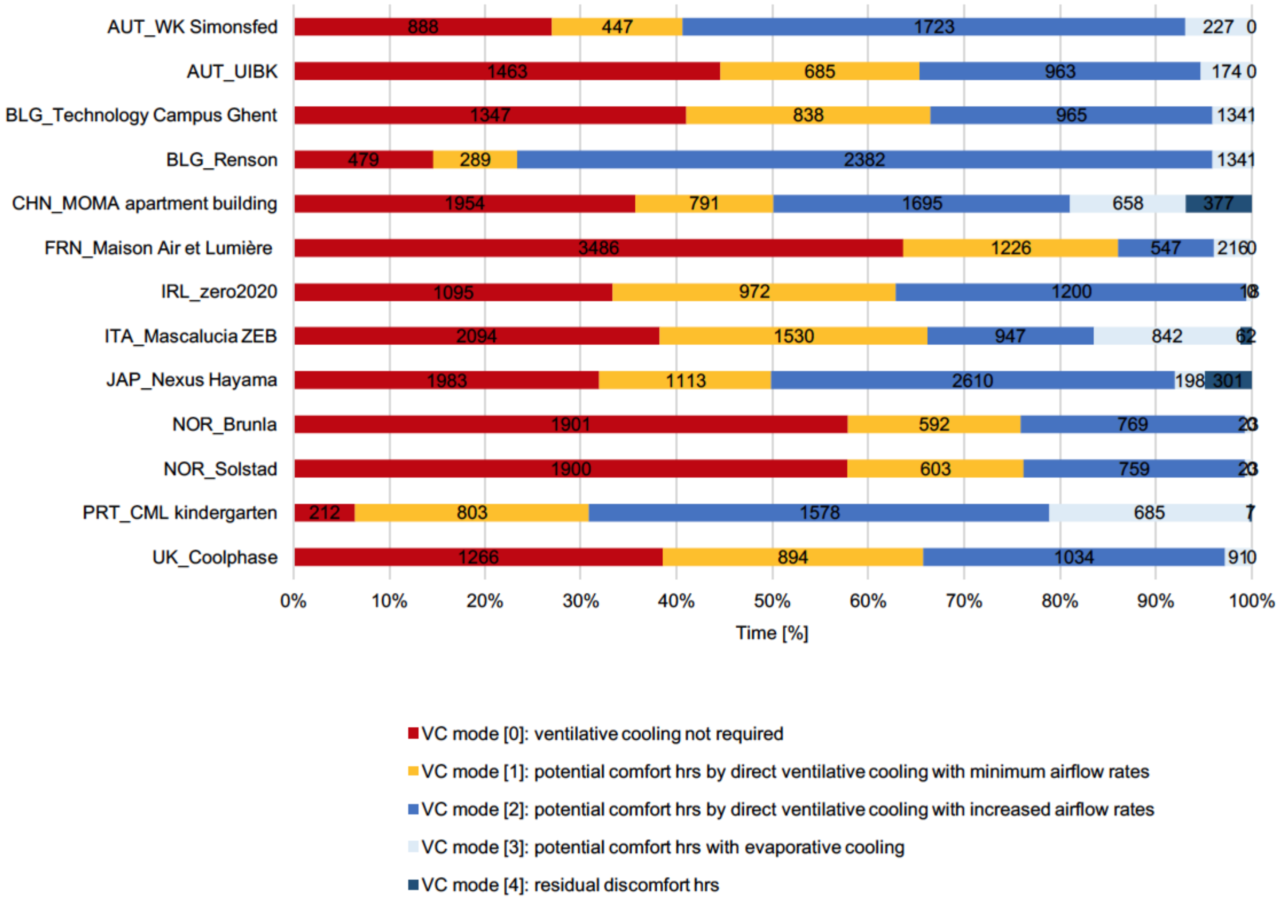

Figure 4. Ventilative cooling potential of the case studies as predicted by the VC Tool [1].

Technologies and System Integration

As such, there are no ventilative cooling technologies and components. Ventilative cooling systems in nearly all cases consist of a combination of technologies and components, which can be used in purely naturally driven or in purely mechanically driven ventilation systems. However, in order to allow a correct design and functioning of a ventilative cooling system the availability and integration of appropriate technologies and components is essential.

Figure 5 shows a way to characterize typical technologies and components used in ventilative cooling systems. The functionality, use and integration of technologies and components into ventilative cooling systems is described in the Ventilative Cooling Source Book [3].

Functionality	Component
Air Flow Guiding	Windows, Rooflights, Doors, Dampers, Flaps, Louvres, Special Effect Vents
Air Flow Enhancing	Chimneys, Atria, Venturi Ventilators, Wind Towers, Wind Scoops
Passive and Natural Cooling	Convective Cooling, Evaporative Cooling, Phase Change Cooling
Control and Automation	Chain Actuators, Linear Actuators, Rotary Actuators, Sensors

Figure 5. Characterization of functionality of typical components in ventilative cooling systems [1].

Different ventilative cooling system solutions were also developed and further optimized in the project and are reported in the Source Book [3]. These projects cover the application of different technologies for ventilative cooling (diffuse ceiling, PCM energy storage, slot louvres, cooling jet, window opening control strategies, etc.), different application areas (office, supermarket, kindergarten, single family house, etc.) and climates.

Recommendations for Standards and Regulation

A review on the treatment of ventilative cooling in national codes and standards was carried out in the Annex focusing on ventilative cooling aspects in (a) building codes, (b) national energy demand calculations and (c) implementation of ventilative cooling in current national building regulations. The results are presented in detail in the review report [4].

It was concluded from the surveys that ventilative cooling requirements in regulations are complex and five categories of parameters were identified that need clarification in the national codes to facilitate ventilative cooling; (a) energy consumption for cooling, (b) building parameters influencing ventilative cooling, (c) ventilation requirements - both ventilation amounts and ventilation openings and positions, (d) safety, and (e) temperature, air velocity and humidity requirements.

Countries in the European Union are required to implement the Energy Performance of Buildings Directive (EPBD). However, for some countries, such as Italy, national implementation is expected but not yet realized. And even if an energy performance level is required, energy demand for cooling is not necessarily considered. This leads to the unwanted situation that a calculation of energy demand for cooling is not required for all countries, thus rendering the energy benefit of ventilative cooling invisible in national regulations.

In the USA every state has its own regulations. In the review report, only the California building codes are discussed in detail. Compared to the European codes, the California building code has no fixed value for the energy demand, or equivalent coefficient, for a building, but a comparison to an energy calculation of a standard building which is described in the code is necessary.

For several countries, The Netherlands, Belgium, Denmark, and Norway, the energy performance certificate requires a total energy demand calculation over a year, not separated in heating and cooling. If energy demand for cooling is not considered separately, the energy demand for cooling can be compensated by other means (reduced heating, sustainable energy production) diminishing the usefulness of ventilative cooling in the regulations.

Several countries include the energy demand from mechanical ventilation and de-humidification in the energy demand calculation. These aspects have an influence on ventilative cooling by influencing the choice for mechanical or natural ventilation if auxiliary and parasitic consumption from mechanical ventilation is considered separately. If de-humidification is considered, this might pose extra demands on the type of ventilative cooling that can be installed, being with or without de-humidification.

In Switzerland, there is a minimum requirement on electricity use in buildings, i.e., electric energy use of buildings estimated at design cannot exceed a given value. Active cooling, lighting, ventilation and use of auxiliary installations are considered in the electric energy use. In other words, if you want to apply active cooling, it poses limits on lighting, ventilation and the use of auxiliary installations. However, according to dynamic calculations based on ISO 15 591, ventilative cooling may reduce cooling needs in Switzerland down to zero.

It was also revealed that energy performance calculations in many countries do not explicitly consider ventilative cooling. Therefore, available tools used for energy performance calculations might not be well suited to model the impact of ventilative cooling, especially in annual and monthly calculations. There might be need for the development of an international standard on ventilative cooling, which should also address calculation methods.

Based on the review participants has investigated, developed and reported future recommendations for adequate implementation of ventilative cooling in standards, legislation and compliance tools with main focus on natural ventilative cooling parameters [5]. The work includes both recommendations in relation to both EN standards, ISO standards and national standards, as well as national/regional legislation. National compliance tools concerning ventilative cooling are evaluated through the status and recommendations of each area.

Annex participants has developed new work items (NWI's) relevant to ventilative cooling applications that recently have been approved in the European Committee for Standardization (CEN). The scope of this work is to make technical documents focusing on design aspects of ventilative cooling, and natural and hybrid ventilation systems in residential and non-residential buildings. The work now officially started up in CEN/TC 156 include three activities:

1. **Ventilative cooling systems**: Main focus is thermal comfort (prevent overheating); Document type is technical specification; Work is started up in WG/21 in CEN/TC 156

2. **Natural and Hybrid ventilation systems in non-residential buildings**: Main focus is indoor air quality; Document type is technical specification; Work is stated up in WG/20 in CEN/TC 156

3. **Design process of natural ventilation for reducing cooling demand in energy-efficient non-residential buildings**: Main focus is thermal comfort (design process to prevent overheating); Document type is ISO standard: Work is started up in WG/2 in ISO/TC 205

And, one project is upcoming:

4. **Expansion of Natural and Hybrid ventilation in residential buildings in upcoming "Revision of EN 15665:2009 and CEN/TR 14788:2006"**: Main focus is indoor air quality; Document type is EN standard; Work is started up in WG/2 in CEN/TC 156

The initiated projects are planned as Technical Specifications (normative documents of lower status than EN Standards) and as an EN standard under CEN/TC 156. The technical documents are a good opportunity to define design aspects of ventilative cooling and natural and hybrid ventilation systems on the European and International scene e.g. by applying findings from the Annex.
As in CEN, new work items relevant to ventilative cooling applications have also recently been proposed in the International Organization for Standardization (ISO) aiming at making a descriptive technical document focusing on the design process or aspects of natural ventilation systems. The project has already started up:

1. **Design process of natural ventilation for reducing cooling demand in energy-efficient non-residential buildings. (ISO/TC 205), NP 22511**
    - Work started up in WG/2

Performance Documentation

Naturally, expectations of ventilative cooling performance will vary between different countries because of climate variations, energy prices and other factors. In countries with cold climate, ventilative cooling can avoid the trend to use mechanical air conditioning in new buildings, which has occurred in response to the heavily insulated and air tight building designs, higher occupant expectations and the requirements of building regulations, codes and standards. In countries with warm climate, it can reduce the reliance on air conditioning and reduce the cost, the energy penalty and the consequential environmental effects of full year-round air conditioning.

Well documented case studies using ventilative cooling from across the world were collected. They include three office buildings, five educational buildings, four residential, one mixed use and one kindergarten. Eight of the case studies have rural surroundings and seven have urban surroundings. Four case studies were refurbishment projects. For these case studies, rich information was available about their design, construction and operational performance that is presented in specific case study brochures available on the IEA-EBC Annex 62 website.

Different ventilative cooling principles are demonstrated in the case studies.

Table 1 and Table 2 give, respectively an overview of the principles, and an overview of the components and supplementary technologies used in every case study. More information can be found in [1].

Table 1. Ventilative cooling principles applied in the investigated case studies, [1].

Ventilative Cooling Principle Case Study No.		Type and location	Day time air supply	Night time air supply	Natural ventilation combined with mechanical exhaust	Mechanical ventilation in winter, natural ventilation in summer	Mechanical ventilation with natural night time ventilation	Mechanical ventilation with increased flow rate
01	IE	Zero2020	x	x				
02	NO.1	Brunla school			x			
03	NO.2	Solstad Kindergarten				x		
04	CN	Wanguo MOMA						x
05	AT.1	UNI Innsbruck	x	x				
06	AT.2	wkSimonsfeld			x			
07	BE.1	Renson	x	x				
08	BE.2	KU Leuven, Ghent					x	
09	FR	Maison air et lumiere				x		
10	IT	Mascalucia ZEB				x		
11	JP.1	Nexus Hayama	x	x				
12	JP.2	GFO	x	x	x			
13	PT	CML Kindergarten	x	x				
14	UK	Bristol University						x
15	NO.3	Living Lab	x		x			x

Table 2. Ventilative cooling components and supplementary technologies applied in the investigated case studies, [1].

Ventilative Cooling Components and Technologies			Air Flow Guiding components				Air Flow Enhancing Components			Supplementary Cooling Technologies					
Case Study No.		Type and location	Windows	Insulated louvre	Overflow vents between rooms	Air pipes and air supply devices	Roof vents	Chimney	Fan	Ground cooling	Evaporative cooling	Ground Source heat pump	Earth to air Heat Exchanger	Radiant solar heat and cooling	PCM storage
01	IE	Zero2020		x											
02	NO.1	Brunla school	x						x						
03	NO.2	Solstad Kindergarten	x			x			x						
04	CN	Wanguo MOMA				x			x			x			
05	AT.1	UNI Innsbruck	x		x					x					
06	AT.2	wkSimonsfeld	x				x			x					
07	BE.1	Renson	x					x							
08	BE.2	KU Leuven, Ghent	x								x				
09	FR	Maison air et lumiere	x			x			x						
10	IT	Mascalucia ZEB	x						x				x		
11	JP.1	Nexus Hayama	x				x							x	
12	JP.2	GFO		x		x			x						
13	PT	CML Kindergarten	x	x				x							
14	UK	Bristol University				x			x						x
15	NO.3	Living Lab	x												

In these case studies, naturally driven ventilative cooling is mainly used in temperate climates and in several different building types. Naturally driven ventilation is both used during daytime for indoor air quality and cooling purposes as well as for night-time cooling of the buildings. Windows and/or louvres are typically used as air supply devices providing outdoor air directly to the occupied zones, while in some buildings roof vents or chimneys are used to enhance air flow. In some cases exhaust ventilation is also used to ensure a satisfactory air flow rate through the building at all times or natural cooling solutions are applied to improve the cooling capacity in warmer periods.

In cold climates and/or in buildings with a low heat load or very limited cooling need during winter, hybrid ventilation systems are typically used. Balanced mechanical ventilation with heat recovery is used in winter (the heating season), while natural ventilation is used in summer (outside the heating season), when outside temperatures are higher and direct supply of outdoor air does not result in draught risks. In some cases, mechanical ventilation is used during occupied hours during the whole year to ensure a controlled and satisfactory air flow rate at all times and combined with natural ventilation for night cooling in the warm periods. In many cases ventilative cooling is supplemented by natural cooling solutions.

Ventilative cooling solutions based on mechanical ventilation with increased flow rates are also among the demonstrated solutions in the case studies. These solutions offer the possibility for better distribution of air inside the buildings and are also used in combination with natural cooling solutions and energy storage/modulation.

From the case studies a number of key lessons learned are reported. A number of these relate to that the design of a building incorporating ventilative cooling can be challenging and may require a lot of detailed building information. While the case studies represent a wide range of building types, building use, climatic conditions, etc. and each design challenge was different, the main key lessons from all cases were as follows:

- Detailed building simulation is important when simulating VC strategies. Most case studies analysed highlighted the need for reliable building simulations in the design phase of a VC system. This was considered most important when designing for hybrid ventilation strategies where multiple mechanical systems need harmonization. Some studies also said that simulating the window opening in detail was important.
- Customisation may be an important factor in designing a VC system. In order to ventilate certain buildings, it may be necessary to design custom components. Some case studies highlighted the need to have custom design systems that were specific to country regulations and the use of a building or space. Some consideration should also be given to the client expectations around specific issues like rain ingress and insect prevention.
- VC systems were considered a cost-effective and energy efficient in design by most case studies, but particularly with naturally ventilated systems. It was indicated that designing with the integration of manual operation and control was important, particularly in a domestic setting.

While systems was designed to have high levels of comfort, IAQ and energy performance, achieving this was difficult. All case studies emphasized that monitoring a buildings performance post occupancy is important if not essential in building performance optimization. While some key lessons were more specific than others the following general observations were made;

- Engaging with the building owners or operators as soon as possible is integral to guaranteeing building performance for IAQ, comfort or energy savings. For some case studies this specifically meant educating or working with the facilities operator or manager for the building, for others it meant educating the building occupiers themselves. It was suggested by some that this engagement should occur already in the design stage.

- VC in operation is generally a good option. Case studies comment on the reduction of overheating and improvement of comfort conditions in the buildings that used outside air. However, correct maintenance and calibration of the systems is integral to maintaining performance.
- Some case studies highlighted the need to exploit the outside air more with lower external air control limits during typical and night-time operation. Others suggested that exploiting the thermal mass of a building was key. However, it was noted that care must be taken with considering these low temperatures as some case studies, particularly in cold climates observed more incidences of overcooling than overheating.

The conclusions from the case studies is that the best contemporary designs combine natural ventilation with conventional mechanical cooling. When properly designed, and implemented, these hybrid approaches maximize the VC potential while avoiding overheating during the warmer months. The study also showed that a lot can be learned from collecting information about ventilative cooling case studies that have demonstrated through measurement that they perform well and their internal environments are comfortable for an acceptable period of the occupied time. However, due to the heterogeneity of the cases analyzed, it was difficult to draw general conclusions regarding recommendations for designers. The characteristics of each case study appeared unique due to the need for the approach to respond to a specific climate, the building usage, morphology and client criteria.

International Ventilative Cooling Application Database

An international ventilative cooling application database has been developed based on desktop research, by Annex participants. The database contains 91 buildings, located in Europe. The building-datasheets offer illustrative descriptions of buildings of different usages, sizes and locations, using ventilative cooling as a mean of indoor comfort improvement and include for each building:

- General building specifications: address, building category, year of construction, special qualities, location, climate;
- Ventilative cooling site design elements: solar site design and wind exposure design, evaporative effects from plants or water;
- Ventilative cooling architectural design elements: shape, morphology, envelope, construction and material;
- Ventilative cooling technical components: airflow guiding components, airflow enhancing components, passive cooling components;
- Actuators, sensors and control strategies;
- Building energy systems: heating, ventilation, cooling, electricity;
- Building ownership and facility management structures.

Overall the main characteristics of the buildings in the database are:

- Building use is dominantly office in (55%), educational (21%) and others (22%). Only 8% residential;
- Location is dominantly urban (60%);

- Ventilative cooling site design elements are applied in 65%, quite equally distributed between solar site design, wind exposure design and evaporative effects;
- Ventilative cooling architectural design elements are applied in 95%, dominantly by morphology, envelope and construction-material (66% to 78%), less by form (49%);
- Airflow guiding ventilation components are used widely in 99% of the buildings, dominantly by windows, rooflights, doors (96%), significantly more seldom by dampers, flaps, louvres (44%) or by special effect vents (5%);
- Airflow enhancing ventilation components are applied in 66%, fully dominated by atria (63%), with some chimneys (16%) and only very rare cases of others;
- Passive cooling components are used in 26%, dominantly by convective cooling components (22%), with only very rare cases of others;
- Actuators are identified in 66%, dominated by chain actuators (57%), followed by linear actuators (9%);
- Sensors are identified in 88%, including the frequent use of temperature, humidity, CO2, wind, rain and solar radiation;
- Control strategy is reported as hybrid in 58%, as automatic in 29%, as manual only in 4%.

The database can be found on: http://venticool.eu/annex-62-publications/deliverables

As presented above the project did succeed in realising its objectives and the results obtained are very useful and will lead to increased application of the technology in new construction as well as deep renovations. It also provides a very good basis for further development and optimization of the technology.

A very important issue highlighted during the project was the challenges in proving the performance of the technology in energy calculations for compliance check. This led to a number of recommendations for improvement of standards and regulations and also to new initiatives related to international standardisation.

Dissemination

During the project results and achievement were published and presented at a number of events internationally. Below are described the Danish contributions to these:

- Ventilative Cooling and EBC Annex 62 (Per Heiselberg, AAU) IEA ERGD workshop Advanced technologies for cooling, April 17-18, 2016 Paris.
- Ventilative Cooling in Standards and Regulations, Country Report from Denmark (Karsten Duer, VELUX A/S). International Workshop on Ventilative Cooling Need, Challenges and Solution Examples. Brussels, Belgium, 19- 20 March 2013

- Ventilative cooling potential of outdoor air now and in the future (Per Heiselberg, AAU). International Workshop on Ventilative Cooling Need, Challenges and Solution Examples. Brussels, Belgium, 19- 20 March 2013
- Recent developments to integrate ventilative cooling in the Danish Regulatory Context (Per Heiselberg, AAU). 34th AIVC conference, Athens, September 25-26, 2013.
- Ventilative Cooling Needs and Outdoor Night Cooling Potential (Michal Pomianowski, AAU). International Seminar ”Cooling Potential with Increased Night Ventilation in Low Energy Buildings” ASHRAE Annual Conference, Seattle, WA, July 2014.
- Evaluation of different concepts for ventilative night cooling by building simulations (Angela Simone, DTU) International Seminar ”Cooling Potential with Increased Night Ventilation in Low Energy Buildings” ASHRAE Annual Conference, Seattle, WA, July 2014.
- ECB Annex 62 (Per Heiselberg, AAU). CIBSE and the venticool network seminar, September 17, 2014, Uxbridge, UK.
- Venticool: The international platform for Ventilative Cooling (Karsten Duer, VELUX A/S). CIBSE and the venticool network seminar, September 17, 2014, Uxbridge, UK.
- International research on ventilative cooling in IEA EBC Annex 62 (Per Heiselberg, AAU). 35th AIVC conference in Poznan, Poland at September 24, 2014.
- Experiences with Ventilative Cooling in Active Houses: Practical Application and Performance, Theoretical Performance and Issues related to Standards and Compliance Tools (Peter Foldbjerg, VELUX A/S). 35th AIVC conference in Poznan, Poland at September 24, 2014.
- Potential and Limitations to Ventilative Cooling. (Per Heiselberg, AAU). Opening plenary lecture, 35th AIVC conference in Poznan, Poland at September 24, 2014.
- Ventilative Cooling and Annex 62 (Per Heiselberg, AAU) Heathy Buildings 2015 conference, Eindhoven, The Netherlands.
- Ventilative Cooling and Annex 62 (Per Heiselberg, AAU). International Symposium of Sustainable City and Built Environment, April 17, 2015, Changsha China
- Evaluation tool of climate potential for ventilative cooling (Per Heiselberg, AAU). AIVC 2015, Madrid.
- Ventilative cooling – Potentials and limitations. (Per Heiselberg, AAU) ASHRAE Seminar, Boston, US, October 2015
- Ventilative Cooling IEA EBC Annex 62 Overview and Status (Per Heiselberg, AAU). Technical seminar, Cork Institute of Technology. April 2016
- Principles and potentials of Ventilative Cooling (Per Heiselberg, AAU). Ventilative Cooling Symposium 2016 organised by Austrian Ministry of Transport, Innovation and Technology and the Institute of Building Research & Innovation, Vienna Austria, October 2016.

- Principles and potentials of Ventilative Cooling (Per Heiselberg, AAU). Building Green, October 2016, København.
- Ventilative Cooling – background, objectives and achievements. (Per Heiselberg, AAU) Seminar organised by University of Lisbon, May 2017, Lissabon, Portugal.
- Introduction to Annex 62: background, objectives and results (Per Heiselberg AAU). International Workshop Ventilative cooling in buildings: now & in the future. Brussels, Belgium, 23 October 2017.
- National energy performance calculation methods (Michal Pomianowski, AAU), International Workshop Ventilative cooling in buildings: now & in the future. Brussels, Belgium, 23 October 2017.
- Solutions and technologies (Theofanis Psomas, AAU). International Workshop Ventilative cooling in buildings: now & in the future. Brussels, Belgium, 23 October 2017.
- Recommendations and challenges for CEN and ISO standards (Christoffer Plesner, VELUX A/S). International Workshop Ventilative cooling in buildings: now & in the future. Brussels, Belgium, 23 October 2017.
- Ventilative cooling in a single-family active house from design stage to user experience (Christoffer Plesner, VELUX A/S). 38th AIVC – 6th TightVent – 4th venticool conference, Nottingham, UK. September 2017.
- The future of hybrid ventilation in office buildings -energy calculation, lifecycle cost and cases (Jannick Roth, WindowMaster), 38th AIVC – 6th TightVent – 4th venticool conference, Nottingham, UK. September 2017.

1.6 Utilization of project results

In the Danish context relevant project results:

- Will be integrated in a design guide for ventilative cooling specifically targeted home builders and homeowners in Denmark both to increase awareness and their possibility to find suitable solutions for new construction and renovation projects.
- Will be used as basis for new proposals for regulation and revised energy performance calculations in Denmark to improve indoor environmental quality and reduce the risk of overheating in buildings in the future.
- Will be used in several low energy building demonstration projects with focus on achieving an excellent indoor environmental quality, among others the EUDP project ”Bolig 2020 med lavt energiforbrug og høj brugerkomfort (J.nr. 64015-0640)”
- Has been used to motivate and initiate (by VELUX A/S) new standardization activities both within CEN and ISO

1.7 Project conclusion and perspective

The project has documented that ventilative cooling is a competitive technology to reduce or even eliminate the risk of overheating in building without increasing the energy use.

The project has also provided new performance indicators for ventilative cooling performance making it possible to compare its performance to other cooling solutions

The project has developed a design process for ventilative cooling and a new tool to to be used in the conceptual design phase to estimate the potential for application of ventilative cooling in a building project.

The lessons learned from the reported case studies has highlighted both the benefits of ventilative cooling, but also the challenges that need to be addressed in future research and development activities. Some of these will be addressed in a new Annex proposal with the name "Resilient Cooling".

The project has provided the basic knowledge that has made it possible to identify the gabs in existing international standardisation and has motivated the need for initiation of new international standardisation activities.

Annex

The following articles has been published during the project period:

- Per Heiselberg, Peter Holzer, Maria Kolokotroni. Ventilative cooling in Buildings – potentials and limitations. REHVA Journal, Vol. 53, nr. 1, 2016,

- Peter Foldbjerg and Karsten Duer. Experiences with Ventilative Cooling in Practical Application. REHVA Journal, Vol. 53, nr. 1, 2016,

- Per Heiselberg, Chen Zhang, Niels Kappel. Ventilative cooling by diffuse ceiling supply. REHVA Journal, Vol. 53, nr. 1, 2016,

- Belleri, A., Heiselberg, P. Evaluation tool of climate potential for ventilative cooling. Proceedings of the 36th AIVC Conference, Madrid, Spain, September 23-24, 2015.

- Pomianowski, Michal Zbigniew; Andersen, Christian Hede; Heiselberg, Per Kvols. Technical potential of evaporative cooling in Danish and European condition. Proceedings of the 6th International Building Physics Conference: Building Physics for a Sustainable Built Environment. Torino, June 2015.

- Wenhui, J., Heiselberg, P., Wang, H., Hu, Y., Zhang, Z. Experimental Assessment of Mechanical Night Ventilation on Inner Wall Surfaces. CLIMA 2016 Proceedings of the 12th REHVA World Congress, 22-25 may 2016, Aalborg Denmark.

- Perino, M., Heiselberg, P. Ventilative Cooling: a tool for the passive control of heat gains in buildings. 33th Convegno Nazionale, Padova 2016, AICARR, ISBN 978-88-95620-68-8.

- Heiselberg, P. The State-of-the-Art for Ventilative Cooling, Current Project: EBC Annex 62. EBC Newsletter November 2016, Issue 64, pp7-8.

- Heiselberg, P., Kolokotroni, M. Ventilative Cooling. State of the Art Review Executive Summary. IEA Energy in Buildings and Communities Programme, published by INIVE EEIG, ISBN 2-930471-47-6, 2017.

- Heiselberg, P., Kolokotroni, M. Ventilative Cooling. State of the Art Review Executive Summary. Ventilation Information Paper no. 35, Air Infiltration and Ventilation Centre, February 2017

- Christoffer Plesner. Ventilative cooling in a single-family active house from design stage to user experience. 38th AIVC – 6th TightVent – 4th venticool conference, Nottingham, UK. September 2017.

- Roth Jannick. The future of hybrid ventilation in office buildings -energy calculation, lifecycle cost and cases. 38th AIVC – 6th TightVent – 4th venticool conference, Nottingham, UK. September 2017.

Official publications of the Annex:

1. Heiselberg, P. Ventilative Cooling Design Guide. IEA-EBC Annex 62 Ventilative Cooling. Available at: www.iea-ebc.org

2. Holzer, P. and Psomas, T. Ventilative cooling Source Book, IEA-EBC Annex 62 Ventilative Cooling. Available at: www.iea-ebc.org

3. Kolokotroni M, Heiselberg P. Ventilative cooling. State of the art review. 2015; ISBN 87--91606--25--X. Available at: www.iea-ebc.org

4. Plesner, C. and Duer, K. Recommendation on ventilative cooling for standards and regulation. IEA-EBC Annex 62 Ventilative Cooling. Available at: www.iea-ebc.org