



Impacts of increased outdoor air flow rates on annual HVAC energy costs in office environment

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Students:

CAMELIN Marion
DESTREZ Adrien

Tutor:

KADRIBEGOVIC Ragib

Abstract

The use of different ventilation systems has an important impact on the energy cost of office buildings. This paper examines the relationship between heating and cooling load, and the associated energy consumption and energy costs with different HVAC system configurations. The influence of the HVAC system using economizer, heat exchanger or both, in CAV and VAV configuration, has been studied in five European cities, which represent the five main climates in Europe. Different heating sources have been examined as well. The free cooling concept analyze has been carried out, in concrete terms, in a classic office building.

The results presented in this paper clearly indicate the advantage of the use of both economizer and heat exchanger over particular climate conditions. Optimization of the HVAC systems is performed by the choice in economizer control and ventilation system (CAV/VAV). Due to the economizer, cooling loads can be brought to zero in very cold and dry climate (Kiruna, Sweden) but it is also efficient in warmer climates such as Mediterranean climate contrary to the common wisdom.

Keywords:

HVAC, free cooling, economizer, office building, ventilation system

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Table of content

Abstract	2
List of Figures and Tables	Error! Bookmark not defined.
Nomenclature	5
1. Introduction	6
1.1. Background	6
1.2. Free cooling principle and economizer mechanism	7
1.3. The software: HAP	8
2. Goal and scope	10
2.1. Goal	10
2.2. Scope	10
2.2.1. Options of simulation	10
2.2.2. Boundaries.....	14
2.2.3. Other data	15
3. Configuration	17
3.1. Building design	17
3.2. Ventilation design	18
4. Results	20
4.1. Energy study	20
4.1.1. Economizer contribution and cut-off study	20
4.1.2. Heat exchanger contribution.....	24
4.1.3. CAV and VAV comparison.....	25
4.1.4. Supply fan energy consumption study	26
4.1.5. Optimum system depending on the location.....	28
4.2. Energy cost study	30
4.2.1. Energy cost improvements for the different cities.....	30
4.2.2. Influence of the energy source on the cost at Goteborg	39
5. Conclusion	42
6. Appendix	44
Appendix 1: Summary of the setting of the VAV system in HAP	45
Appendix 2: Summary of the setting of the CAV system in HAP	47
Appendix 3: Space input data for the room in the corner	49
Appendix 4: Space input data for the room in the middle oriented North	50
Appendix 5: Energy consumption for CAV and VAV system	51
Appendix 6: Comparison of the cooling loads reduction due to the economizer between the enthalpy-based and the temperature-based controls	56
Appendix 7: Influence of an heat exchanger on the cooling load for a VAV system	57
Appendix 8: Detail energy consumption in CAV and VAV systems n°2-5-6	58

Nomenclature

- ASHRAE: American Society of Heating, Refrigerating and Air Conditioning Engineers
- CAV: Constant Air Volume
- VAV: Variable Air Volume
- VVT: Variable Volume/Variable Temperature
- DX: Direct-Expansion
- HAP: Hourly Analysis Program 4.50, the software used for the simulation
- HVAC: Heating, Ventilation and Air Conditioning
- LW: Light Weight
- RSI: R-value (thermal resistance) in the SI definition
- SI: International System of units

1. Introduction

1.1. Background



Figure 1: Swedish energy certificate

Regarding the actual environmental challenges, every sector must improve its efficiency especially regarding energy use. The building sector accounting for 40 % of the world total energy use ¹, it has a huge impact and has a lot of improvements to do in order to perform better, environmentally speaking. Moreover, the development of green certifications for building, such as Green Building in Europe, and of energy certifications, as the Swedish one shown on figure 1, encourage the building sector to improve its efficiency with some benefits such a good corporate image or the possibility to practice higher rents ². Thus, reducing the use of energy of a building can be profitable for both the owners for marketing and/or for an economic point of view and for the environment. Besides, the governments also exert pressure on the building owners through energy requirements in regulations, laws, and agreements, etc... For instance, in certain cities, as London, energy efficiency study for a new building is a requirement for getting a building permit.

Reduction in the building energy consumption can be achieved by the use of a more efficient ventilation system as well as by reducing the internal load or by improving the thermal efficiency of the building. Of course the strategy adopted depends on the location and the loads of the building. Indeed the techniques to reduce cooling demand by designing the building structure differently (orientation, solar shading, etc...) are not the same than the one to reduce the heating load. ² However, many improvements have been achieved in the insulation and construction design in the past decades, therefore it is now quiet obvious that the HVAC system is the next area to provide energy savings in the buildings.

The introduction of outdoor air is necessary for indoor air quality but it is also a huge source of energy use in the building. Indeed the outside air needs to be conditioned before being delivered to the indoor spaces. Thus, since about half of a building's energy budget is for conditioning the air³, it is interesting to consider a minimization of the entry of outdoor air. However, increasing the amount of outdoor air by using an economizer is an interesting way to profit of 'free cooling'. This concept means that the cold outside air is used to provide cooling instead of the mechanical cooling when the outdoor air is cooler than the return air.

The idea of using outside air to reduce the mechanical cooling is not new and some studies can already be found in the 80s ^{4,5}. However there is a lack of knowledge about the benefits of economizer because they vary largely depending on the location of the building and are not widely use yet in building office, even if it is now commonly use in other application such as the cooling of data centre.⁶ Several studies can be found regarding specific locations but it seems that the literature lack of more

general studies to draw conclusions on the relation between economizers' contributions and geographical location. One aim of the present study is thus to draw general conclusions on the use of economizer in the different European climates.

In addition, most of the time, the quick conclusion is drawn that in warm climate, such as Mediterranean climate, an economizer won't be efficient because the outside air temperature is too high most of the year. However this is thought is not always true. For instance, a study has been realised in Istanbul, Turkey, and has shown that consequent energy saving can be realized during a large portion of the year. Of course, it has as well shown than between June and August, the use of economizer does not benefit the cooling load, exception made if the supply temperature is high.⁷

1.2. Free cooling principle and economizer mechanism

Free cooling principle is to take advantage of the outside air temperature to cool the room instead of using a mechanical cooling device. This is done by using an outdoor air economizer which increases or decreases the amount of outside air use in the ventilation system by the mean of dampers. Thus, the load of the cooling coil can be reduce or even bring to zero, therefore energy saving is realized. If the cooling load is reduced, then the cooling device can be reduced and thus, some space saving can be realized as well.⁸ This kind of device is particularly interesting in cold and temperate climates but most of the time it is not relevant in hot and humid climates.⁹ Two global types of economizers exist: air economizer and water economizer. However, this study concerns only air economizer and thus because of the software but also because the efficiency of air economizer is better.¹⁰

One of the most important components of an economizer is the high limit control. Its role is to define whether or not the conditions are such that the economizer should be in function. The main types of high limit controls⁹ are:

- Fixed dry-bulb temperature
- Differential dry-bulb temperature
- Fixed enthalpy
- Differential enthalpy
- Combination of the above

Historically, the first one is the fixed dry-bulb temperature, this also the simplest and cheapest one. All those kinds of control are doing some errors, i.e. choosing the wrong way of cooling the air. As HAP only provides differential integrated dry-bulb temperature, differential integrated enthalpy controls and differential non-integrated dry-bulb temperature control, the study is thus restricted to those three types. However, it would have been interesting to realize the simulation with a control taking in account integrated enthalpy and dry-bulb temperature. Indeed, as shown in the article of the ASHRAE Journal⁹, with the combination of both controls, the theoretical error is almost reduced to zero. Below, the mechanism of the three considered control is presented as well as their advantages/drawbacks according to the study mentioned above.⁵

Firstly the difference between an integrated and a non-integrated control is that in an integrated control the economizer and the mechanical cooling device can operate simultaneously which is not the case in a non-integrated control.

In the case of the differential integrated dry-bulb control, the economizer is activated when the return air dry bulb temperature is greater than the one of the outdoor air.

When the outdoor air is dry, the control makes most of the time the right choice between return air and outside air. However, when the outdoor air is cold and humid, this control most of the time does a mistake. Therefore, differential dry-bulb control is more efficient in some climate, and should be preferred in dry climates rather than in humid ones. Moreover, this control is more widely spread because temperature sensors are cheaper and more reliable.⁹

In the case of the differential enthalpy control, when the outside air enthalpy is less than the one of the recirculated air, the dampers are put in a position such as the outdoor air allows to reduce or eliminate the mechanical cooling. This control requires four sensors, the temperatures of the return air and outdoor air plus the relative humidity of those two streams, thus it is the most expensive one and moreover the occurrence of errors due to sensor calibration is higher.

Contrary to the dry-bulb control, the error occurs when the outdoor air is dry and warm. According to the study present in the article, this is not the best case of control principally because of the sensor errors.

For the differential non-integrated enthalpy control, the economizer is activated when the outdoor air temperature is below the coil outlet temperature. Consequently, it always achieves 100% free cooling, but misses the opportunity for partial free cooling provided by the integrated controls.

After having presenting the economizer mechanism and the different possibilities to controls this device, it is time to present the software use for the simulation: HAP.

1.3. The software: HAP

Hourly Analysis Program (HAP) is a computer tool produced by Carrier, a company providing solutions for air conditioning, heating and refrigeration. The aim of the program is to assist engineers in designing HVAC systems for commercial building. It presents two tools in one: estimation of the loads and designing system, and simulation of the energy use and calculation of energy costs. The program is thus split in two parts: HAP System Design Features and HAP Energy Analysis Features.

In the first part, HAP is able to perform the following tasks:

- To calculate design cooling and heating loads for spaces, zones, and coils.
- To determine required airflow rates for spaces, zones and system.
- To size cooling and heating coils.
- To size air circulation fans.
- To size chillers and boilers.

During the energy analysis, HAP executes the following tasks:

- To simulate hour-by-hour operation of all heating and air conditioning systems.
- To simulate hour-by-hour operation of all plant equipment.
- To simulate hour-by-hour operation of non-HVAC systems.
- To calculate the total energy use and energy costs based on the previous simulations.
- To generate tabular and graphical reports of hourly, daily, monthly and annual data.

HAP uses the ASHRAE-endorsed transfer function method for the load calculation. Indeed, ASHRAE is an international technical society for all individuals and organizations interested in HVAC. The society publishes a well-recognized series of standard, guidelines and building codes relating to HVAC systems and issues, which are commonly accepted by architects and engineers. Thus

HAP's calculation method is made according to the ASHRAE's standards. Moreover, it runs detailed 8 760 hour-by-hour simulation for energy analysis purpose. ¹¹

2. Goal and scope

2.1. Goal

Since outdoor air flow is important to the maintenance of indoor air quality, it is worthwhile to examine the relationship between outdoor air flow and energy use in more detail. The purpose of this study is to examine the energy load and the energy cost impact of raising outdoor air ventilation rates in office buildings using both constant air volume and variable air volume ventilation configurations.

This study aims to find out how HVAC systems can be improved, and over which conditions, regarding the use of mechanical devices to reduce the energy loads. Thus, the purpose may be formulated as the following questions:

- What are the improvements provided by an economizer, a heat exchanger or both?
- Which type of economizer control is preferable depending on the type of climate?
- Which ventilation configuration (type of equipment and ventilation configuration) is the best for a certain type of climate according to the energy consumption?
- Which ventilation configuration (type of equipment and ventilation configuration) is the best for a certain type of climate according to an economical point of view?
- How the choice of the heating source influences the annual cost of the building?

The purpose of the study is to provide solutions about how the energy consumption of an office building can be optimized over certain specific conditions, as climate, ventilation equipment and energy source.

The goal of the study having been defined, the next part presents the choices made and boundaries defined during the study.

2.2. Scope

2.2.1. Options of simulation

- Ventilation system

The software provides three types of ventilation systems CAV, VAV and VVT.

CAV systems provide a constant volume of air to the conditioned space. The supply air temperature is varied in response to the space load. The ventilation unit is controlled in two steps, which correspond to the “occupied” and “unoccupied” times.

VAV system allows a variation of the airflow rates during the day. The fan capacity control reduces the energy consumed by fans, which can be a substantial part of the total energy requirement of the office building.

VVT is a “time-sharing” system in which the same set of equipment and controls alternately provides cooling and heating depending of the need of the zones it serves. Thus this system is more adapted to the case of great variation in the load in short laps of times. This control is therefore not adapted to the simulated building and has not been taken in consideration.

The choice was made to simulate both CAV and VAV but not VVT as stated before. A single zone system was chosen because the load is considered to vary uniformly.

Options for type of ventilation systems include single zone (or single duct), dual duct or multiple zones. A single zone system has a low initial and operating costs but the temperature control is the same for all the rooms. However, since the load is considered to vary uniformly, it has been chosen for the study.

The summary of the setting for VAV and CAV systems is presented in appendix 1 and 2 respectively.

For each ventilation system, eight different configurations have been considered:

1. CAV, or VAV
2. CAV, or VAV, with integrated enthalpy-based economizer
3. CAV, or VAV, with integrated temperature-based economizer
4. CAV, or VAV, with non-integrated temperature-based economizer
5. CAV, or VAV, with heat exchanger
6. CAV, or VAV, with heat exchanger and integrated enthalpy-based economizer
7. CAV, or VAV, with heat exchanger and integrated temperature-based economizer
8. CAV, or VAV, with heat exchanger and non integrated temperature-based economizer

“enthalpy-based economizer” is an economizer with a differential enthalpy control.

“temperature-based economizer” is an economizer with a differential dry-bulb temperature control.

Systems n°1 without economizer and heat exchanger is sometimes called “classic” system.

On Figures 2, 3 and 4, a schematic view of the CAV ventilation system with the three different associations of component are presented. In the following parts, the settings for the different elements of the ventilation system are given in details.

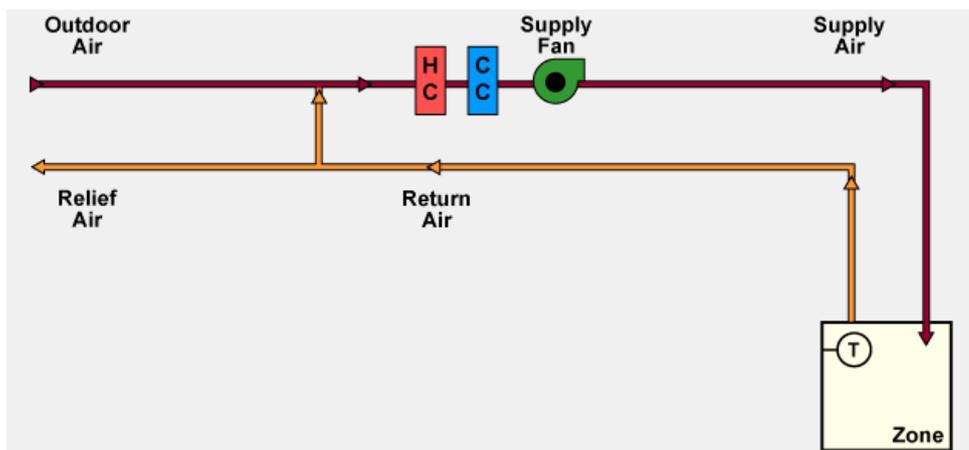


Figure 2: CAV system

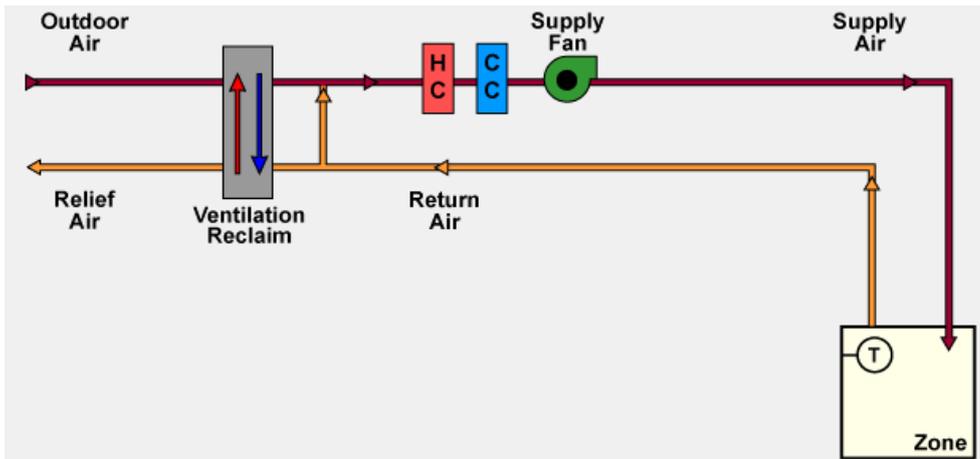


Figure 3: CAV system with heat exchanger

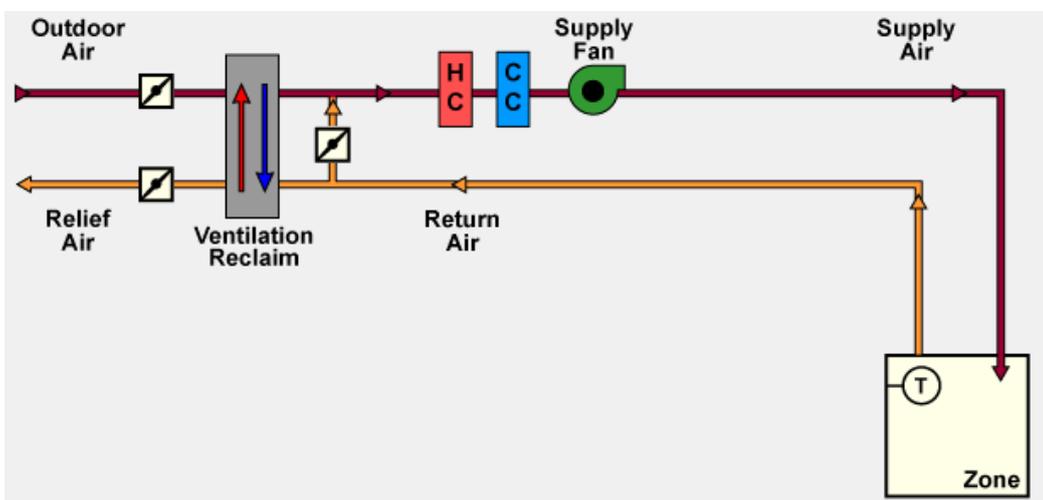


Figure 4: CAV system with heat exchanger and economizer

- Packaged Rooftop unit:



Figure 5: Package rooftop unit

For the equipment type, packaged rooftop unit was chosen for all the studies performed. This equipment contains a supply fan, condenser fan, DX cooling apparatus and heating apparatus in CAV configuration, all in one packaged unit as seen on figure 5¹² and 6¹³. Even if most of those items are on the rooftops, it can also be installed on a concrete pad at ground level. Heating options in CAV configuration are electric resistance, combustion, heat pump and hot water. This is a common system. For instance, about half of all U.S. commercial floor spaces is cooled by packaged air-conditioning units.¹³

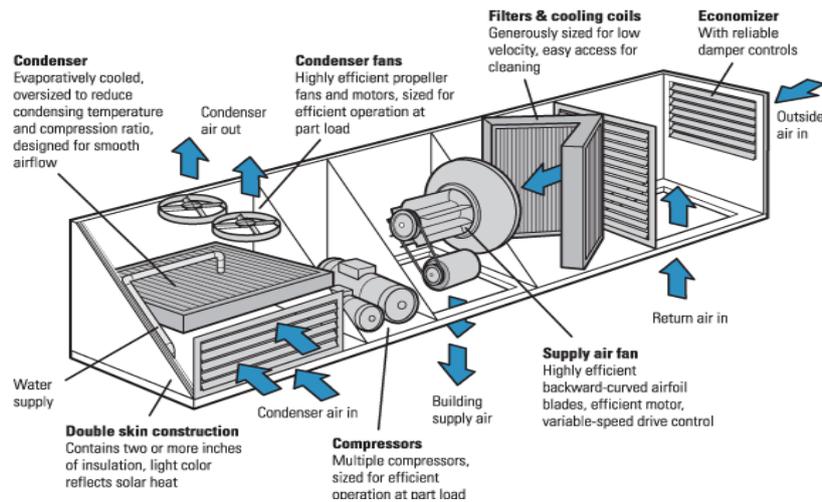


Figure 6: Components and features of efficient packaged rooftop unit design

- Economizer

The general mechanisms of the economizer and of the different controls have been described in section 1.2. Three types of economizer control are the subjects of study:

- Integrated differential enthalpy control economizer
- Integrated differential dry-bulb temperature control economizer
- Non-integrated differential dry-bulb temperature economizer

In some situation, it can be useful to enable the use of the economizer below or above a certain temperature called cut-off temperature. For instance, if an integrated enthalpy economizer is used in a hot and dry climate, the device might be activated when it should not. Indeed, when the outdoor air enthalpy is slightly less than the return air enthalpy, it is possible that the outdoor air dry-bulb temperature is warmer than the return air temperature. Therefore, the use of the economizer would tend to have the reverse action: increase the cooling load instead of reducing it. Thus, an upper cut-off can be set to enable automatically the device when the temperature is higher than a certain limit.

No cut-off temperatures were set for the simulations, but a specific study is carried out in order to see the influence of these cut-off limits. The results of this study are presented in section 4.1.1.

- Heat exchanger

Several kinds of heat exchanger device exist: air-to-air heat exchangers, heat pipes, heat wheels, pump around systems, etc... The available options in HAP are:

- Sensible heat exchange only.
- Sensible and latent heat exchange.
- Electricity input in kW (a zero value refers here to air-to-air heat exchanger and heat pipes which do not need electricity input).

Since sensible and latent heat exchange is more complete, it has been chosen. Also, heat exchanger with electricity input, as rotating heat wheel, has been preferred. The input value is fixed at 10% of the supply fan electricity input value.

2.2.2. Boundaries

- Geographical boundaries

The studies are conducted only on the European continent. In order to choose different types of climate, which is one of the most important factors of the study, the Köppen–Geiger climate classification system was used. This classification is one of the widely used classifications and it provides detail information about the climate in the world, and especially in Europe.¹⁴

Thus, five different types of climate were chosen in Europe and one city for each climate was chosen as presented in figure 7 below. The characteristics of each climate are presented below:

- **Mediterranean climate, or dry-summer subtropical – Csa:** It is characterized by hot, dry summers and mild, humid winters. It experiences average monthly temperature above 21.8°C during its warmest month and an average between 18°C and -3°C during its coldest month. Madrid in Spain was chosen.
- **Humid subtropical climate – Cfa:** It is characterized by hot, humid summers and dry, cool winters. The temperatures lie roughly in the same range as Mediterranean climate but the humidity is different. Although this climate lies mainly on the southeast side of all continents (North America, South America, Africa, Asia and Australia), it occurs also in the north of Italy. Thus, Milan, Italy, was selected.
- **Oceanic climate, or maritime temperate climate – Cfb:** It is characterized by moderately cool summers and comparatively warm winters, with a narrow annual temperature range. Average temperature of the warmest month must be less than 22°C and that of the coldest month warmer than -3°C. Oceanic climates are most dominant in Europe. London, in United Kingdom, was chosen.
- **Warm summer humid continental climate – Dfb:** It is characterized by warm, humid summers and cold to very cold winters with large seasonal temperature differences. Highest temperatures in summer are between 21 and 28°C and the average temperatures in the coldest month are generally far below -3°C. Gothenburg, Sweden, was chosen.
- **Continental subarctic climate, or Boreal climate – Dfc:** It is characterized by long, very cold winters and short, cool summers. In winter temperature can drop below -20°C. Kiruna, Sweden, was chosen.

Figure 8 presents the characteristics of each chosen climate (humidity and temperature), in winter and summer times, respectively to each others.

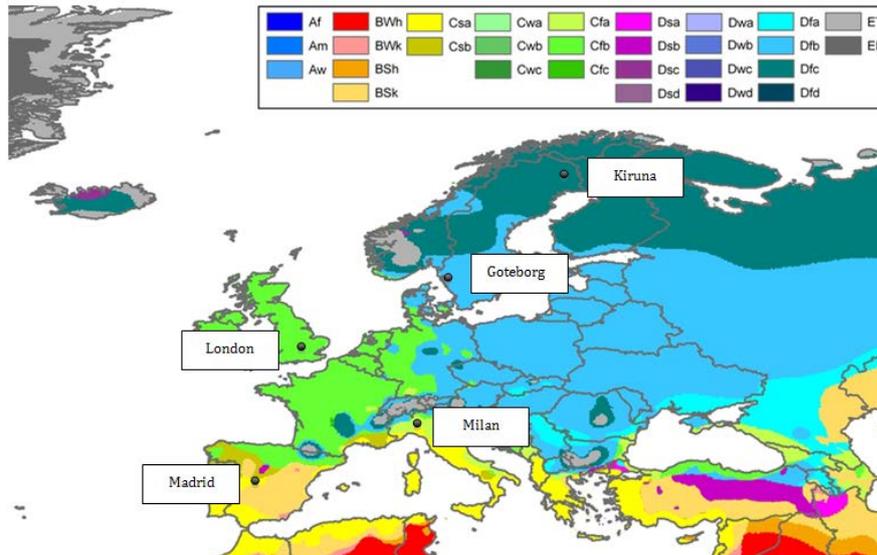


Figure 7: Climate map of Europe with the selected cities, according to the Köppen–Geiger classification system

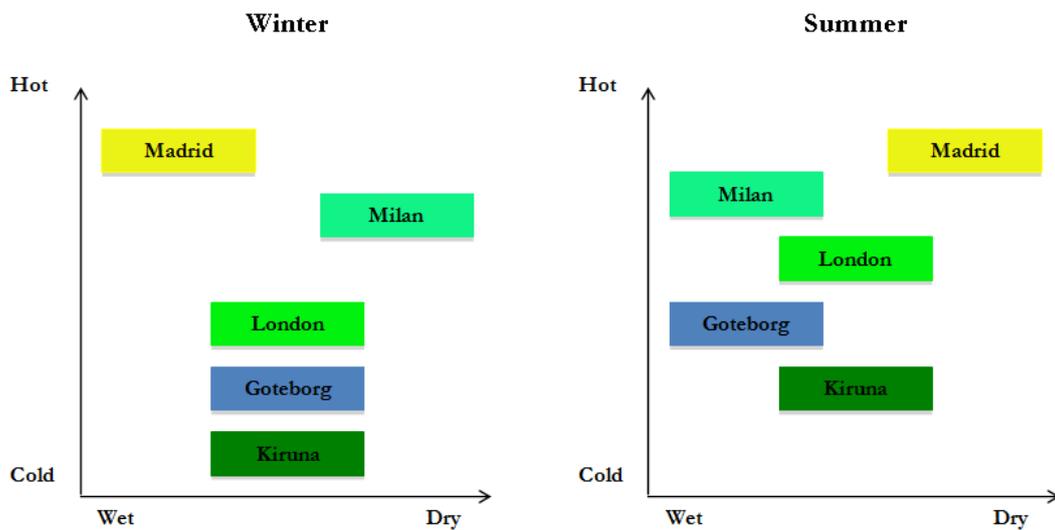


Figure 8: Climate re-partitioning of the selected cities

2.2.3. Other data

- Economic consideration

In order to perform a study of the cost of the different ventilation systems, the price of electricity in the different countries and the price of the different kinds of energy in Sweden have been collected and presented in table 1 and 2 respectively. The price of chilled water has been approximated at the same as the one of hot water. The economic study of the different types of energy has been restricted to Sweden.

	Electricity price (€kWh)	Value added tax (%)
Sweden	0.0767	25
Italy	0.1327	20
Spain	0.1175	18
United Kingdom	0.1064	18

Table 1: Electricity price per country ¹⁵

	Price
Gas ¹⁵	0,0566 €kWh
Fuel Oil ¹⁵	1,376 €L
Hot Water (District Heating) ¹⁶	0,06181 €kWh
Chilled Water	0,06181 €kWh

Table 2: Energy price in Sweden, VAT included

3. Configuration

3.1. Building design

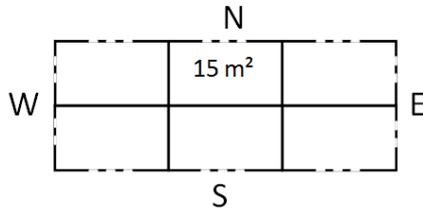


Figure 9: Scheme of the floor (nota: each square represent a 3*5 m² office and no scale was used)

The building used for the simulation is not an existing one but has been created for the purpose of the study, trying to stay as close as possible to a real office building. The simulation refers to one floor of a building office in which there are 6 rooms of 15 m² each, cf. Figure 9. The aim was to realize the simulation on a standard office building. Thus, the building design parameters were chosen with average and/or standard values found in the literature. Below, the details of the assumptions made and the building parameters chosen are detailed.

The space characteristics of the rooms in the corner North-East and of the room in the middle of the North facade are presented respectively in appendix 3 and 4.

- Construction parameters

For the characteristic of the wall, one of the pre-defined walls of the software was used with an overall U-value of 0.31 W/m²/K (Face Brick + RSI-2.5 Board + 102mm LW Concrete Block). The windows used had a U-value of 1.2 W/m²/K and an overall shading coefficient of 0.4. Moreover, the floor was considered between two conditioned spaces thus no roof or floor characteristics have been set, considering that there would be no influence for the spaces below and above the rooms.

- Internal Load

The building was considered occupied from 8 am to 7 pm on week days, i.e. from Monday to Friday. During the unoccupied time, i.e. during night and week-end, all the equipment and light were considered to be switched off, i.e. no internal load. The internal loads in occupied time were set as follow:

- Lighting: 7 W/m².
- Equipment: 50 W (one computer).
- People: one person per office with an activity level of an office, i.e. sensible load: 71.8 W/pers. and latent load: 60.1 W/pers. (values from HAP).

- Infiltration

During the design part, the question of considering infiltration for the calculation has been raised. After having look in the literature for some average value of infiltration coefficients ¹⁷, two simulations have been run on the CAV system n°1, one with air infiltration values and one without, in order to see the influence on the cooling and heating load. The results are presented in table 3 and based on it, the decision was made to take into account the infiltration in the simulation in order to fit better with a real building.

	With no infiltration	With infiltration	Percentage
Central Cooling Coil Load kWh	4766	4480	- 6,0 %
Central Heating Coil Load kWh	90	149	+ 65,5 %

Table 3: Influence of the infiltration on the cooling and heating load, simulation run on the CAV system in London.

3.2. Ventilation design

- Central cooling and heating

When cooling was requested, the supply air was at 18°C and a by-pass factor of 0.1 was set for the cooling device. When heating was requested, a supply air temperature of 27°C was used.

In this case, one of the setting differences between CAV and VAV systems is the heating device. Indeed, for single-duct configuration, heating is provided by a heating coil directly in the ventilation system for the CAV configuration while an external heating unit, which can be a baseboard or a fan coil unit, provides it in the VAV configuration. A baseboard, simpler to define in the software, has been chosen.

- Supply fan

A forward curved fan with variable speed drive was chosen for the VAV system and a forward curved fan was used in the CAV system. The motor input was set at 1.2 kW.

- Airflow control

Two parameters were available for the VAV system: constant or proportional air flow control. In order to choose between those two possibilities a preliminary study was made to compare them and is presented below. But firstly, let's explain the characteristics of the two controls.

Constant control specifies that outdoor ventilation will be maintained at the design airflow value for all occupied period and for unoccupied period when the ventilation dampers are open. For constant volume systems, constant ventilation airflow can be maintained without special controls. For VAV systems, it is assumed that special damper controls or booster fans are used to maintain a constant ventilation airflow rate as the supply airflow varies. If the supply airflow rate in a VAV system drops below the design ventilation flow rate, the system will operate with 100% outdoor air, but will be below the design ventilation specification.

In proportional control models, uncontrolled or partially controlled ventilation air for variable volume systems is used. With this control the ventilation airflow rate varies as the supply airflow varies. Uncontrolled outdoor airflow tends to vary as a constant percentage of supply air. Thus, if the supply fan has throttled to 60% of its design flow rate, then the outdoor ventilation airflow is at 60% of the design outdoor airflow rate. This control option is only available for VAV systems.

On figure 10, the energy impact of those two controls is presented. This comparison was realized on system VAV n°1 for the five locations. The energy consumption is split in three categories: energy for the supply fan, heating load and cooling load. This has been done in order to compare the energy request by the supply fan between the two possible options.

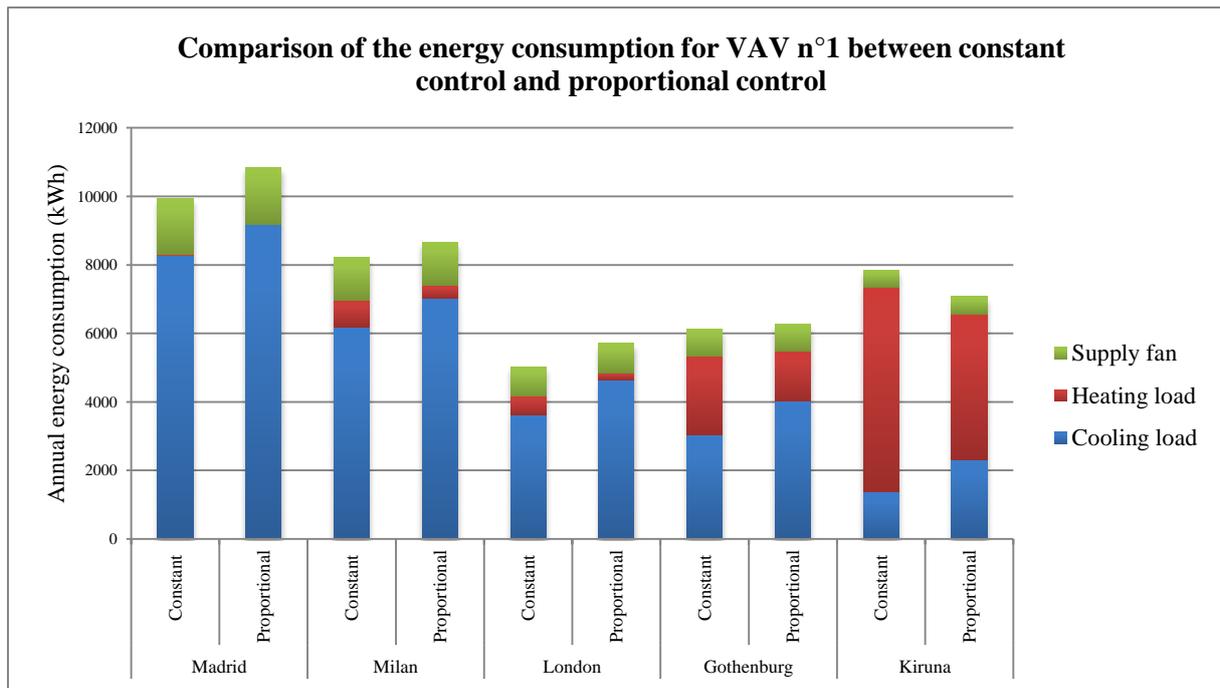


Figure 10: Comparison of the energy consumption between constant and proportional controls for VAV n°1

The proportional control provides less heating load but more cooling load than the constant one, with roughly the same energy consumption for supply fan. Thus, in cold climates, such as in Gothenburg or Kiruna, where the heating demand is substantial, proportional control is preferable, while constant control is better for warmer climates. However, since heating or cooling can be provided by different sources of energy at different prices, no definitive conclusions can be drawn regarding the economic cost of the system.

Keeping in mind that the study is a comparative one, constant control has been chosen since the optimal choice of the control is different depending on the location and since constant control is available for both CAV and VAV systems which is not the case of the proportional control.

The settings and assumptions made have been presented and thus all the necessary parameters for simulation have been stated. Therefore, simulation can be run and the results are presented in the next section.

4. Results

4.1. Energy study

As presented in the section 3, the main study concerns the comparison of eight different ventilation systems in five different European cities. The aim was to find out which system is more appropriate depending on the climate and to see the difference between the three economizer controls. A conclusion will also be drawn concerning the use of a CAV system or of a VAV system. Thus, in a first part, the results for the economizer are presented. In a second part, the heat exchanger contribution is presented, the third part is the comparison of the CAV and VAV systems and the fourth part a study of fan consumption is presented. Finally a fifth part sum up the previous parts in order to define the optimum system for each city.

The global results of the simulation are presented in appendix 5 on figures 33 to 37 for the CAV system and on figure 38 to 42 for the VAV system. Those figures represent the energy load for cooling and heating in each city and for the eight different systems.

4.1.1. Economizer contribution and cut-off study

- Economizer contribution:

The main purpose of this study is the use of free cooling to reduce mechanical cooling. Thus, this section presents the results of the economizer contribution for the cooling load reduction and also a comparison of the three different controls. The reduction on the cooling load is only considered because an economizer cannot bring any heating load reduction. Indeed, in an office building when the heating is needed it means that the outside air temperature is really cold and thus colder than the return air temperature because of the internal load of the building. Therefore, the case where heating is required with an outside air warmer than the return air does not exist. Consequently, in the following part, the cooling load is only considered.

By a quick look at figure 33 to 42 in appendix 5, it can be conclude that the economizer with the non integrated dry-bulb temperature control is less efficient than the two other kinds of controls and consequently the two others should be preferred to this one. This is logical regarding the principle of this control. Indeed, it is either 100 % free cooling and no mechanical cooling or only mechanical cooling. Thus, it misses the opportunity to take advantage of free cooling with a partial mechanical cooling. For this reason, this control is not considered in the following comparisons.

To continue with the comparison of the different types of control, the contribution in the load reduction of the integrated enthalpy and integrated dry-bulb temperature controls has been analysed. The results are presented in appendix 6 on figures 43 and 44 for CAV and VAV respectively. It appears that the only city where the difference in the load reduction is relevant is Milan. Figure 11 shows the comparison between those two controls in Milan.

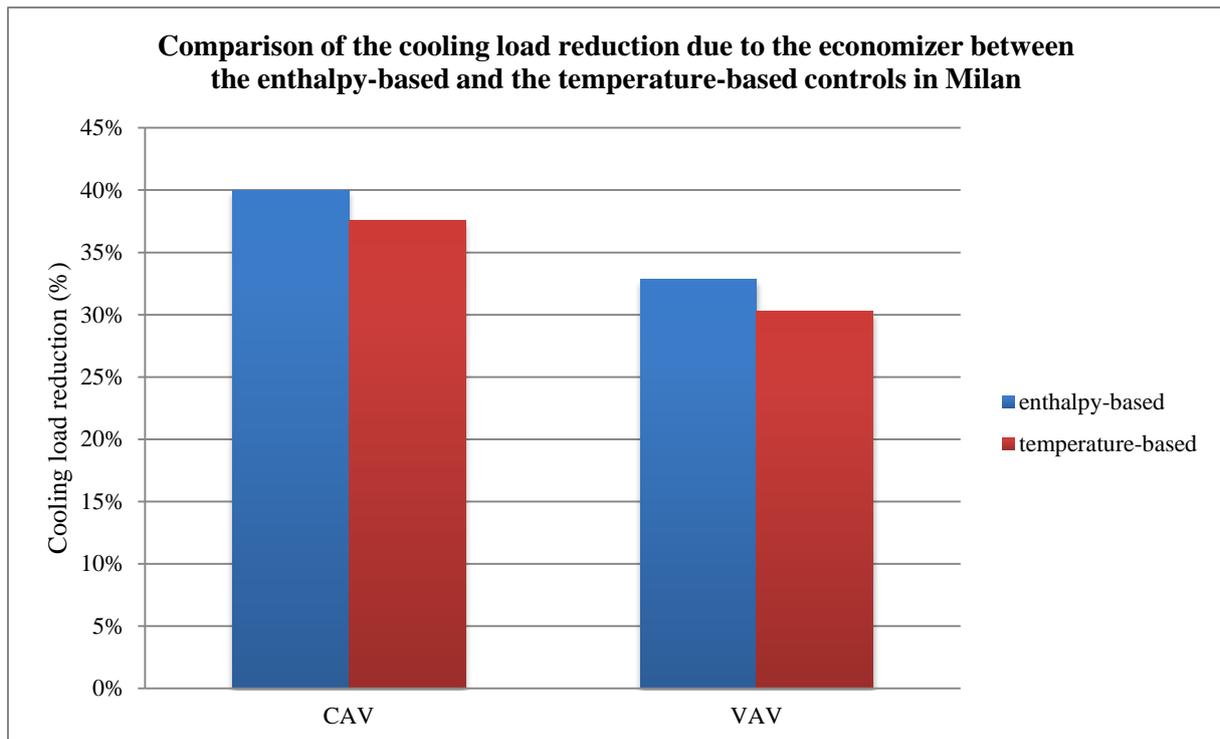


Figure 11: Comparison of the cooling loads reduction due to the economizer between the integrated enthalpy and temperature controls in Milan

However, the reduction is not so significant even in Milan. This is due to the fact that in the selected climates, the relation temperature/humidity does not vary so much. The result would be totally different in a humid, hot climate, such as a tropical one.

Consequently, to analyse the benefit of the use of an economizer in the load reductions, the integrated dry-bulb temperature control, system n°3, has been chosen because it is generally more accurate. Indeed, the integrated enthalpy control has a higher probability of sensor errors (it has four sensors against two for the integrated temperature control).

The reduction in the cooling load is presented in table 4 for the integrated dry-bulb temperature control. The percentages are relative: the difference in the cooling load provides by the economizer is reported relatively to the cooling load of the CAV or VAV system n°1. The energy saving is important in all locations. However, the colder the climate is, the higher the load reduction will be. At Kiruna, for instance, the cooling load is reduced by 95 % in the CAV system. To conclude, the use of an economizer is interesting even in warm climate such as Madrid (Mediterranean climate) and should definitely be used in cold climate such as oceanic (London), warm summer humid continental (Gothenburg) and continental subarctic (Kiruna) where the energy saving is between 70 and 95 %.

	Madrid	Milan	London	Gothenburg	Kiruna
CAV	44%	38%	78%	87%	95%
VAV	37%	30%	74%	84%	92%

Table 4: Cooling load reduction between systems n°1 and n°3 in CAV and VAV with heat exchanger

In order to have a clearer idea of the advantage of an economizer but on an economical point of view this time, an economic study has been performed in section 4.2.1.

One setting of the economizer, called cut-off temperatures, is to enable the use of the device only above and/or below a certain temperature, as explained in section 2.1. "Options of simulation".

Therefore, to evaluate if this setting should be used to prevent an increase in the load because of the economizer, a study has been performed and is presented below.

- Cut-off limit study

In some situations, air economizer is only allowed between specific outdoor air temperatures referred as “cut-off” temperatures. For the previous study, no cut-off temperatures were set, i.e. the cut-off temperatures were set to extreme values, which are -46°C and 66°C (HAP definition). The cut-off principle has been explained in a more detail way in section 2.2.1 “options of simulation”

However, cut-off limits are subject of interest. Thus, in a first time, the influence of the cut-off limits at Goteborg has been studied, and then at Milan. This last city has been selected because the difference between integrated enthalpy economizer and integrated dry-bulb temperature economizer was the most visible for this location. Indeed, setting cut-off temperature is useful when the sensors of the economizer are making mistakes.

Before presenting the results it must be clarify that the software set by itself a lower cut-off at 0°C to prevent any freezing in the system.

- Gothenburg:

By changing the cut-off limits of the economizer, the optimal temperatures for the cut-off can be found. These values represent the minimum and maximum outdoor air temperatures used by the economizer. The results are presented in Table 5 depending on the type of control and the type of ventilation.

	Control type	Lower cut-off ($^{\circ}\text{C}$)	Upper cut-off ($^{\circ}\text{C}$)
CAV	Enthalpy	0	27
	Temperature	0	26
VAV	Enthalpy	2	27
	Temperature	2	27

Table 5: Optimal cut-off temperature for CAV and VAV on systems n°2 and 3 in Gothenburg

The upper cut-off temperature is 27°C , which seems high since the supply air temperature is 18°C . However, the cooling set point, which represents the upper limit of the temperature interval where cooling is needed, is fixed at 27°C when the office is unoccupied. Thus, if the return air temperature is above 27°C and the outdoor air is at 27°C , it is useful to use the outdoor air even if it needs to be cooled.

However, if no cut-off is set the cooling load is the same than if the optimum cut-off defined above is set. Thereby, it is not possible to improve the performance of the economizer in Gothenburg by setting cut-off temperatures.

- Milan:

Milan’s climate is characterized by hot and humid summer. In such climates, the integrated-enthalpy economizer is usually preferred because humidity has a great importance on the air quality. Therefore, the upper cut-off can be useful to prevent an increase in cooling load because of the use of the economizer. To evaluate if it was the case in Milan, some simulations were run and the results are presented on figure 12 and 13 below. The figures represent the cooling load obtained depending on the upper cut-off temperature set.

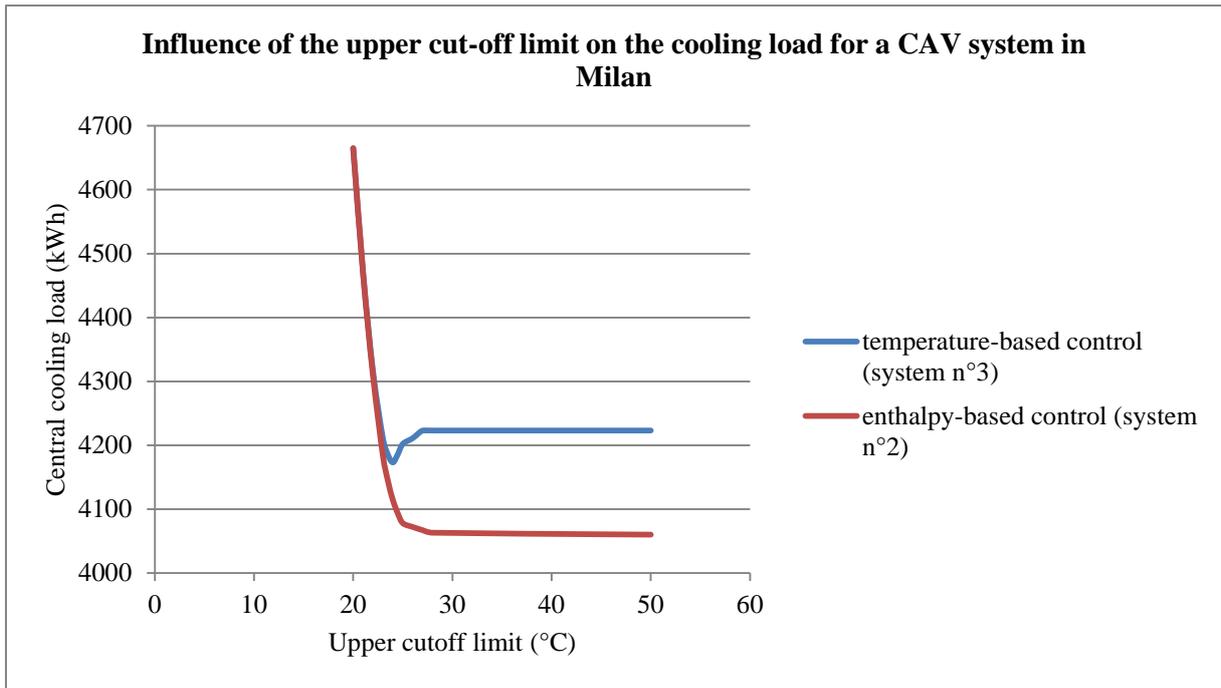


Figure 12: Influence of the use of an upper cut-off limit for CAV systems n°2 and n°3 in Milan

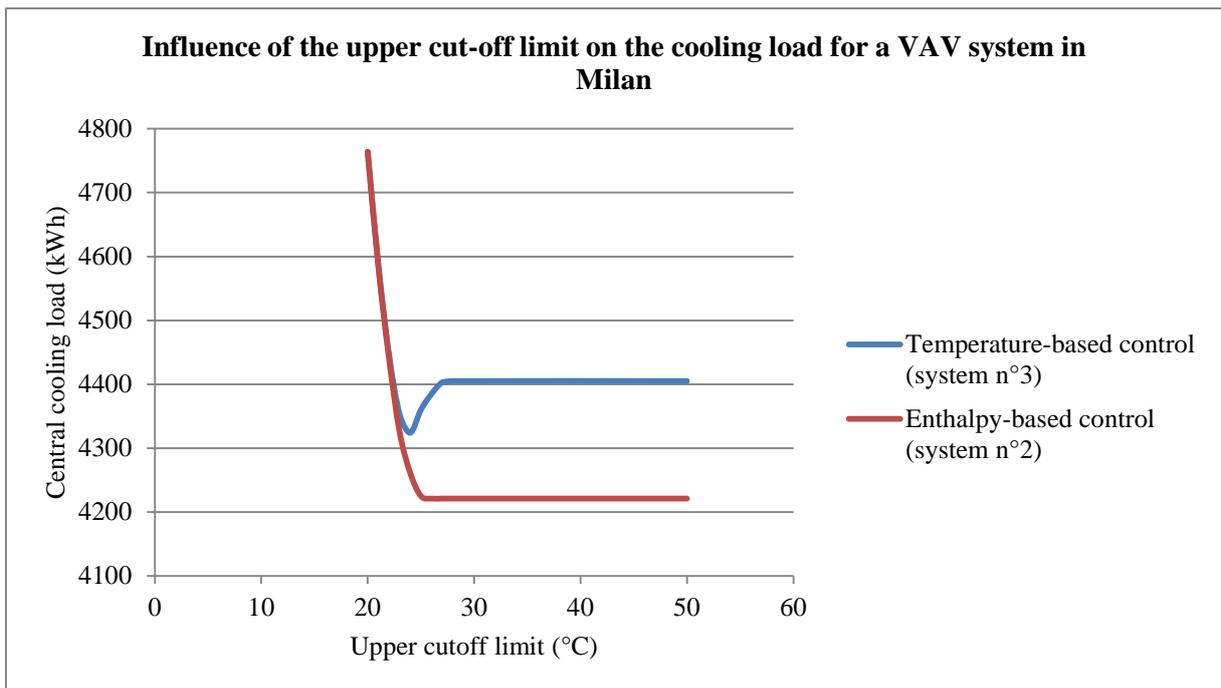


Figure 13: Influence of the use of an upper cut-off limit for VAV systems n°2 and n°3 in Milan

As the figures 12 and 13 above show, 38 kWh of cooling in CAV mode and 81 kWh in VAV mode can be saved by using an upper cut-off limit at 24°C for the integrated temperature economizer. That indicates a wrong control for this economizer. Indeed, at Milan, above the dry-bulb temperature of 24°C, the economizer should not be activated because using the outdoor air would increase the latent cooling coil load. Thus, in order to prevent this increase in the energy load, a upper cut-off of 24°C should be set if a temperature-based control is used or a enthalpy-based control should be chosen.

The results above show that in order to perform a higher energy efficiency of the ventilation system, the use of an economizer should be considered when designing the system. Moreover, in humid subtropical climate (Milan), attention should be paid to the type of control chosen and to the cut-off limits set.

However, the use of an economizer is not the only way to achieve energy savings: it can also be achieved by reducing the heating load. Therefore, the next part presents the contribution of the use of a heat exchanger.

4.1.2. Heat exchanger contribution

First of all, a heat exchanger can also have the reverse effect, i.e. cooling the supply air with the return air when the outside air is warmer than the return air. Therefore, a first study has been performed to determine if the heat exchanger brings any reduction in the cooling load. In order to do so, system n°3 and system n°7 were compared in CAV and VAV. The results for CAV and VAV were similar. Thus, only the results for CAV are presented here (Figure 14) and the results for VAV can be found in Appendix 7 on figure 45.

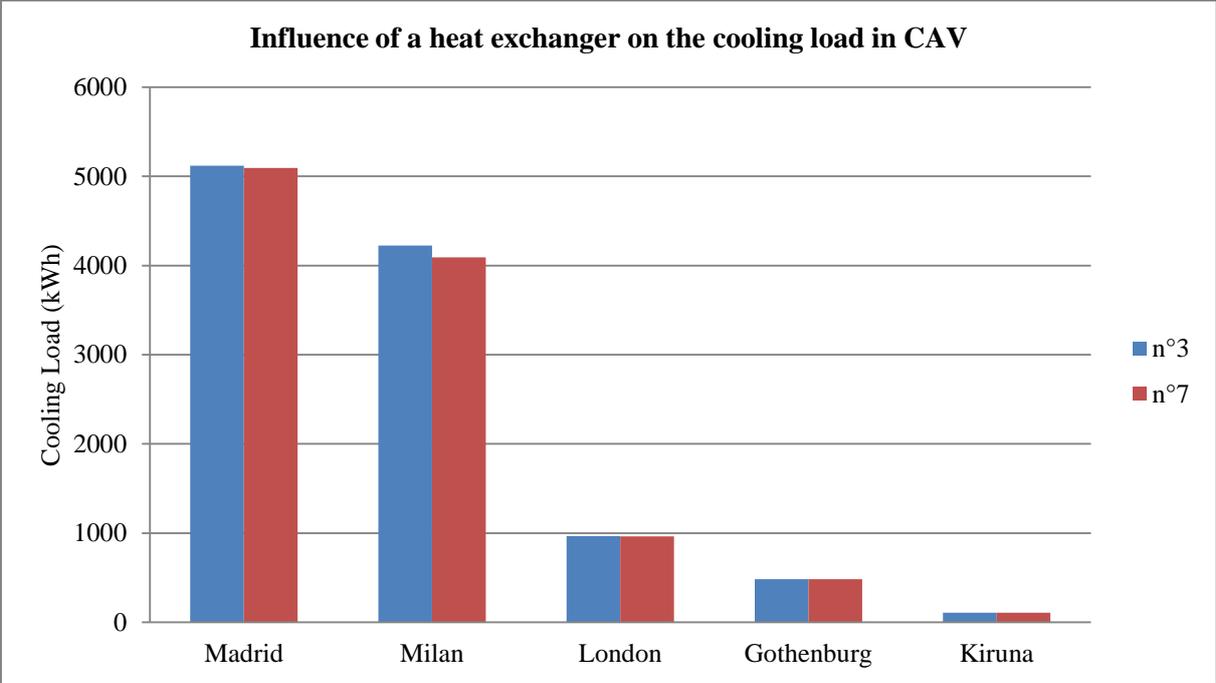


Figure 14: Influence of a heat exchanger on the cooling load in CAV for systems n°3 and n°7

On Figure 14, it can be seen that in rather cold climate (Kiruna, Gothenburg, and London), the heat exchanger doesn't contribute to reduce the cooling load significantly. However, in rather warm climate (Madrid and Milan), a cooling load reduction is observed. Yet, this difference is not huge: 26 kWh, corresponding to a reduction of 0.5 %, in Madrid and 132 kWh, corresponding to a reduction of 3 %, in Milan. Consequently, the choice of a heat exchanger should not be based on the cooling load reduction brought but rather on the heating load reduction, as presented in the study below.

For this study, concerning the heating load, Madrid is excluded from the study because no heating (figure 33 in appendix 5) or almost no heating (figure 38 in appendix 5) is required. So, the use of a heat exchanger is not relevant.

In order to see the impact of the heat exchanger, the reduction of heating load between the systems CAV and VAV n°1 and n°4, have been calculated and the results are presented in table 6. For the CAV system, independently of the location, the use of a heat exchanger brings a reduction of approximately 10% of the heating load. However for the VAV system, the load reduction is higher and presents some differences depending of the location. Indeed, the heat exchanger brings the most reduction in London where the load is almost divided by two. Thus the heat exchanger is more interesting in climate such as Milan or London for a VAV system. However, for all the locations, the reduction is significant and thus, the use of a heat exchanger should always be considered. However, the conclusion is only based on the load reductions, an in order to have a more complete view of the advantages of a heat exchanger, an economic study is presented in section 4.2.1.

	Milan	London	Gothenburg	Kiruna
CAV	11%	11%	10%	12%
VAV	47%	59%	32%	24%

Table 6: Reduction of the load between due to the heat exchanger for CAV system n°1/5

In this part and in the previous, results have been presented generally for the use of the two considered devices independently from the system use, i.e. CAV or VAV.

4.1.3. CAV and VAV comparison

CAV and VAV systems have different functioning behaviours and thus the influence of the use of a device on those systems can be different.

For a start, in table 4, the use of an economizer in a CAV system allows a higher reduction in the cooling load than with a VAV system. At the contrary, the use of a heat exchanger in a VAV system brings more heating load reduction than in a CAV system as shown in table 6.

Figure 15 presents a global comparison of the CAV and VAV system n°1 at each location. The figure represents the contribution of the supply fan and the cooling and heating loads. At Kiruna, the CAV system is globally more efficient than the VAV system while at Madrid, Milan, London, and Gothenburg it is the opposite. Thus, CAV system should be preferred in really cold climate and VAV system in the other cases.

In VAV, the cooling load is always smaller than in CAV. However, for the heating load it is the opposite. This confirms the choice of CAV in really cold climate to reduce the heating load and the choice of VAV system in rather warm climate to reduce the cooling load which is the most important one. This also explains why in Gothenburg the two systems are almost equivalent because the climate of this city is neither warm nor really cold.

This is coherent with the previous comparison of the two systems with heat exchanger or economizer. Indeed as the heating load is higher with a VAV system, it is logical that the use of a heat exchanger brings more reduction in relative percentage and vice-versa for the use of an economizer.

To comment quickly the supply fan consumption, it can be seen that the difference of consumption between CAV and VAV is significant for cold climate such as in Gothenburg and Kiruna. This result can be seen on Figure 15 for system n°1 and in appendix 8 for all the other systems on Figure 46-47-48 for systems n°2-5-6 respectively.

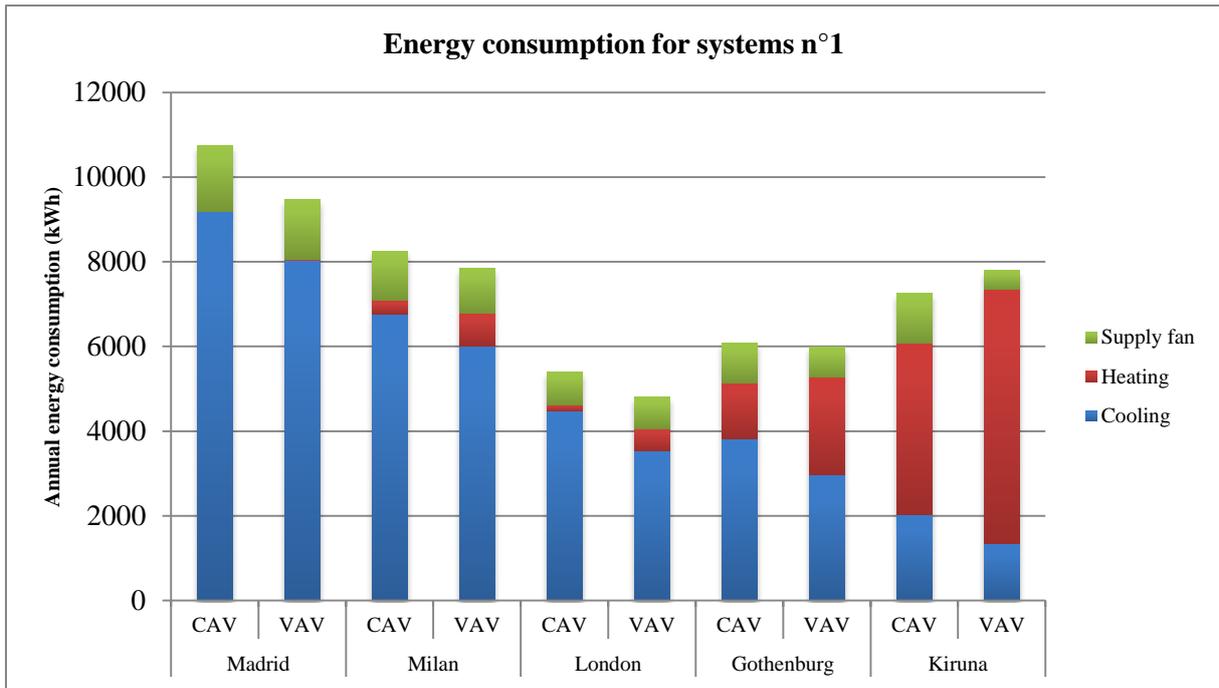


Figure 15: Comparison of the CAV and VAV systems in each chosen location

4.1.4. Supply fan energy consumption study

As described previously, the main advantage of using a VAV system rather than a CAV system is the reduction of the supply fan energy consumption. Indeed, in every city, the maximum supply airflow rate is 703 L/s in CAV, while it is 468 L/s in VAV. The design ventilation airflow rate is at 42 L/s in both situations.

The supply fan energy consumption for systems n°1 is compared in the different cities in the figure 16 below.

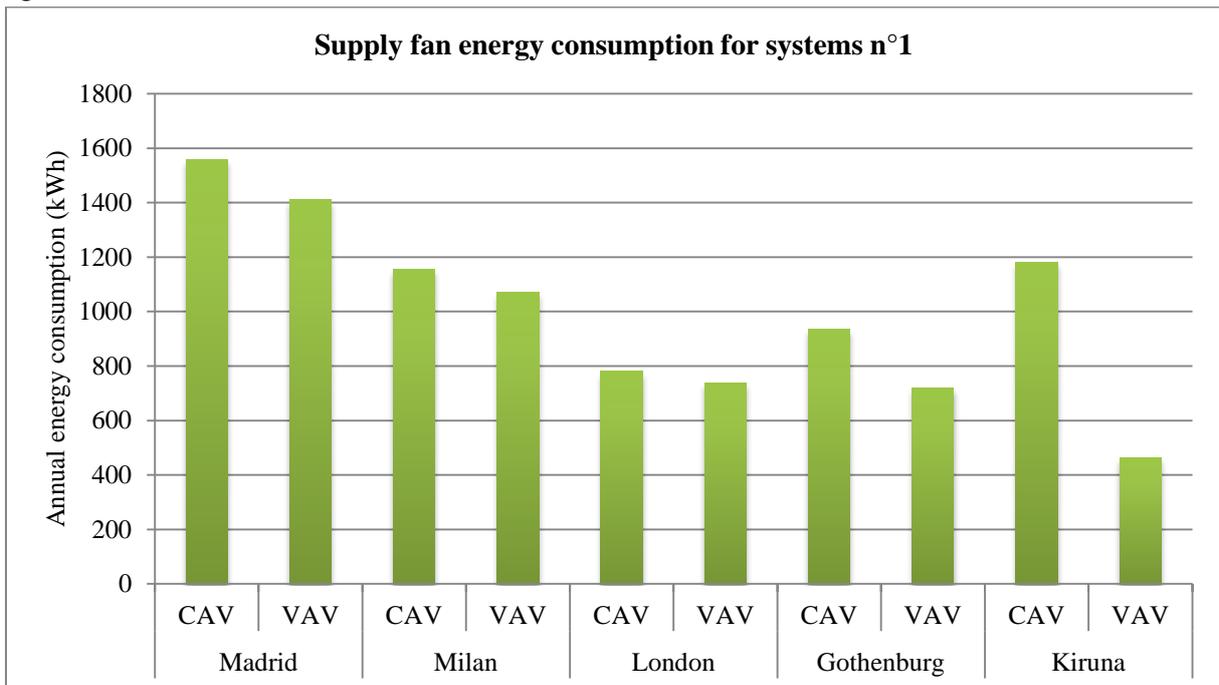


Figure 16: Supply fan energy consumption comparison for CAV and VAV system n°1

Madrid	Milan	London	Gothenburg	Kiruna
9%	7%	6%	23%	61%

Table 7: Supply fan energy consumption improvement due to VAV system compare to the CAV system

As shown in Table 7, the improvement is less than 10% for the three first cities, 23% for Gothenburg and 61% for Kiruna. In order to explain these results and to get a better understanding of the process, the supply fan consumption annual profiles has been drawn for London, Gothenburg and Kiruna and are presented in Figures 17, 18 and 19 respectively.

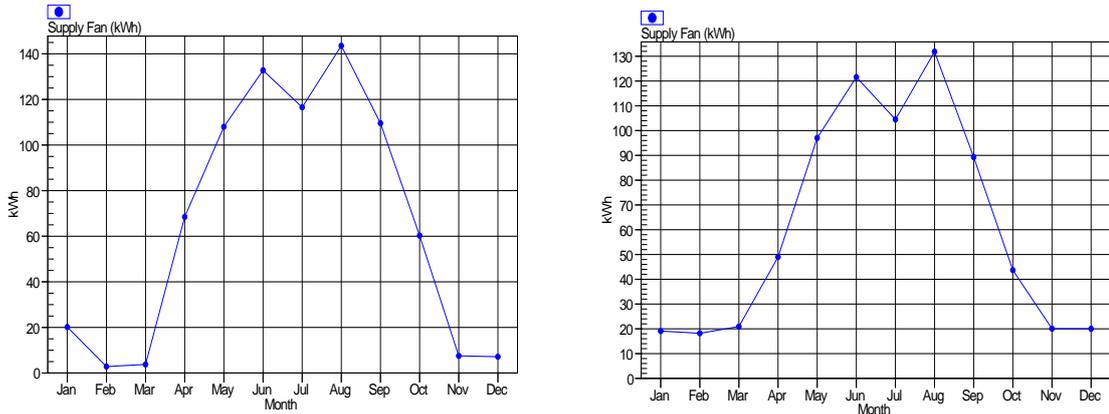


Figure 17: Supply fan consumption profile in London, CAV system on the left graphic and VAV system on the right one. Nota: the scale is not the same on both graphics.

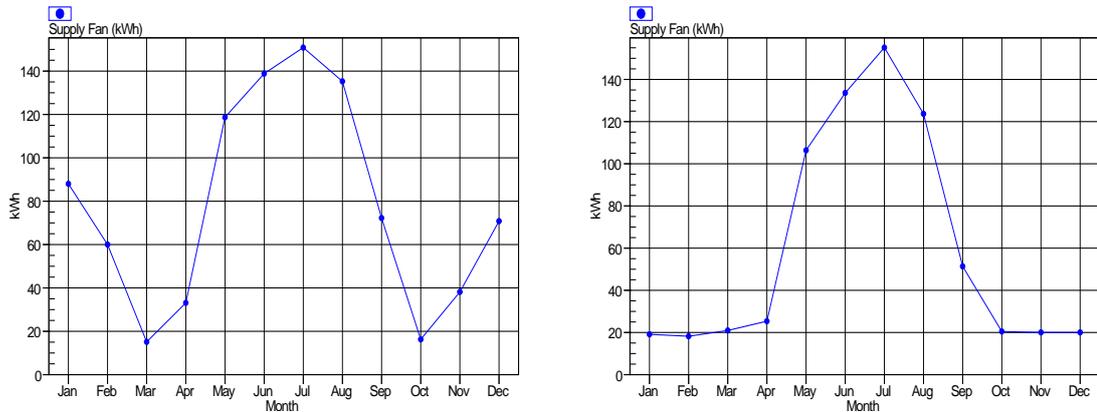


Figure 18: Supply fan consumption profile in Gothenburg, CAV system on the left graphic and VAV system on the right one.

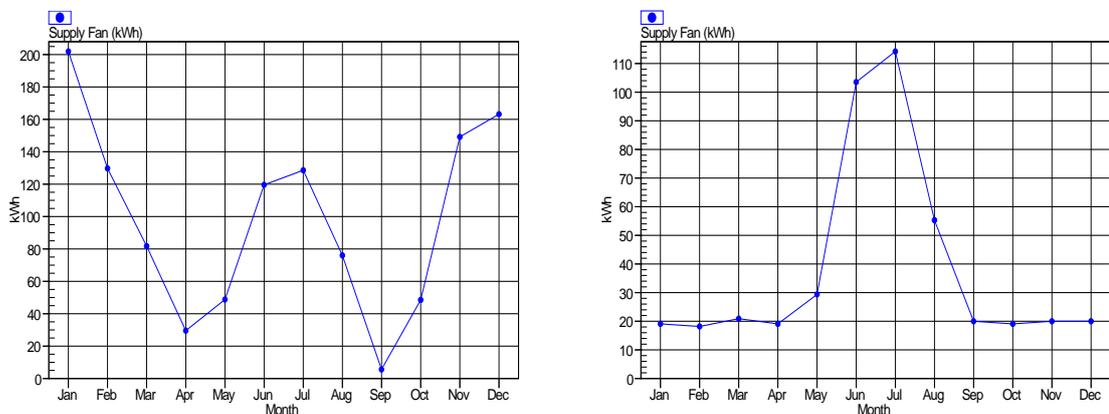


Figure 19: Supply fan consumption profile in Kiruna, CAV system on the left graphic and VAV system on the right one. Nota: the scale is not the same on both graphics.

According to the figures 17 to 19, the VAV systems have the same profile in the three cities. Indeed, the supply fan consumption is approximately constant during the “cold” period, which is more or less long according to the climate, and follows a “bell-shape” during the “hot” period of the year. Although the CAV systems profile follows also this “bell-shape”, with higher values, the main difference occurs during the “cold” period. Indeed, the colder the outdoor air, the higher the supply fan consumption. This difference is the main cause of the fan consumption reduction for VAV system, and it is strongly marked in Kiruna.

The explanation lies in the difference in the heating process in CAV and VAV. In CAV, heating is provided directly in the ventilation system, while in VAV it is provided in the room without any influence on the ventilation rate. Thus, when the outdoor temperature decreases, the heating demand increases, and, in order to supply the heating in the room, more supply fan energy is needed in CAV, while it remains constant in VAV.

Consequently, the global reductions in the table 7 above represent more the differences due to the heating devices than the real difference between CAV and VAV. The traditional difference between CAV and VAV, i.e. reduction in the fan consumption due to variable airflow volume, is better characterized by the difference of “central” shapes, i.e. during the “hot” period. Thereby, the real improvements in supply fan energy consumption due to VAV configuration are less than indicated above.

In order to correctly compare the consumption, CAV and VAV should use the same heating process, i.e. a heating coil directly in the ventilation system, which is possible in HAP for dual-duct and multiple zone systems but not for single zone systems in VAV.

4.1.5. Optimum system depending on the location

One of the aims of the study, as stated in section 2.1., is to define which system is appropriate depending on the climate. Thus, five cities have been chosen corresponding to the five main European climates. The characteristics of those climates are presented in section 2.2.2. After having performed the energy studies presented above in sections 4.1.1. to 4.1.3, it is now time to sum up those results and to relate them to the climates. However, it must be clarify than the following conclusions are only based on the energy consumption and not on an economic point of view. The energy cost study in section 4.2.1. draws conclusion regarding the cost efficiency of each system.

In this section, the total energy load includes the HVAC load but not the non-HVAC load such as electrical equipment and lighting because the electrical equipment consumption is not of interest of this study and does not depend on the ventilation system type.

- Mediterranean climate: Madrid

First of all, it has been concluded in section 4.1.2. that the use of a heat exchanger in Mediterranean climate is pointless regarding the fact that the cooling load is null (CAV) or really small (VAV). However, contrary to what can be thought in a first approach, the use of an economizer contributes to reduce the cooling load. Indeed, in Madrid, the cooling load reduction was of 44 % and 37 % for CAV and VAV system respectively. Finally, VAV system should be preferred because it reduces the cooling load more significantly.

To sum up, the optimal system in Mediterranean climate is a VAV system with an economizer (the type of control does not have any strong influence). By choosing this configuration a reduction of around 32 % of the total energy load can be hoped compared to a VAV system without economizer.

- Humid subtropical climate: Milan

In humid subtropical climate, regarding the devices to be selected for the ventilation system both a heat exchanger and an economizer should be considered in the design part. When the two devices are used, a CAV system is more efficient than a VAV system and should thus be preferred (cf. figure 48 in appendix 8). At Milan for the CAV system with a heat exchanger, a heating load reduction of 11 % was found. For the economizer, the situation is a bit tougher. Indeed, it appears that in that kind of climate, the economizer with temperature-based control is committing an error and activates the economizer when it should not be. Thus if the choice is made to install an economizer an enthalpy-based control should be preferred. In Milan, with that type of control in CAV, a reduction of 40 % of the cooling load was realized.

To summarize, the optimal system in a humid subtropical climate is a CAV system with both heat exchanger and economizer devices. The type of control for the economizer should be integrated enthalpy. With this configuration, a reduction of around 33 % of the total energy load can be hoped compared to a CAV system without those two devices.

- Oceanic climate: London

In oceanic climate, both a heat exchanger and an economizer should be used. Besides, a CAV system should be preferred to a VAV one (cf. figure 48 in appendix 8). At London, for a CAV system with a heat exchanger, a heat load reduction of 11 % was observed. For the economizer, the type of control does not have any significant influence. In London, in CAV, a cooling load reduction of 78 % was realized thanks to the economizer with dry-bulb control.

To sum up, in oceanic climate, CAV system with both economizer and heat exchanger should be designed. With this configuration, a reduction of around 65 % of the total energy load can be hoped compared to a CAV system without those two devices.

- Warm summer humid continental climate: Gothenburg

In warm summer humid continental climate, a heat exchanger and an economizer should be considered in the design part. Moreover, a CAV system should be preferred to a VAV system because even if the supply fan consumption is higher, this is balanced by a smaller heat exchanger load and heating load (cf. figure 48 in appendix 6). With the addition of a heat exchanger, a heating load reduction of 10 % was observed at Gothenburg. When a temperature-based economizer is used in the ventilation system a cooling load reduction of 87 % can be achieved at Gothenburg and a similar result is found with an enthalpy-based control.

To sum up, in a warm summer humid continental climate, CAV system with economizer and heat exchanger should provide the optimum energy efficiency for the ventilation system. With this configuration, a reduction of around 57 % of the total energy load can be hoped compared to a CAV system without those two devices.

- Continental subarctic climate: Kiruna

In continental subarctic climate, both heat exchanger and economizer should be implemented in the HVAC system. A CAV system should be preferred to a VAV system. Indeed, the increase in the fan consumption is largely balanced by a reduction in the heating load. For a CAV system with heat exchanger, a heating load reduction of 12 % is realized compared to the same system without heat exchanger. With the addition of a temperature-based economizer in a CAV system (without heat exchanger), the cooling load is reduced by 95 % compared to the CAV system without any of the two considered devices.

To summarize, in continental subarctic climate, CAV system with economizer (the type of control does not really matter) and a heat exchanger should be preferred. With this configuration, a reduction of around 32 % of the total energy load can be hoped compared to a CAV system without those two devices.

To conclude the energy study, the use of an economizer is strongly recommended, even in a Mediterranean climate, and can provide huge reduction, as in Kiruna with 95 % of reduction of the cooling load in CAV. Moreover, the integrated dry-bulb temperature control should always be preferred to the enthalpy one to prevent sensors mistake, except in humid subtropical climate where an enthalpy control should be used. The use of a heat exchanger is as well recommended in all the climates except in the Mediterranean one. Surprisingly, it can also be concluded that CAV system should be preferred to VAV system in all the climates, except the Mediterranean one, when the HVAC system uses both the heat exchanger and the economizer.

In the coming section, an energy cost study is performed to determine if the optimum system is as well the cheapest one according to the running costs.

4.2. Energy cost study

This energy cost study is split in two parts. The first one concerns the running costs in the different cities for the systems determined as more efficient in the previous part. The second part presents a comparative energy study between different types of energy in Gothenburg.

The software provides the annual energy costs under two categories and several sub-categories:

- HVAC costs: Cooling cost, heating cost, air system fan cost.
- Non-HVAC costs: Light cost, electric components cost.

Since non-HVAV costs are constant for one city independently of the ventilation system, they are not taken in account in the main study. However, they are presented for the best configurations in the form of a pie diagram in order to show the percentage of total cost of the non-HVAC part compared to HVAC costs.

4.2.1. Energy cost improvements for the different cities

In the part 4.1., the best ventilation configurations have been found for the five cities for both CAV and VAV systems. One of the aims of this study is to find out the impacts of those configurations on the annual energy costs of the building.

In order to perform this study, among the eight available configurations, one or two have been chosen for both CAV and VAV systems per city. The energy consumption costs of the selection have been studied in comparison with the ones for “classic” systems, i.e. CAV n°1 and VAV n°1.

In this part, the energy consumption costs are based on the electricity prices and the tax rates, which depend on the country. These values have been presented previously in the section 2.2.3. For this study, electrical resistance has been chosen as heating source and the cooling coil runs only with electricity. Even if it is not the most common case, it allows a preliminary view of the economical HVAC costs. The influence of the use of different energy sources has been performed for Gothenburg and is presented in section 4.2.2.

- Madrid

In Madrid, Mediterranean climate, due to a hot and dry climate, the heating demand is almost inexistent and consequently, the use of a heat exchanger is obviously inadequate. As described previously in section 4.1.5., the configuration n°3, i.e. a system with temperature-based economizer, seems the more appropriated. Thus, the cost study for this city has been performed for CAV and VAV systems n°3 and compare with the CAV and VAV systems n°1, as shown on figure 20.

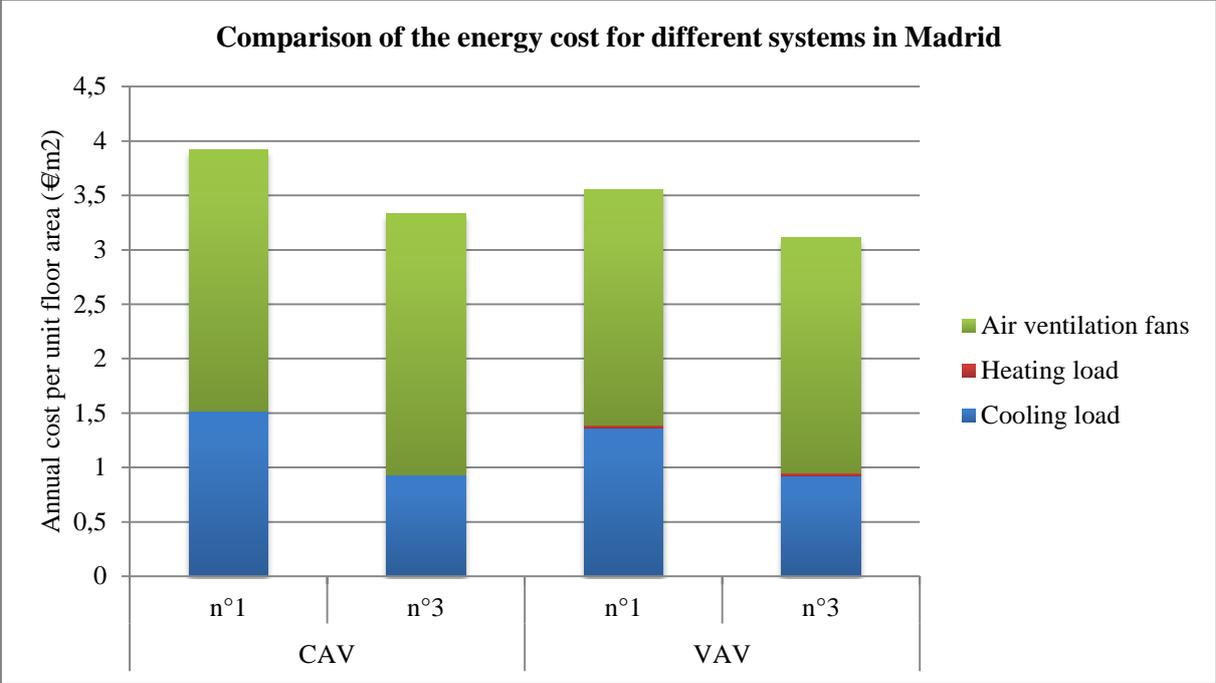


Figure 18: Energy cost for CAV and VAV systems n°1 and n°3 in Madrid

In CAV configuration, the cooling cost reduction is about 38% and about 32% in VAV configuration compared to the classic system. However, the air ventilation fans are costly, more than the double of the cooling costs. Consequently, an enhancement of the fans should also be envisaged.

According to those results, a VAV system with an economizer is the best economical option for the Mediterranean climate. This confirms the recommendation made in the energy study in section 4.1.5. for this climate. Besides, VAV systems are less costly for the air ventilation fans. This result fits with the definition of the VAV technology, which primarily aims to reduce the fans consumption. Below, on Figure 21, is presented the pie diagram with the cost repartition of each load for the VAV system n°3.

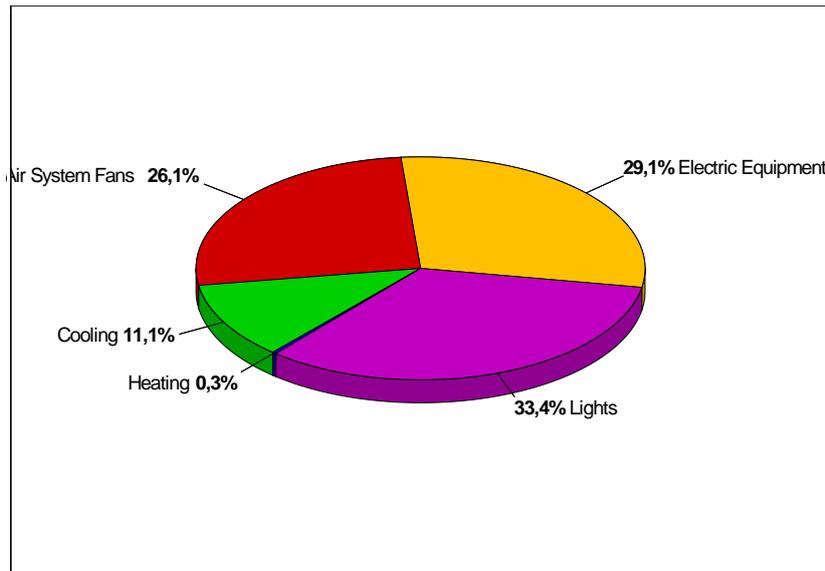


Figure 19: Energy costs repartition depending on the type of load for the VAV system n°3 in Madrid

This diagram shows that the non-HVAC load (electric equipment and lights) is more costly than the HVAC load. Thus it is as well important to reduce or to improve the non-HVAC equipment in order to reduce the energy costs. Figure 21 also shows that even in VAV, the fan running cost is important (26.1 %) and confirms the fact that the choice of the fan characteristics should be made carefully.

- Milan

In Milan, humid subtropical climate, due to the hot and humid summers, the enthalpy-based economizer is preferred. Also, since the heat exchanger allows a reduction of the heating load, configuration n°6, system with enthalpy-based economizer and heat exchanger, has been selected and compared with system n°1 for both CAV and VAV. Moreover, in order to see the influence of a heat exchanger, system n°2 has been simulated as well. The results of those simulations are presented below on Figure 22.

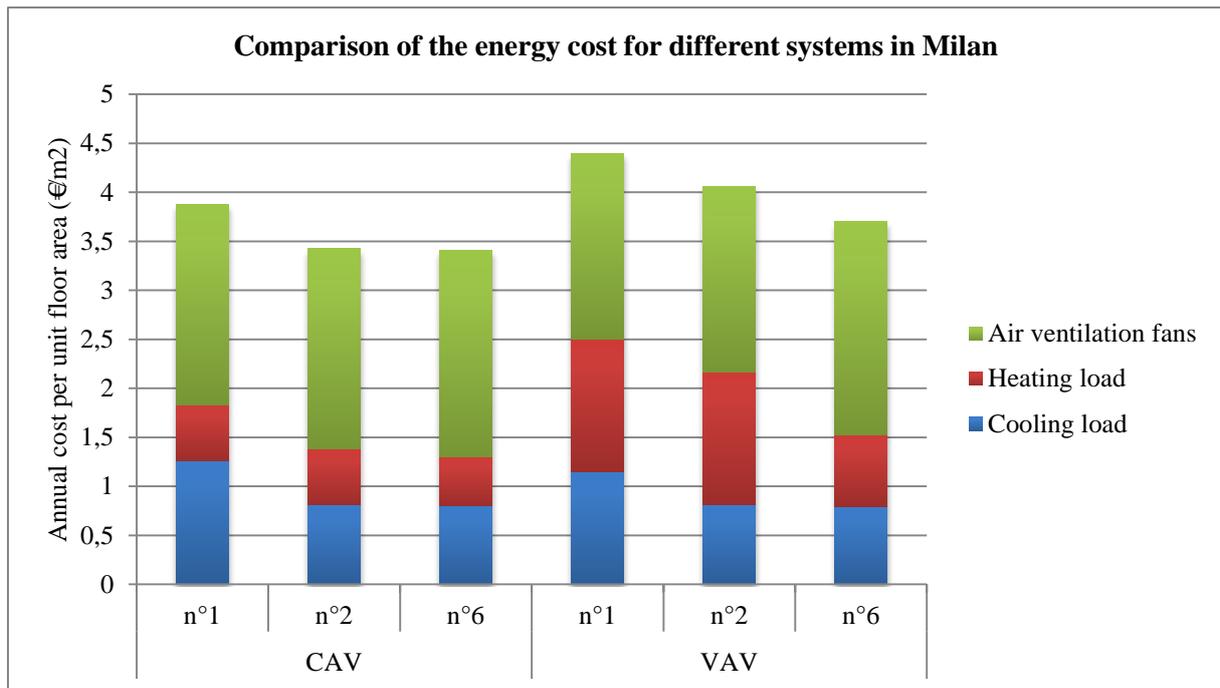


Figure 20: Energy cost for CAV and VAV systems n°1-2-6 in Milan

With system n°2, the economizer provides a reduction of the cooling cost of 36% in CAV, and 29% in VAV. However, in CAV configuration, the addition of a heat exchanger (system n°6) does not bring a significant total cost reduction. Consequently, the investment in this type of heat exchanger (rotating wheel) is not recommended in this configuration if an economic advice is asked. By contrast, in VAV, it provides a reduction of the heating cost of 46%. Although the cooling and air ventilation fans costs are lower in VAV, the total cost is higher than in CAV. This is due to the difference of heating technology. In CAV systems, a heating coil provides the heating directly in the ventilation system, while baseboards provide it in the rooms in VAV systems. The baseboards configured in this study are less efficient and more costly than the heating coil. A new study with more efficient heating units for VAV systems should be done in order to get better results for the heating costs. Another interesting fact is the increase of the air ventilation fans by adding a heat exchanger, especially in VAV (15%).

To sum up, a CAV system with enthalpy-based economizer is the best option. However in the energy study, the less consuming system was a CAV system with an enthalpy-based economizer and a heat exchanger. Thus, if an energy target has been fixed, in order to have a certification for instance, it can be useful to use a heat exchanger.

Below, on Figure 23, is presented the pie diagram with the cost repartition of each load for the CAV system n°2.

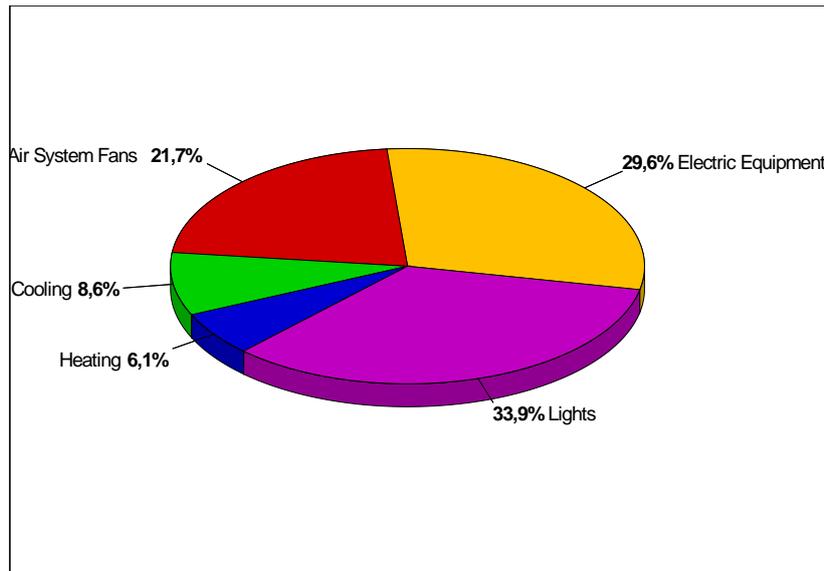


Figure 21: Energy costs repartition depending on the type of load for the CAV system n°2 in Milan

As in the case of Madrid, the pie diagram above shows that the non-HVAC load is more costly than the HVAC load. Thus it is as well important to reduce or to improve the non-HVAC equipments in order to reduce the energy costs.

- London

In London, the optimal energy system was determined in section 4.1.5. as a CAV system with heat exchanger and temperature-based economizer. The cost simulation was consequently run for CAV and VAV systems n°1-3-7 and the results are presented in figure 24 below.

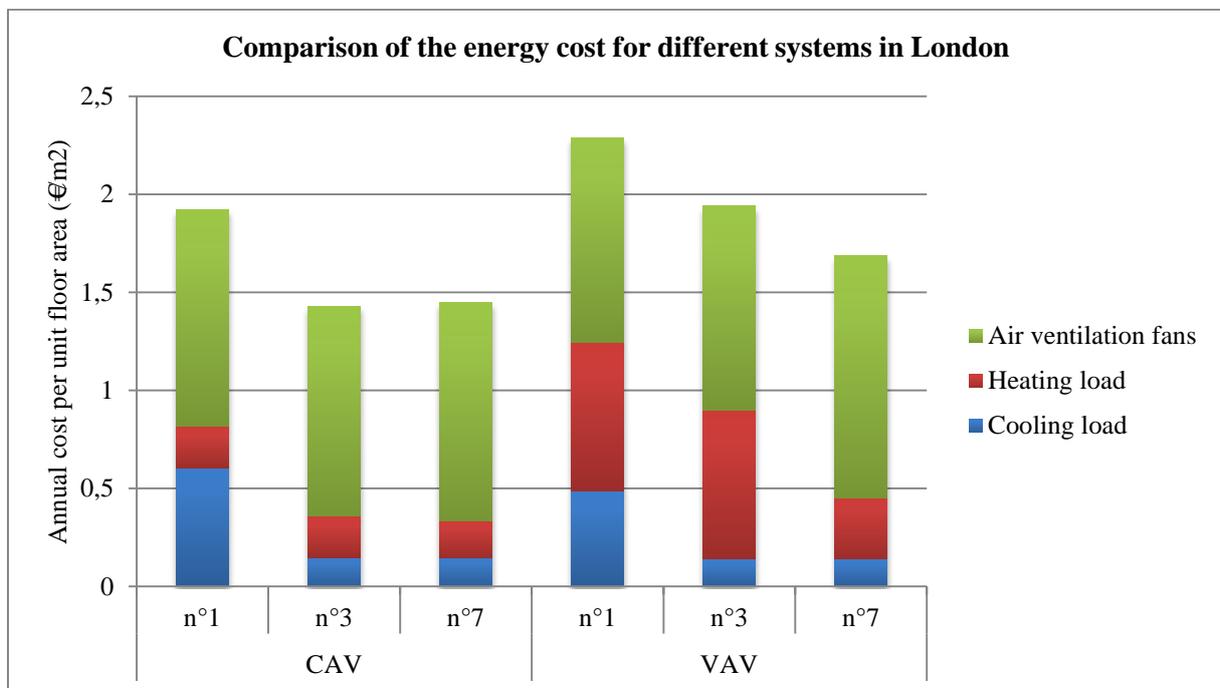


Figure 22: Energy cost for CAV and VAV systems n°1-3-7 in London

Figure 24 shows clearly that the CAV system is cheaper than the VAV one and thus should be preferred. The use of the heat exchanger decreases the running cost of the heating load but increases the cost of the fans. Thus a small increase in the total cost is observed with the use of a heat exchanger. Consequently, economically speaking, the heat exchanger is not recommended in London. To sum up, the CAV system with temperature-based economizer is the cheapest one. Moreover, the cooling cost reduction is 75% in CAV and 71% in VAV. Thereby, the use of the economizer is strongly recommended.

Below, on Figure 25, is presented the pie diagram with the cost repartition of each load for the CAV system n°3.

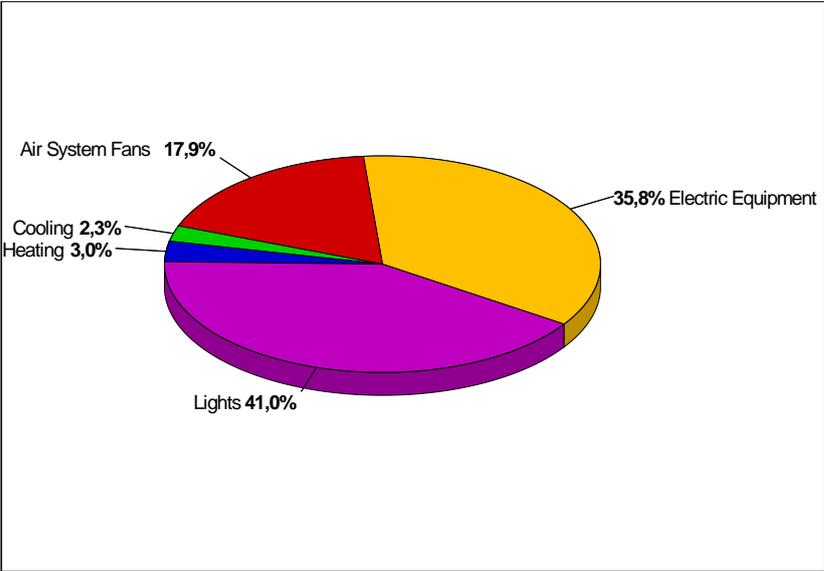


Figure 23: Energy costs repartition depending on the type of load for the CAV system n°3 in London

The pie diagram above shows that the non-HVAC load is more costly than the HVAC load. Thus it is as well important to reduce or to improve the non-HVAC equipments in order to reduce the energy costs.

- Gothenburg

In Gothenburg, due to the cold climate, configuration n°7 (system with temperature-based economizer and heat exchanger) has been defined as preferable in the energy study section 4.1.5. Moreover, as the climate is cold, the heat load reduction thanks to the heat exchanger is huge. Thus, the influence of the heat exchanger on the cost, in order to determine whether or not the use of this device is economically relevant, has not been done. Figure 26, below, presents the results for CAV and VAV systems n°1 and n°7.

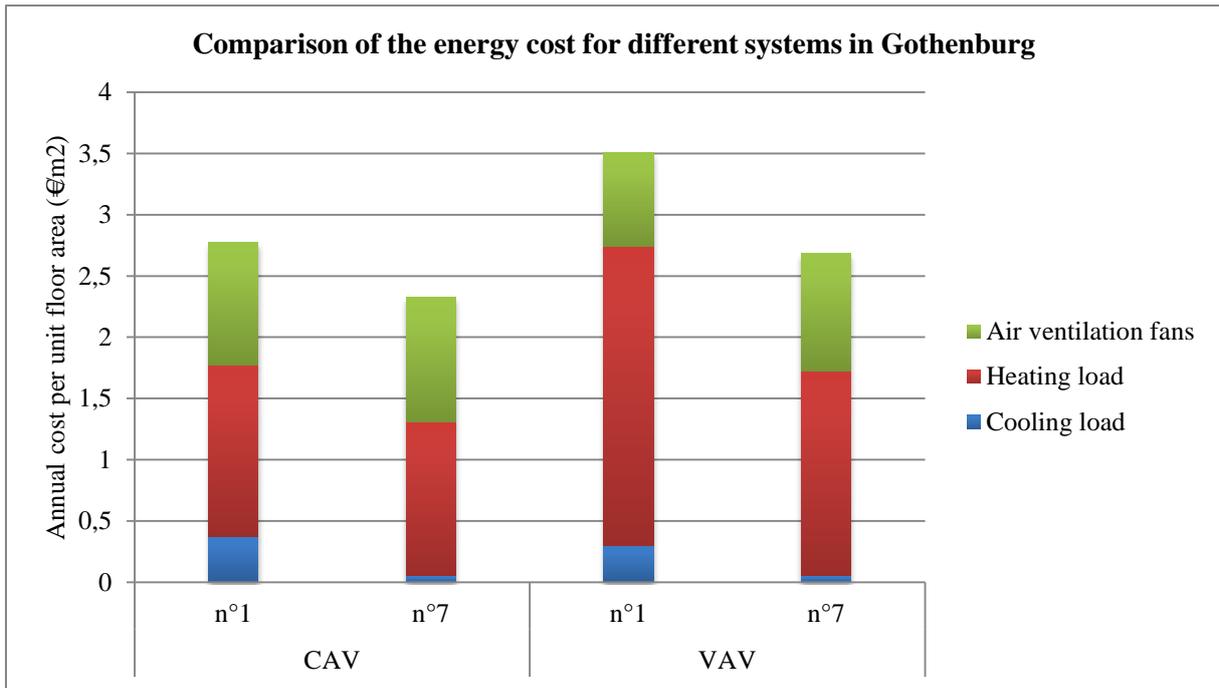


Figure 24: Energy cost for CAV and VAV systems n°1-7 in Gothenburg

On Figure 26, it is clearly seen that with an economizer, the cooling costs become almost negligible. Consequently, the use of an economizer is economically strongly recommendable. On another hand, the cost for heating are substantial and it would be interesting to find a way to improve the heating system. Investment in heat exchanger technologies with a higher efficiency is recommended. As concluded in section 4.1.5. with energy consumption consideration, the CAV system n°7 is the best economical option.

Below, on Figure 27, is presented the pie diagram with the cost repartition of each load for the CAV system n°7.

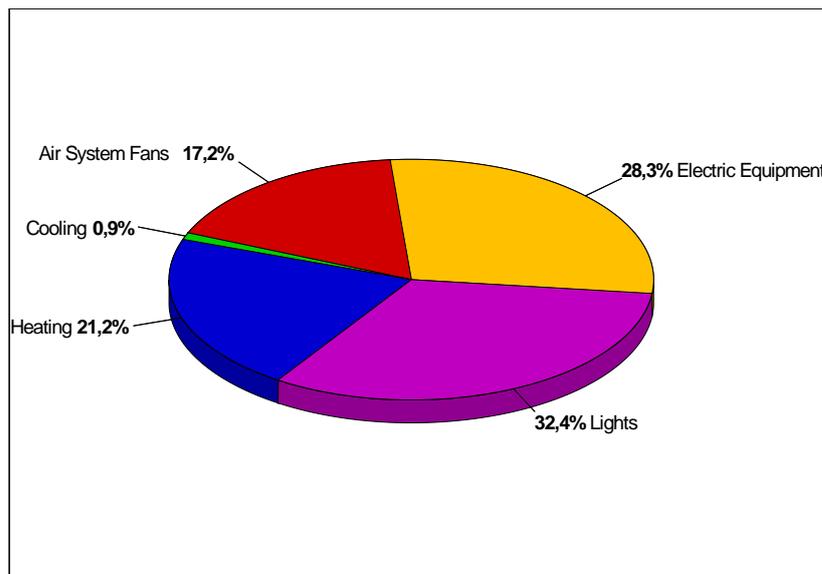


Figure 25: Energy costs repartition depending on the type of load for the CAV system n°7 in Gothenburg

The pie diagram above shows that the non-HVAC load is more costly than the HVAC load. Thus it is as well important to reduce or to improve the non-HVAC equipments in order to reduce the energy costs.

- Kiruna

In Kiruna, according to the energy consumption study, the best option is to use an economizer and a heat exchanger. Thus CAV and VAV systems n°1 and n°7 have been compared in this study and the results are presented on Figure 28. During this HVAC cost study, the VAV proportional control has been tried at all locations and it has been observed that in Kiruna, this type of VAV presents an interest. Indeed, as shown on Figure 28, with VAV proportional control, the HVAC cost are similar to the one with a CAV system.

On Figure 28, it can be observed that the cooling costs are negligible when an economizer is used. However, the presence of the heat exchanger does not provide an important reduction of the heating costs, which are still huge with 43.5 % of the total energy costs as shown in Figure 29 below. The cheapest system is therefore a CAV system with heat exchanger and economizer, which concurs with the recommendation made according to the energy study in part 4.1.5.

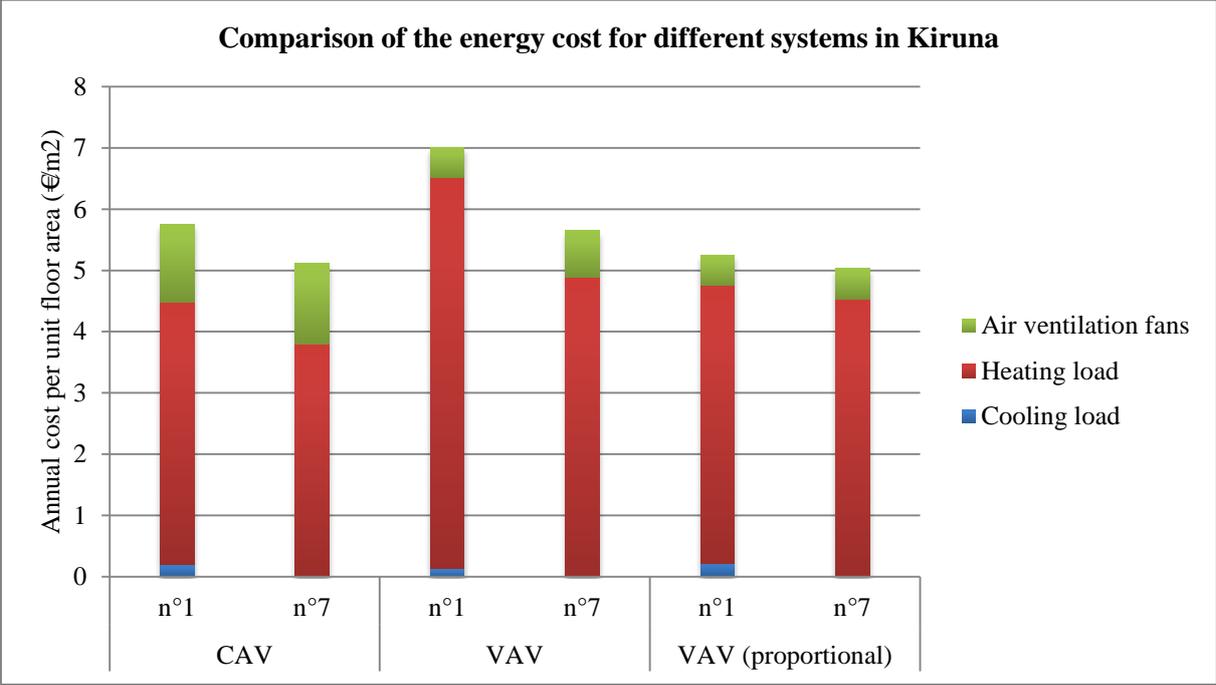


Figure 26: Energy cost for CAV, constant VAV and proportional VAV systems n°1-7 in Kiruna

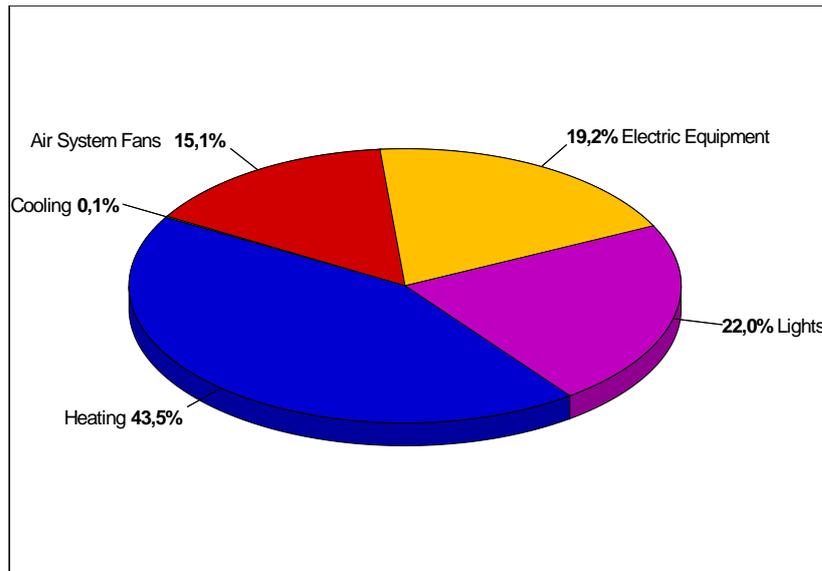


Figure 27: Energy costs repartition depending on the type of load for the CAV system n°7 in Kiruna

On Figure 29, which presents the pie diagram with the cost repartition of each load for the CAV system n°7, the results observed are different from the one in the four others cities. Indeed, the total HVAC load represents 58.7 % of the total costs. This is due to the high heating load necessary in this continental subarctic climate.

- Summary of the energy cost study

In order to have a global point of view about the best economical improvements, the following Figure 30 compares the “classic” system with the best economical option defined previously, for each city of the study.

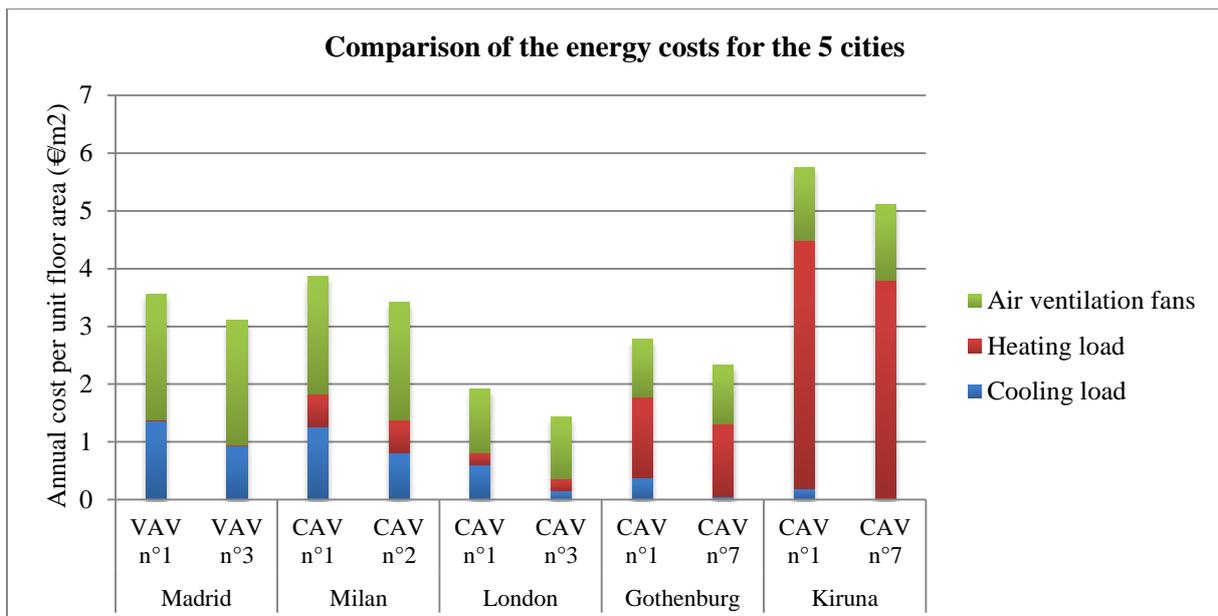


Figure 28: Comparison of the energy cost between system n°1 and the optimal economic option in each city

As it is shown in the figure 30, although the cooling cost or the heating cost can be reduced, the air ventilation fans cost is always substantial. Thereby, improvements of this device efficiency have to be realized in order to have better performance and thus less cost.

Besides, HVAC annual costs are very different between the studied cities. Indeed, it is only around 1.5 €/m² in London, while it is more than 5 €/m² in Kiruna. Thus, it may be easier to reduce the costs in Kiruna than in London.

The economic recommendations according to the choices in the ventilation system type and devices match the recommendations based on the energy study (section 4.1.5.).

The study below has not taken in account the different possibilities for the energy source. Indeed, heating and cooling costs depend mainly on the energy source used. Thus, in the coming part, other sources have been considered, such as hot water.

4.2.2. Influence of the energy source on the cost at Goteborg

This study has been restricted to Gothenburg because the differences between the prices of the different energy types are similar in the different countries. In Gothenburg, it has been determined in the two previous studies, in sections 4.1.5 and 4.2.1, that the use of both economizer and heat exchanger is recommended. Consequently, for both CAV and VAV, the influence of the use of different energy sources for heating has been studied for systems n°1 and n°7. In HAP, the CAV configuration allows more types of heating source than the VAV one. Different cooling sources, provided by different equipment type, as chilled water air handling unit, are not studied.

Heating options are:

- Electrical resistance: CAV and VAV systems.
- Hot water: CAV and VAV systems.
- Combustion of natural gas: CAV system.
- Combustion of oil fuel: CAV system.

- Influence of the heating source

Based on the system CAV n°1, the annual heating costs for four sources are presented in Figure 31 below.

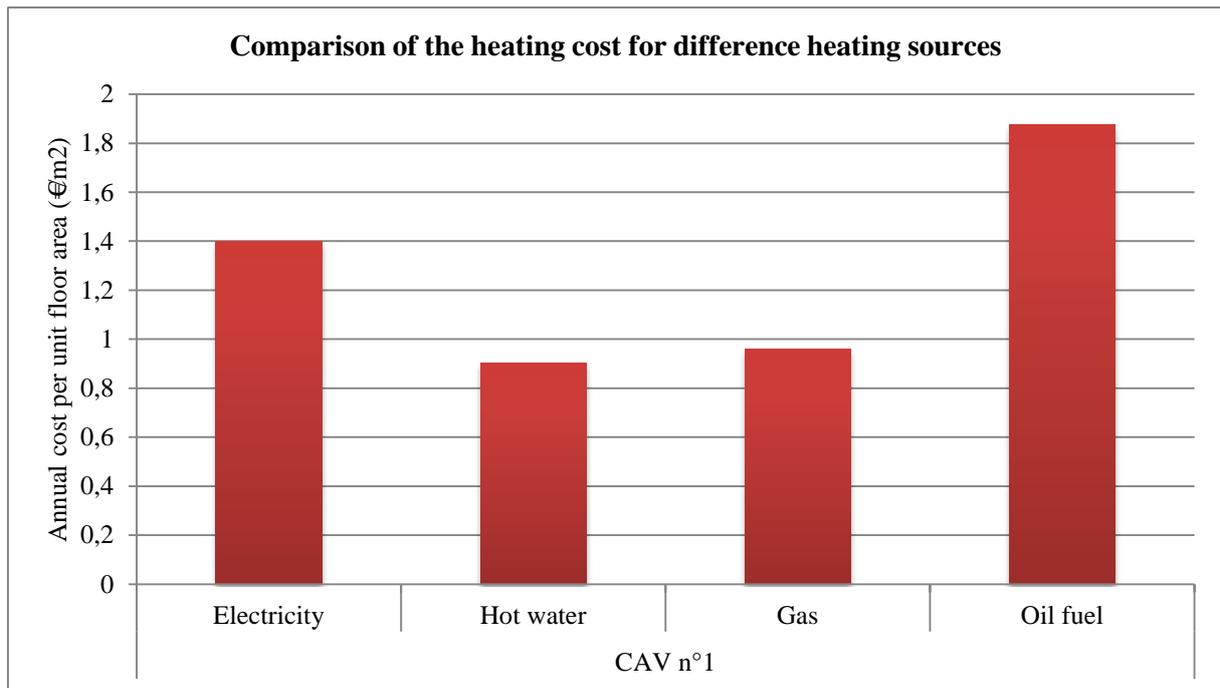


Figure 29: Comparison of the heating cost for four different energy sources for CAV system n°1 in Gothenburg

As shown on the figure 31, the electrical resistance use is not the cheapest way to heat the building. Indeed, both hot water from district heating and combustion of natural gas provide a lower annual heating cost. On another hand, combustion of oil fuel is the most costly process, probably due to the actual high price of this energy. The hot water has the lowest heating cost. This hot water is provided by district heating. This source is more common for residential building and is not widely spread in Europe, even if quiet common in Sweden. However, this type of energy production tends to spread in all the countries and to supply more and more the industry and services sectors. This is due to the fact that it is cheaper than the other energy and most of the time more sustainable.¹⁸

On figure 32, the total HVAC cost in Gothenburg is presented for CAV and VAV systems n°1 and n°7. “Electric” means that both the cooling and the heating energy sources are based on electricity. “Mix” means that the cooling is provided by an electric process and the heating source is hot water from district heating, the cheapest heating source according to the study above. This figure put forward the fact that the cheapest options in Gothenburg is the CAV with a heat exchanger and an economizer ventilation system with electricity as cooling energy source and hot water from district heating as heating energy source. In addition, it can be noticed that the cooling load is reduced to almost nothing thanks to the use of an economizer.

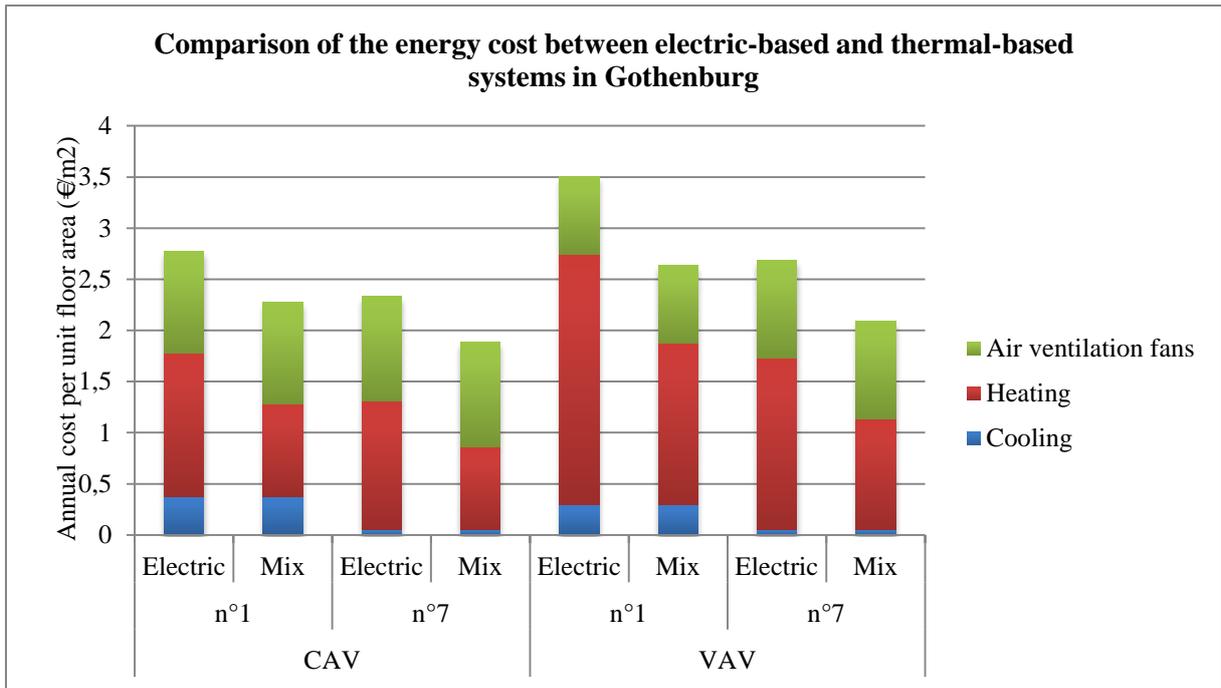


Figure 30: Energy cost comparison between an electric-based and thermal-based source for the heating energy supply for CAV and VAV systems n°1 and n°7 in Gothenburg

5. Conclusion

The main interest of the study concerns the economizer contribution in a HVAC system. The study shows that the energy saving due to an economiser is important for all locations. However, the colder the climate is, the higher the load reduction will be. Consequently, an economizer should definitely be used in cold climate such as oceanic climate (London), warm summer humid continental climate (Gothenburg) and continental subarctic climate (Kiruna) where the energy saving is between 70 and 95 %. However, contrary to the common wisdom, the use of an economizer is interesting even in warm climate such as Mediterranean climate (Madrid).

The economizer presents three types of control, integrated temperature or enthalpy based control and non-integrated temperature-based control, that have been compared in this report. Among those three different controls, the non-integrated one should be avoided, while the two others give approximately the same performances, except at Milan. Indeed, in humid subtropical climate (Milan), the enthalpy-based economizer should be preferred. A particular attention should also be given to the cut-off limits, which can avoid the control errors. However, the integrated dry-bulb temperature control should be generally chosen because this control is more accurate due to the four sensors needed for the enthalpy control against two for the integrated temperature control.

Concerning the heat exchanger contribution, the reduction in the heating load is significant, except for Madrid where the heating demand is inexistent or really small. Therefore the use of a heat exchanger should always be considered, except in Mediterranean climate where a closer look to the estimate heating load should be taken. For the CAV system, the use of a heat exchanger brings a reduction of approximately 10% of the heating load, while, for VAV systems, the load reduction is higher and presents some differences depending on the location. Indeed, the heat exchanger brings the higher reduction at London where the heating load is almost divided by two. Thus the heat exchanger is more interesting in climate such as humid subtropical or oceanic for a VAV system. Although, the heat exchanger provides reduction of the heating loads, it can also slightly reduce the cooling load, as in Madrid and Milan.

In the HVAC cost study, the conclusions drawn were similar to the one of the energy load study, except in Milan and London. Indeed in those two cities, the use of a heating exchanger was not interesting for a cost reduction. However, the consideration of a heat exchanger should always be done in the design part for those two climates, i.e. humid subtropical and oceanic climates, because the energy reduction is interesting. Thus depending on the motivation of the building's owner, i.e. energy saving or costs saving related, the use of a heat exchanger may or may not be subject of interest.

To sum up, for each city of the study, the best configurations recommended according to the performed studies are presented in the table 8. These conclusions are only valid for the geographical zones of the study, i.e. Europe, and for locations with similar behaviours than the five cities because in a same climate, the weather conditions can present some variations. The "Yes/No" means that a closer look should be taken in the design part to the selection of an economizer or not, and in those locations the type of heat exchanger should rather be oriented toward one without input power requirement such as an air-to-air or heat pipe heat exchangers.

Climate	Mediterranean	Humid subtropical	Oceanic	Warm summer humid continental	Continental subarctic
City	Madrid	Milan	London	Gothenburg	Kiruna
CAV or VAV	VAV	CAV	CAV	CAV	CAV
Economizer control	Temperature	Enthalpy	Temperature	Temperature	Temperature
Heat-exchanger	No	Yes/No	Yes/No	Yes	Yes
System	VAV n°3	CAV n°6	CAV n°7	CAV n°7	CAV n°7

Table 8: Recommended configuration based on energy loads and energy costs study

From the economic study, it can be concluded that several types of heating sources are profitable. Indeed, heating by combustion of natural gas or by hot water from district heating provide notable reductions of the heating costs compare to electric or fuel sources. However, in a sustainable point of view, the recommendation is the preference for district heating if this solution is available.

In addition, the study has as well disclosed some other possible improvements. Replacing the constant control in VAV by a proportional one can reduce the heating costs in cold climates. Also, architects and engineers should be aware that the internal loads constitute often the most energy/cost consuming part of the building consumption and thus some improvements are as well possible in that area.

6. Limits and further investigations

In this study, the quality of the indoor air has not been considered. This can be a problem for instance when a huge part of the return air is recycled. In that case some filters should be added and thus the pressure drop can increase. However, in air based HVAC system, the rate at which the air is circulated is in most of the case higher than the one needed to remove the contaminant from the room. In that case, the indoor air quality is not an issue anymore.¹⁹

For the cost calculation study, the comparison has been made between different types of energy source and between different types of ventilation equipment. However, due to the difficulty to find prices from manufacturer for the specific studied space and because of the variation of the HVAC equipment characteristic, the costs for investment have not been taken account.

An improvement of the study can be regarding the environmental load. Indeed, it seems likely that in the coming year, a dioxide de carbon tax will be in application and thus some of the energy sources such as fuel or electricity maybe not profitable at all compare to cleaner energy such as district heating or cooling.

7. Appendix

Appendix 1: Summary of the setting of the VAV system in HAP

1. General Details:

Air System Name VAV-HX-E-NIT
 Equipment Type Packaged Rooftop Units
 Air System Type VAV
 Number of zones 1

2. System Components:

Ventilation Air Data:

Airflow Control Constant Ventilation Airflow
 Ventilation Sizing Method Sum of Space OA Airflows
 Unocc. Damper Position Closed
 Damper Leak Rate 0 %
 Outdoor Air CO2 Level 400 ppm

Economizer Data:

Control Non-integrated dry-bulb control
 Upper Cut-off 66,0 °C
 Lower Cut-off -46,0 °C

Ventilation Reclaim Data:

Reclaim Type Sensible and Latent Heat
 Thermal Efficiency 70 %
 Input kW 0,120 kW
 Schedule JFMAMJJASOND

Central Cooling Data:

Supply Air Temperature 18,0 °C
 Coil Bypass Factor 0,100
 Cooling Source Air-Cooled DX
 Schedule JFMAMJJASOND
 Capacity Control Constant Temperature - Fan On

Supply Fan Data:

Fan Type Forward Curved with variable speed drive
 Configuration Draw-thru
 Fan Performance 1,2 kW

% Airflow	100	90	80	70	60	50
% kW	100	91	81	72	61	54

% Airflow	40	30	20	10	0
% kW	46	40	33	27	21

Duct System Data:

Supply Duct Data:

Duct Heat Gain 0 %
 Duct Leakage 0 %

Return Duct or Plenum Data:

Return Air Via Ducted Return

3. Zone Components:

Space Assignments:

Zone 1: Zone 1	
room_angle_EN	x1
room_angle_ES	x1
room_angle_WN	x1
room_angle_WS	x1
room_milieu_N	x1
room_milieu_S	x1

Thermostats and Zone Data:

Zone	All
Cooling T-stat: Occ.	24,5 °C
Cooling T-stat: Unocc.	27,0 °C
Heating T-stat: Occ.	20,5 °C
Heating T-stat: Unocc.	17,0 °C
T-stat Throttling Range	1,00 °K
Diversity Factor	100 %
Direct Exhaust Airflow	0,0 L/s
Direct Exhaust Fan kW	0,0 kW
Thermostat Schedule	thermostat_sch
Unoccupied Cooling is	Available

Supply Terminals Data:

Zone	All
Terminal Type	VAV box
Minimum Airflow	7,00 L/s/person

Zone Heating Units:

Zone	All
Zone Heating Unit Type	Baseboard, room T-stat control
Zone Unit Heat Source	Electric Resistance
Zone Heating Unit Schedule	JFMAMJJASOND

4. Sizing Data (Computer-Generated):

System Sizing Data:

Hydronic Sizing Specifications:

Chilled Water Delta-T	5,6 °K
Hot Water Delta-T	11,1 °K

Safety Factors:

Cooling Sensible	0 %
Cooling Latent	0 %
Heating	0 %

Zone Sizing Data:

Zone Airflow Sizing Method	Peak zone sensible load
Space Airflow Sizing Method	Individual peak space loads

5. Equipment Data

Central Cooling Unit - Air-Cooled DX

Design OAT	35,0 °C
Equipment Sizing	Auto-Sized
Capacity Oversizing Factor	0 %
ARI Performance Rating	3,22 EER
Conventional Cut-off OAT	12,8 °C
Low Temperature Operation	Used
Low Temperature Cut-off OAT	-17,8 °C

Appendix 2: Summary of the setting of the CAV system in HAP

1. General Details:

Air System Name CAV_HX-E_NIT
 Equipment Type Packaged Rooftop Units
 Air System Type Single Zone CAV
 Number of zones 1

2. System Components:

Ventilation Air Data:

Airflow Control Constant Ventilation Airflow
 Ventilation Sizing Method Sum of Space OA Airflows
 Unocc. Damper Position Closed
 Damper Leak Rate 0 %
 Outdoor Air CO2 Level 400 ppm

Economizer Data:

Control Non-integrated dry-bulb control
 Upper Cut-off 66,0 °C
 Lower Cut-off -46,0 °C

Ventilation Reclaim Data:

Reclaim Type Sensible and Latent Heat
 Thermal Efficiency 70 %
 Input kW 0,800 kW
 Schedule JFMAMJJASOND

Central Cooling Data:

Supply Air Temperature 18,0 °C
 Coil Bypass Factor 0,100
 Cooling Source Air-Cooled DX
 Schedule JFMAMJJASOND
 Capacity Control Constant Temperature - Fan Cycled

Central Heating Data:

Supply Temperature 27,0 °C
 Heating Source Electric Resistance
 Schedule JFMAMJJASOND
 Capacity Control Constant Temperature - Fan Cycled

Supply Fan Data:

Fan Type Forward Curved
 Configuration Draw-thru
 Fan Performance 1,2 kW

Duct System Data:

Supply Duct Data:

Duct Heat Gain 0 %
 Duct Leakage 0 %

Return Duct or Plenum Data:

Return Air Via Ducted Return

3. Zone Components:

Space Assignments:

Zone 1: Zone 1	
room_angle_EN	x1
room_angle_ES	x1
room_angle_WN	x1
room_angle_WS	x1
room_milieu_N	x1
room_milieu_S	x1

Thermostats and Zone Data:

Zone	All
Cooling T-stat: Occ.	24,5 °C
Cooling T-stat: Unocc.	27,0 °C
Heating T-stat: Occ.	20,5 °C
Heating T-stat: Unocc.	17,0 °C
T-stat Throttling Range	1,00 °K
Diversity Factor	100 %
Direct Exhaust Airflow	0,0 L/s
Direct Exhaust Fan kW	0,0 kW
Thermostat Schedule	thermostat_sch
Unoccupied Cooling is	Available

Supply Terminals Data:

Zone	All
Terminal Type	Diffuser
Minimum Airflow	7,00 L/(s-m ²)

Zone Heating Units:

Zone	All
Zone Heating Unit Type	None
Zone Unit Heat Source	Electric Resistance
Zone Heating Unit Schedule	JFMAMJJASOND

4. Sizing Data (Computer-Generated):

System Sizing Data:

Hydronic Sizing Specifications:

Chilled Water Delta-T	5,6 °K
Hot Water Delta-T	11,1 °K

Safety Factors:

Cooling Sensible	0 %
Cooling Latent	0 %
Heating	0 %

Zone Sizing Data:

Zone Airflow Sizing Method	Sum of space airflow rates
Space Airflow Sizing Method	Individual peak space loads

5. Equipment Data

Central Cooling Unit - Air-Cooled DX

Design OAT	35,0 °C
Equipment Sizing	Auto-Sized
Capacity Oversizing Factor	0 %
ARI Performance Rating	3,22 EER
Conventional Cut-off OAT	12,8 °C
Low Temperature Operation	Used
Low Temperature Cut-off OAT	-17,8 °C

Appendix 3: Space input data for the room in the corner

1. General Details:

Floor Area 15,0 m²
 Avg. Ceiling Height 2,5 m
 Building Weight 341,8 kg/m²

1.1. OA Ventilation Requirements:

Space Usage OFFICE: Office space
 OA Requirement 1 2,5 L/s/person
 OA Requirement 2 0,30 L/(s·m²)
 Space Usage Defaults ASHRAE Std 62.1-2004

2. Internals:

2.1. Overhead Lighting:

Fixture Type Recessed (Unvented)
 Wattage 7,00 W/m²
 Ballast Multiplier 1,00
 Schedule occupancy_schedule

2.2. Task Lighting:

Wattage 0,00 W/m²
 Schedule None

2.3. Electrical Equipment:

Wattage 50,0 Watts
 Schedule occupancy_schedule

2.4. People:

Occupancy 1,0 Person
 Activity Level Office Work
 Sensible 71,8 W/person
 Latent 60,1 W/person
 Schedule occupancy_schedule

2.5. Miscellaneous Loads:

Sensible 0 W
 Schedule None
 Latent 0 W
 Schedule None

3. Walls, Windows, Doors:

Exp.	Wall Gross Area (m ²)	Window 1 Qty.	Window 2 Qty.	Door 1 Qty.
N	12,5	1	0	0
E	7,5	0	1	0

3.1. Construction Types for Exposure N

Wall Type Face Brick + RSI-2.5 Board + 102mm LW Block
 1st Window Type Window_standard

3.2. Construction Types for Exposure E

Wall Type Face Brick + RSI-2.5 Board + 102mm LW Block
 2nd Window Type small

4. Roofs, Skylights:

(No Roof or Skylight data).

5. Infiltration:

Design Cooling 1,00 L/s
 Design Heating 1,00 L/s
 Energy Analysis 1,00 L/s
 Infiltration occurs only when the fan is off.

6. Floors:

Type Floor Above Conditioned Space
 (No additional input required for this floor type).

Appendix 4: Space input data for the room in the middle oriented North

1. General Details:

Floor Area **15,0** m²
 Avg. Ceiling Height **2,5** m
 Building Weight **341,8** kg/m²

1.1. OA Ventilation Requirements:

Space Usage **OFFICE: Office space**
 OA Requirement 1 **2,5** L/s/person
 OA Requirement 2 **0,30** L/(s-m²)
 Space Usage Defaults **ASHRAE Std 62.1-2004**

2. Internals:

2.1. Overhead Lighting:

Fixture Type **Recessed (Unvented)**
 Wattage **7,00** W/m²
 Ballast Multiplier **1,00**
 Schedule **light_schedule**

2.2. Task Lighting:

Wattage **0,00** W/m²
 Schedule **None**

2.3. Electrical Equipment:

Wattage **100,0** Watts
 Schedule **occupancy_schedule**

2.4. People:

Occupancy **1,0** Person
 Activity Level **Office Work**
 Sensible **71,8** W/person
 Latent **60,1** W/person
 Schedule **occupancy_schedule**

2.5. Miscellaneous Loads:

Sensible **0** W
 Schedule **None**
 Latent **0** W
 Schedule **None**

3. Walls, Windows, Doors:

Exp.	Wall Gross Area (m ²)	Window 1 Qty.	Window 2 Qty.	Door 1 Qty.
N	15,0	1	0	0

3.1. Construction Types for Exposure N

Wall Type **Face Brick + RSI-2.5 Board + 102mm LW Block**
 1st Window Type **Window_standard**

4. Roofs, Skylights:

(No Roof or Skylight data).

5. Infiltration:

Design Cooling **0,60** L/s
 Design Heating **0,60** L/s
 Energy Analysis **0,60** L/s
 Infiltration occurs only when the fan is off.

6. Floors:

Type **Floor Above Conditioned Space**
(No additional input required for this floor type).

Appendix 5: Energy consumption for CAV and VAV system

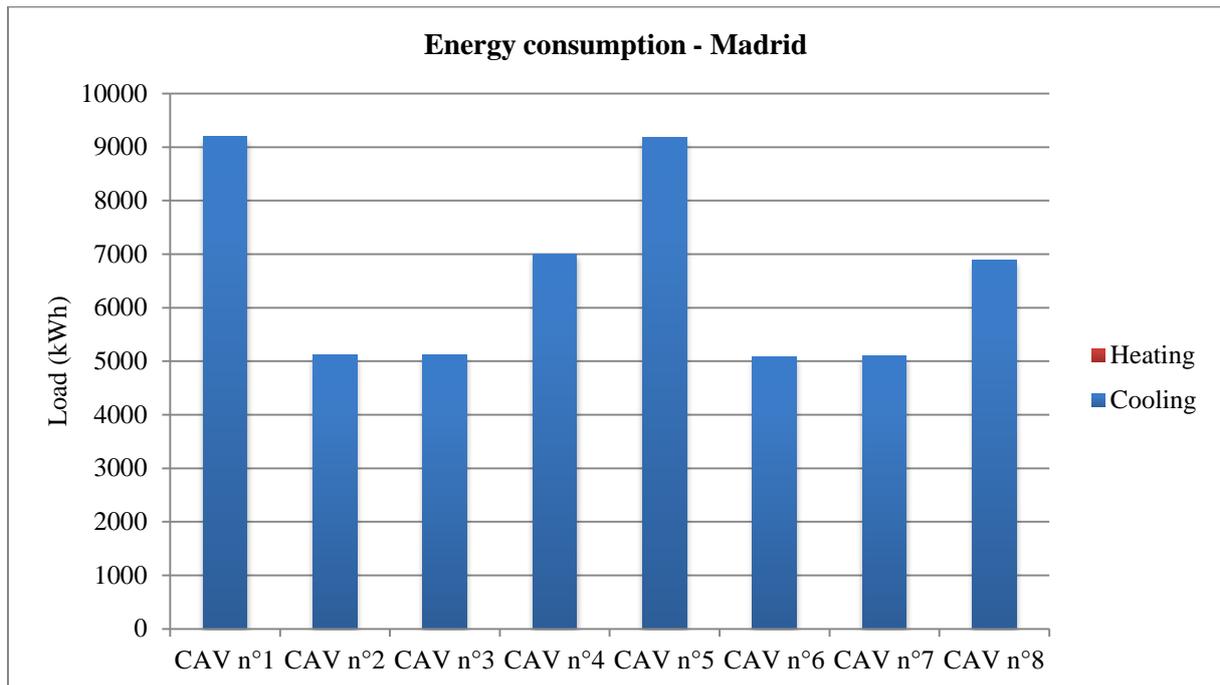


Figure 31: Energy consumption in Madrid for the CAV system

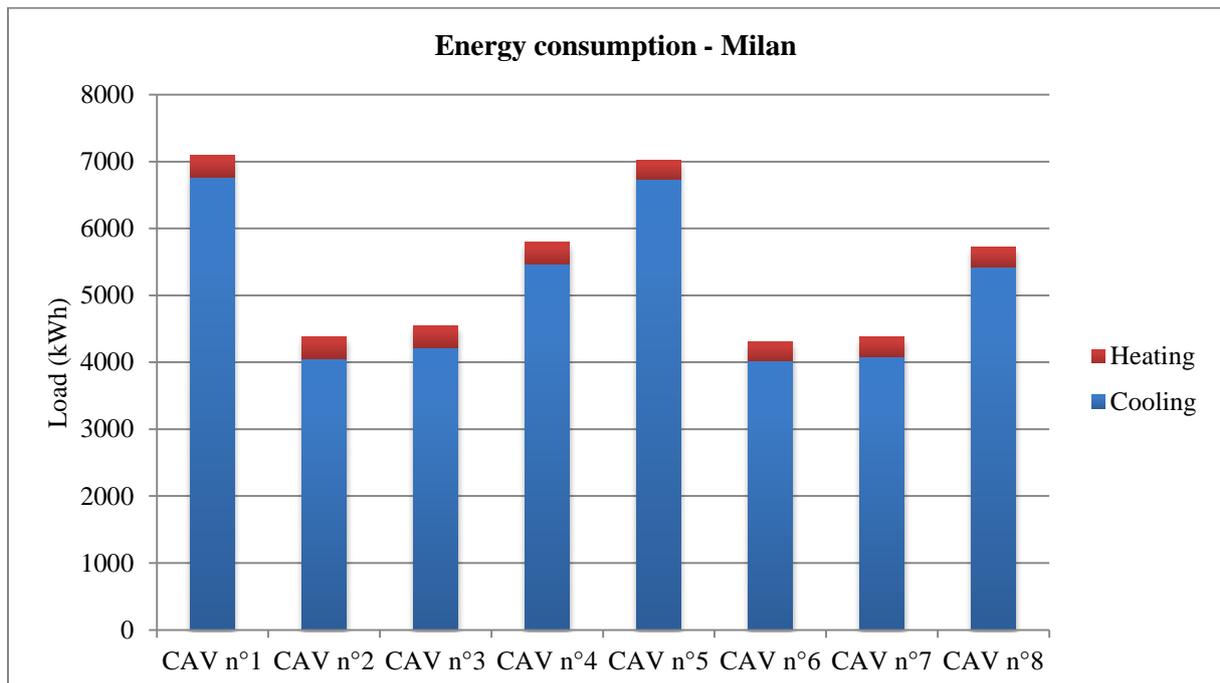


Figure 32: Energy consumption in Milan for the CAV system

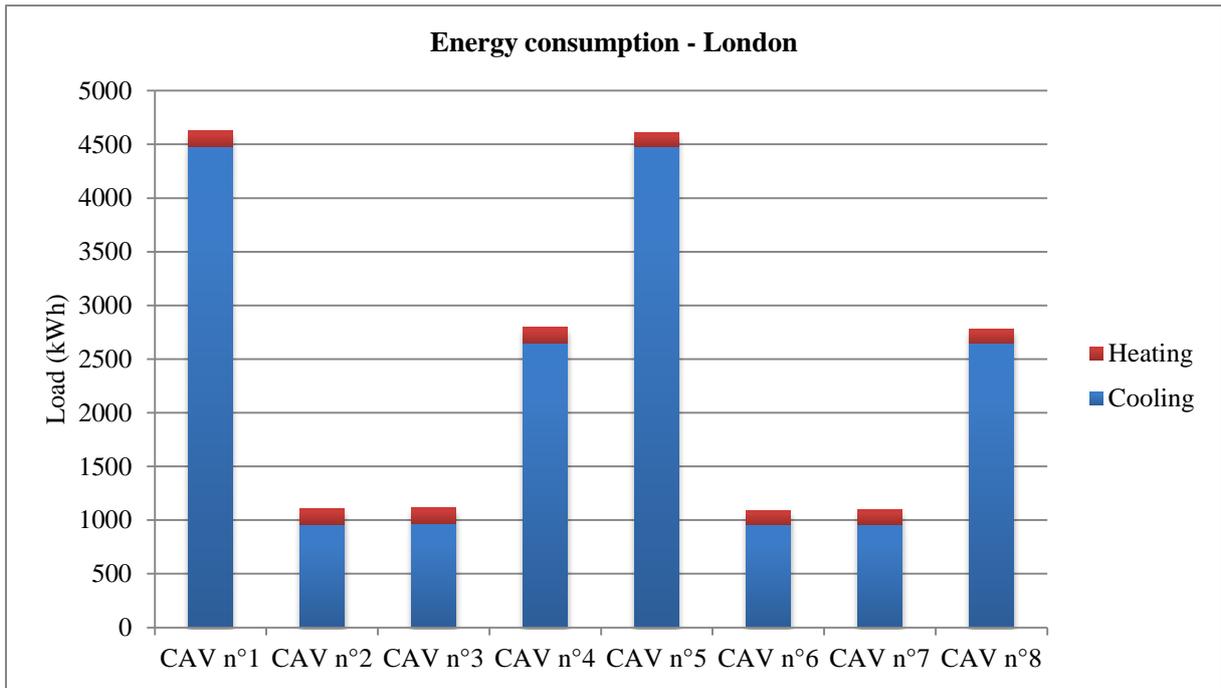


Figure 33: Energy consumption in London for the CAV system

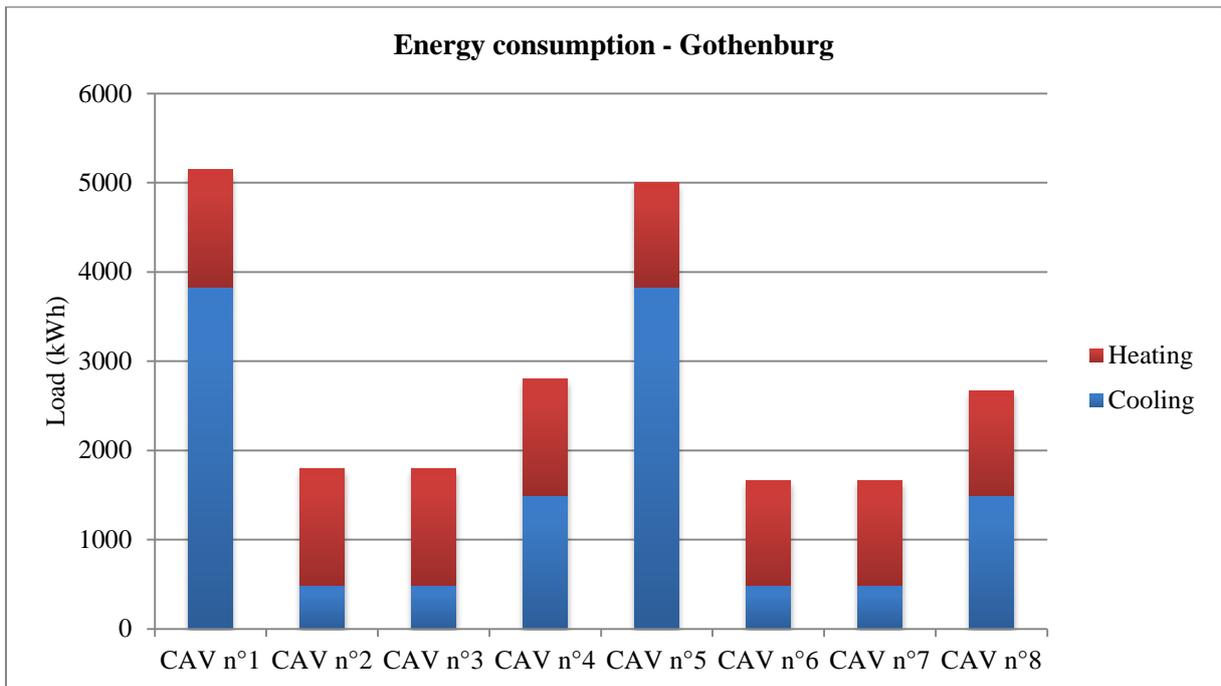


Figure 34: Energy consumption in Gothenburg for the CAV system

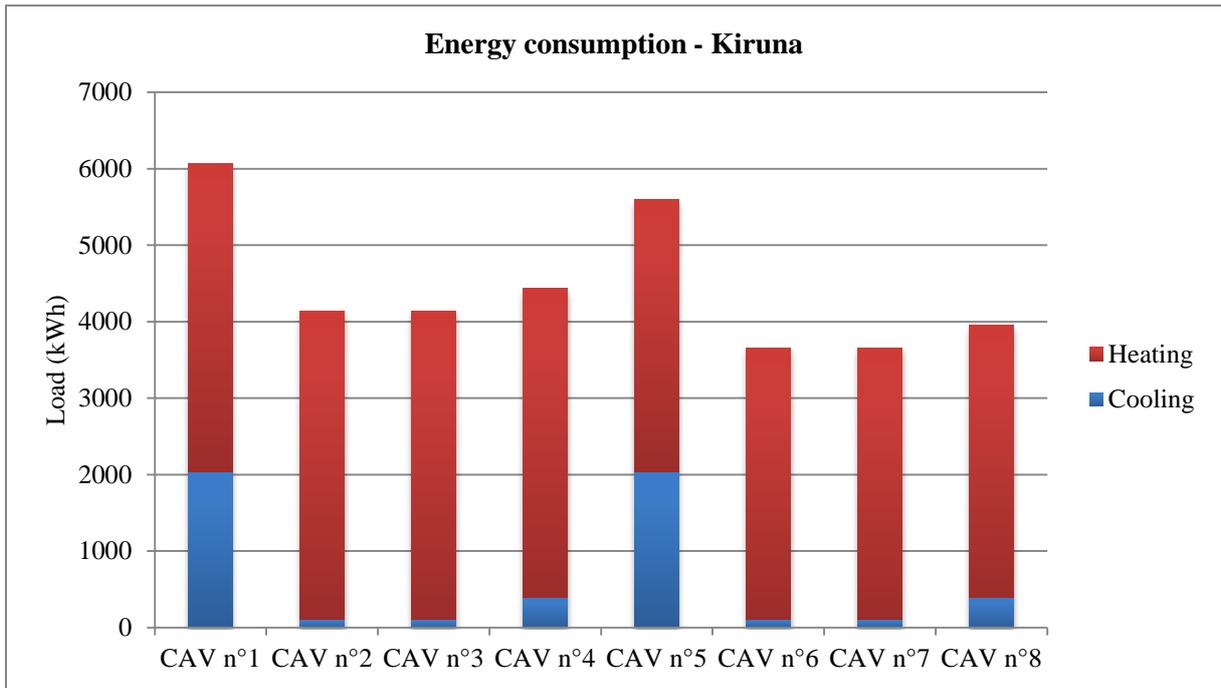


Figure 35: Energy consumption in Kiruna for the CAV system

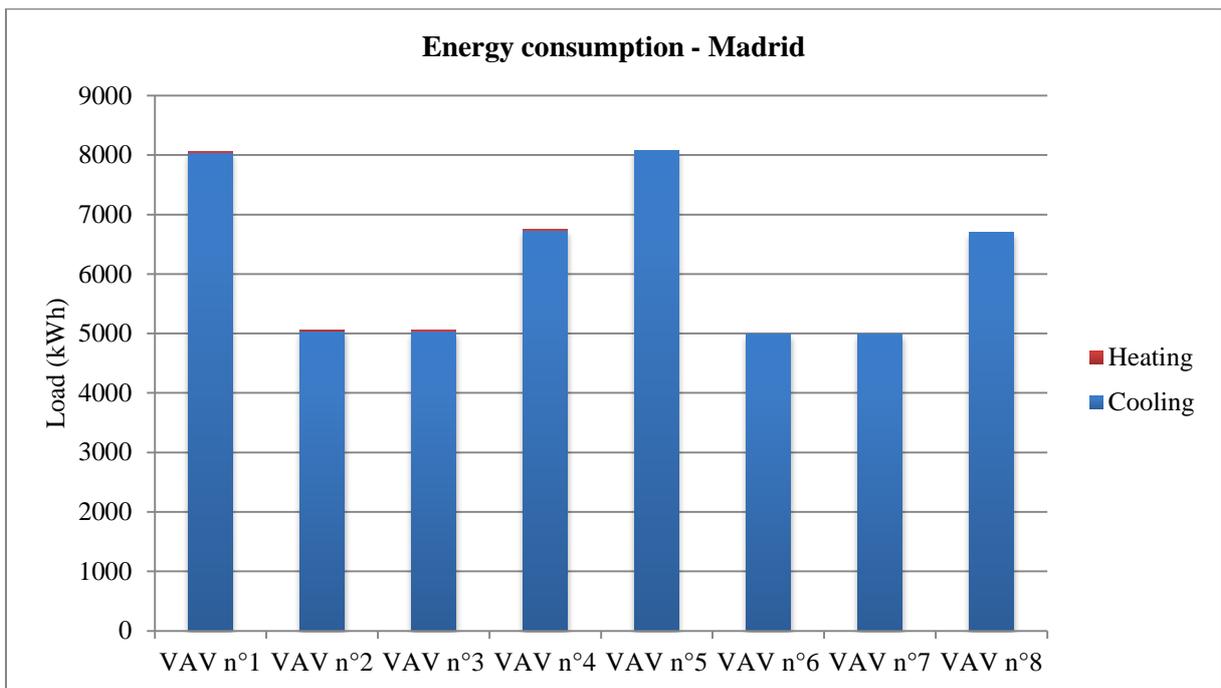


Figure 36: Energy consumption in Madrid for the VAV system

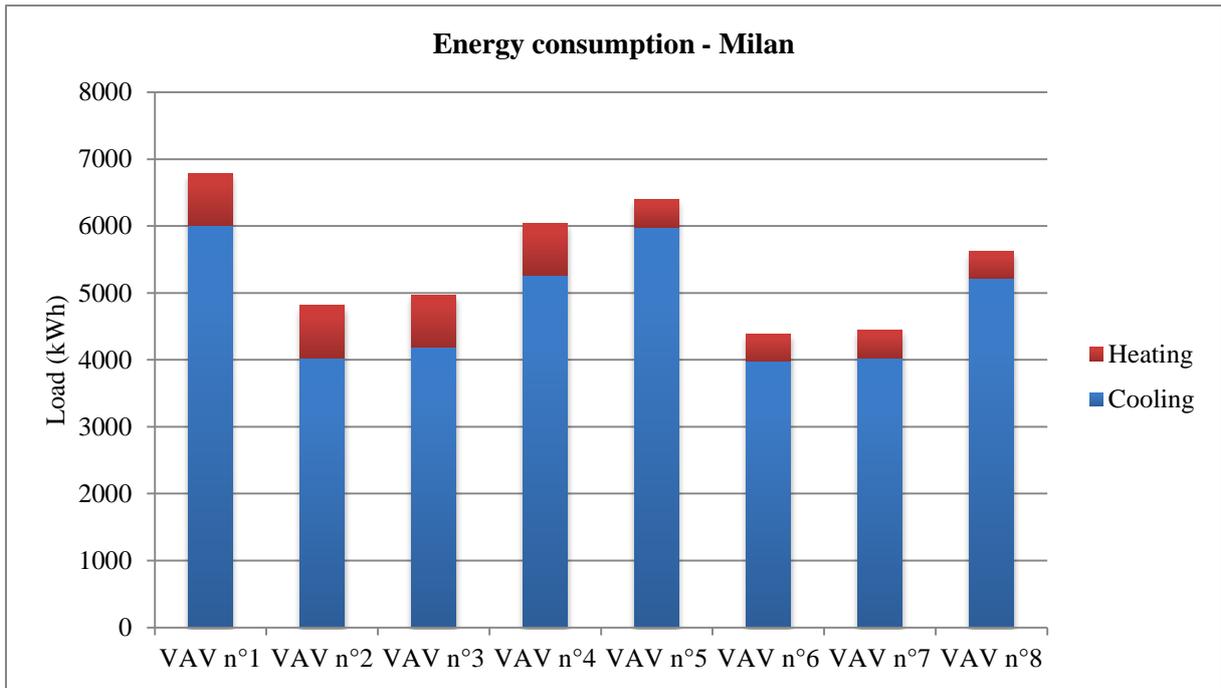


Figure 37: Energy consumption in Milan for the VAV system

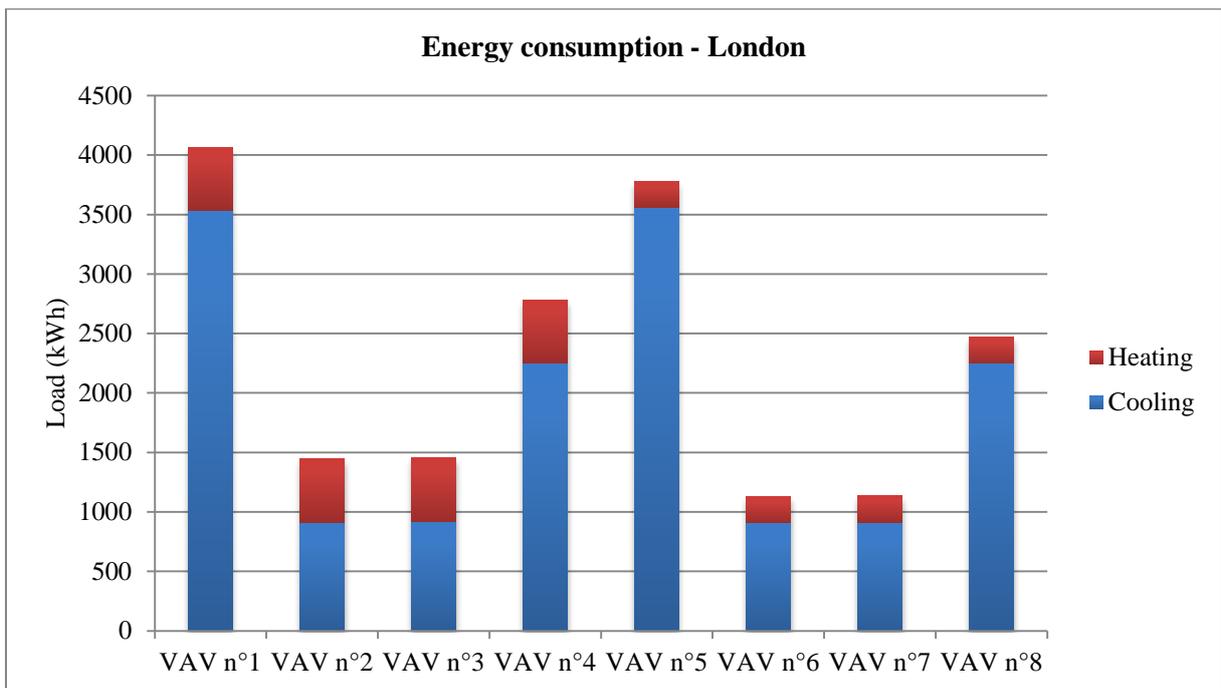


Figure 38: Energy consumption in London for the VAV system

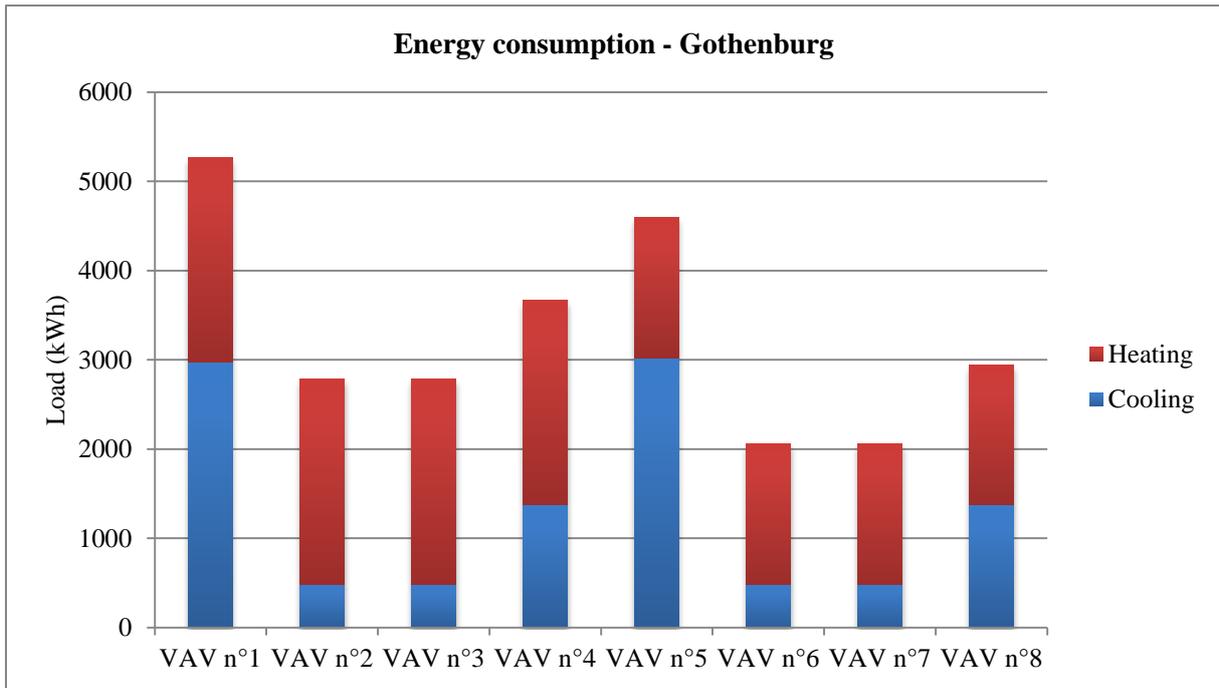


Figure 39: Energy consumption in Gothenburg for the VAV system

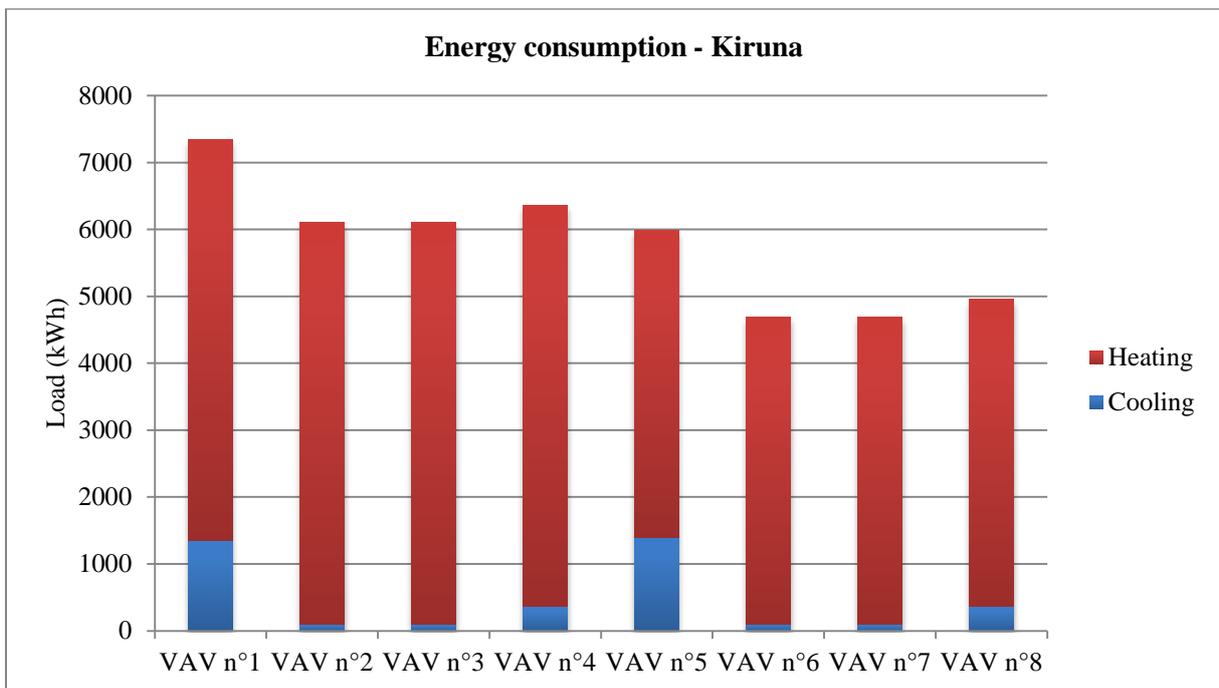


Figure 40: Energy consumption in Kiruna for the VAV system

Appendix 6: Comparison of the cooling loads reduction due to the economizer between the enthalpy-based and the temperature-based controls

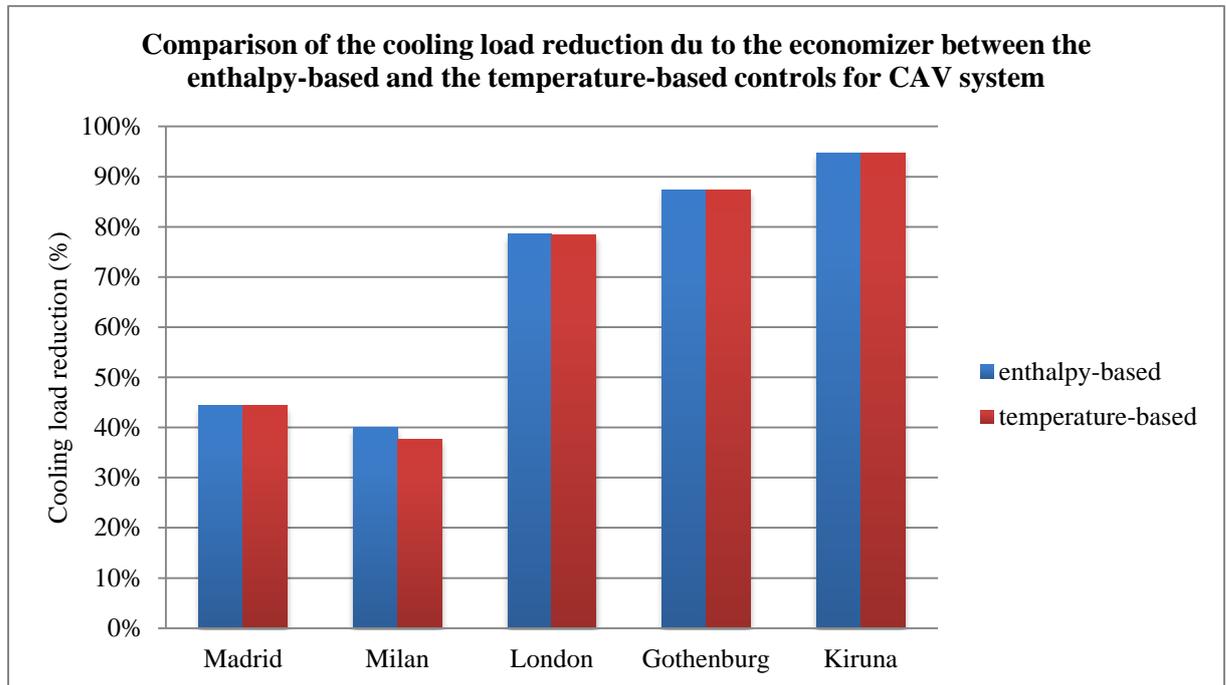


Figure 41: Comparison of the cooling load reduction provide by the economizer between the enthalpy-based and the temperature-based controls in CAV

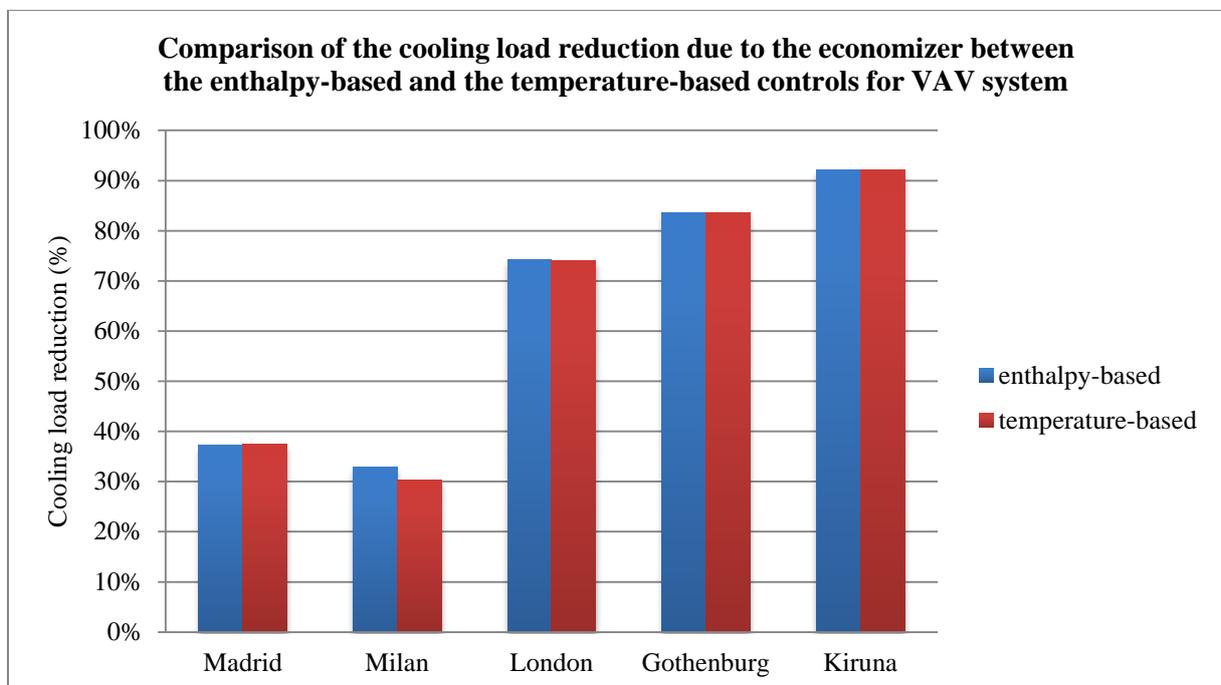


Figure 42: Comparison of the cooling load reduction provide by the economizer between the enthalpy-based and the temperature-based controls in VA

Appendix 7: Influence of an heat exchanger on the cooling load for a VAV system

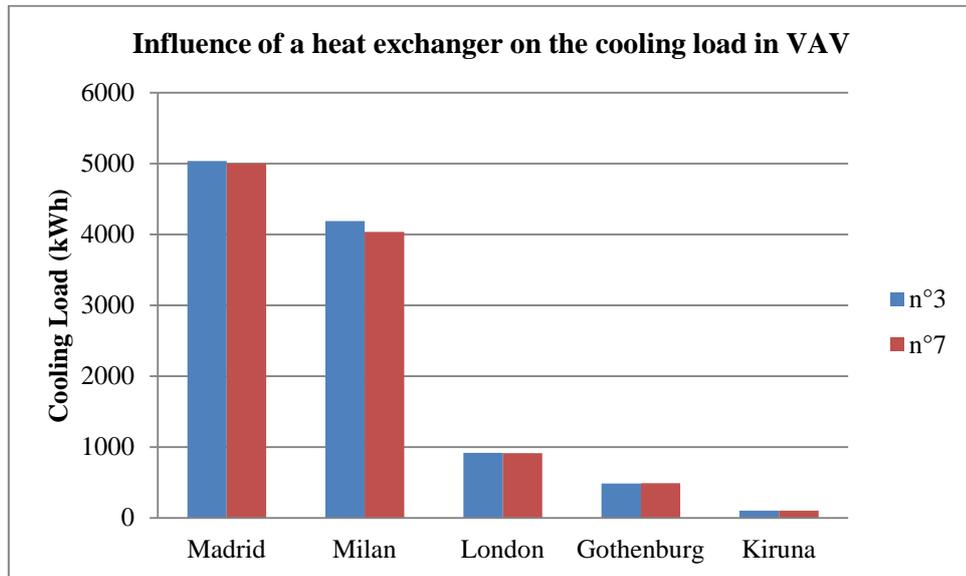


Figure 43: Influence of a heat exchanger on the cooling load in VAV for systems n°3 and n°7

Appendix 8: Detail energy consumption in CAV and VAV systems n°2-5-6

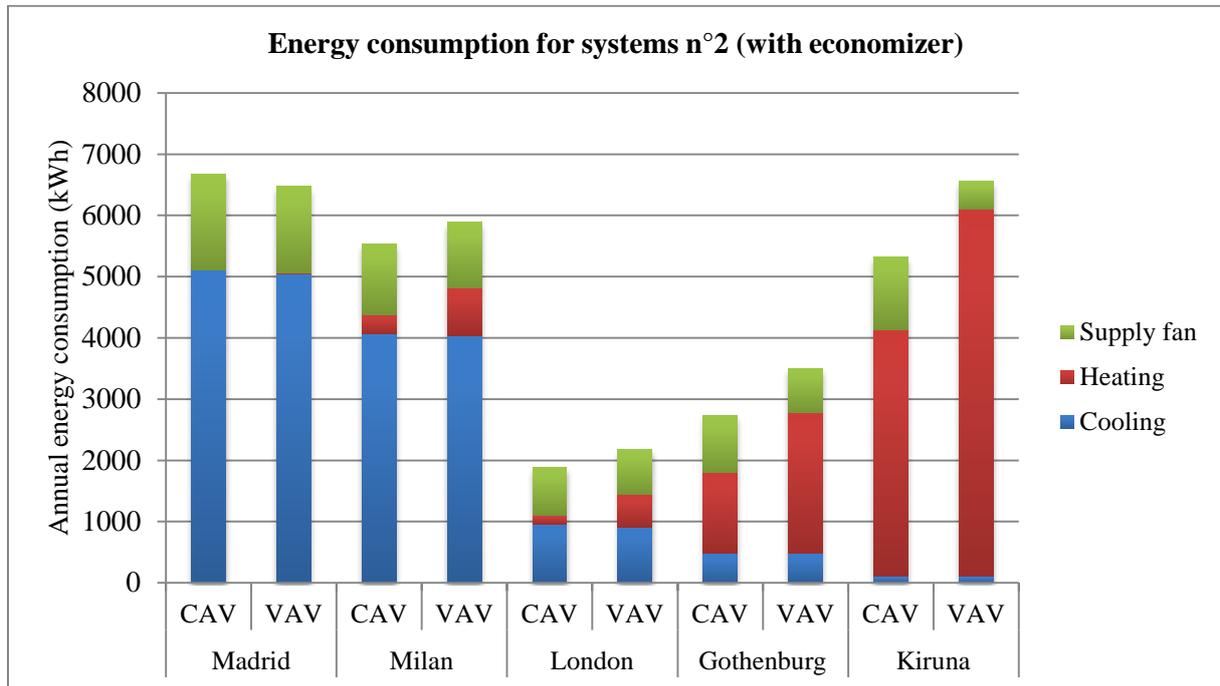


Figure 44: Detail energy consumption for VAV and CAV system n°2

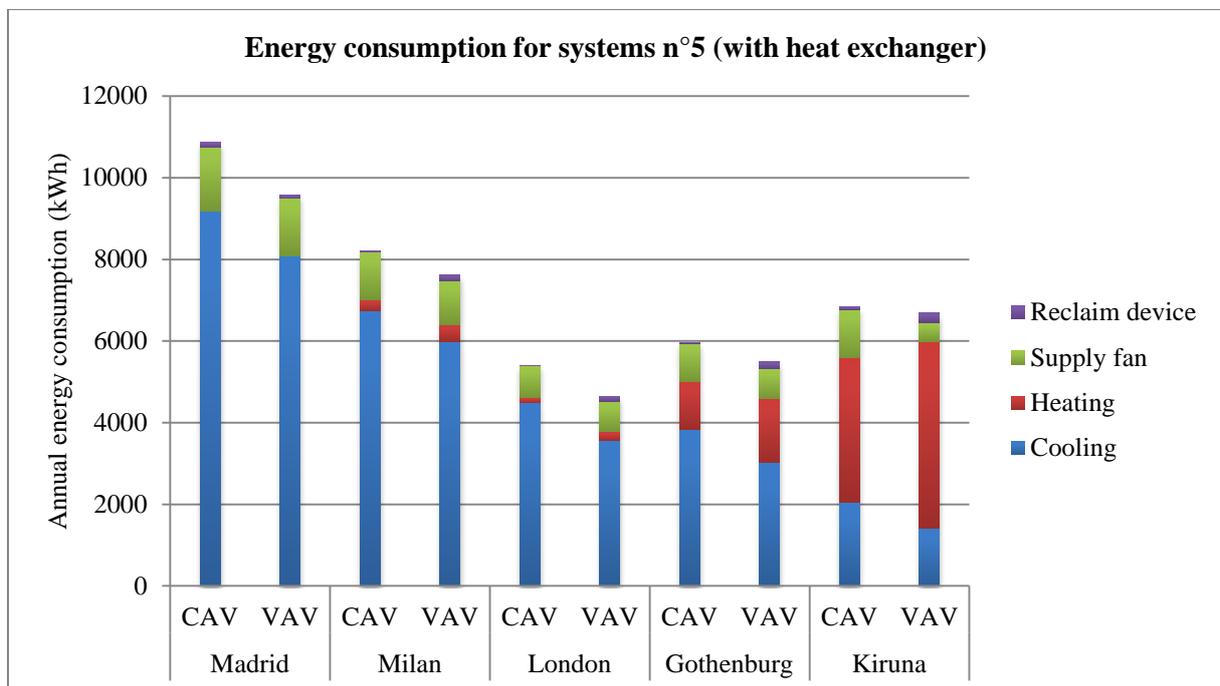


Figure 45: Detail energy consumption for VAV and CAV system n°5

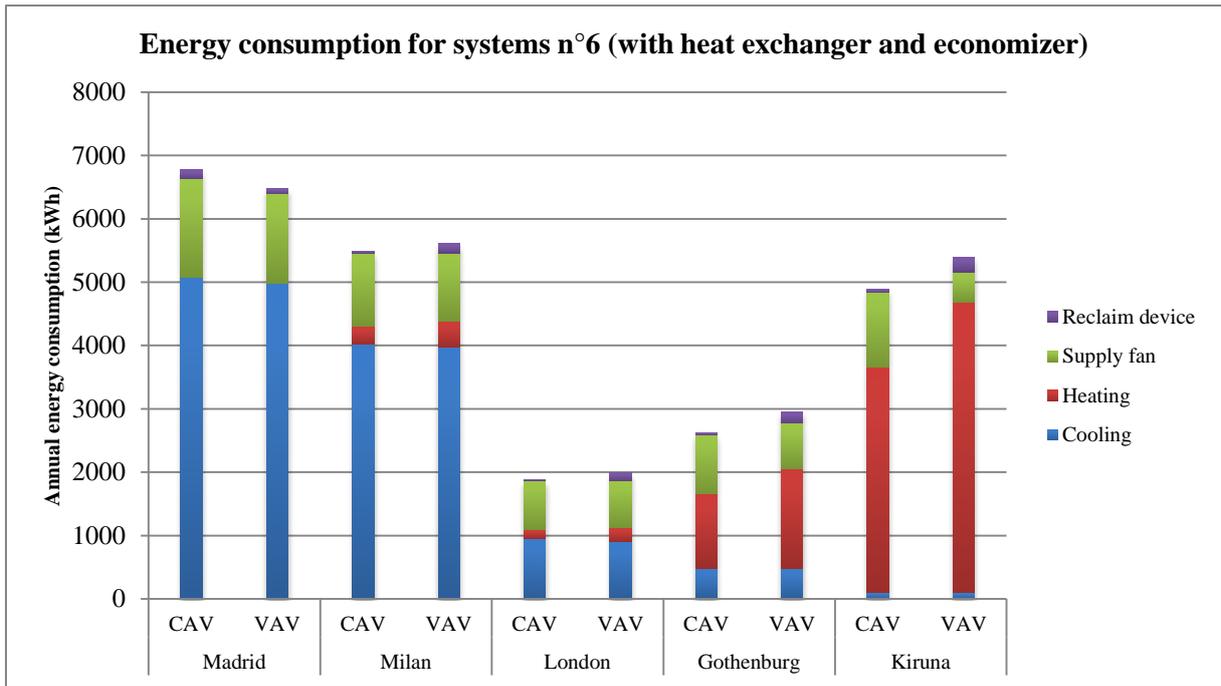


Figure 46: Detail energy consumption for VAV and CAV system n°6

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