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Development and Evaluation of Demand-Controlled Ventilation Strategies for Hospitals

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Abstract

The building sector accounts for up to nearly half of the final energy consumption in developed countries. Where a considerable amount of this energy is consumed by the HVAC system. Therefore, there is a remarkable energy-saving potential. Hospitals as commercial types of buildings, especially, consume a high amount of energy. Applying demand-controlled ventilation is one way to reduce the final use. It is important to note that the hospital’s needs for ventilation differ from those of other buildings. This work will identify and represent the results for adjusting demand-controlled ventilation in hospitals considering two specific cases. The University Hospital Aachen (UKA) and the Helsinki University Hospital (HUS) are the cases for the scope of this work. Minimum requirements are also shown for this specified sector. Additionally, different methods and strategies are developed and simulated for some room usage types and then applied to a calibrated model. The strategies are developed for specific room usage types of regular care room, isolation care room, office, and consulting and treatment room and then simulated. Therefore, a discussion over the results of the simulation is provided as well.

To avoid legal risks for the operation of the HVAC systems in hospitals, standards, and guidelines must be followed. These include national and international ones for our case. Supply air volume flow rate and room air temperature are the main control variables. By applying demand-controlled ventilation, the supply air will be adjusted for the occupancy as the current demand in the room. This is calculated by measuring the CO2 concentration inside the area as an indication for occupancy detection.

Lastly, an economic assessment and a study over the influence of occupancy difference in energy consumption are provided. The results for simulated strategies and economic analysis show a notable amount of energy-saving, as well as financial benefits, in all room usage types.

Key words: Demand-base Ventilation – energy consumption – energy saving – building – hospital – occupancy

Sommario

Il settore edile rappresenta quasi la metà del consumo finale di energia nei paesi sviluppati. Dove una quantità considerevole di questa energia viene consumata dal sistema HVAC. Pertanto, esiste un notevole potenziale di risparmio energetico. Gli ospedali come tipi di edifici commerciali, in particolare, consumano un'elevata quantità di energia. L'applicazione della ventilazione controllata dalla domanda è un modo per ridurre l'uso finale. È importante notare che le esigenze di ventilazione dell'ospedale differiscono da quelle di altri edifici. Questo lavoro identificherà e rappresenterà i risultati per l'adeguamento della ventilazione controllata dalla domanda negli ospedali considerando due casi specifici. L'University Hospital Aachen (UKA) e l'Helsinki University Hospital (HUS) sono i casi oggetto di questo lavoro. I requisiti minimi sono indicati anche per questo settore specifico. Inoltre, diversi metodi e strategie vengono sviluppati e simulati per alcuni tipi di utilizzo della stanza e quindi applicati a un modello calibrato. Le strategie vengono sviluppate per specifici tipi di utilizzo della stanza di stanza di cura regolare, stanza di isolamento, ufficio e stanza di consulenza e trattamento e quindi simulate. Pertanto, viene fornita anche una discussione sui risultati della simulazione.

Per evitare rischi legali per il funzionamento dei sistemi HVAC negli ospedali, è necessario seguire gli standard e le linee guida. Questi includono quelli nazionali e internazionali per il nostro caso. La portata volumetrica dell'aria di mandata e la temperatura dell'aria ambiente sono le principali variabili di controllo. Applicando la ventilazione controllata dalla domanda, l'aria di mandata sarà adattata all'occupazione come richiesta attuale nella stanza. Questo viene calcolato misurando la concentrazione di CO2 all'interno dell'area come indicazione per il rilevamento dell'occupazione.

Infine, viene fornita una valutazione economica e uno studio sull'influenza della differenza di occupazione sul consumo energetico. I risultati delle strategie simulate e dell'analisi economica mostrano un notevole risparmio energetico, oltre a vantaggi finanziari, in tutti i tipi di utilizzo delle stanze.

parole chiave: Ventilazione in base alla domanda – consumo di energia – risparmio energetico – costruzione – Ospedale – occupazione

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Nomenclature

Symbols	Meaning	Unit
T	Temperature	K
t	Time	s
$\dot{V}$	Volume flow rate	m^3/s
$\dot{n}$	Mole flow rate	mol/s
x	Mole fraction	-
ΔCO_2	CO_2 concentration difference	ppm

Indices and Acronyms

Symbols	Meaning
O	Outdoor air
S	Source
In	Inlet
out	Outlet
ppm	Part per million
HVAC	Heating, Ventilation, and Air Conditioning
TEASER	Tool for Energy Analysis and Simulation for Efficient Retrofit
UKA	Unikilink Aachen (Aachen university hospital)
HUS	Helsinki University Hospital

AHU	Air Handling Unit
DCV	Demand-based Control Ventilation
OP	Operation room (Operation theater)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
$\mathbf{P_{coolAHU}}$	Cooling consumption of Air handling unit
$\mathbf{P_{heatAHU}}$	Heating consumption of Air handling unit
$\mathbf{P_{el}}$	Electrical consumption of Air handling unit
$\mathbf{P_{heater}}$	Decentral heater energy consumption
ACH	Air Change rate
PID	Proportional–Integral–Derivative
OCC.	Occupancy

Executive Summary

Introduction

Nowadays studies show an increase in energy consumption in developed countries where the building sector reached between 20% to 40% of the share, which is higher than industry and transportation [1]. Where the HVAC systems utilize nearly half of the energy in buildings [1]. Therefore, there are improvements and investigations being conducted to optimize this consumption. Hospital and health care centers as commercial buildings are one of the greatest consumers in the building sector[2]. One of the ways that HVAC systems can be made more energy efficient is to apply demand-controlled ventilation. This project is developed for a similar purpose with the cooperation of the Aachen University Hospital (UKA) and Helsinki University Hospital (HUS). Demand-based ventilation is a strategy in which the required ventilation is provided to the room by considering the demand inside the room. The application is already existing in some sort of buildings, however, considering hospitals and health care centers the situation regarding requirements and specifications are distinguished. The aim of this work is to implement the appropriate values in developed model and simulate the results for the mentioned case study. Therefore, a dynamic model is created based on AixLib library of Modelica software and TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit) for simulation and evaluation of demand-controlled strategies developed for hospitals.

Development of Ventilation Strategies

In existing and reference cases for the mentioned hospitals, the ventilation takes place with constant supply air volume flow to condition the rooms. Here the general idea of this work is to control ventilation regarding the demand inside the room. Therefore, considering the occupancy trend inside the rooms as the major demand sources for heating and cooling as well as fresh air, there are two main strategies developed:

Demand-Controlled Ventilation (DCV):

Basically, in this strategy, we will take the number of people inside the room into account, and we will apply a linear relationship between this value and the supply air volume flow.

Time-controlled (Schedule-based) Ventilation:

In some rooms with typical occupancy behaviors, such as offices and consulting and treatment rooms, it may be feasible to operate the reference ventilation strategy just during some periods of time. In addition, it is possible to have a minimum supply of outdoor air for the rest of the period. Mainly, we considered a daily schedule for working hours when the room is occupied to have the reference ventilation and provide the room with minimum supply air volume flow for the rest of the day.

As mentioned before, the requirements are different in hospitals compared to other types of buildings. In order to clarify the requirements for hospitals, we took four different room usage types into account (regular care room, isolation care room, office room, and consulting and treatment room). Since there are different standards for each room usage type, a deep review is done in a study by J. Fischer regarding standards and guidelines for each country as well as international ones [3],[4],[5]. Mostly the outdoor air volume flow and room temperature are mentioned as the requirements for different room usage types 2.3). So, considering this, we come up with the values shown below for each room usage type as a requirement to be met.

Table 1 Selected requirements of outdoor air volume flow for each room

Rooms	Minimum outdoor air $[m^3/h/person]$
Regular care room	36
Isolation care room	100
Office room	21.6
Consulting and treatment room	72

These requirements are taken as inputs for energy simulations. Also, some other controlling boundaries are needed to be maintained. Room air temperature is one of those. Due to standards which are later explained in detail (Chapter 2), there is a variable recommended thermal comfort zone considering the ambient air temperature for each hospital (3.2.3 and 3.2.4). Controllers are developed for each case using the aforementioned data to maintain the thermal comfort zone in all strategies. The operating AHU in HUS is a single duct AHU that provides the supply air with a constant temperature. Therefore, for controlling the room air temperature in the DCV strategy, a dedicated PID controller would change the supply air volume flow rate. However, since the air handling unit in UKA is a dual duct AHU, there is the possibility to control the supply air temperature entering the room. So, to maintain thermal comfort in the DCV method, it is necessary to regulate the supply air temperature in advance. When the supply air temperature is not adequate to keep the room temperature in the thermal comfort zone, increasing the volume flow rate will help the process.

Occupancy detection in the mentioned methods is done by calculations on the concentration of CO_2 in the room which is detected using specific sensors. All people during a similar activity, produce a predictable rate of CO_2 which is used as an indicator of human bioeffluent concentration and/or occupancy. for example, the CO_2 concentration will approximately double when the number of people changes to twice its value in a specific area [6].

Usually, the outdoor concentration of CO_2 is between 375 and 450 ppm. It can be found normally at a level of 400 to 2000 ppm in buildings and is not considered harmful or even a contaminant. In fact, it is established by OSHA that the limit for eight-hour exposure to CO_2 is 5000 ppm. But the experienced situation in commercial and residential buildings is far away from these limits [6].

CO_2 concentration inside the room is the variable that also indicates room air quality for our purpose. It is also considered not to exceed 2000 ppm of CO_2 concentration in the rooms to maintain room air quality. Where except for some specific conditions, which will be explained later, it is always kept lower than 1000 ppm.

Result and discussion

Here the result of simulation for a regular care room of the HUS as the most dominant room usage type in the hospital is indicated.

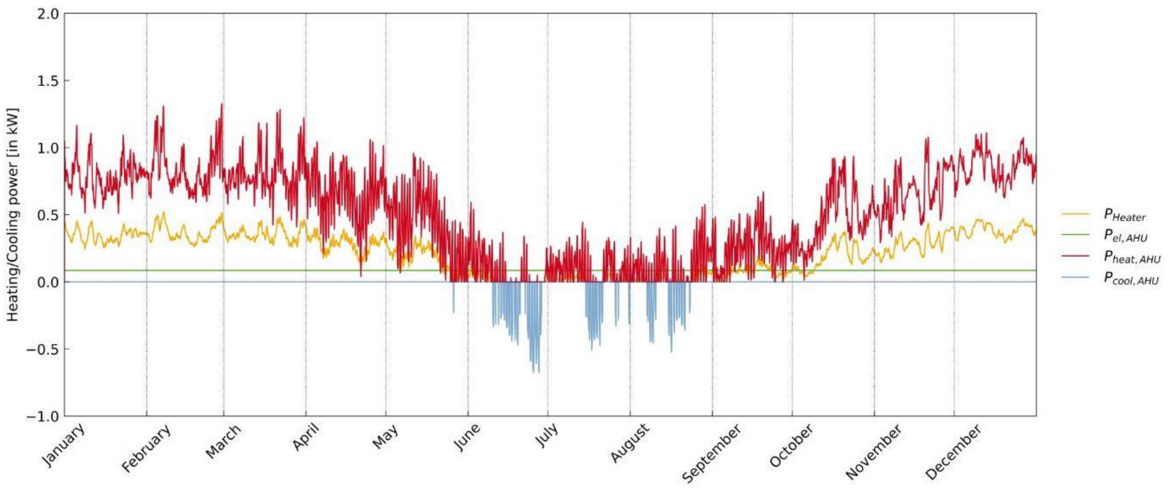

Figure 1 Reference energy consumption of regular care room (HUS)

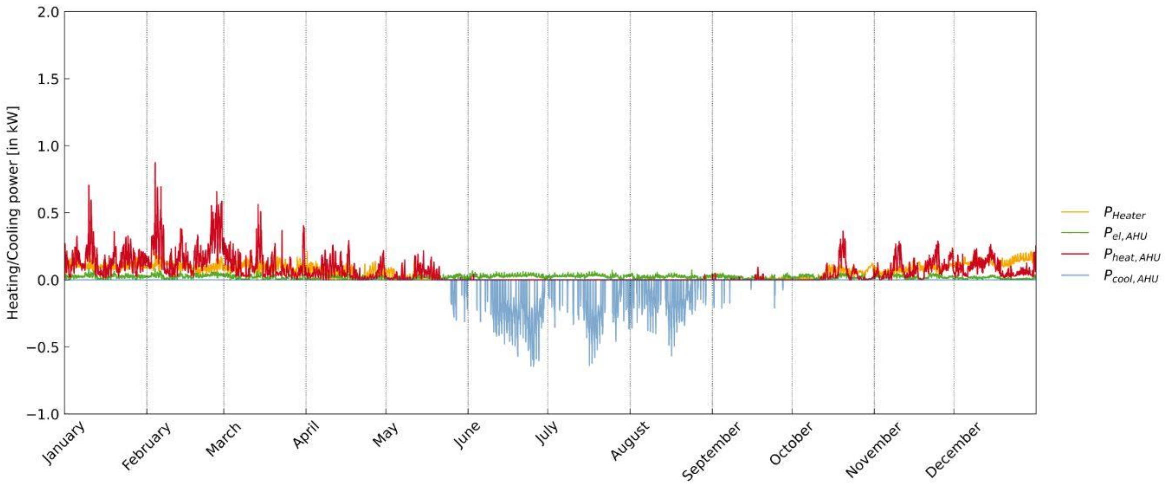

Figure 2 DCV strategy energy consumption of regular care room (HUS)

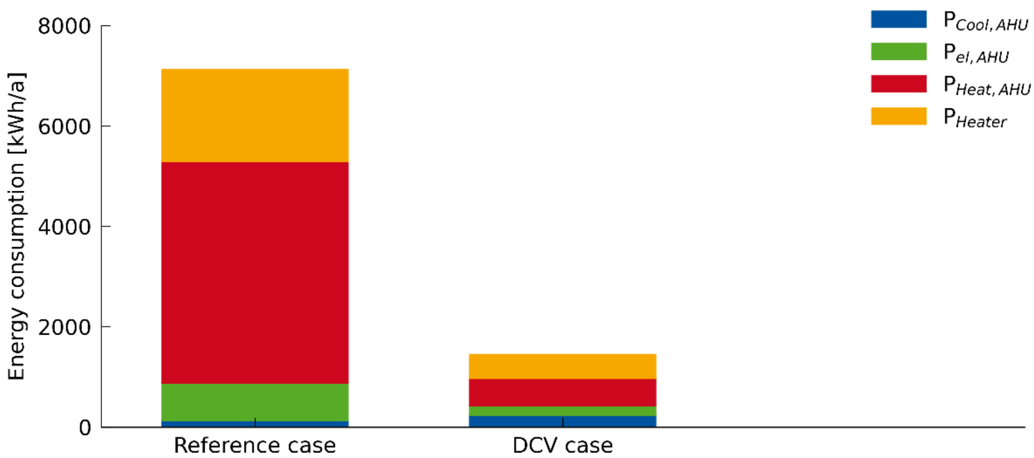

Figure 3 Cumulative energy consumption of 2 strategies for regular care room (HUS)

Table 2 Regular care room energy consumption and saving (HUS)

	$P_{coolAHU}$ [KWh]	$P_{heatAHU}$ [KWh]	P_{el} [KWh]	P_{heater} [KWh]	Total [KWh]
Reference case	131.8	4409.44	752.91	1821.94	7116.09
DCV case	246.47	545.44	189.28	455.36	1436.55
Saving %	-87%	87.63%	74.86%	75.01%	79.81%

It is shown from the provided plots and table that there is a notable potential for energy-saving by applying demand-controlled ventilation to the considered room. Additionally, the increase in cooling consumption of the AHU is due to changing the supply air temperature from 21.5°C to 18°C for the DCV case because of the possibility to save more energy in total.

Actually, it will lead to lower heating consumption during the cold season considering the dedicated thermal comfort zone for this season.

Mostly, saving a remarkable amount of energy is due to lowering the supply air volume flow rate by devoting appropriate values to the current demand of the room.

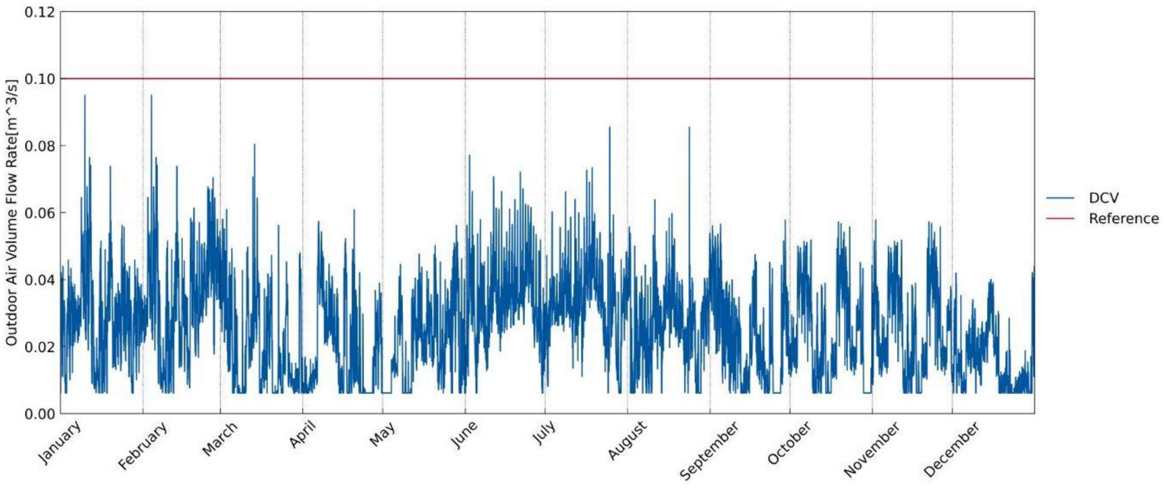

Figure 4 DCV strategy and reference outdoor air volume flow rate of regular care room (HUS)

As mentioned before, the thermal comfort zone is different for various ambient temperatures(Figure 3-4). Generally, considering a whole year, we try to keep the room air temperature between 22˚C to 26˚C. In the figure below (Figure 5) a comparison of the room air temperature for DCV and reference case is revealed which also validates the comfort zone control for the DCV method.

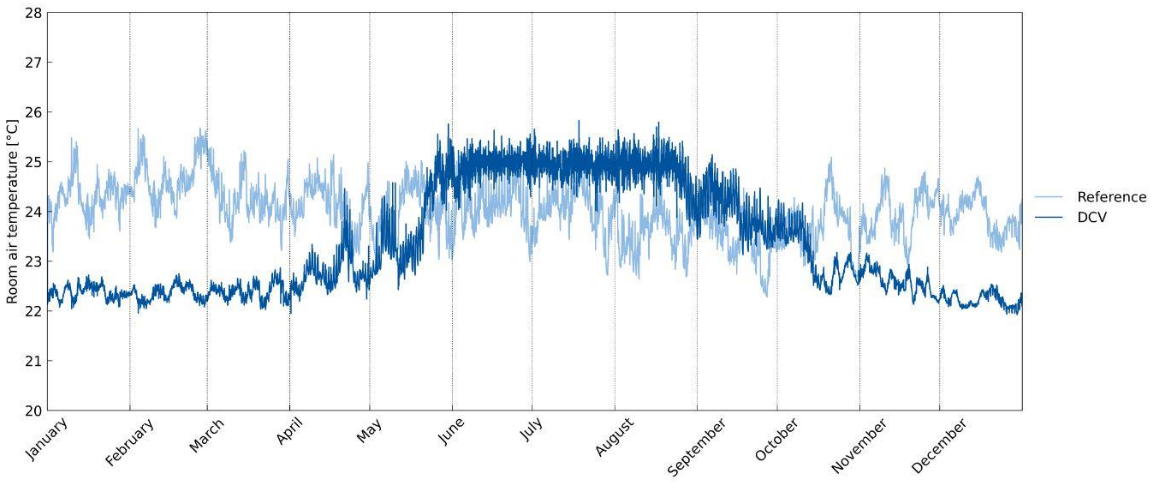

Figure 5 DCV strategy and reference room air temperature of regular care room (HUS)

Moreover, to indicate room air quality, a comparison is made for CO_2 concentration among both cases that are provided in the plot below.

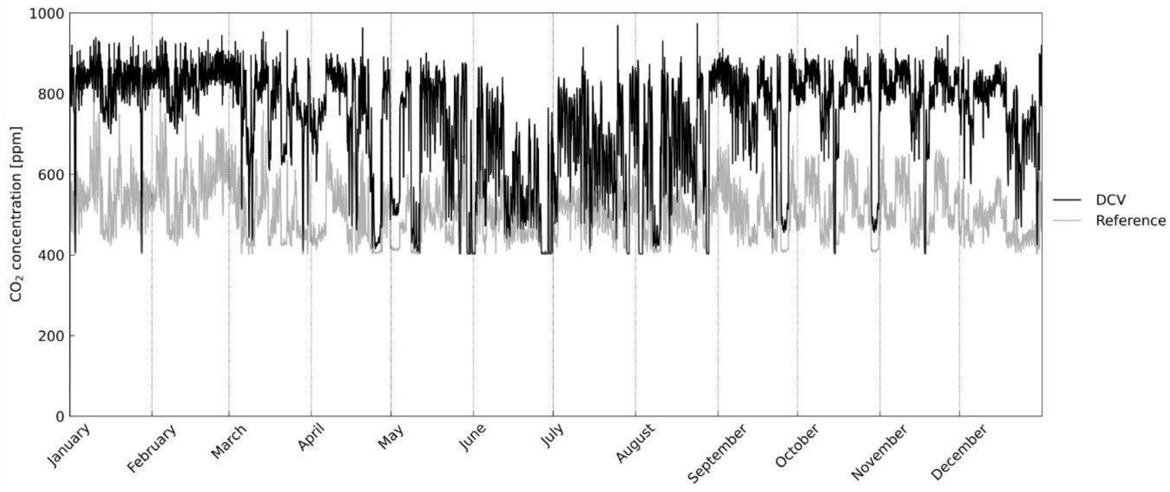

Figure 6 DCV strategy and reference CO_2 concentration of regular care room (HUS)

As it is obvious, there is an increase in CO_2 concentration in the room by applying the DCV method which is expectable because of the lower supply volume flow rate. However, the room air quality is kept in the range for the whole period of the year.

Lastly, here is an economic assessment is done for the energy saving in this room to indicate how much profit is achievable by implementing the DCV method instead of the existing ventilation method. For doing the assessment two distinguished scenarios with different variables are taken into account, for the first scenario electricity and energy price are taken from a reference, and for the second one from reports in the field [7],[8],[9]. The result is given in the table below.

Table 3 Regular care room economic assessment results (HUS)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	131.8	4409.44	752.91	1821.94	7116.09
DCV case consumptions [KWh/a]	246.47	545.44	189.28	455.36	1436.55
Benefits (scenario 1) [€/a]	-10.70	146.83	78.91	51.93	266.97
Benefits (scenario 2) [€/a]	-5.31	198.22	39.17	70.11	302.19

Considering that the results are only for a single room, it implies that there is a considerable financial benefit for the whole hospital by adjusting the DCV strategy for ventilation.

Further explanation and more results for other considered room usage types also in another hospital, as well as the result of simulation for new occupancy generated, are provided in the body of the thesis.

Chapter 1 Introduction

In recent years, the researches show a huge increase in energy consumption in developed countries in which buildings have a big share among all sectors that stand for almost 40% of total energy use. [1]

Referring to building sector energy consumption, close to 50% of this energy goes to the HVAC system which illustrates a great potential for energy saving [1]. Improvements in the buildings' energy system and new rules and standards are provided in order to benefit from this potential. But there is still so much energy waste due to over-pressurizing the building by having air handling units (AHUs) work at their maximum capacity without considering the occupancy in the area.

One of the major energy consumers in the building sector is the commercial or non-residential buildings in which hospitals or health care centers have a particularly high energy requirement and therefore there is a considerable need for energy saving measurements in this building sector [2].

One approach to use the potential of saving, in this case, is demand-controlled ventilation. This project focuses on developing practicable methods of demand-controlled ventilation in hospitals. Developed concepts are in bilateral cooperation at the university hospital Aachen (UKA) and Helsinki University Hospital (HUS).

Demand-controlled ventilation is a method that takes the number of people into account in the conditioned area as the major parameter. it presents suitable and variable ventilation to meet thermal comfort and requirements to omit odors and keep the remarkable gases in the acceptable range, in other words, to maintain indoor air quality.

Although DCV is already successfully being used in other buildings, the situation for hospitals and health care buildings is different [10]. As a fact, there are many requirements for ventilation and air conditioning that are specific for hospitals. Thus, ventilation strategies that are used in other types of buildings, are not necessarily transferable.

The pursued goal in this thesis is to illustrate the HVAC system's energy-saving potential as indicated by the usage of the DCV method, which is not currently used in hospitals. The simulation models are created based on the AixLib library of Modelica software, and TEASER to assess the energy consumption of a single room for different applications.

As the focus of this work is on two cases of University Hospital Aachen (UKA) and the Helsinki University Hospital (HUS), only for these cases of study there is a dynamic model developed that is representative of their details. However, it is possible to apply the results to any other hospital with similar conditions.

1.1 Objective and highlights

This work has two following objectives:

1. Development, Simulation, and assessment of different demand-controlled ventilation strategies on the created model.
2. Discussion and comparison review over results and effective parameters.

1.2 Structure of the thesis

In accordance with the objective of the thesis, the contents of this work are divided into four parts:

- The first part introduces a short description of the theoretical background and presents a literature review done over standards and guidelines
- In the second part, there is the model indication with control boundaries dedicated to each case of study.
- The third part presents the results for all strategies simulated and discussion on the represented data. Consequently, the energy-saving potential of each method is shown in this part.
- In the last part, a comparison among different strategies and hospitals takes place. Additionally, the results for economic assessment and new occupancy data generated are also provided.

Chapter 2
State of the Art

In this chapter, the scientific context of the project is placed. Subsequently, there is a detailed explanation of the principles of demand-controlled ventilation, as well as the elaboration of the requirements and standards for the indoor climate in hospitals. Finally, the current state of the art in hospitals.

2.1 Theoretical backgrounds

2.1.1 Ventilation

Ventilation is defined as the procedure of providing conditioned or not conditioned air to a specific area or taking it out by natural or mechanical means [11].

Thus, mainly there are two types of ventilation:

The first one is natural ventilation which happens due to only the presence of natural forces, like wind pressure or air density differences, which can occur by opening windows and doors. The other one is mechanical ventilation in which the process of ventilation is occurring actively with a device such as motor-driven fans and blowers. In addition, it is necessary to consider that utilizing devices like a wind-driven turbine and mechanically operated windows are not a type of mechanical ventilation[11].

Ventilation systems are designed to create an acceptable microclimate within the ventilated space. While referring to microclimate, we are referring to both thermal content and air quality. When designing a ventilation system for a space or building, these two factors must be considered since they affect the comfort and well-being of the occupants and the performance of industrial processes. [12].

2.1.2 Thermal comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined it as ‘‘the condition of the mind in which satisfaction is expressed with the thermal environment’’ [4].

The six factors affecting thermal comfort are both environmental and personal. These factors may be independent of each other but together contribute to a person's thermal comfort.

Environmental factors:

- Air temperature
- Radiant temperature
- Air velocity
- Humidity

Personal factors:

- Clothing Insulation
- Metabolic heat

2.2 Demand-controlled ventilation

There are many ventilation systems in which a constant supply volume of air is applied to the area under ventilation. considering the buildings with variable occupancy, a notable waste of energy occurs due to this method of ventilation. The reason for the waste of energy is that mostly this constant amount of the supply air is considered for the maximum demand. As an example, when there is no one in the ventilated area, most of the consuming energy in the HVAC system is wasted. Thus, there is the possibility to save a remarkable amount of energy in such a room. Demand-controlled ventilation describes a control strategy in which the ventilation system adjusts the supply airflow to the room's occupancy needs. So, by applying this strategy it is possible to avoid the waste of energy and save more on the consumption of the HVAC system. It is also notable that by adjusting this strategy, we still can benefit from thermal comfort and indoor air quality too. [13] There is another method considering the occupancy recording status and consequently controlling the HVAC system explained in the following:

2.2.3 Schedule-based control

The recurring condition of the occupancy in some room usage types brings the possibility of a schedule-based control. This control strategy for the HVAC system defines that when a room is occupied, the ventilation is applied with reference values, but also when a room is not occupied the outside air volume flow can be reduced to a minimum rate. A typical plan can be for day and night control. For example, in rooms which people only exist during working hours like an office. Overall, this control method is easy to apply. However, it is difficult to manage this control in emergencies such as those that frequently arise in hospitals [13]. Thus, for this work, Although this method could be used for specific room usage types like offices and consulting rooms with repeatedly scheduled occupations, it is not possible to implement it for other usage types such as regular care or isolation care room where there are variable occupancy records during the night.

2.2.4 Occupancy recording sensors

For both aforementioned strategies, we need to know the occupancy trend of the room. The recorded occupancies for this work are calculated via CO_2 detection sensors.

Generally, there are various kinds of occupancy sensors that is tracking the occupancy status of a room. These can be combined or used individually, resulting in different high precision. Basically, there are audio/infrared and motion sensors that can provide good accuracy when use in combination [13]. Also, the measurement of CO_2 is particularly suitable because CO_2 is representative of the lead gas that can be used for emissions caused by humans [14]. The pre-condition is that the only source of CO_2 in the room is people [15]. For the scope of this project, we use CO_2 detection sensors to rather relate the occupancy to CO_2 concentration and to have more precise ventilation control. However, the complex regulation of the control unit for the ventilation system, same as the utilization of sensors in order to record the occupancy status of the room is still a drawback for both explained strategies.

2.3 Requirements for the indoor climate in hospitals

As it is mentioned before, the standards and requirements for health care buildings and hospitals are quite different from other commercial buildings in which else than thermal comfort and indoor air quality there are some specifications for ventilation of contaminants and infections. Meanwhile, for the scope of this thesis we considered 4 different room usage types in hospitals:

1. Regular care room (patient room)
2. Isolation care room
3. Office room
4. Consulting and treatment room.

It is important to mention that there are various requirements like supply air volume flow rate for ventilation considering different usage types.

Although there are International recommendations and standards like ASHRAE, it also should be taken into account that the local or national standards and guidelines are needed to be met as well.

2.3.5 National and international requirements

There are some legal requirements regarding the operation of AHUs in the hospital that must be observed. Despite international standards and recommendations, there are also national ones issued as well. In Germany, they have geographical scope due to different climate conditions [5]. Referring to technical rules for the workplace there is a workplace ordinance in which it defined the objectives in general terms and is published by Federal Institute for Occupational Safety and Health [16]. Considering nationwide standards for room temperature, in order to avoid legal risks, we would apply DIN 1946-4 [3]. However, it is mentioned in detail in a study by J. Fischer that the state of the art regarding these standards and recommendations is not clear [5].

Also for international requirements, we took ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) into account. It is an American industry association but due to its international participation, it is considered worldwide [17]. There are more specific standards and guidelines in ASHRAE regarding the patient in comparison to German standards. However, because of the different requirements, they are not directly comparable [5].

Since, we consider different hospitals in two different countries, else than international ASHRAE standards we also take the German (DIN 1946-4 and DIN EN 16798-1) and Finish (Finvac guideline) guidelines into consideration. Table 2-1 shows the result for supply air volume flow rates taken from standards for selected rooms.

Table 2-1 Supply volume flow rate for different room usage types

Room usage types	German standards DIN 1946-4	Finish guideline Finvac	ASHRAE 170
	Minimum outdoor air $[m^3/h/person]$	Minimum outdoor air $[m^3/h/person]$	Minimum total air $[m^3/h/m^2]$
Regular care room	Not required	36	10
Isolation care room	100	No information	30
Office	Not required	21.6	-
Consulting and treatment room	40	72	15

2.4 Case study

This section first introduces the current state of the art in general and is followed by more details about the UKA and HUS case of study.

Currently, all rooms in both of these health care systems, especially those of our interest, patient room, isolation care room, consulting and treatment room, and offices are always ventilated with a constant ventilation flow rate and no demand-controlled strategy is applied for the ventilation system. If there is no occupancy in any of those, still they are ventilated with full volume flow. In other words, the ventilation system is operated regardless of the occupancy of hospital rooms.

2.4.6 University Hospital Aachen

The University Hospital Aachen (UKA) as one of the cases of study for this thesis, is a great hospital located in the west part of Germany and approximately has 1300 beds.

A considerable point about this hospital is, because of the existence and operation of an old air handling unit, the supply air is regulated by 2 ducts, one for cold air and the other one for heated air. Thus, the supply air temperature is not constant, and it is heated or cooled depending on the outside ambient temperature and requirements of the room. Additionally, there are mixing boxes that regulate the supply air temperature to a specific temperature to enter the room. The interpretation of this regulation is not known, which is not the context of this work, and to simplify the model we assume a constant supply air volume flow. Furthermore, when the relative humidity of the outdoor air is low, the supply air is humidified. Moreover, rooms are equipped with decentralized heating, which is the primary heat source when heating represents. The decentralized cooling system is not modeled which means that the ventilation and cooling process is done only by the air handling unit.

2.4.7 Helsinki University Hospital

It is a part of formally the Hospital District of Helsinki and Uusimaa, which is made up of five hospital areas where Helsinki University Hospital is one of those which is the other case study. Additionally, the hospital is one of the largest hospitals in Europe.

In contrast with UKA, the operating air handling unit system in the HUS building is regulated by only one duct. Therefore, there is no mixing occurs in this system. So, the temperature of the supply air that reaches the room is fixed and constant. It is not possible to adjust a controller for supply air temperature for this case as it is considered to be the same as the existing operating system with a constant supply air temperature. To maintain the optimum thermal comfort and air quality in the rooms, it is only possible to control the supply air volume flow rate.

Chapter 3
Methodology

3.1 Development of ventilation strategies

The development of the demand-controlled ventilation strategies is based on comprehensive literature research on legal requirements and guidelines recommended by various national institutions and international viewpoints. A suitable approach for demand-controlled ventilation and schedule-based ventilation in hospitals will be identified as well. For this purpose, the current situation of the hospitals is provided, and subsequently, compared with the DCV strategies developed.

We aim to achieve maximum energy savings by applying demand-based ventilation methods while meeting all the discussed legal requirements. As the requirements vary for different functional types of room, the ventilation strategy implemented must also be adapted to the room usage type.

Basically, a decrease in the supply of outdoor air adjusted to each room is aimed through the development of strategies that could save a remarkable amount of energy. However, a change in the fresh air flow rate influences the indoor thermal climate by changing the heating and cooling provided by the HVAC system. Also, it would affect the indoor air quality as well. A precise measurement of the air demand is needed to maximize the energy-saving potential while meeting the requirements. Since this is not known in advance, the use of control by the feedback of the actual variable for applying DCV is essential.

3.1.1 Identification of the controlled variables

To identify the control variables we need to comply with the requirements provided by standards not to have any legal risks. Outdoor air volume flow rate as the main variable for design needs to be maintained in an appropriate amount to dilute the building emissions. Regarding these emissions, for the scope of the project, CO_2 is considered as the leading gas for impurities caused by people. The limit values of CO_2 are specified for the conditioned space by the standards[18],[19],[6]. Therefore, we developed our strategies considering the CO_2 concentration inside the room with the advantage of natural ventilation that can lead to an additional reduction of the outdoor air volume flow[5].

In order to select the outdoor air volume flow rate for each room usage type, a comparison between all standards and guidelines is done (Table 2-1). Therefore, the appropriate value is taken to satisfy all the requirements. Consequently, in the table below all the chosen values are implied. Due to the fact that demand-controlled ventilation is going to be simulated, all the given values are converted to a per-person basis. The isolation care room as the most critical case is supplied with the greatest volume flow.

Table 3-1 Selected requirements of outdoor air volume flow for each room

Rooms	Minimum outdoor air $[m^3/h/person]$
Regular care room	36
Isolation care room	100
Office	21.6
Consulting and treatment room	72

The other controlling variable we took into consideration in our case is the room temperature which is should comply with the standards as well. The limit values of the room air temperature are considered 22°C as the lower bound and 26°C for the upper bound for all usage types. An indication of standards and guidelines regarding room air temperature is given in Table 3-2 [5]. If the permissible temperature is exceeded, heat should be dissipated or in the case of lower temperature, the heating should be applied. For this purpose, we propose control of the supply air volume flow to apply heating or cooling if the permissible temperature is exceeded.

Additionally, for UKA because of the possibility of controlling supply air temperature, a controller is devoted to that. In case of exceeding temperatures from considered boundaries, a supply of outdoor air with lower or higher temperatures is adjusted in advance. If the supply air with adjusted temperature was not adequate for heating or cooling, the increase of supply air volume flow will take place.

Table 3-2 Standards requirements for room air temperature

Room usage type	T_{min}[°C]	T_{max}[°C]	Satandard
OP	19	26	DIN 1946-4
Isolation care room	22	26	DIN 1946-4
Regular care room	20	26	ASHRAE
Office	20	26	ASHRAE
Consulting and treatment room	22	26	DIN 1946-4

As another controlling variable, air humidity can be determined with the help of humidity sensors. The primary sources of humidity are people, processes, and supply air. The humidity content of the supply air can be adjusted using air handling systems[20]. For increasing numbers of people, the supply air volume flow rate should also be increased by the control system, whereby excess humidity can be removed. If the room humidity is too low, the supply air can be humidified in the same way. Since this is not considered in this project, the limit values for the relative room humidity are not presented in the following.

3.1.2 Determination of CO_2 concentration for occupancy detection

As mentioned before, we can detect the concentration of CO_2 by using some sensors. We take this measured data for the calculation of the occupancy inside the rooms. The CO_2 concentration can be determined for the stationary case as a function of the outdoor air volume flow via a mass balance for the CO_2 in the room. Occupancy detection based on the CO_2 concentration is also based on this approach [21], [22]. Here the applied equations for the determination of CO_2 concentration are presented. Also, the derivation of the equations is provided in a study by J. Fischer in more detail [5].

Basically, the mass balance is provided as below and a person as a CO_2 source is represented by $\dot{n}_S$.

$$\frac{dn}{dt} = \dot{n}_{in} - \dot{n}_{out} + \dot{n}_S \qquad \text{(Chapter 3.1)}$$

Thus, the difference in the CO_2 content to the outside air $x - x_0$ is determined and expressed in ppm.

$$x - x_0 = 10^6 \,.\frac{\dot{V}_S}{\dot{V}_O} \qquad \text{(Chapter 3.2)}$$

According to a study, CO_2 generation by a human is affected by their sex, age, and activity [23]. Additionally, for not very active occupants the average generation rate per person considering different room usage types is between 0.004 l/s to 0.005 l/s [24].

Figure 3-1 shows the determined ΔCO_2 concentration difference from indoor air to ambient as a function of the outdoor air volume flow. However, the measurement accuracy of the sensors must be considered [5].

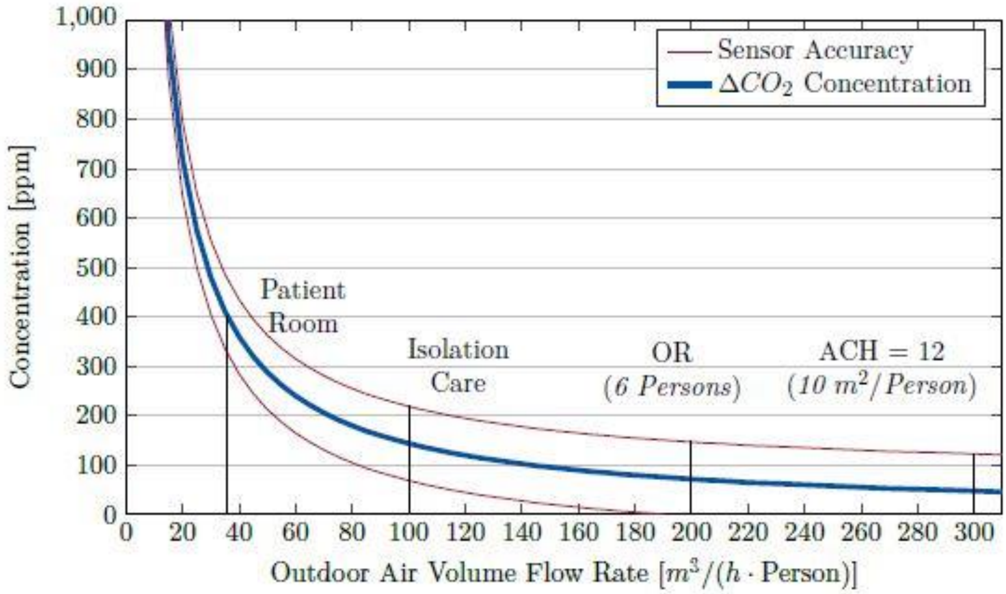

Figure 3-1 ΔCO_2 concentration as a function of the fresh air flow rate [m^3/h/person][5]

In addition, an isolation care room and a regular care room are marked as examples. The required fresh air flow rate of 1200 m3/h in the operating room is shown as an example for the presence of 6 persons [5]. The concentration is also shown at an air exchange rate of 12, as the upper boundary limit applied to the supply volume flow rate controller. It can be seen that high outdoor air volume flows lead to a low CO_2 concentration, which means that detection is no longer possible, reliably. A change in CO_2 concentration at high values leads to a smaller effect on the outdoor air volume flow.

In the operating theatre, Since the pattern of the flow of the supply air is important (whether it is laminar or turbulent), a reduction would lead to a change in the flow field. In addition, load peaks occurring in the room should be dissipated without delay at all times. Moreover, the measuring accuracy of CO_2 sensors for high fresh air volume flows must be taken into account. As a result, demand-controlled ventilation on the CO_2 concentration basis cannot be implemented in the operating theatre [5].

For all the rooms (see Table 3-1), we propose the use of demand-controlled ventilation, using CO_2 concentration. The outdoor air volume flow rate is controlled by implementing a PID controller, using the concentration difference ΔCO_2 to the outdoor air for identifying the occupancy. Since the AHU cannot provide unlimited outdoor air, an air change rate of 12 is defined as the upper limit.

Finally, When a room is not occupied, a lower limit value of the outdoor air volume flow is set at 0.72 $[m^3/h/m^2]$ for all the rooms to dilute the emissions. Due to the abovementioned, Since there is no occupancy in the room as the source of CO_2 emission, after a while the supply air component has the same CO_2 concentration as the room air and therefore does not influence the CO_2 concentration in the room.

3.2 Description of the simulation model

There are some assumptions taken into account during the development of the model in the AixLib library. For sake of simplicity in our simulations, here some of the considered assumptions are given. First of all, since we are going to consider a single room in simulations, the interaction of the room with other surrounding rooms is neglected. Thus, the room is considered isolated and only has heat transfer from the surrounding without the influence of any other room on it. Second, pressure drop inside the air ducts is constant. In reality, the pressure drop from AHU to the room will increase along the duct, but for simplifying the simulations the pressure drop is considered constant.

For simulation of the ventilation strategies, a building model for both cases is developed in Dymola based on the low order building model for the Modelica library AixLib [25]. The behavior of the room and the systems are already implemented. In order to keep the model as close as possible to the existing building, a calibration process is done by our team using measured data from hospitals. Here in Figure 3-2 and Figure 3-3, a result of calibration for room air temperature is provided for each case.

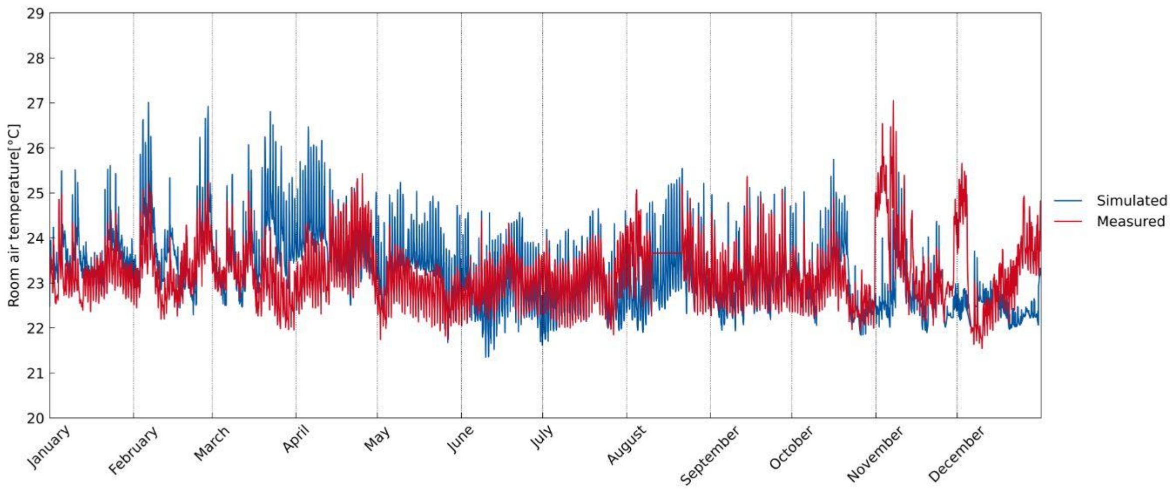

Figure 3-2 Room air temperature comparison for calibration (HUS Isolation care room)

Considering Figure 3-2, it is conveyed a good and well-matched data calibration for the model. However, there are some out-of-range data in calibrating the model, but the general trend shows an accurate overall simulation.

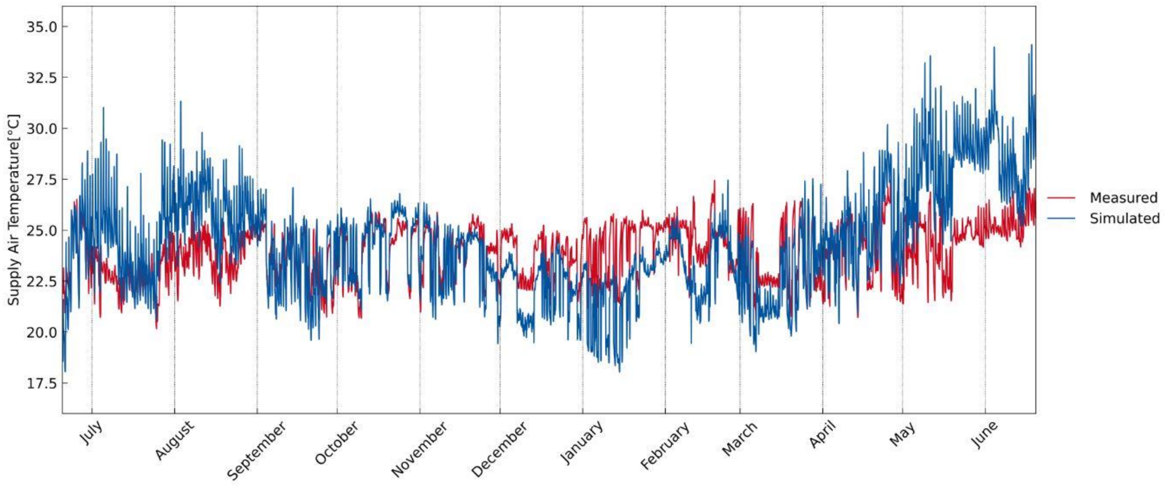

Figure 3-3 Room air temperature comparison for calibration (UKA Regular care room)

The result of calibration for the regular care room in UKA as well as the isolation care room is not as precise as in other cases (the data for calibration of other rooms is given in Appendix A). This could happen because of unreliable and untrustworthy measurement of some data in these rooms; because even in the office and the consulting room where there is a very accurate calibration is done, still the data for room air temperature for reference case is not reliable. It might occur due to unreliable supply air temperature records. Since it is out of the scope of this thesis, here the plots are mentioned just to show the accuracy of the simulation data. Additionally, data on weather, occupancy, and operation of air handling units are also available. Despite heating and cooling provided by AHU, decentral heating is also available in the rooms, but decentralized cooling is not considered in model development. The CO_2 content in the ambient air is 402 ppm. In detailed boundaries for each room and hospital are explained in the following.

3.2.3 Controlling boundaries in HUS

A reference case is simulated based on the existing data of the real case. In this case, the outdoor air volume flow rate is constant and reported for each type of room in Table 3-3.

Table 3-3 Reference supply air volume flow rate

Rooms	Volume flow rate $[m^3/h/m^2]$	Volume flow rate $[m^3/h/m^2]$
	HUS	UKA
Regular care room	11.69	9.08
Isolation care room	21.82	10.58
Office	14.9	22.29
Consulting and treatment room	15.03	14.54

The supply air is centrally tempered and made available at 21.5°C. In addition, there is a decentral heater operation that provides heat to the room. Since all field checks have shown a maximum setting for thermostats, this is assumed for the whole period in the HUS model. The temperature setting of the thermostats is very high in the medical department to which the rooms belong. The decentral heating is operated at a constant temperature of 28°C. The reference case is going to be compared with the developed ventilation strategies. In HUS, a PID controller is dedicated to demand-control of the outdoor airflow rate. As the supply air temperature is constant and it is possible to be adjusted for the DCV case, we decided to use 18°C in order to save more energy compared to the supply air temperature in the reference case. Figure 3-4 Target values for operating temperature (The shaded area describes the target range)[26]. is providing a guideline from Finish recommendations and presents the technical target values for the thermal environment for the indoor air temperature considering ambient air temperature, which is contemplated to set the temperature boundaries for volume flow controller[26].

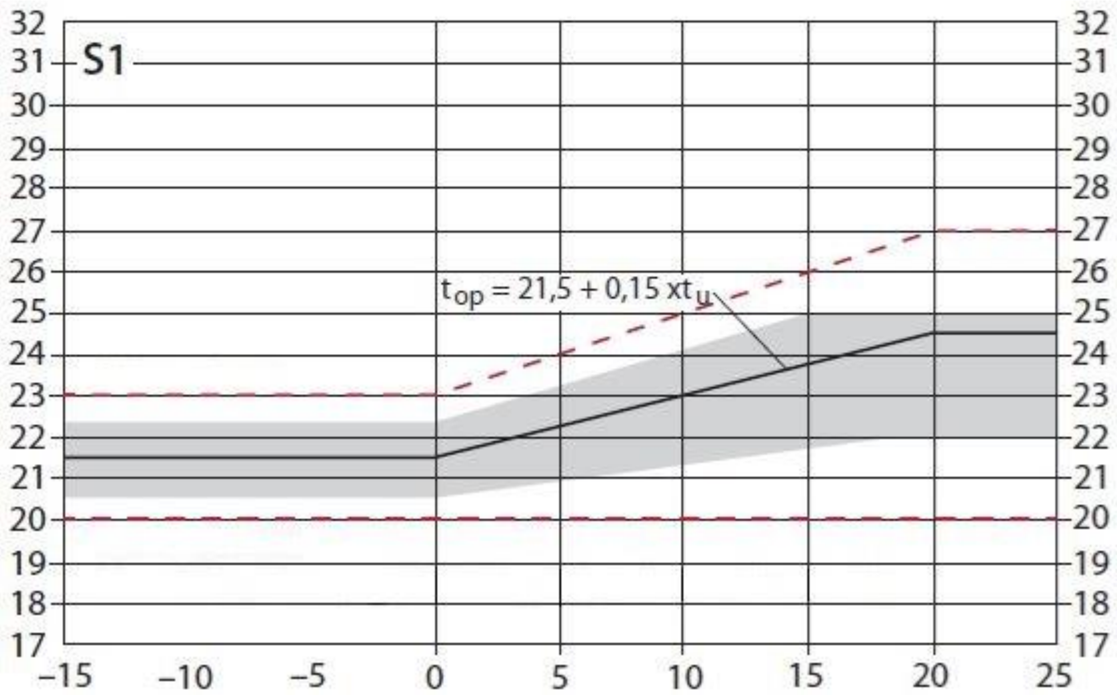

Figure 3-4 Target values for operating temperature (The shaded area describes the target range)[26].

A minimum outdoor air volume flow of 0.72 $m^3/h/m^2$ is the lower boundary for the non-occupied condition in order to emit the emissions of the room. Also, it is controlled by an air exchange rate of 12 as the upper boundary limit. The result for the room air temperature should be comparable to the reference case in order to ensure the comparability of the energy demand and also to reflect the user behavior. Therefore, in deviation from the proposed strategy, an upper temperature of 25°C is aimed mostly during summer when the ambient temperature is above 15°C (Figure 3-4). This is sufficient in comparison to the reference case to dissipate excess heat. Moreover, in Figure 3-5 the ambient air temperature plot is available for the considered period In Helsinki.

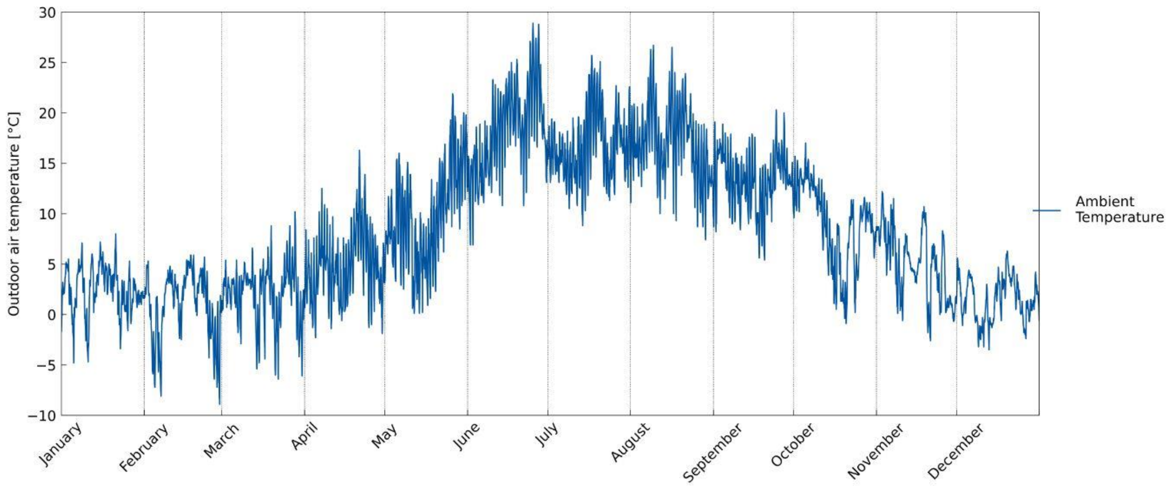

Figure 3-5 Dry-bulb temperature for HUS model

The temperature boundaries for decentral heating operation are following the very bottom line of the gray area in the guideline (Figure 3-4), where the valve is fully open. Two degrees increase in this value is considered as the boundary for the decentral heater to stop operating. Interpolation is done for the calculation of the heating power provided in between these limits. If the simulation shows that these assumptions do not allow effective regulation of the thermal indoor climate, the heating and cooling behavior must be adjusted.

Regarding demand-controlled ventilation, there is a recommendation for the protective environment in ASHRAE which can be implemented only for isolation care rooms. in this guideline, we need to take the occupancy state into account. In this strategy, we only consider if the room is occupied or not. The occupation data more than 0.5 $person$ is assumed as occupied and lower than this amount is considered non-occupied. For applying this strategy there will be a reference supply air volume flow in case of occupancy existence and adjusting the minimum volume flow rate of 0.72 $m^3/h/m^2$ during the non-occupied time. Also, in order to keep the room air temperature in the thermal comfort region, the supply air controller is adjusted for this strategy as well.

Lastly, as a time-controlled strategy, the scheduled-based ventilation is applied for office and consulting and treatment room in which the reference volume flow rate is devoted only 12 hours a day containing working hours. The rest of the day as there is mostly no occupancy in the rooms the ventilation takes place with the minimum volume flow rate.

3.2.4 Controlling boundaries in UKA

Despite HUS, the supply air temperature is variable for UKA as the situation is different with ventilation in this health care system (2.4.6). Since it is possible to control supply air temperature, a controller is allocated for this purpose only in this model. The boundaries and set points in this controller are applied considering the guideline and recommendations for indoor environmental input parameters for the design and assessment of energy performance of building in Germany with respect to ambient air temperature (Figure 3-6 below). The upper boundary set point for the controller concerning high ambient air temperature during the warm season is 25.5°C and subsequently, the lower set point is set as 22.5°C for lower ambient temperatures. These values are also taken for the fact of the responding time of the control system.

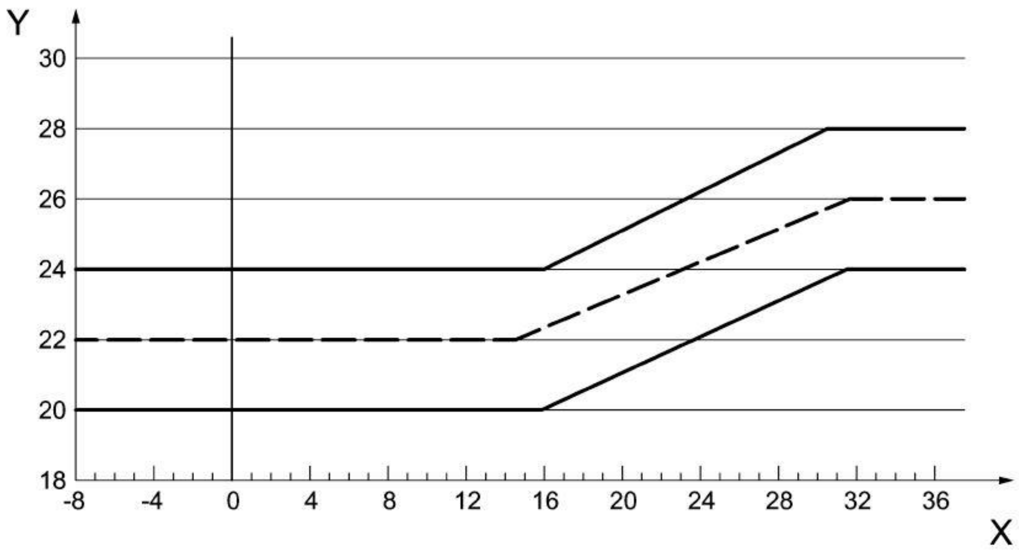

Figure 3-6 Comfort room temperature (dashed line) with the permitted tolerance range for operative room temperature (solid line) as a function of hourly mean outside air temperature[27].

Here also the dry-bulb temperature in Aachen for the UKA model is provided as well (Figure 3-7).

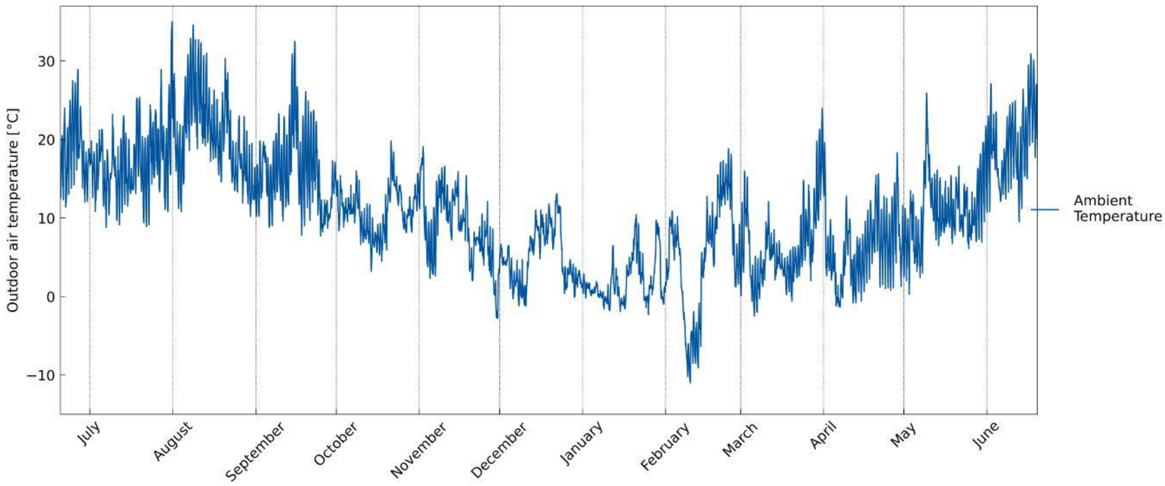

Figure 3-7 Dry-bulb temperature for UKA model

Also, for considered room usage types the reference ventilation flow rates are reported from measurements in (Table 3-3). Moreover, decentral heating is existing in this case too. Controlling the decentral heater is also done with respect to the guidelines. For ambient temperatures lower than 24°C, the lower boundary controlling temperature is 22.5°C, where the heater operates in a full load. Consequently, in such ambient temperature, the upper bound limit is set at 23 in order to close the valves of the heater. Similarly, for outdoor air temperatures above 32°C, the lower and upper bound limits are set as 24.5°C and 25°C. for the ambient temperature between 24°C and 32°C, a linear interpolation is done between values adjusted for boundaries. There is also a PID controller set for outdoor air volume flow rate same as the one used in HUS. Due to the thermal loads, when the room air temperature exceeds the considered thermal comfort zone also when the supply air temperature with the allocated supply volume flow rate is not enough to compensate for it, the controller increases the supply volume flow in order to keep the room air temperature in the thermal comfort region. Additionally, the supply air temperature boundaries are set as 18°C for the minimum and 28°C as the upper bound not to maintain uncomfortable conditions for people in direct exposure to the supply air [28].

Chapter 4
Results and Discussion

The strategies are simulated based on the model data and compared with a reference case (3.2). The behavior of the air handling units and the indoor climate is simulated for a period of one year. The period is different among the two cases due to the availability of the measured occupancy data, for the HUS model the period is 01.01.2020 till 31.12.2020 and for the UKA this period is from 20.06.2020 till 20.062021. Therefore, the shape of the plots is distinguished since the warm and cold seasons are located differently during these periods.

4.1 Results for HUS

4.1.1 Regular care room

Considering the aforementioned parameters and variables for the reference case and selected values for developed strategies, here the results are provided for the energy consumption of a regular care room.

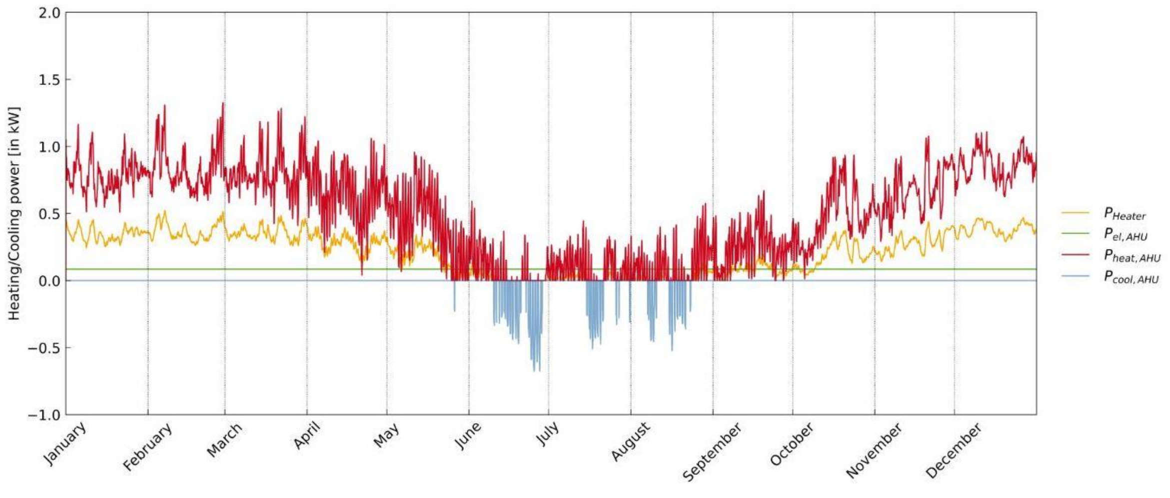

Figure 4-1 Reference energy consumption of regular care room (HUS)

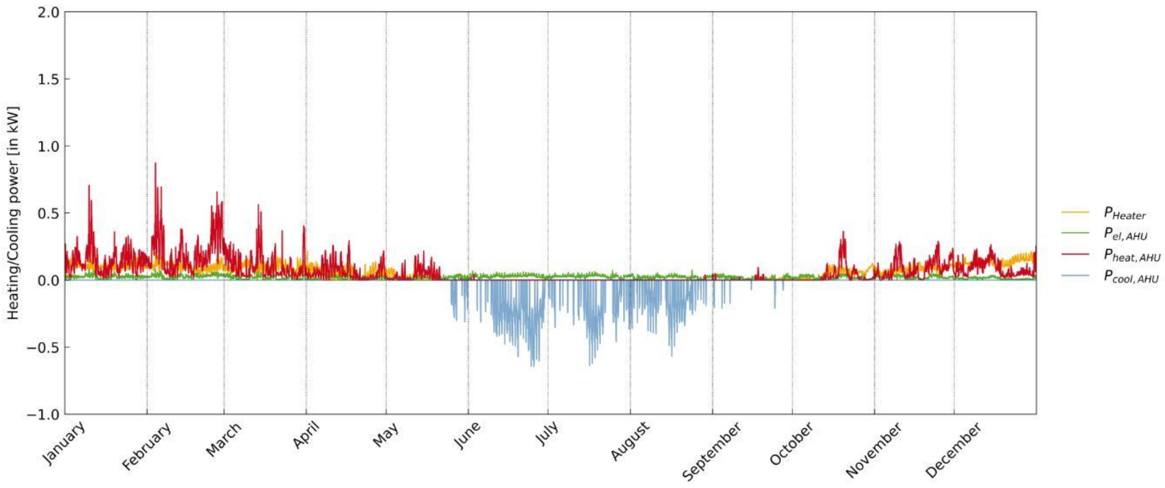

Figure 4-2 DCV strategy energy consumption of regular care room (HUS)

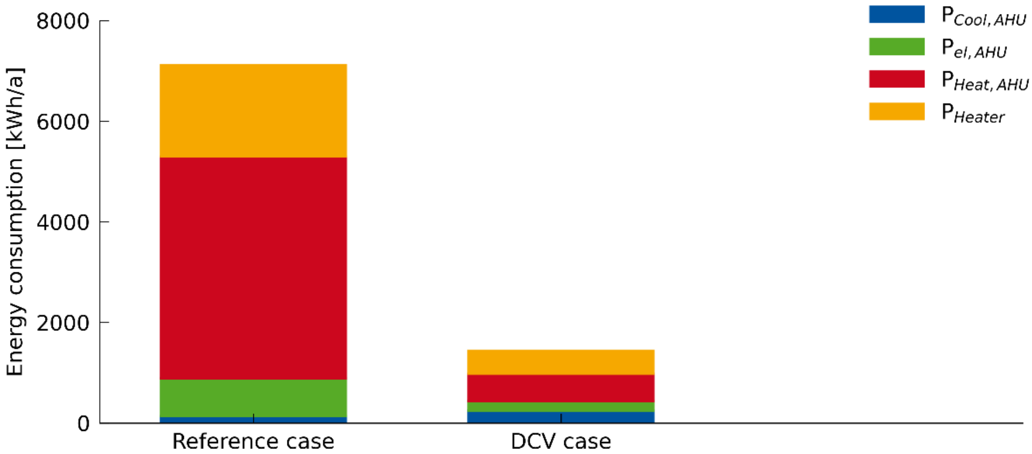

Figure 4-3 Cumulative energy consumption of 2 strategies for regular care room (HUS)

Table 4-1 Regular care room energy consumption and saving (HUS)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	131.8	4409.44	752.91	1821.94	7116.09
DCV case	246.47	545.44	189.28	455.36	1436.55
Saving %	-87%	87.63%	74.86%	75.01%	79.81%

As is visible in the figures and table above, there is a major decrease in energy consumption of the AHU same as the decentral heater in the DCV strategy compared to the reference case. This reduction is due to the lower outdoor air volume flow rate adopted which means lower fan work and lower energy needed to heat up the air. On the other hand, we would expect a higher cooling power of AHU due to the lower temperature of supply air considered for the

DCV strategy. In Figure 4-4 the outdoor air volume flow rate for both cases is provided. Since in reference and existing situation the AHU works with high and constant outdoor air volume flow, it is shown how this value changes in the demand-controlled ventilation method compared with the reference case.

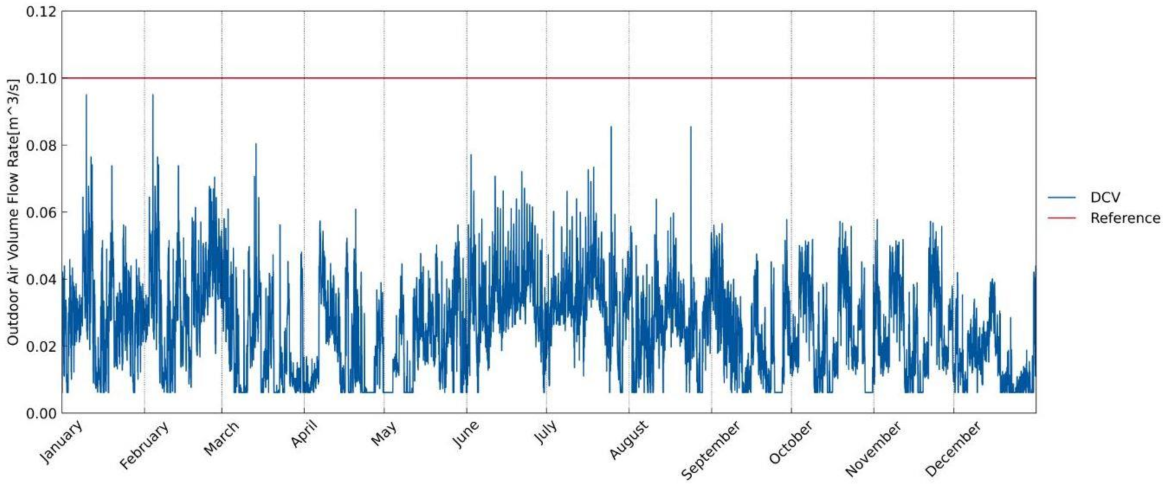

Figure 4-4 DCV strategy and reference outdoor air volume flow rate of regular care room (HUS)

The thing that is in a high level of importance is whether the DCV strategy could meet the thermal comfort requirements of the room or not. In order to see the result for controlling thermal comfort and indoor air quality, here the plots for room air temperature and CO_2 level of the room are taken into account.

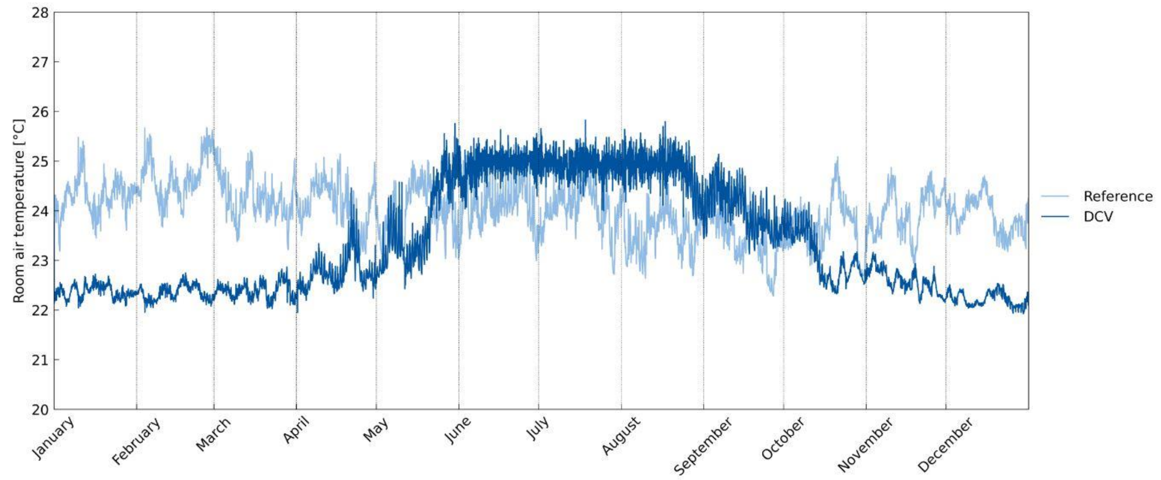

Figure 4-5 DCV strategy and reference room air temperature of regular care room (HUS)

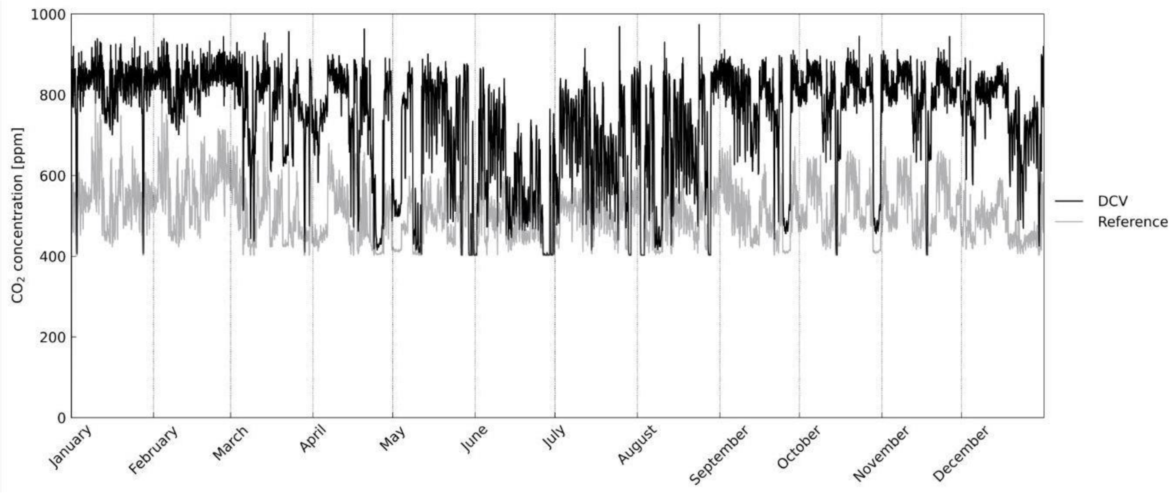

Figure 4-6 DCV strategy and reference CO_2 concentration of regular care room (HUS)

It is expressed that the room air temperature would be kept in a comfort zone of 22°C to 26°C as defined to be considered as boundaries. A notable difference in room air temperature behavior during the year is comparable between the 2 scenarios. In DCV strategy, since the focus is on boundaries and not exceeding those, mostly during hot and cold seasons the room air temperature fluctuates near the boundary. But, in the reference case, as there is a constant outdoor air volume flow rate with a constant supply air temperature the room air temperature almost stays in a constant range during the year.

Considering indoor air quality, a small increase happens in the CO_2 concentration of the room in the DCV case. Lower outdoor air volume flow rate and relatively lower fresh air in the room cause the increase. However, it is worthful to mention that the air quality is met for concentrations lower than 2000 ppm since it is not considered harmful nor a contaminant [6]. Even though, the concentration is lower than 1000 ppm for the whole period. It expresses that indoor air quality is maintained completely without any consideration needed in this strategy as well as reference case [29].

4.1.2 Isolation care room

In the isolation care room, as there were 2 types of standards available, we took both into account for the simulation. In one case we offer a DCV control regarding the occupancy of the room. In the other case, the occupancy state is considered in which when the occupation of the room is more than 0.5 $person$ the reference amount of outdoor air volume flow rate (21.82 $m3/h$) is dedicated while for lower occupations, the minimum ventilation rate is provided. Firstly, in the following figures, the energy consumption of the air handling unit and decentral heater for the period is expressed.

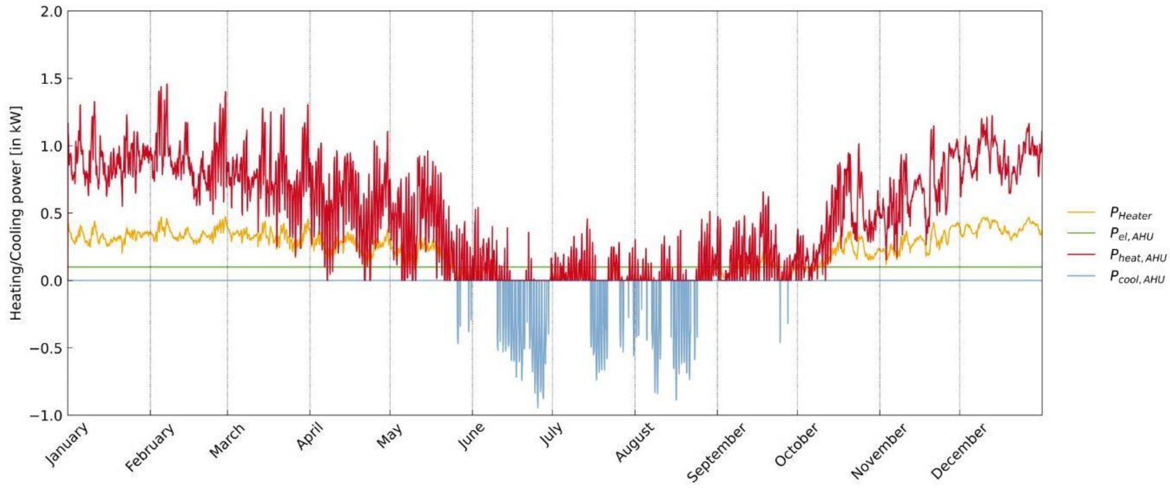

Figure 4-7 Reference energy consumption of isolation care room (HUS)

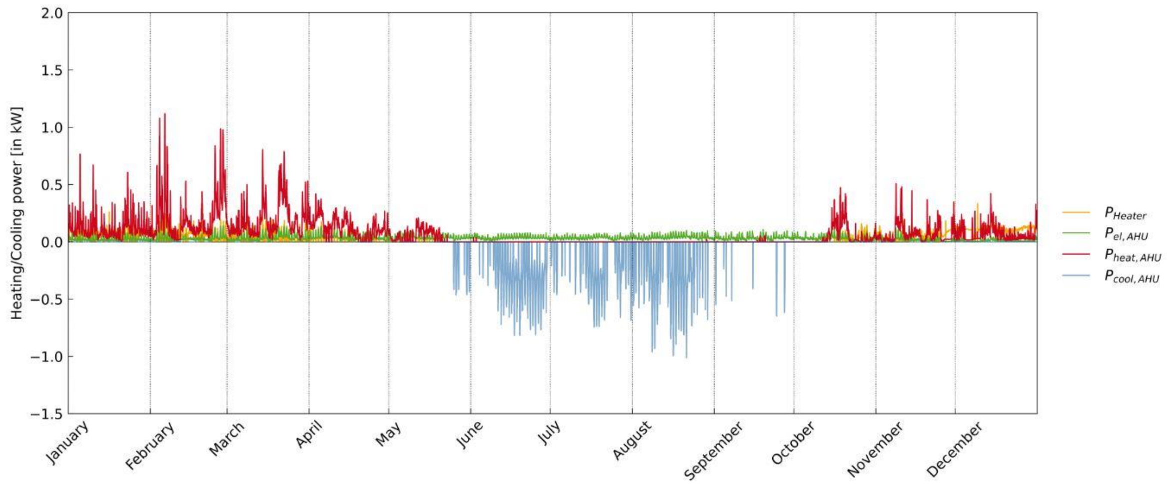

Figure 4-8 DCV strategy energy consumption of isolation care room

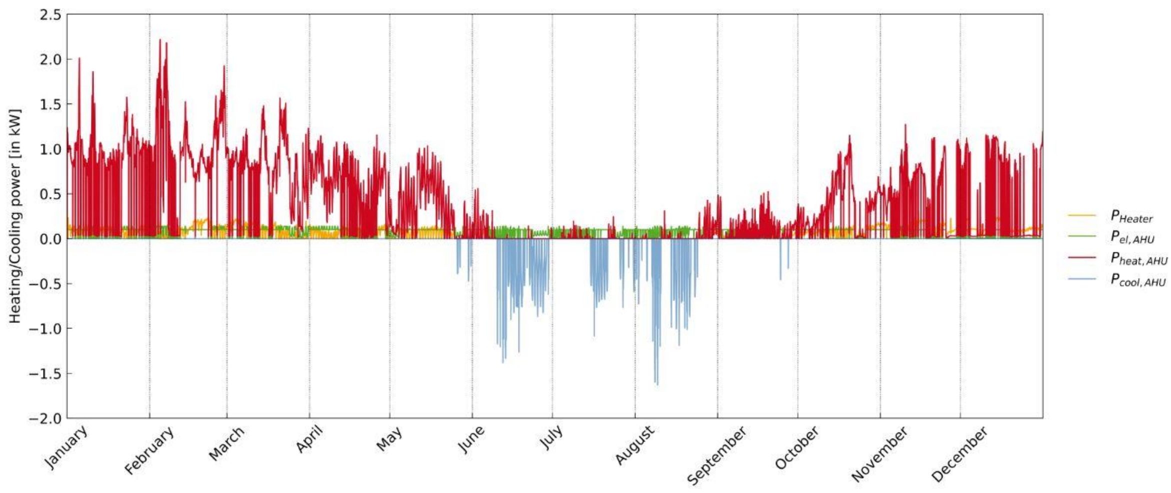

Figure 4-9 Occupancy state strategy energy consumption of isolation care room

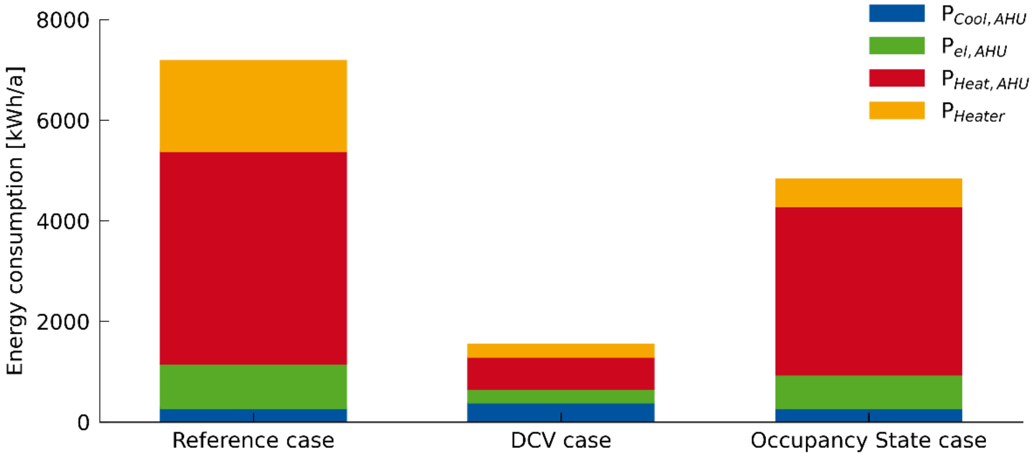

Figure 4-10 Cumulative energy consumption of 3 strategies for isolation care room (HUS)

Table 4-2 Isolation care room energy consumption and saving (HUS)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	278.97	4232.24	880.75	1781.65	7173.61
DCV case	392.63	630.5	247.73	239.27	1510.13
Occupancy state case	277.68	3339.21	671.72	528.77	4817.38
Saving for DCV %	-40.74%	85.10%	71.87%	86.57%	78.95%
Saving for occupancy state %	0.46%	21.10%	23.73%	70.32%	32.85%

Comparing DCV and reference cases, as it is expected there is a reduction in all power sectors except cooling power of AHU which is due to lower supply air temperature devoted to DCV strategy. Although in the occupancy state strategy there are higher peaks for air handling unit power because of a higher ventilation rate in occupied periods, the cumulative energy consumption during the year is still lower than the reference case (Figure 4-10).

Likewise previous case, here in Figure 4-11and Figure 4-12 it is possible to compare the outdoor air volume flow rate of different strategies.

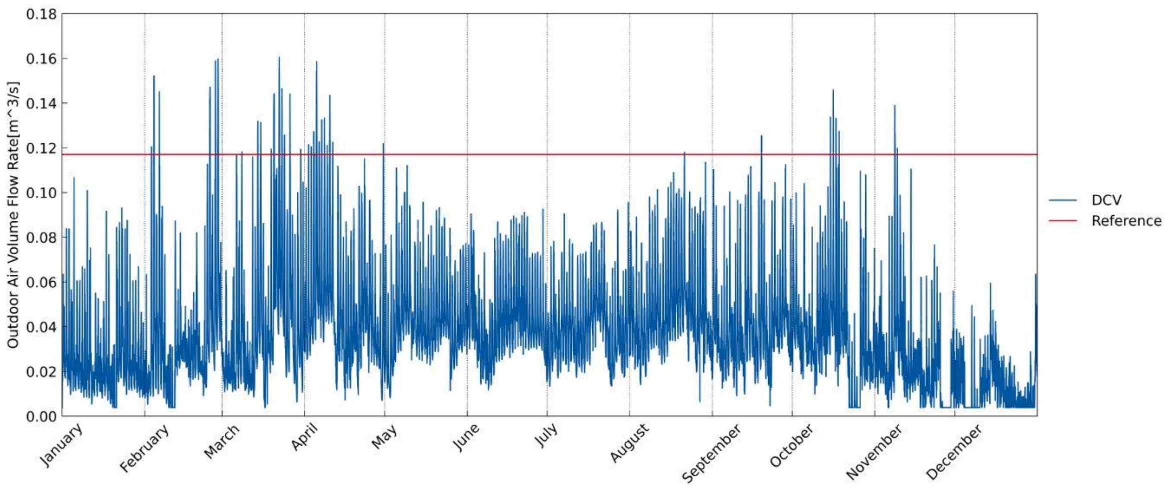

Figure 4-11 DCV strategy and reference outdoor air volume flow rate of isolation care room (HUS)

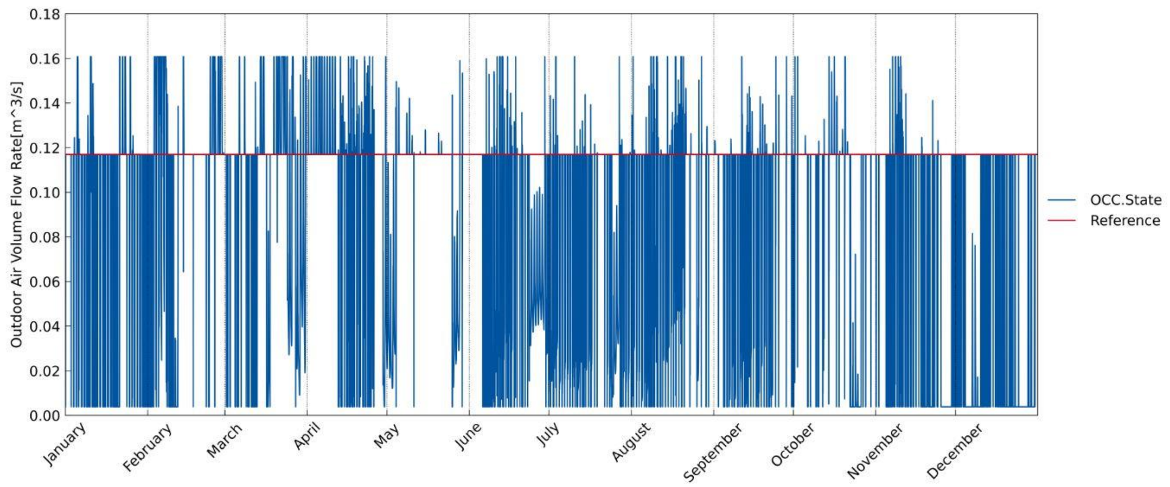

Figure 4-12 Occupancy state strategy and reference outdoor air volume flow rate of isolation care room (HUS)

Considering thermal loads in the room, there are some points during the year in which the outdoor airflow rate exceeds the reference case because of the controllers applied to the model to maintain the room's thermal comfort. But, overall electric consumption of the fans is lower than the existing situation.

In order to keep the thermal comfort of the room, it is decided to use the same supply air temperature of the reference case for the occupancy state strategy. Therefore, in Figure 4-13 and Figure 4-14 the room air temperature of these two cases is provided.

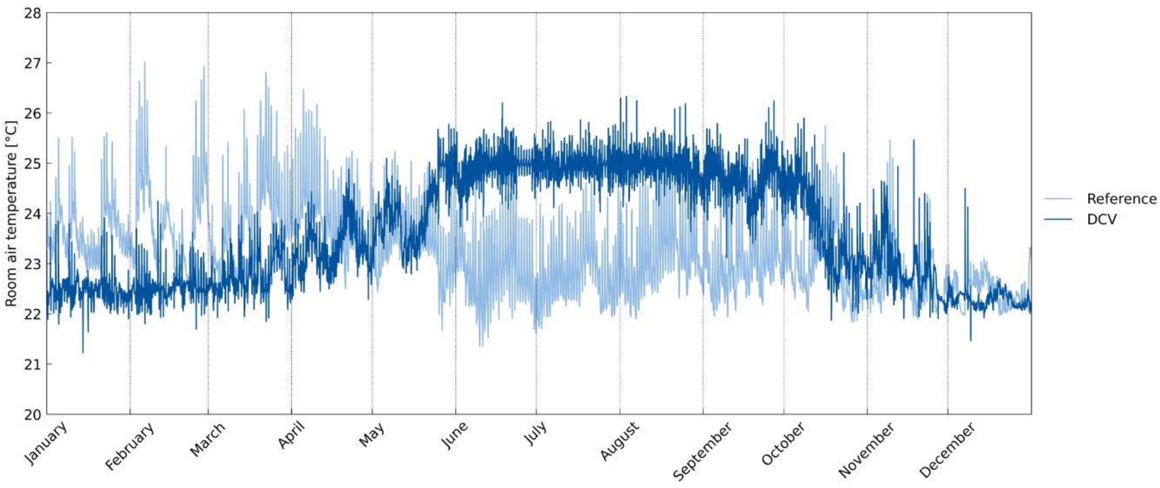

Figure 4-13 DCV strategy and reference room air temperature of isolation care room (HUS)

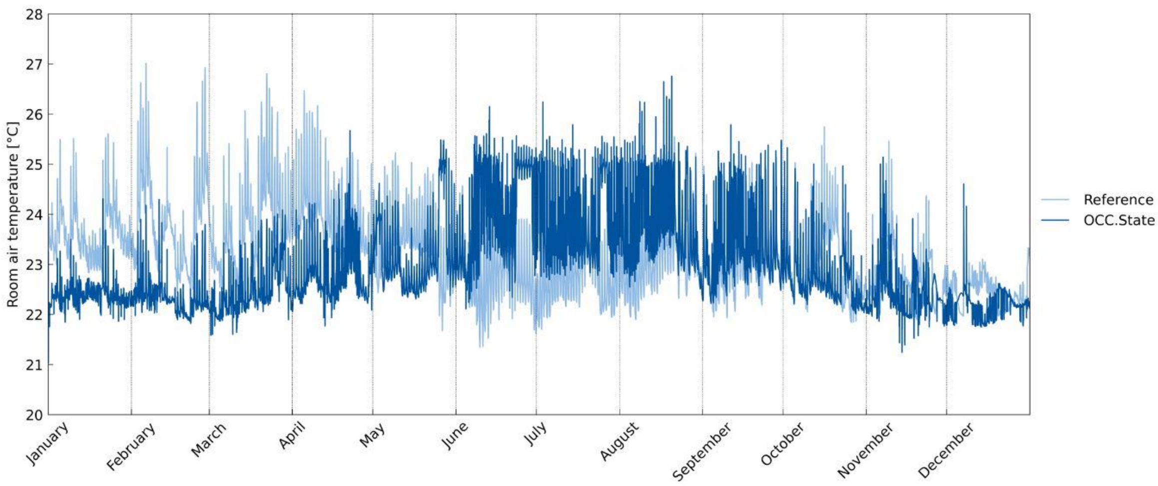

Figure 4-14 Occupancy state strategy and reference room air temperature of isolation care room (HUS)

Regarding indoor air quality, CO_2 concentration plots are provided in the following figures. On one hand, same as regular care room, the indoor air quality is maintained during the whole year for both strategies. On the other hand, there is a lower CO_2 concentration difference among DCV strategy and reference simulation compared to regular care which is due to lower occupation of the room and higher applied supply air volume flow rate regulated to this room usage type in guidelines. A set of plots is given in Appendix B regarding the visualization of occupancy in all the rooms. Additionally, there is some sharper increase in CO_2 concentration of occupancy state strategy in comparison to DCV, which could happen because of dedicating minimum ventilation rate to occupancies lower than 0.5 person as well as higher volume flows for occupied periods in DCV method.

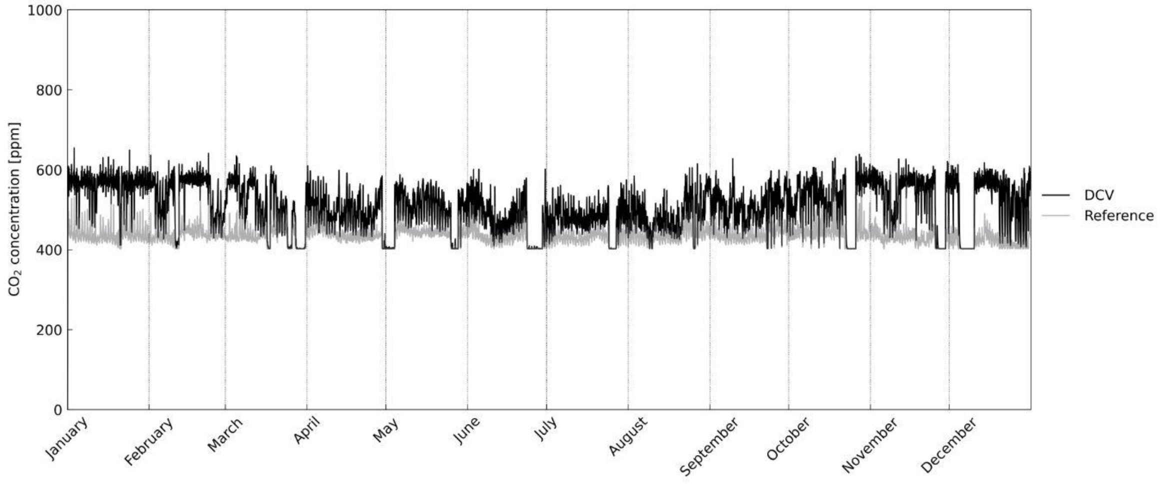

Figure 4-15 DCV strategy and reference CO_2 concentration of isolation care room (HUS)

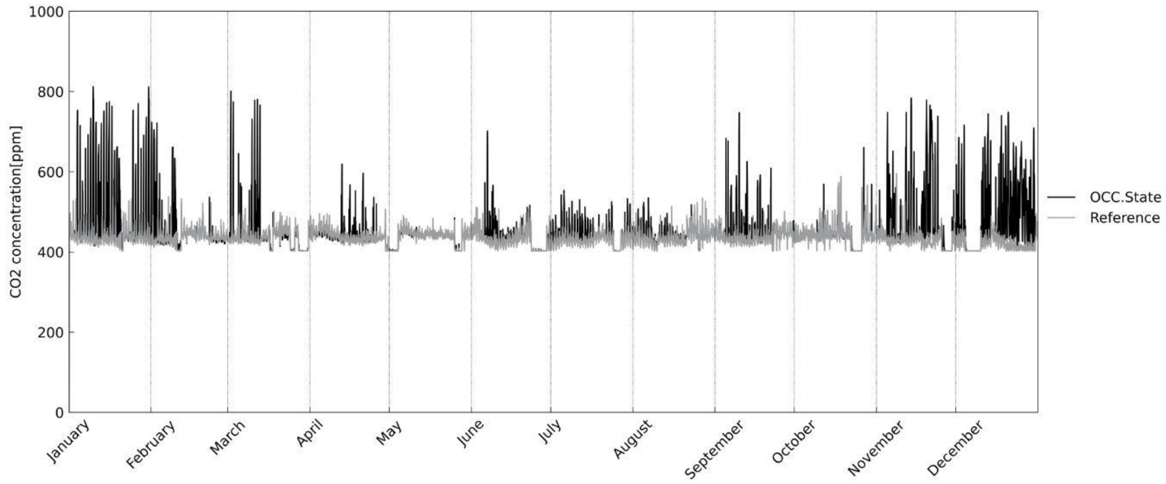

Figure 4-16 Occupancy state strategy and reference CO_2 concentration of isolation care room (HUS)

4.1.3 Office room

Considering the occupancy trend, there is a scheduled behavior in some sort of room usage types like office and consulting and treatment rooms. This schedule trend of occupation is following daily official hours in which there is almost occupancy detected only during working hours. This trend of occupation brought a possibility to simulate the schedule-based ventilation control that maintains the reference dedicated outdoor air volume flow rate for 12 hours per day during working hours and only provides minimum supply ventilation for rest of the day. Here for the office room, the schedule-based ventilation strategy is simulated as well as the DCV case. In flowing figures, the result for energy consumption of AHU and decentral heater during the year 2020 for each strategy is shown.

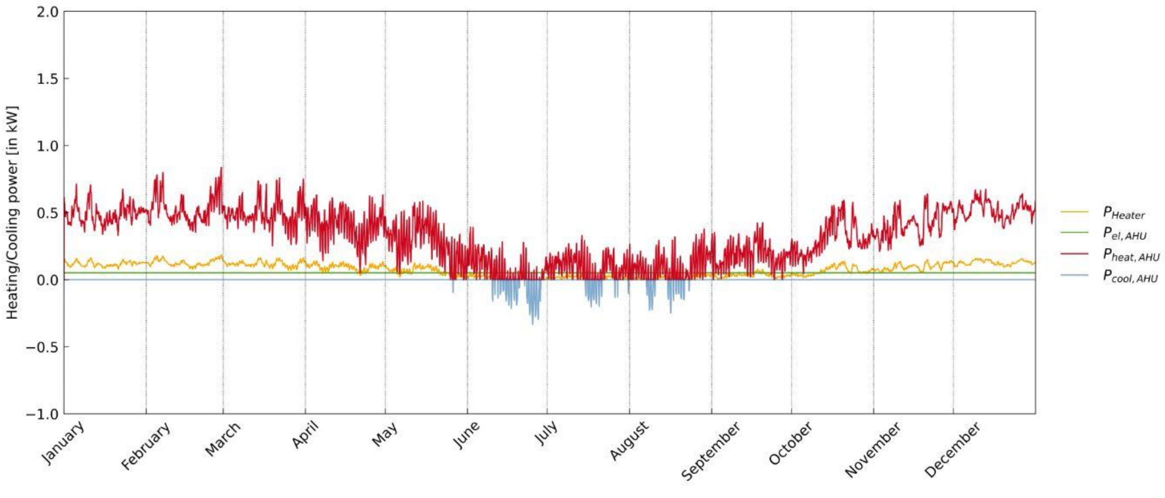

Figure 4-17 Reference energy consumption of office room (HUS)

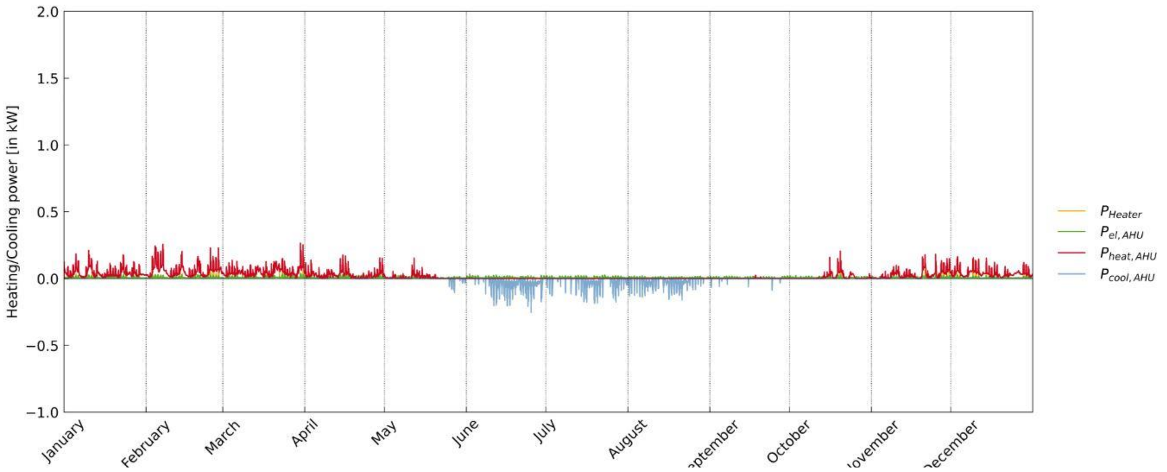

Figure 4-18 DCV strategy energy consumption of office room (HUS)

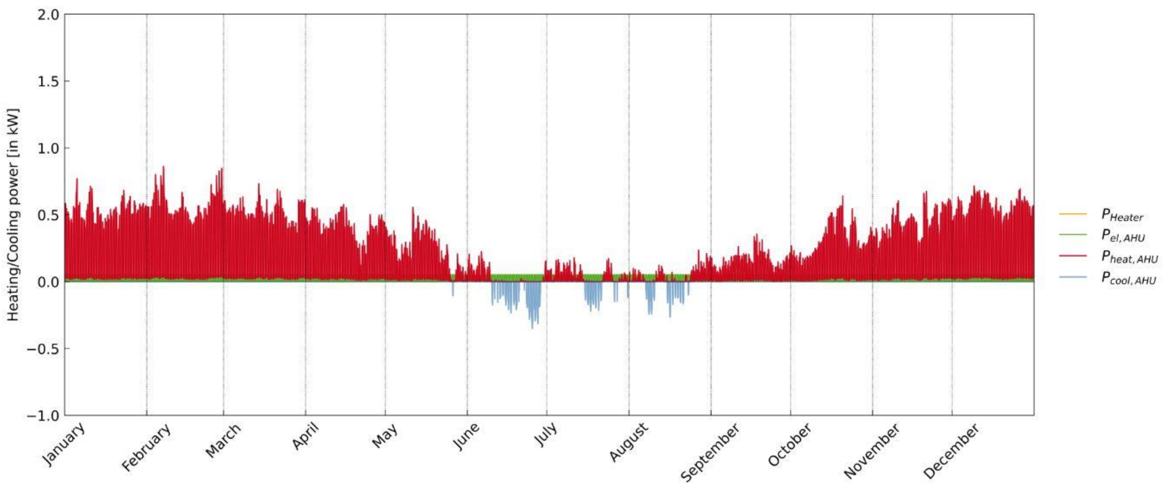

Figure 4-19 Schedule-based strategy energy consumption of office room (HUS)

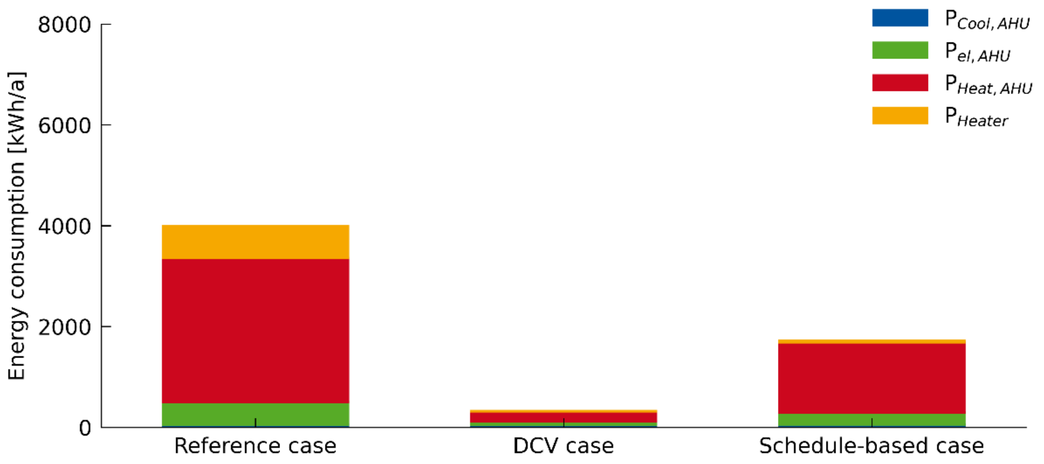

Figure 4-20 Cumulative energy consumption of 3 strategies for office room (HUS)

Table 4-3 Office room energy consumption and saving (HUS)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	51.15	2853.43	451.75	640.95	3997.28
DCV case	52.4	202.6	63.3	4.55	322.85
Schedule based	55.02	1397.3	236.79	27.67	1716.78
Saving for DCV %	-2.44%	92.90%	85.99%	99.29%	91.92%
Saving for schedule-based%	-7.57%	51.03%	47.58%	95.68%	57.05%

There is a huge energy saving potential comparing the DCV strategy and reference case which is about 91% that happens because of some reasons. One is the occupancy of the room is very low (most of the time non-occupied during the year). So, by adjusting demand-controlled ventilation there is the possibility to avoid energy dissipation of not required ventilation in the room. Additionally, it is shown a remarkable energy consumption reduction in the reference case compared to two previous simulated rooms. The other reason is the location of this room. Office room 3.049 which is the one picked for the simulation is located inside the building on the third floor and is isolated from exposing the outdoor environment since there is no external wall in this room. Accordingly, the room is thermally isolated from ambient, also the internal gains related to occupancy are low but highly affect indoor air temperature. In order to keep the thermal comfort of the room the decentral heater controller is adjusted for a schedule-based strategy similar to DCV. In Figure 4-21and Figure 4-22 outdoor air volume flow simulated for reference case in comparison with DCV and schedule-based control are provided.

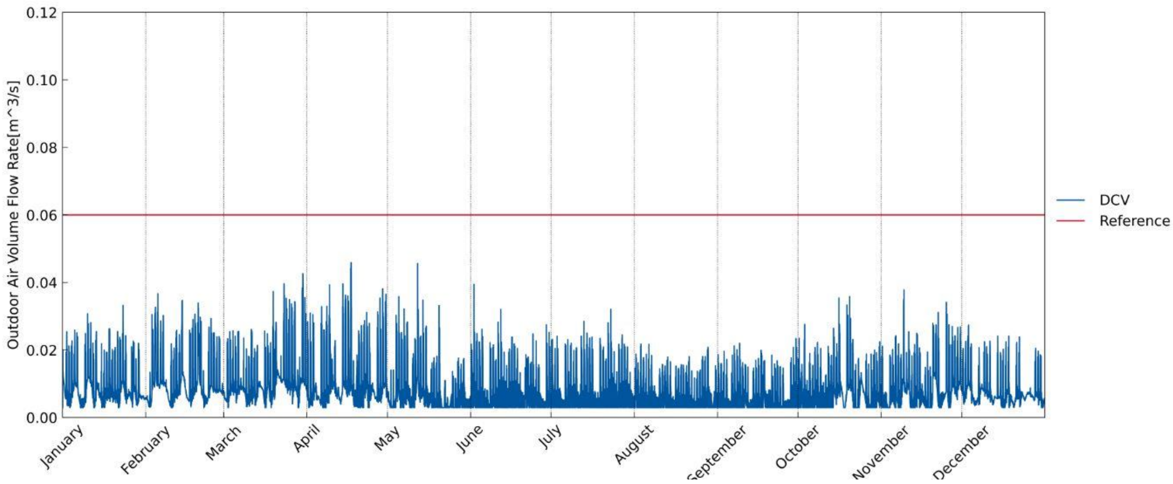

Figure 4-21 DCV strategy and reference outdoor air volume flow rate of office room (HUS)

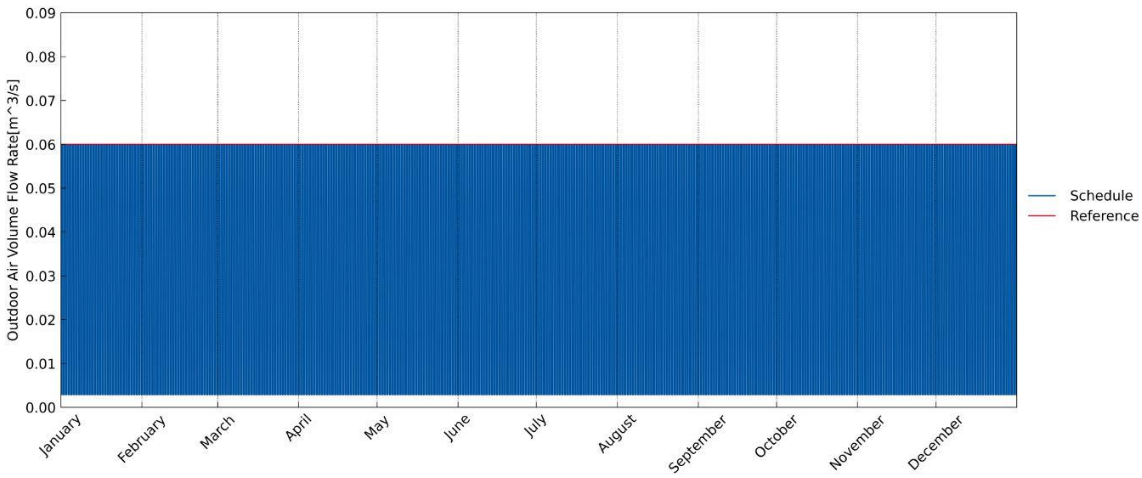

Figure 4-22 Schedule-based strategy and reference outdoor air volume flow rate of office room (HUS)

It is worth it to mention that there is a much lower outdoor air volume flow rate in the DCV method compared to two other cases which are because of low occupancy of the room during the whole year as well as lower required outdoor air for the office. Consequently, it ends up in a much lower electric consumption of the fans.

Due to the supply air volume flow changing every half a day during the year the plot for the schedule-based case is not constant and changes a lot. Meanwhile, both methods maintain room thermal comfort correspondingly.

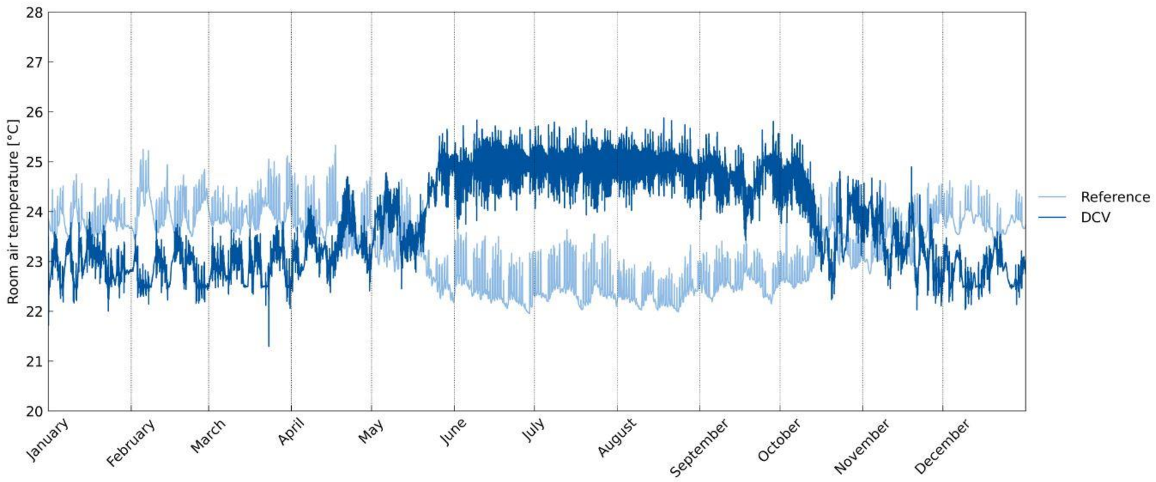

Figure 4-23 DCV strategy and reference room air temperature of office room (HUS)

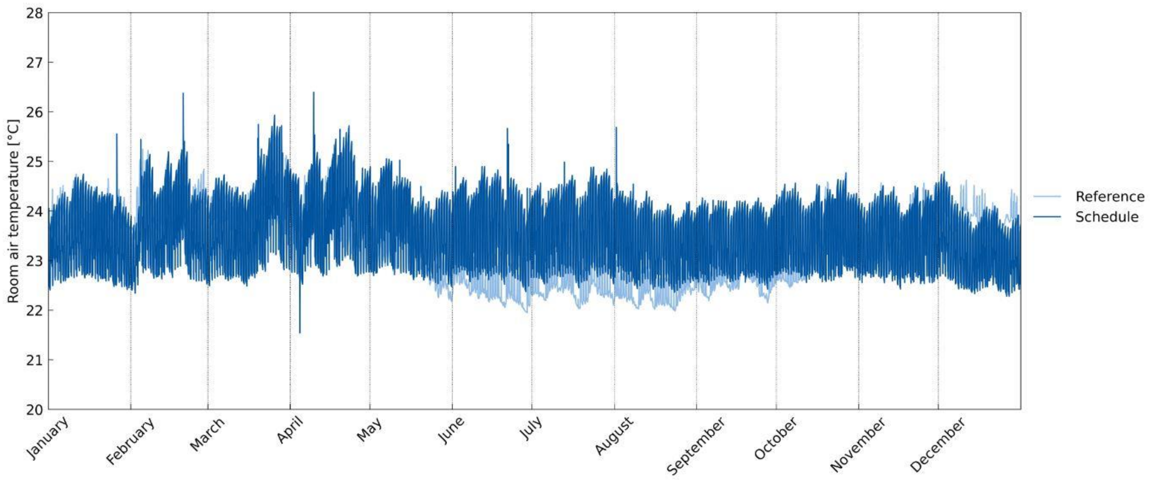

Figure 4-24 Schedule-based strategy and reference room air temperature of office room (HUS)

Additionally, to make sure about indoor air quality we need to always keep the CO_2 concentration lower than 2000 ppm. Reviewing the CO_2 concentration plots in comparison with the reference case, there is an increase in the concentration of leading gas as is expected due to a lower supply of fresh air. Referring to ASHRAE standards for concentrations lower than 1000 ppm there is no action or even ventilation checking is needed [29]. The result shows just a few hours may exceed this amount during a whole year which is negligible.

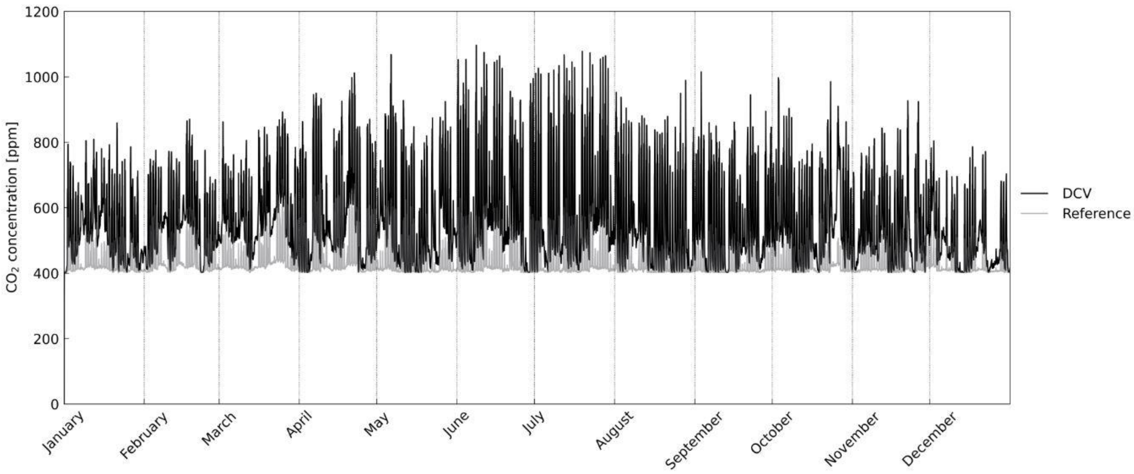

Figure 4-25 DCV strategy and reference CO_2 concentration of office room (HUS)

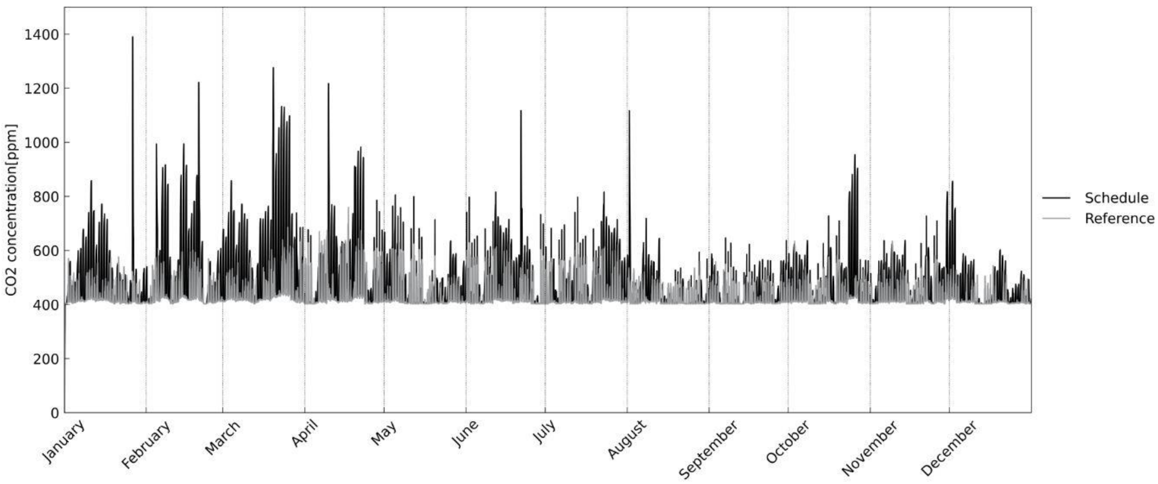

Figure 4-26 Schedule-based strategy and reference CO_2 concentration of office room (HUS)

For the DCV strategy, the higher concentration of CO_2 during the year compared with the reference case is happened because of devoted supply air during occupied time is lower, even compared to supply air volume flow in the schedule-based case. Moreover, there are some points with high values of concentration in the schedule-based method which could occur due to the unordinary presence of a person during the time of minimum ventilation rate, for instance, a cleaning person after working hours.

4.1.4 Consulting and treatment room

As previously mentioned in section 4.1.3, there is also a schedule trend in the occupancy of the consulting and treatment room. Hence, for this room, the schedule-based control ventilation is applied as well as the DCV strategy. The following plots reveal the energy consumption of the consulting and treatment room for three scenarios.

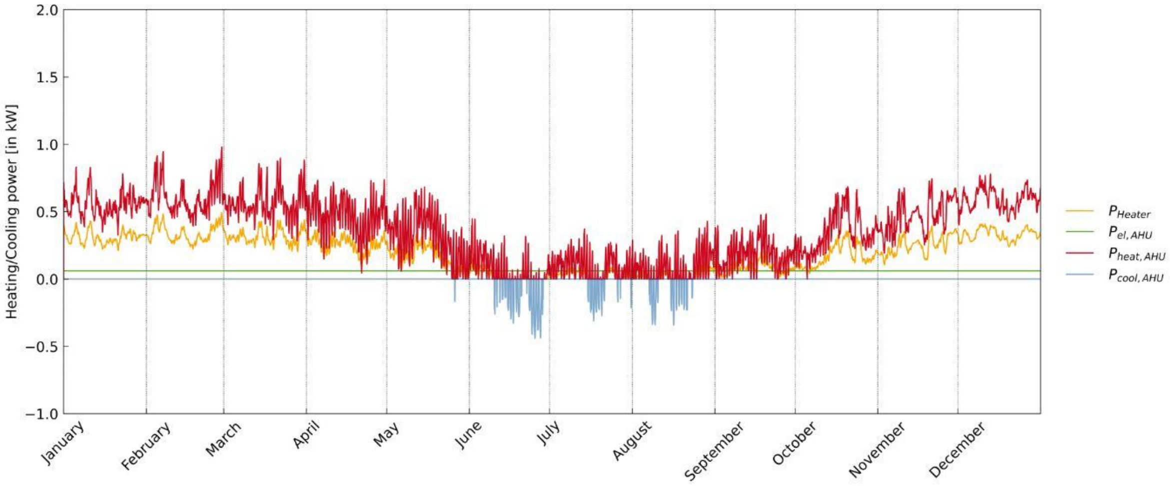

Figure 4-27 Reference energy consumption of consulting and treatment room (HUS)

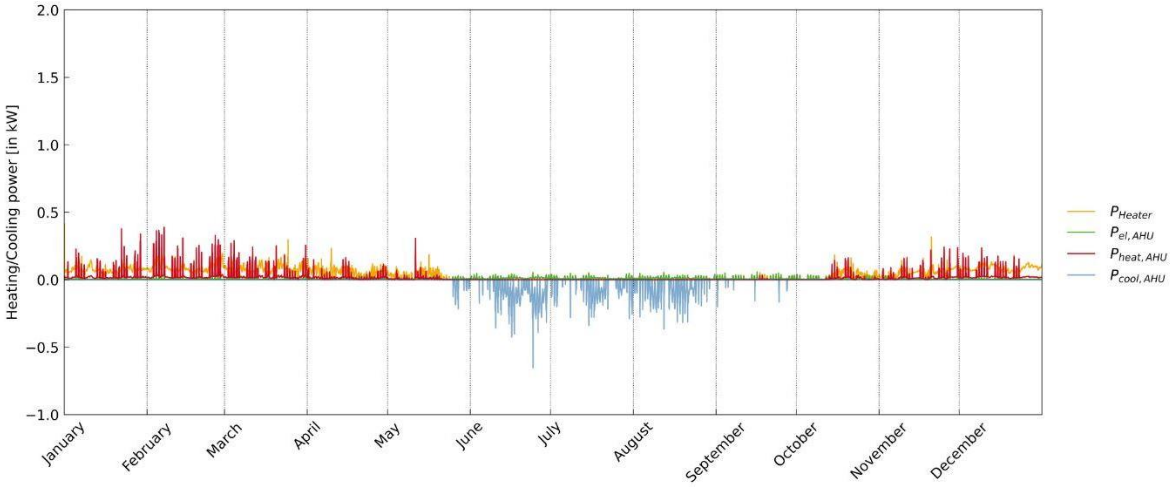

Figure 4-28 DCV strategy energy consumption of consulting and treatment room (HUS)

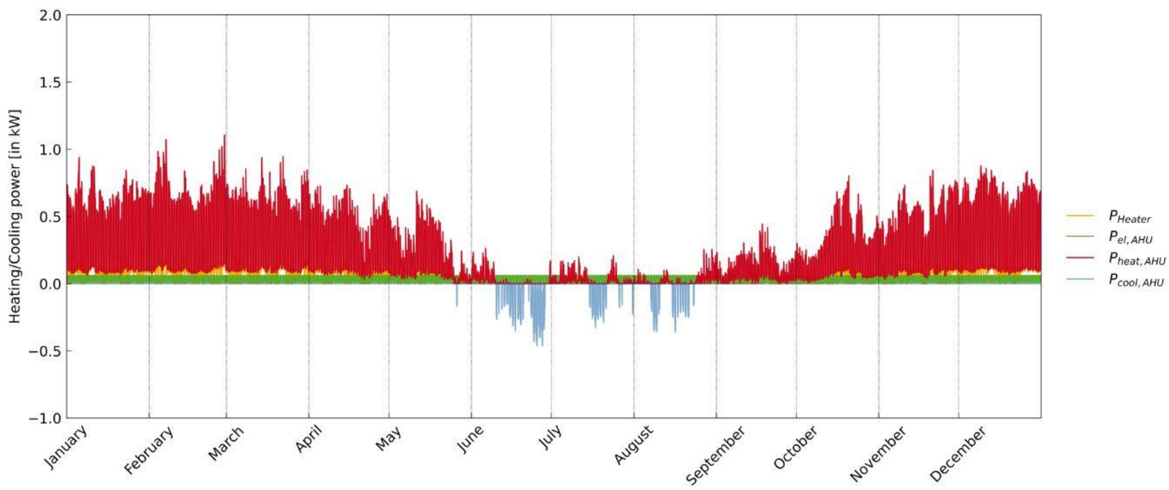

Figure 4-29 Schedule-based strategy energy consumption of consulting and treatment room (HUS)

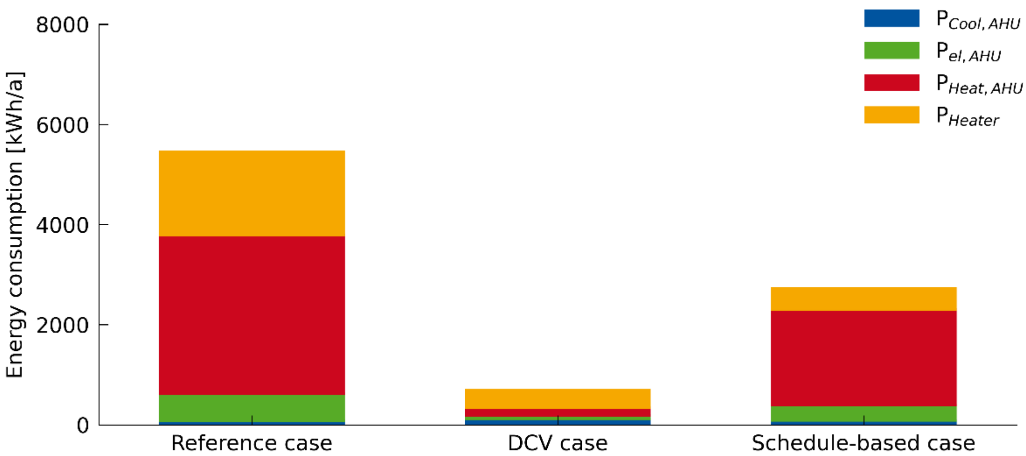

Figure 4-30 Cumulative energy consumption comparison of 3 strategies for consulting and treatment (HUS)

Table 4-4 Consulting and treatment room energy consumption and saving (HUS)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	81.16	3173.39	534.57	1663.97	5453.09
DCV case	121.36	150.51	65.47	353.85	691.19
Schedule based	84.05	1912.68	305.68	422.54	2724.95
Saving for DCV %	-49.53%	95.26%	87.75%	78.73%	87.32%
Saving for schedule-based%	-3.56%	39.73%	42.82%	74.61%	50.03%

Similar to the office room as the occupancy of this room is lower compared to the regular care room and isolation care room, hence the energy consumption of the reference case is lower than those rooms. In the same manner as all previous room usage types by adjusting a lower supply air temperature in the DCV strategy, the supply air heating demand in winter decreases. On the other hand, the cooling demand in summer increases. The phases of parallel heating and cooling are almost completely eliminated. Additionally, lower occupation during the year again would result in higher energy saving for the DCV strategy (87.32%). Fluctuation in AHU heating and electrical power indicated in Figure 4-31 is thanks to the dedicated supply air volume flow rate for schedule-based strategy.

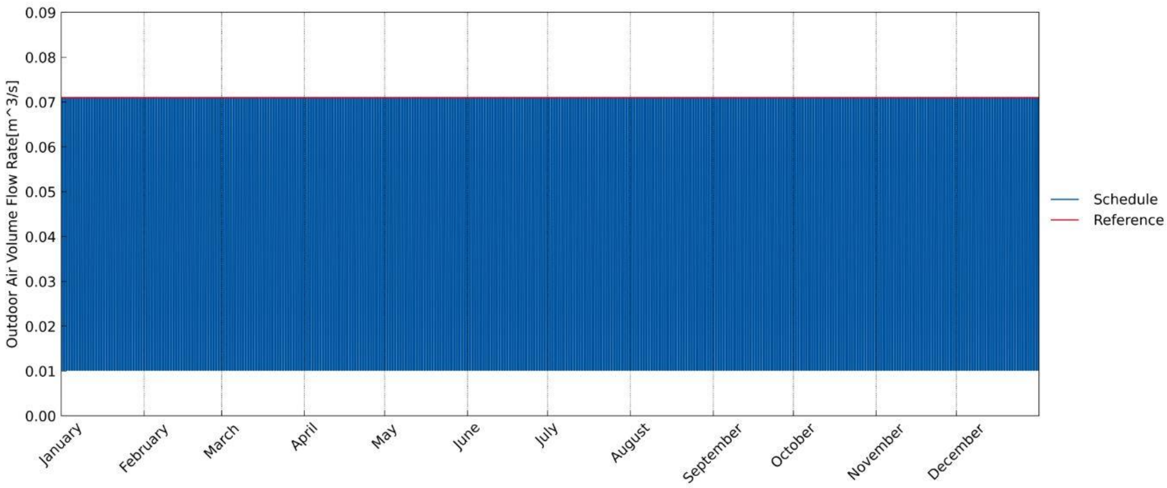

Figure 4-31 Schedule-based strategy and reference outdoor air volume flow rate of consulting and treatment room (HUS)

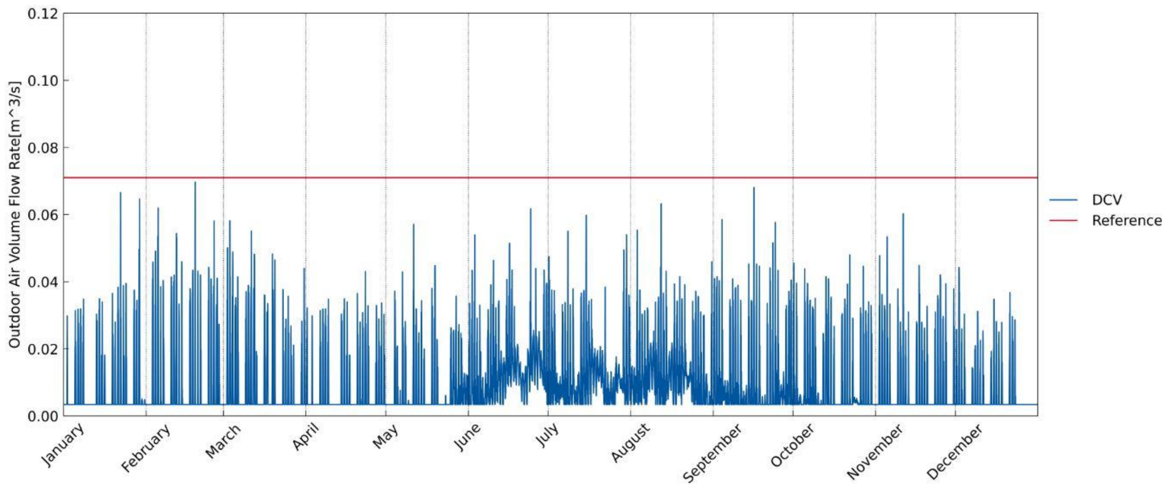

Figure 4-32 DCV strategy and reference outdoor air volume flow rate of consulting and treatment room (HUS)

Considering consulting and treatment room and office room as two close usage types, there are distinguished standards submitted for them. For consulting and treatment room adjusted supply airflow rate per person is more than 3 times the one for the office room. Expecting results in a higher amount of outdoor air volume flow rate and more electric energy consumption of fans. However, the electric consumption of these two cases is almost the same because the occupancy distribution is different.

In contrast to the office room, the minimum volume flow rate for the other half of the day could not compensate the thermal loads, therefore 3 times higher value is adjusted for this period in order to maintain the thermal comfort of the room for the schedule-based strategy during the year as expressed in Figure 4-34.

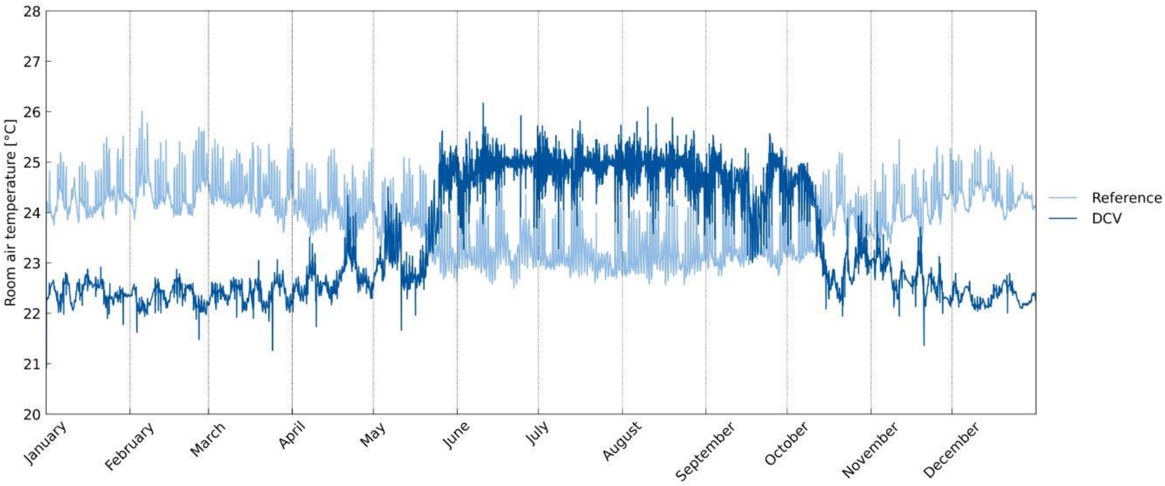

Figure 4-33 DCV strategy and reference room air temperature of consulting and treatment room (HUS)

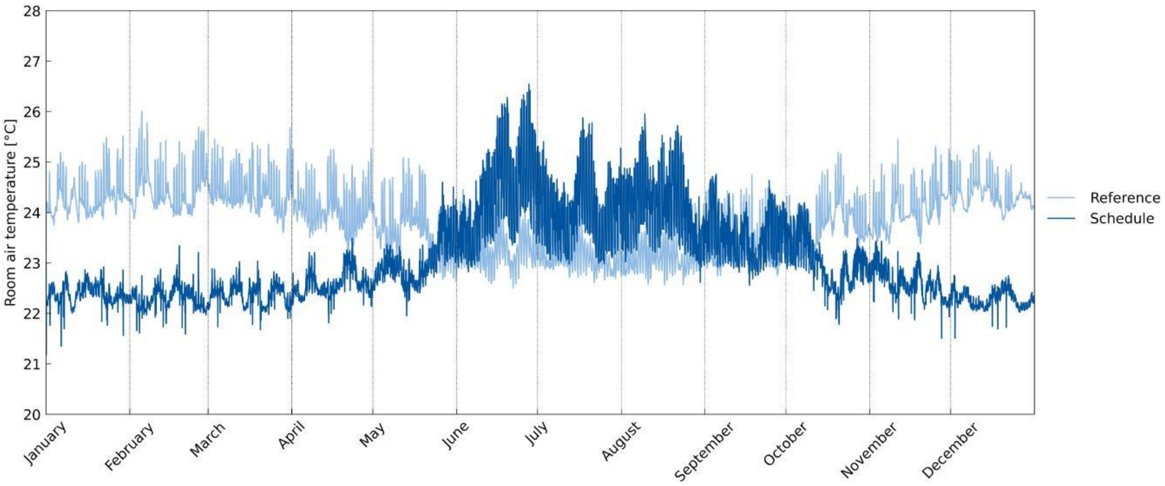

Figure 4-34 Schedule-based strategy and reference room air temperature of consulting and treatment room (HUS)

Since the supply air volume flow dedicated to this room usage type is much higher than the office room, it is expected to reveal a lower CO_2 concentration increase in the DCV method (Figure 4-35).

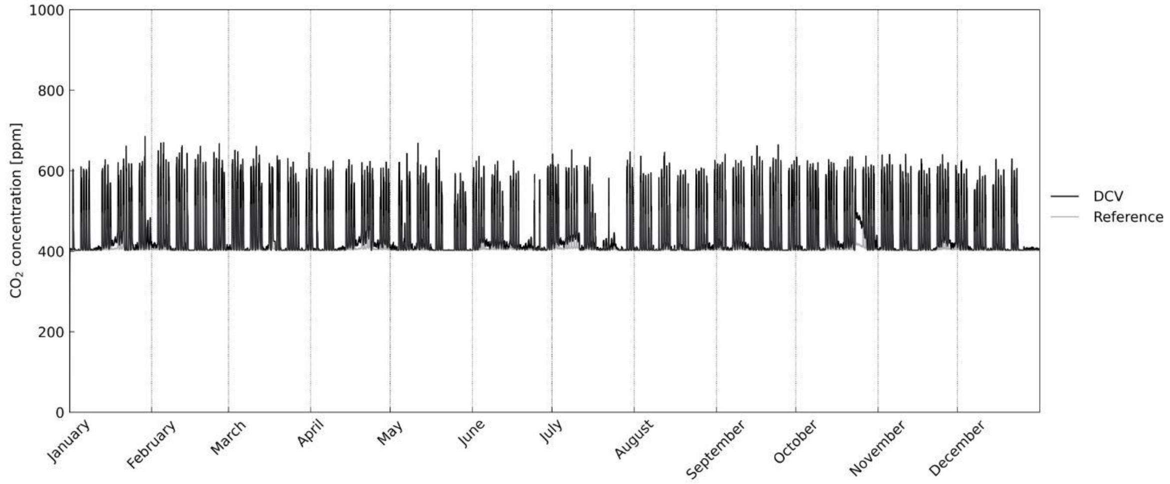

Figure 4-35 DCV strategy and reference CO_2 concentration of consulting and treatment room (HUS)

In the meantime, the CO_2 concentration of schedule-based ventilation control perfectly fits the reference case simulation which demonstrates an ideal placement of the strategy for this room with its occupancy distribution.

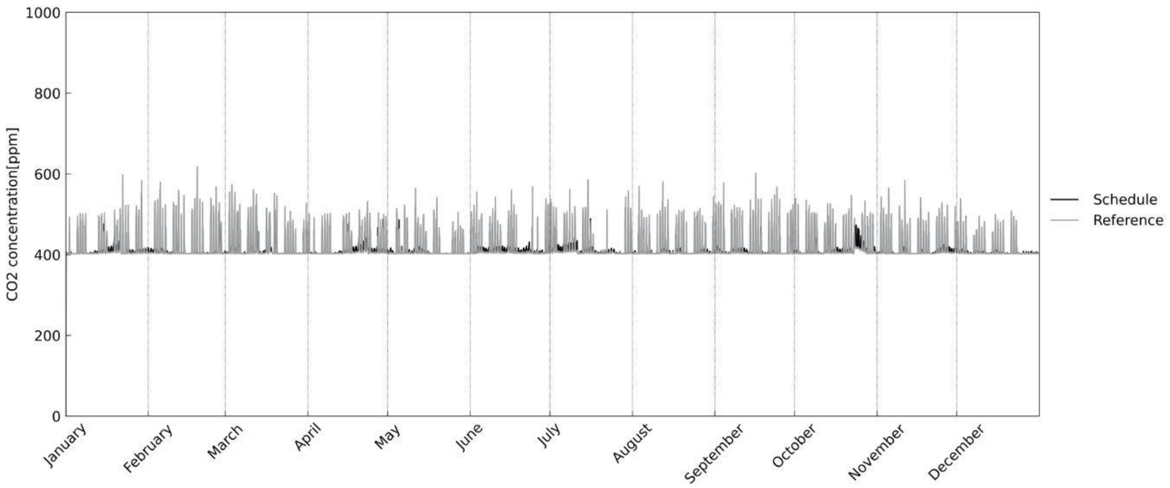

Figure 4-36 Schedule-based strategy and reference CO_2 concentration of consulting and treatment room (HUS)

Both figures manifest likewise preserving complete indoor air quality.

4.2 Results for UKA

As discussed in Chapter 3, the calibration result for this model is a bit different from the measured data. Despite this, the building is older than HUS and the materials used in construction are different. Additionally, the air handling unit is more likely inefficient in comparison to the one in Helsinki university hospital. Considering all the aforementioned details, the results of simulations for UKA are indicated below.

4.2.5 Regular care room

In the same manner as previous results and discussions, here the energy consumption of different strategies is provided for regular care room in UKA.

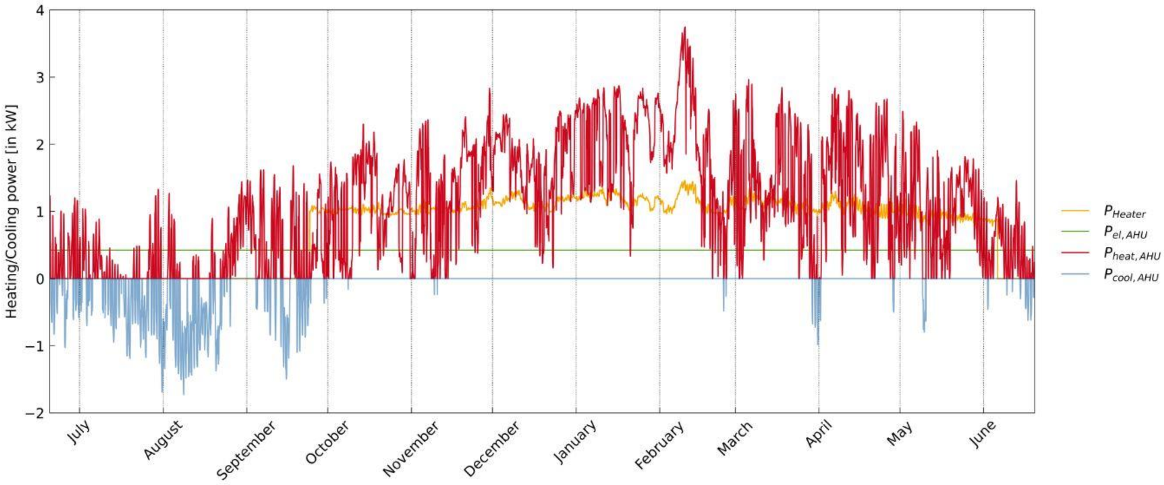

Figure 4-37 Reference energy consumption of regular care room (UKA)

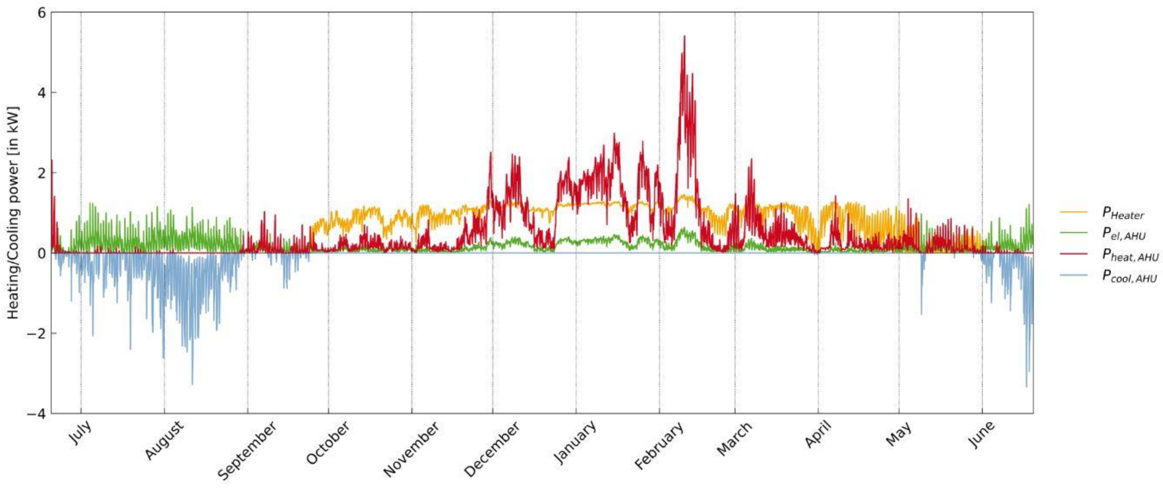

Figure 4-38 DCV strategy energy consumption of regular care room (UKA)

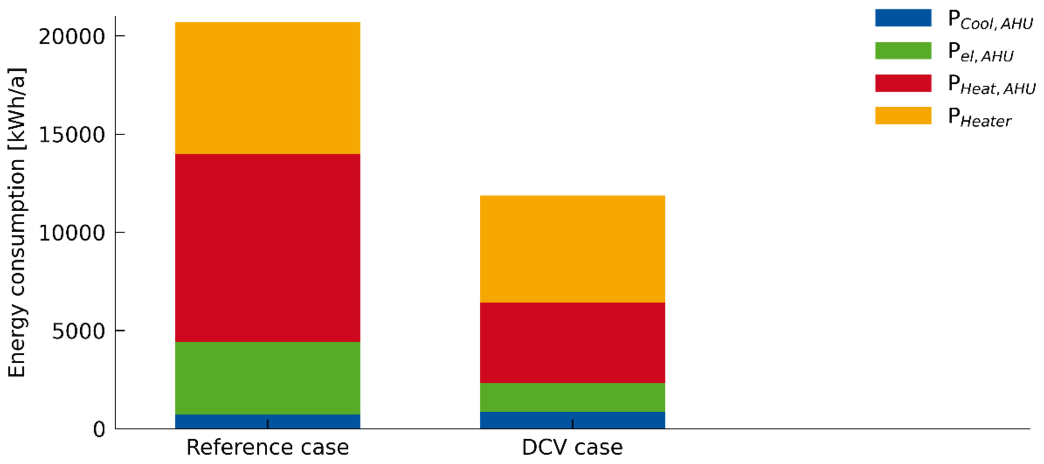

Figure 4-39 Cumulative energy consumption of 2 strategies for regular care room (UKA)

Table 4-5 Regular care room energy consumption and saving (UKA)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	765.15	9574.15	3714.27	6586.87	20640.44
DCV case	906.07	4102.94	1480.66	5320.97	11810.64
Saving %	-18.42%	57.15%`	60.14%	19.22%	42.78%

Due to the fact that in the DCV strategy ventilation is regulated with the occupancy, there is always an expectation of lower energy consumption compared to the reference case. In UKA, by reason of using dual duct air handling unit and the possibility of supplying outdoor air into the room with variable temperature, the supply air temperature needs to be taken into account as well as supply air volume flow to reason whether we have an increase or decrease in cooling power of air handling unit. Lately, a comparison of supply air temperature for each strategy will be demonstrated. In this case, the cooling power of AHU increases for the DCV method, but as heating power is much more dominant during the year it would decrease by reduction of supply air volume flow. In parallel with AHU heating power, the electric consumption of the fans also decreases when the supply air volume flow is not constant. By adjusting the temperature controller to the decentral heater for DCV strategy the consumption of the heater is reduced as well. It is interesting to mention that, on the dry-bulb temperature plot for UKA there is a sharp decrease in ambient air temperature recorded in February (Figure 3-7). Therefore, in all simulations for this model a rapid increase in heating demand is observed in the meantime.

In the following figure, it is visualized how distinguished is the supply air temperature among two cases.

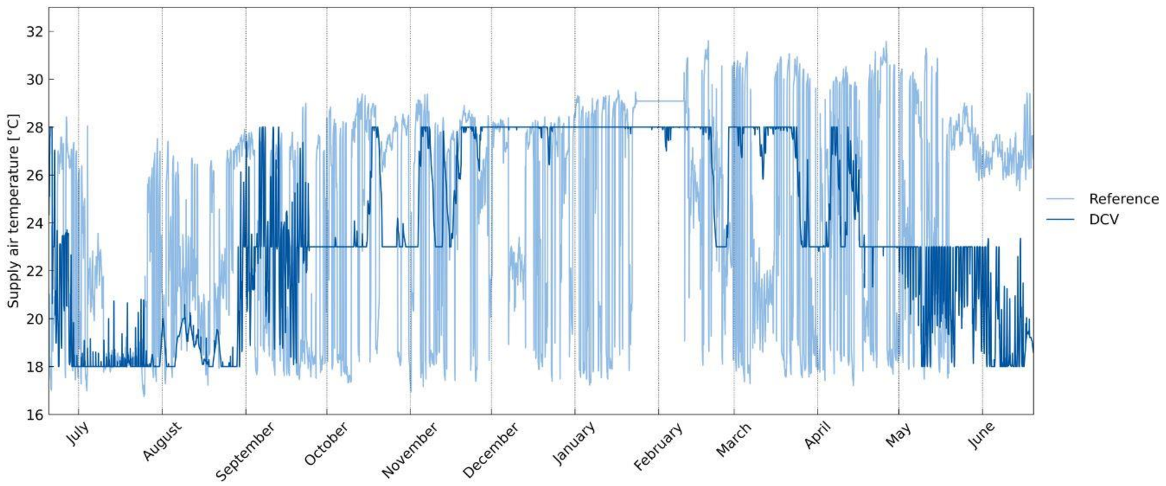

Figure 4-40 DCV strategy and reference supply air temperature of regular care room (UKA)

Regarding the adjusted controllers for supply air temperature and supply air volume flow in case of need, there is a comparison of outdoor air volume flow rate between the reference case and DCV method in Figure 4-41.

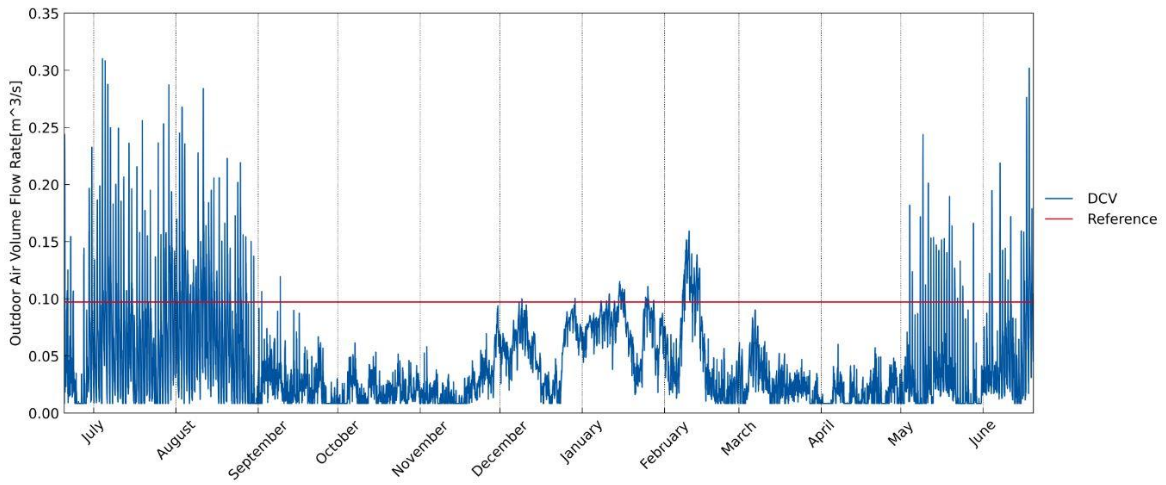

Figure 4-41 DCV strategy and reference outdoor air volume flow rate of regular care room (UKA)

Although at some points supply volume flow rate is much higher than the reference case for DCV strategy, it never reaches the maximum ACH dedicated to the air handling unit. Moreover, with such a high ventilation rate, still, the electrical consumption of the fans is much lower than constant ventilation, cumulating over one year.

Because of the abovementioned reasons for calibration and measuring data, the indoor air temperature of the reference case for the room is out of the thermal comfort region as is revealed in Figure 4-42. On the other hand, concerning thermal comfort of the room as one of the controlling boundaries for the DCV method and by controlling supply air temperature and volume flow rate we could also preserve indoor air temperature in the thermal comfort zone.

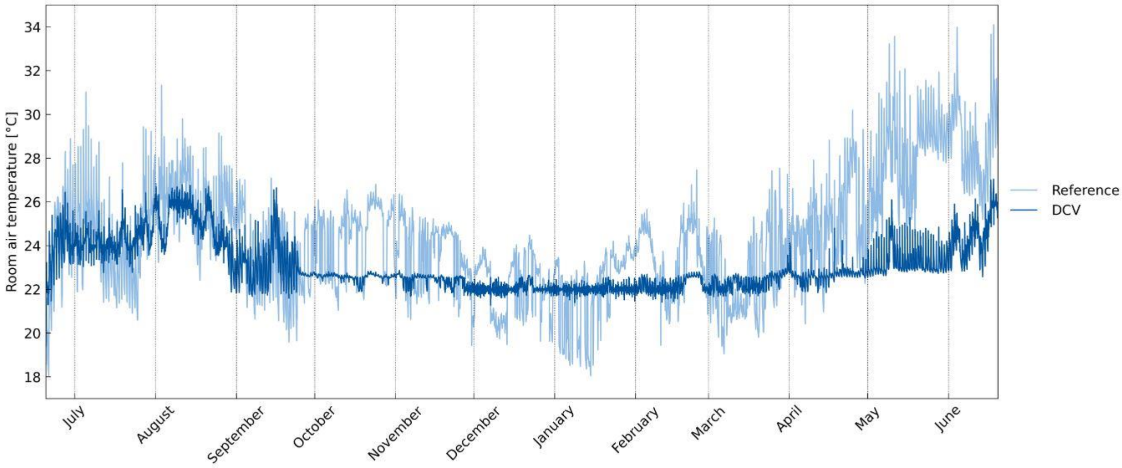

Figure 4-42 DCV strategy and reference room air temperature of regular care room (UKA)

The other indication of controlling boundary for the DCV method which is indoor air quality is shown in the next figure in comparison with the reference case.

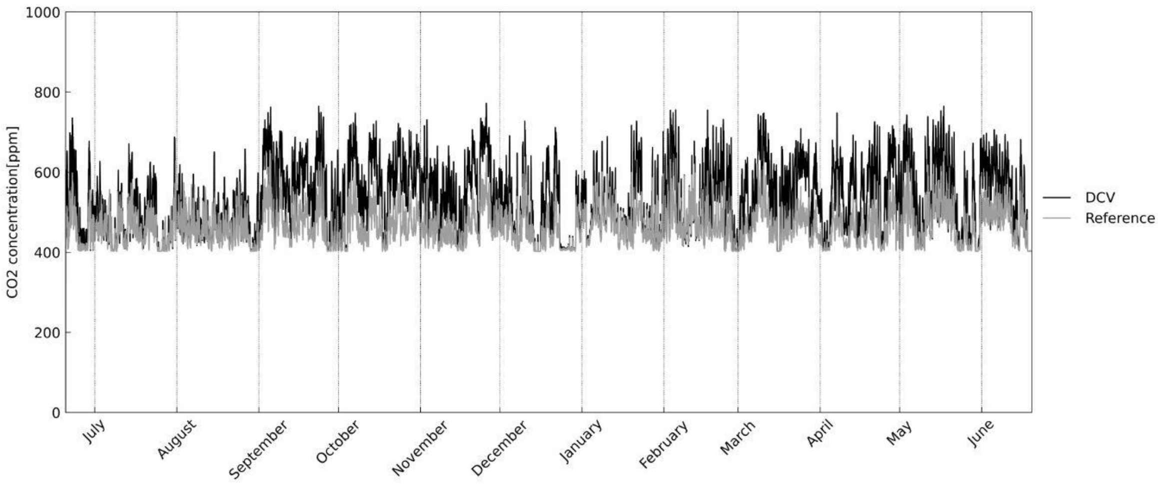

Figure 4-43 DCV strategy and reference CO_2 concentration of regular care room (UKA)

Obviously, the indoor air quality is guaranteed by the DCV method for the regular care room. Despite thermal comfort, as the supply air volume flow is high for the reference case, CO_2 concentration is kept very low.

4.2.6 Isolation care room

Firstly, the indication of energy consumption for all strategies is given. By the reason of existing two guidelines for isolation care room, there is also a simulation of occupancy state ventilation control provided like before as well as DCV simulation.

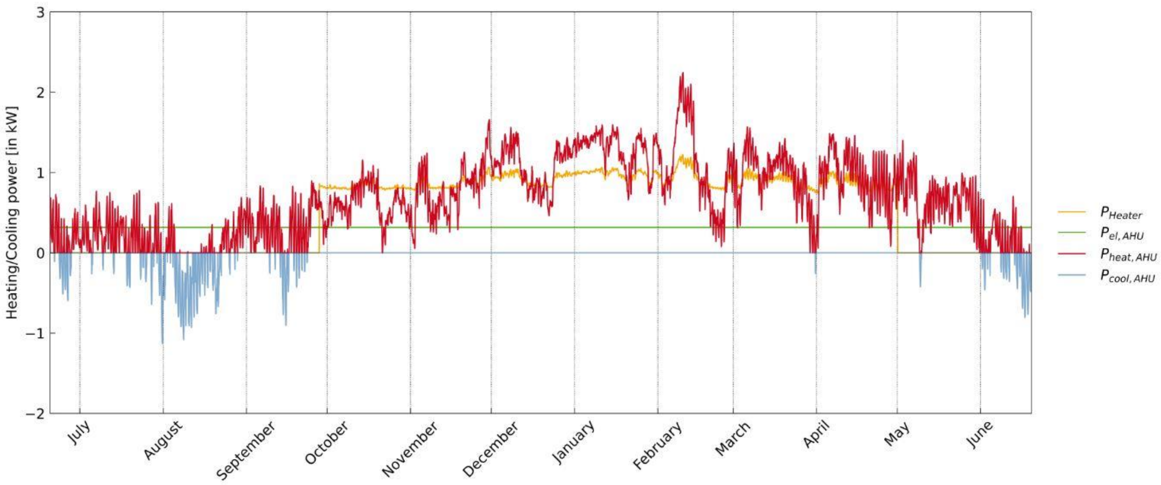

Figure 4-44 Reference energy consumption of isolation care room (UKA)

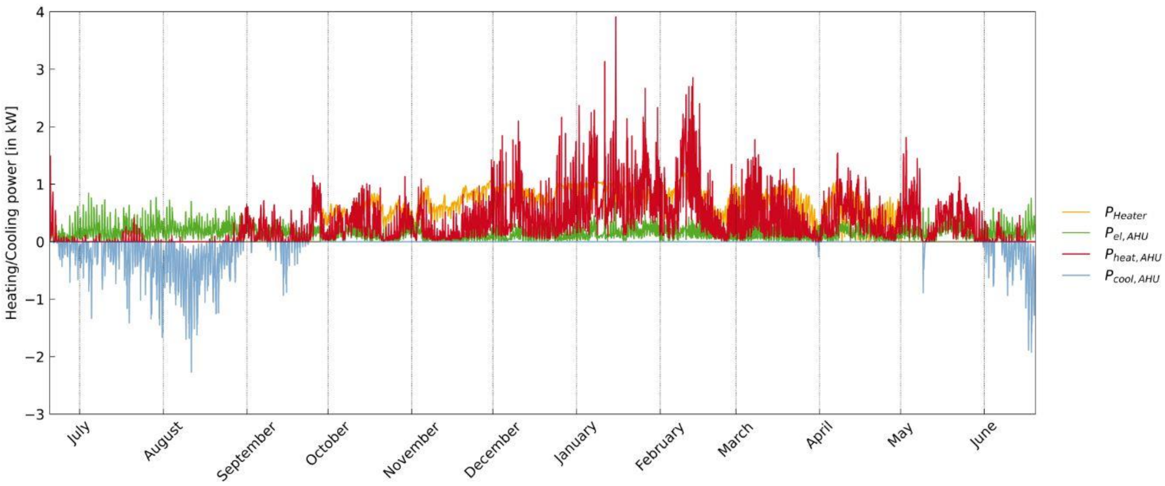

Figure 4-45 DCV strategy energy consumption of isolation care room (UKA)

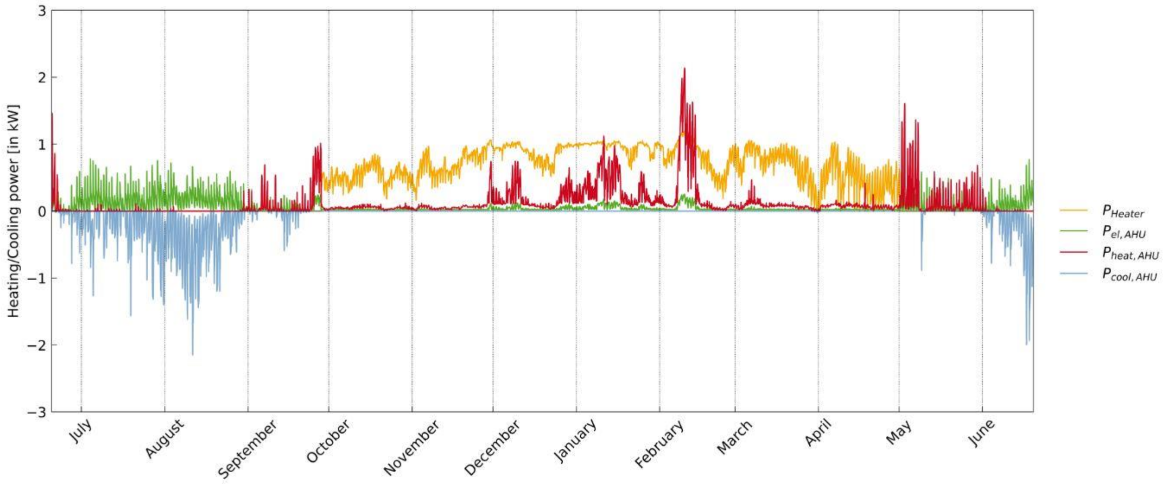

Figure 4-46 Occupancy State strategy energy consumption of isolation care room (UKA)

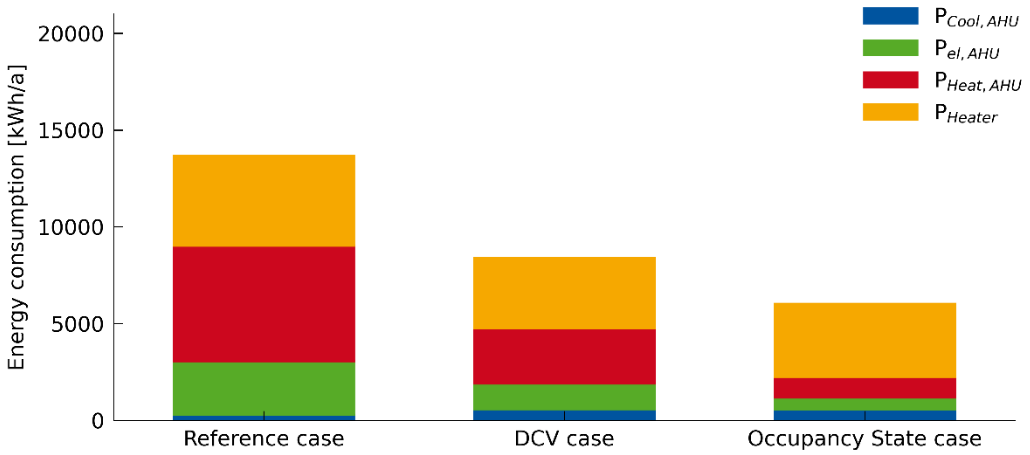

Figure 4-47 Cumulative energy consumption of 3 strategies for isolation care room (UKA)

Table 4-6 Isolation care room energy consumption and saving (UKA)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	283.48	5972.78	2778.08	4633.86	13668.2
DCV case	575.45	2864.74	1331.3	3610.32	8381.81
Occupancy state	568.54	1059.96	615.99	3764.52	6009.01
Saving for DCV %	-102.99	52.04	52.08	22.09	38.68
Saving for occupancy state %	-100.56	82.25	77.83	18.76	56.04

Although, by controlling the supply air temperature in DCV method, cooling power of AHU increases more than twice in comparison to reference case and also during some periods in winter the heating power of air handling unit is more than reference, still cumulative energy consumption of DCV method is lower. In order to keep the thermal comfort of the room, a supply air temperature controller is also applied in the occupancy state strategy. Therefore, the AHU cooling power raises compared to the reference case because of maintaining the low temperature of supply air during summer. However, as the occupancy of the room is relatively high and the recommended supply volume flow rate per person for isolation care room in standards is high too, we could observe a lower yearly energy consumption in the occupancy state method where we adjusted reference supply air volume flow for occupied times. After applying supply air temperature control for both strategies, the visualization of its behavior is expressed in Figure 4-48and Figure 4-49.

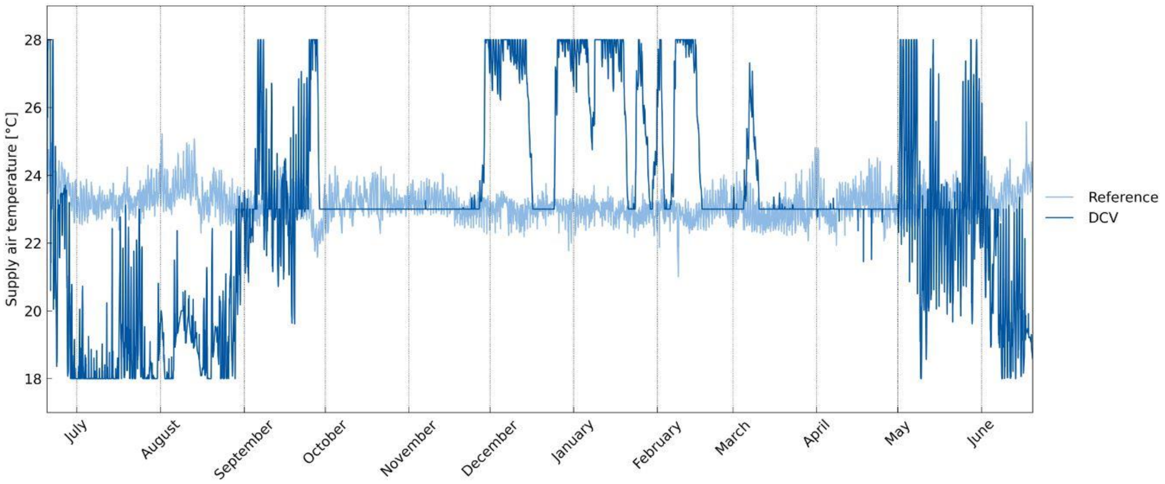

Figure 4-48 DCV strategy and reference supply air temperature of isolation care room (UKA)

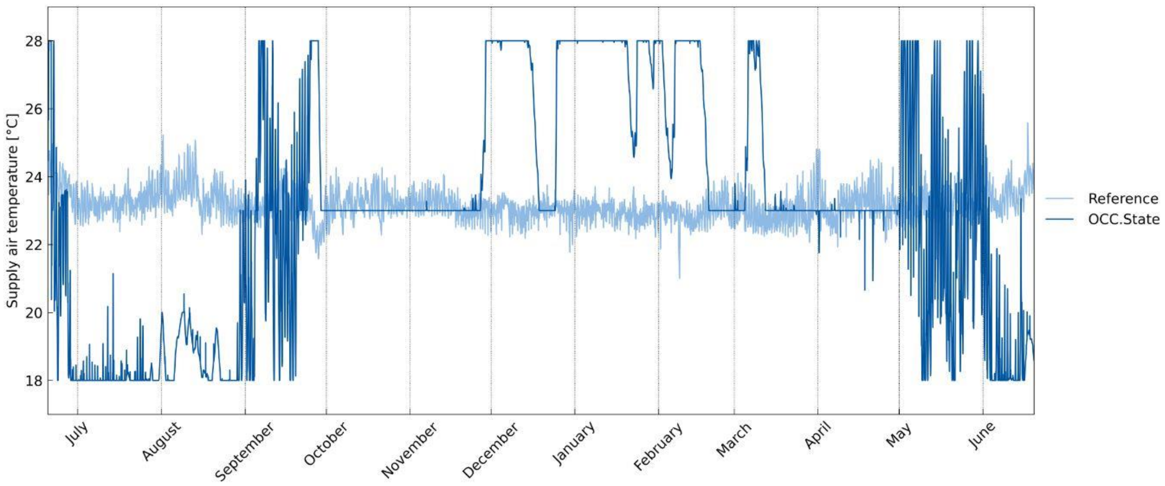

Figure 4-49 Occupancy state strategy and reference supply air temperature of isolation care room (UKA)

From the plots above, it can be understood that the difference in energy consumption of air handling units among the two considered strategies is due to distinguished supply air volume flow as the supply air temperature is almost the same comparing occupancy state and DCV strategy. In parallel, the decentral heater consumes almost the same amount of energy in both cases. Thus, we can compare the outdoor air volume flow rate in the following figures.

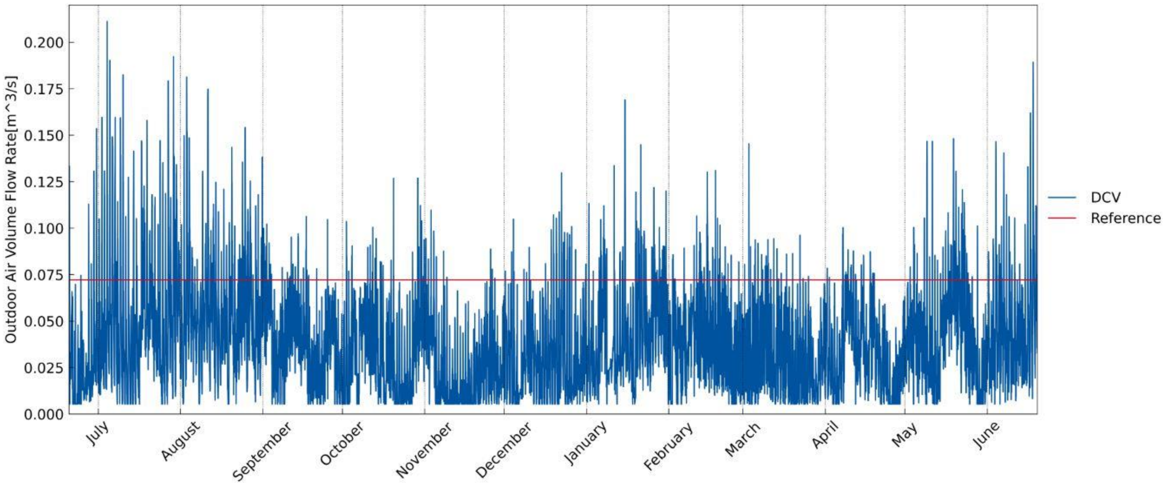

Figure 4-50 DCV strategy and reference outdoor air volume flow rate of isolation care room (UKA)

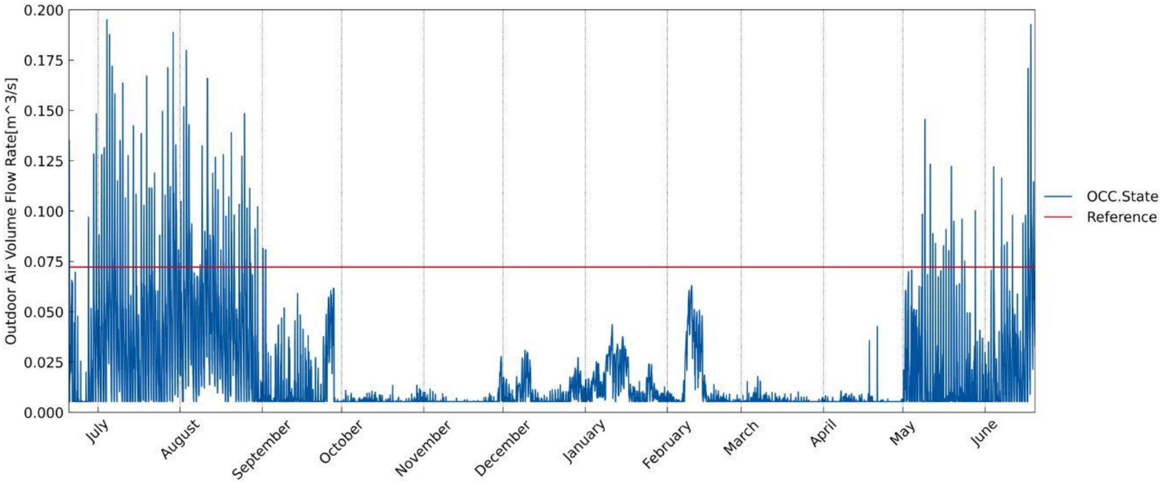

Figure 4-51 Occupancy state and reference outdoor air volume flow rate of isolation care room (UKA)

The ventilation rate is lower in the occupancy state method compared to DCV, especially during winter, hence there is lower electrical consumption of fans and heating power of AHU. It is a bit more complicated controlling system dedicated to UKA since the supply air is not constant. Comparing the occupancy state method simulation of this room to the one in HUS, the supply volume flow plot seems strange. But the reason for this is that the operation of the supply air temperature controller and volume flow rate controller in parallel would make the plot look different from the one for the HUS model.

By reviewing room air temperature plots, we see a quite small difference between the two simulated strategies. Considering that the DCV case has more energy consumption, we could reason that during winter most of the heating power is maintained by the decentral heater.

Thus, higher supply air volume flows only keep the CO_2 concentration of the room lower in comparison to the occupancy state case (higher indoor air quality). (Figure 4-54and Figure 4-55)

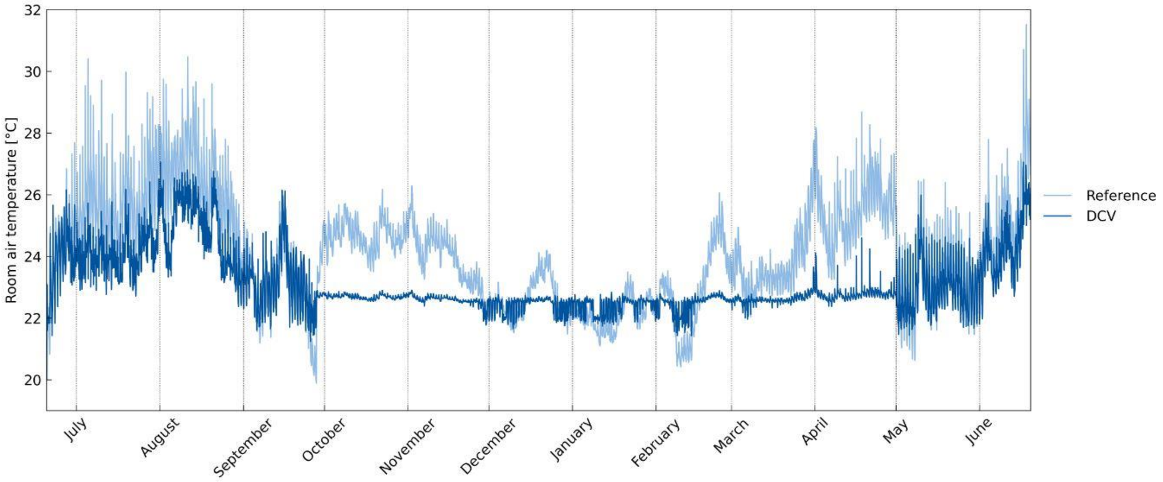

Figure 4-52 DCV strategy and reference room air temperature of isolation care room (UKA)

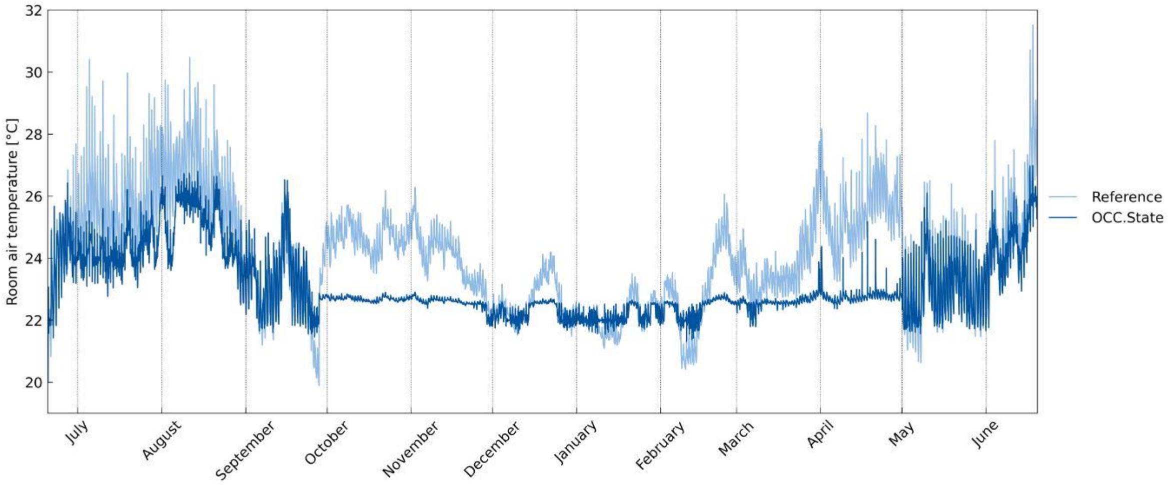

Figure 4-53 Occupancy state strategy and reference room air temperature of isolation care room (UKA)

As it is indicated in previous sets of figures, the thermal comfort of the room is kept similarly among both strategies.

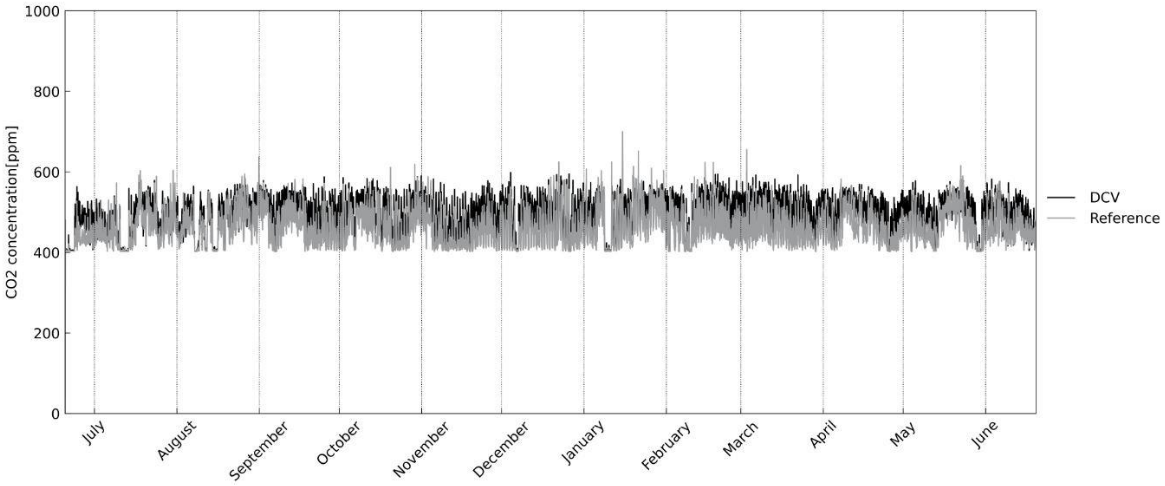

Figure 4-54 DCV strategy and reference CO_2 concentration of isolation care room (UKA)

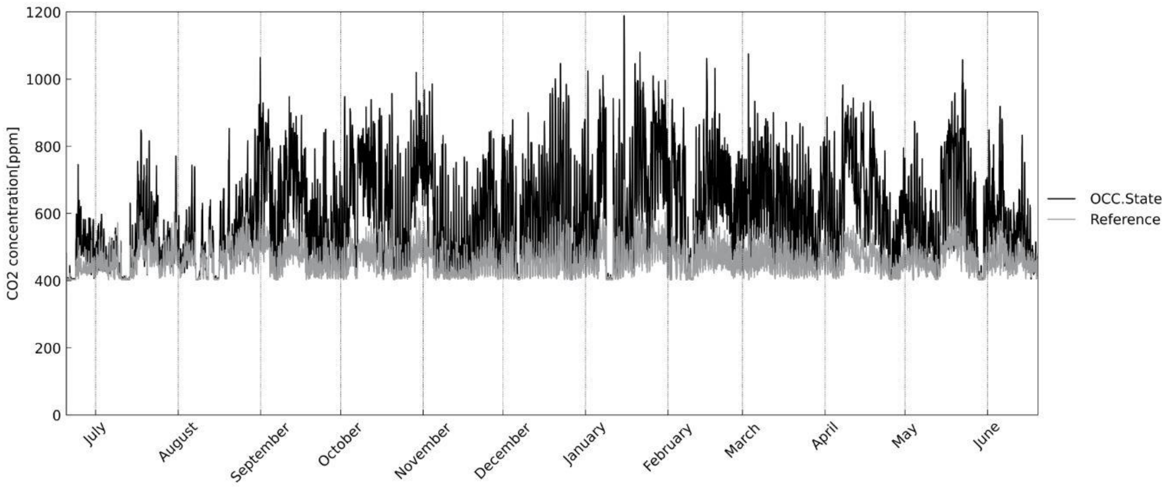

Figure 4-55 Occupancy state strategy and reference CO_2 concentration of isolation care room (UKA)

4.2.7 Office room

In the same manner as previous results and discussion, primely we start with an indication of energy consumption plots. For this room, we also considered the schedule-based strategy by dedicating a 12-hour of supply air for ventilation with the existing outdoor air volume flow rate in the reference case and 12 hours of minimum supply air volume flow.

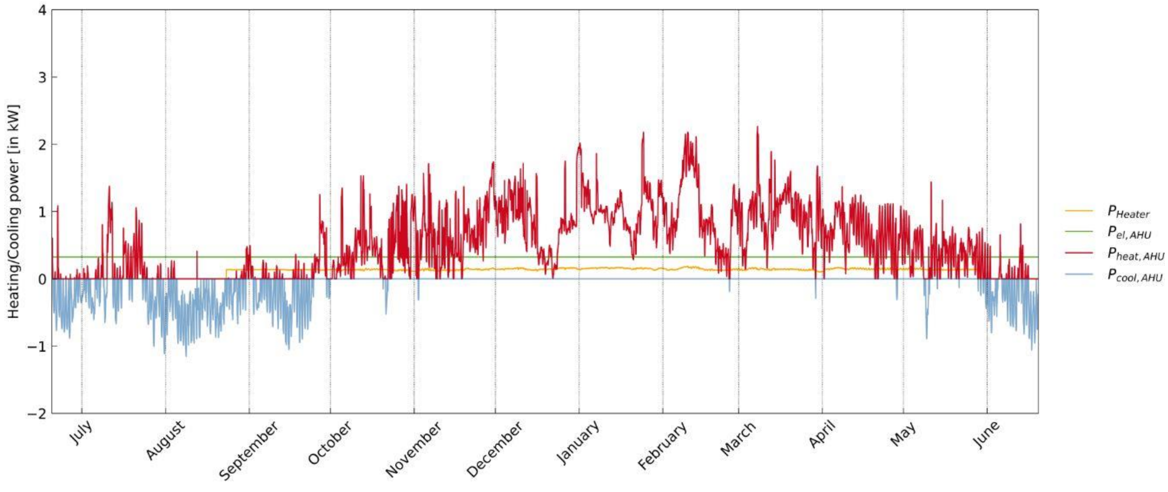

Figure 4-56 Reference energy consumption of office room (UKA)

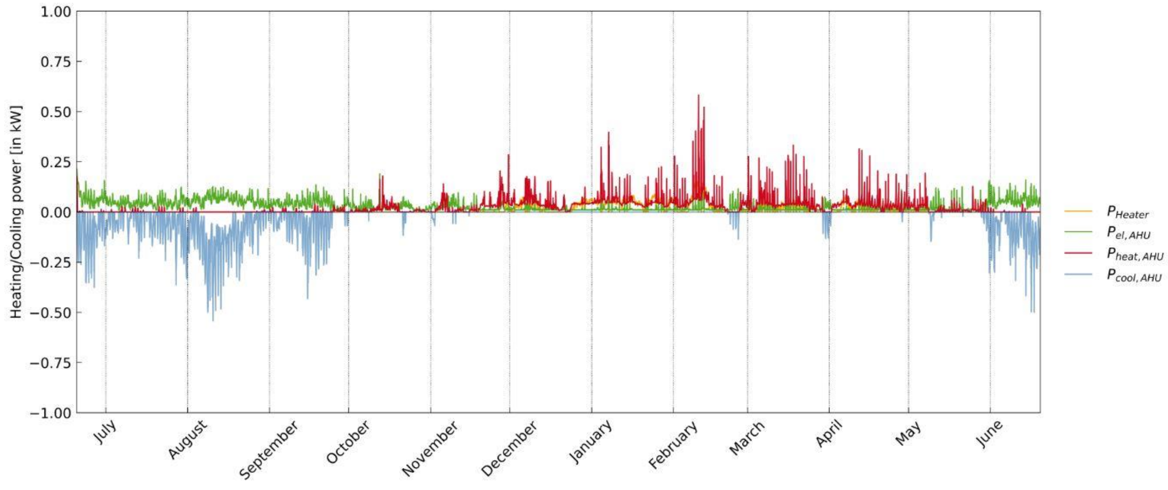

Figure 4-57 DCV strategy energy consumption of office room (UKA)

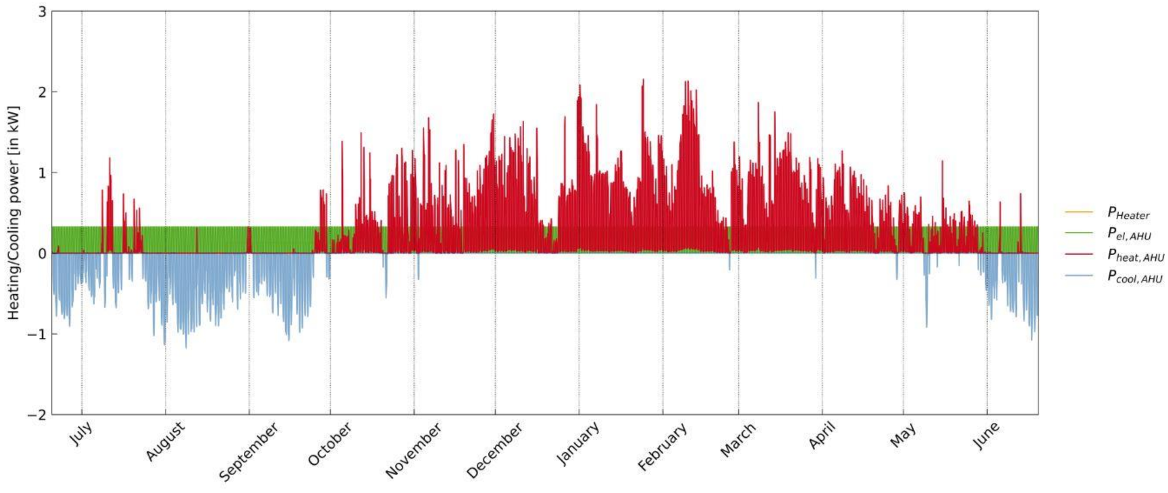

Figure 4-58 Schedule-based energy consumption of office room (UKA)

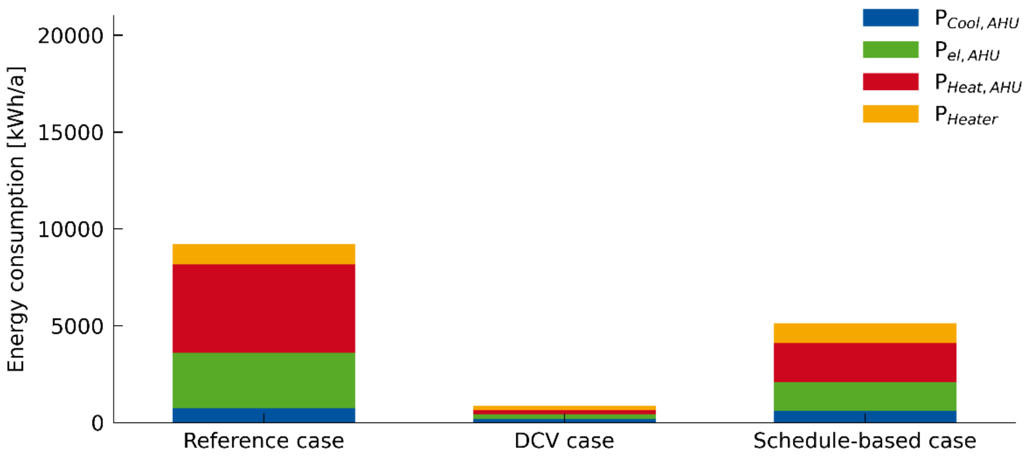

Figure 4-59 Energy consumption comparison of 3 strategies for office room (UKA)

Table 4-7 Office room energy consumption and saving (UKA)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	799.31	4564.5	2855.11	951.11	9170.03
DCV case	232.24	213.53	258.51	89.76	794.04
Schedule based	661.78	2023.02	1473.67	911.84	5070.31
Saving for DCV %	70.94%	95.32%	90.95%	90.56%	91.34%
Saving for schedule-based%	17.21%	55.68%	48.38%	4.13%	44.71%

Like other figures, it is taken into account to have them almost in the same range. But for the DCV method, the selected range in the y axis is lower because of low energy consumption, and to visualize it better smaller values are considered. Since the occupancy of the room is very low, this space has a lot of energy-saving potential.

Peaks for heating, cooling, and electrical power of the air handling unit, as well as decentral heater power, are quite the same compared to the reference case. So, a decrease in energy consumption in the schedule-based strategy happens due to a reduction of supply air volume flow rate in non-working hours.

Adjusting a controller for supply air temperature will result in a temperature difference in supply air of the DCV method and our benchmark (Figure 4-60). It is notable that for the schedule-based strategy the reference supply air temperature is considered (Figure 4-61).

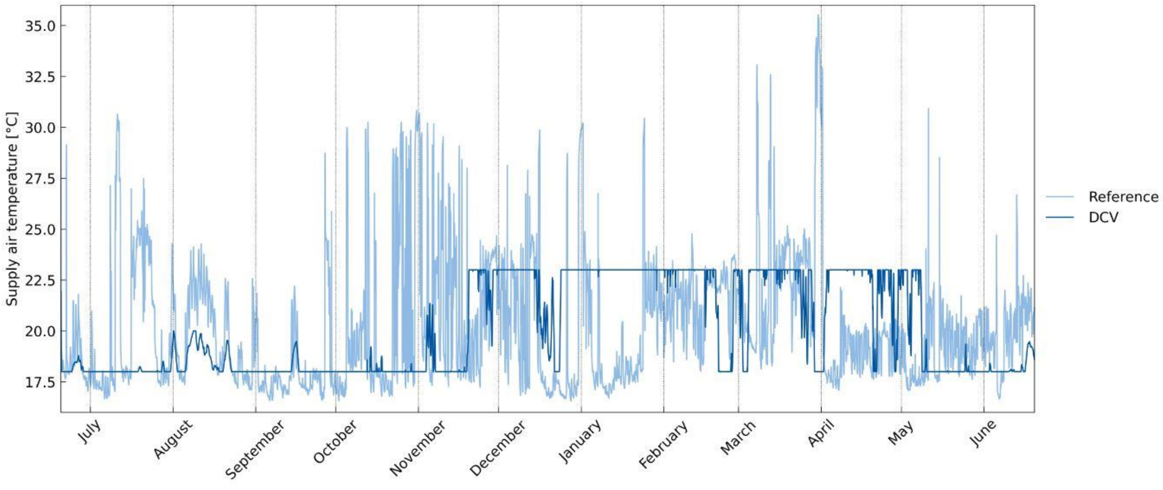

Figure 4-60 DCV strategy and reference supply air temperature of office room (UKA)

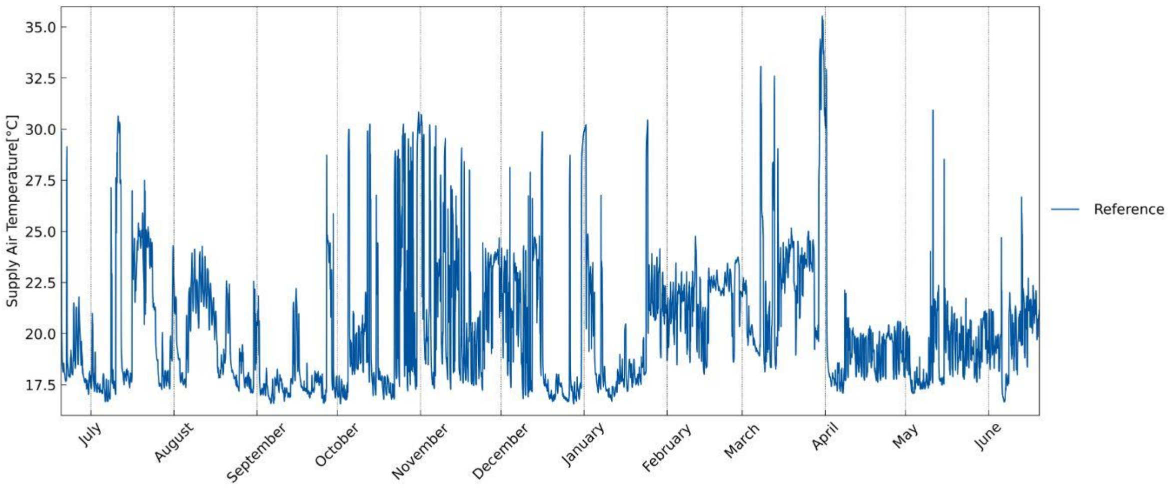

Figure 4-61 Schedule-based strategy and reference supply air temperature of office room (UKA)

It is worth it to mention that with a dedicated outdoor air volume flow rate per person in the DCV strategy the supply air temperature won't exceed the setpoint adjusted for controlling the room air temperature and does not cross the boundary selected for winter. consequently, there is no need to supply air with higher temperatures. Unfortunately, the supply air temperature measured in the real case is not trustworthy as explained before (Chapter 3).

Referring to the volume flow rate of supply air for the DCV method in Figure 4-62 and considering its difference with the reference case, the effect of low occupancy is shown. However, for the schedule-based method, the occupancy is not the effective parameter and we only consider the timely scheduled ventilation rate (Figure 4-63).

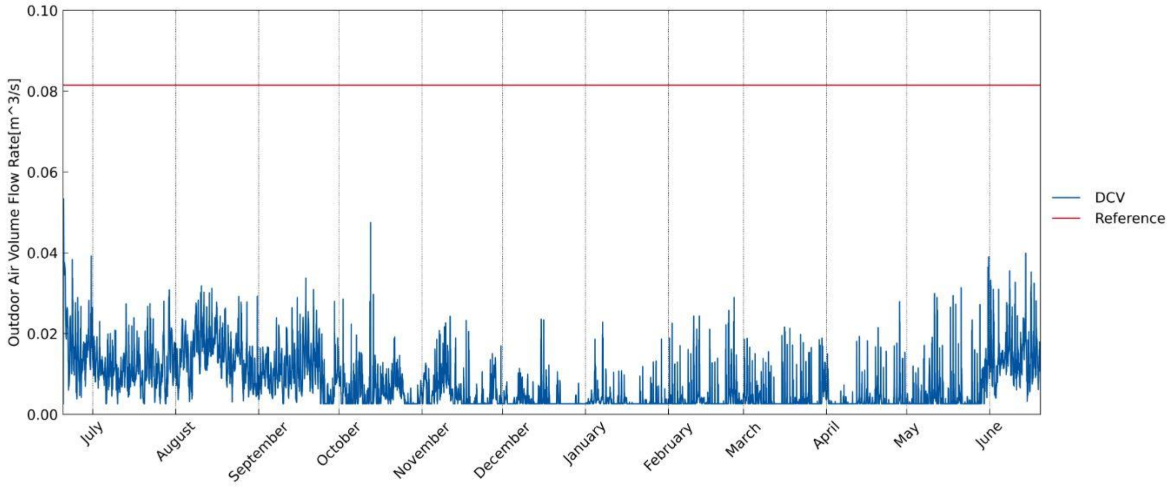

Figure 4-62 DCV strategy and reference outdoor air volume flow rate of office room (UKA)

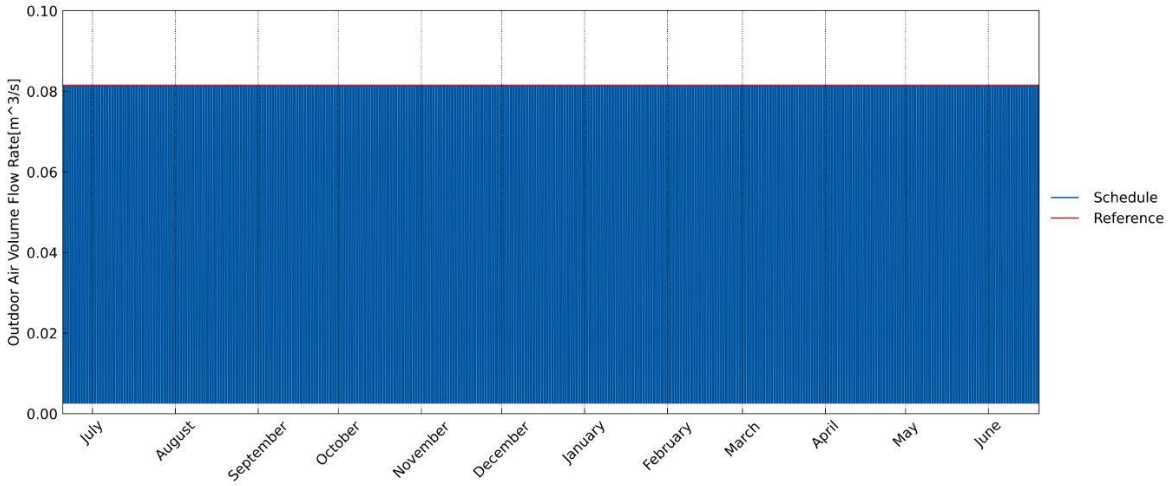

Figure 4-63 Schedule-based strategy and reference outdoor air volume flow rate of office room (HUS)

Dedicating the controller to supply air temperature for this room always assures keeping the room air temperature in a thermal comfort zone. However, by considering reference supply air temperature for the schedule-based method it could be expected to have values out of the thermal comfort zone. Notably, using supply air control for this method does not make sense. As a result, when overheating happens in the room it would be compensated by increasing the supply air volume flow and this is in contrast to what the strategy considered.

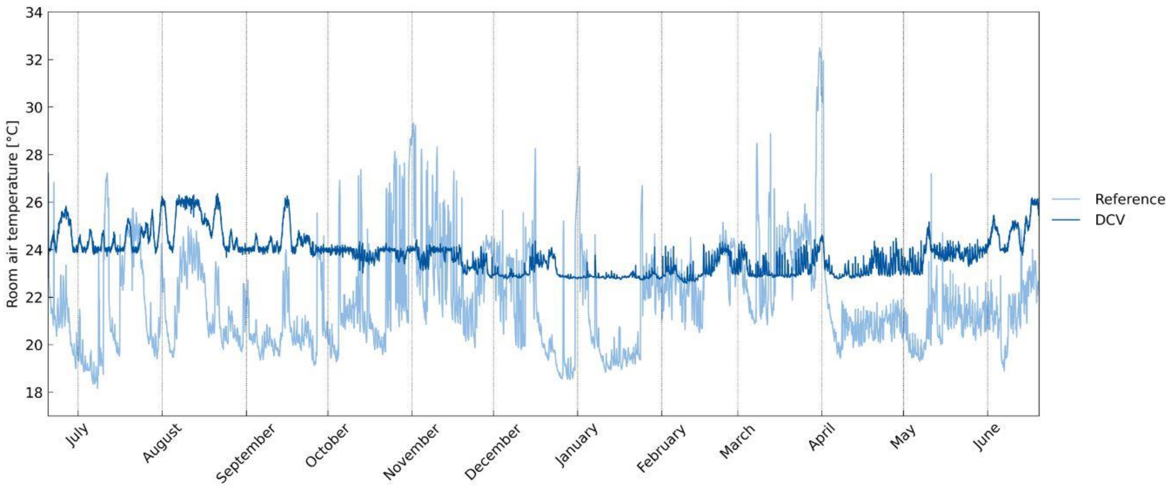

Figure 4-64 DCV strategy and reference room air temperature of office room (UKA)

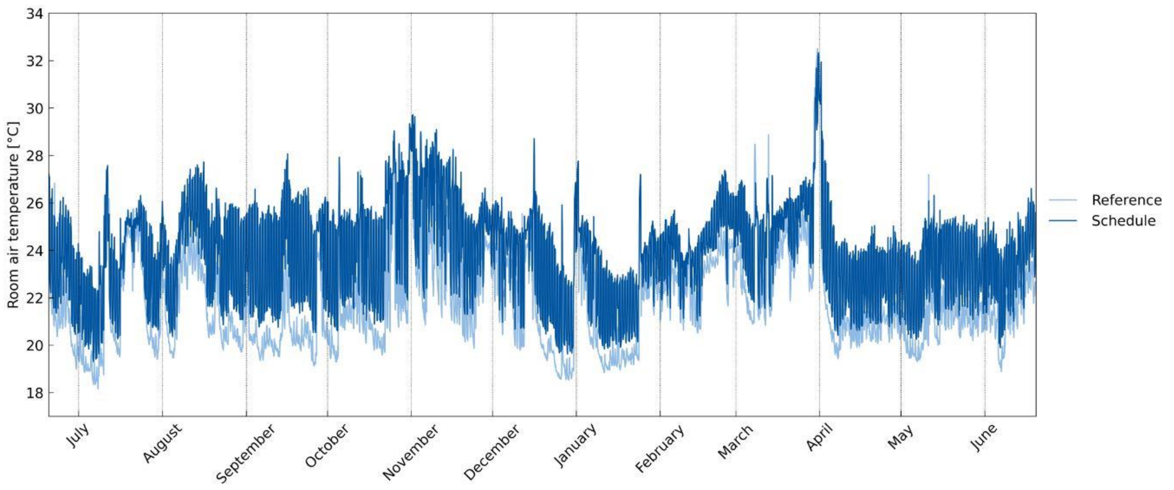

Figure 4-65 Schedule-based strategy and reference room air temperature of office room (UKA)

Due to low occupancy, room air temperature for the reference case completely follows the supply air temperature since the supply volume flow is high and thermal loads are quite low. Accordingly, in the schedule-based strategy with the same supply air temperature, the room air temperature would nearly get the same result and only lower amounts occur during the operation of AHU with minimum supply air volume flow.

Although standards and guidelines allocated a small amount of supply air for this room usage type, it could completely maintain thermal comfort. but the difference in CO_2 concentration with the reference case is higher compared to other room usage types.

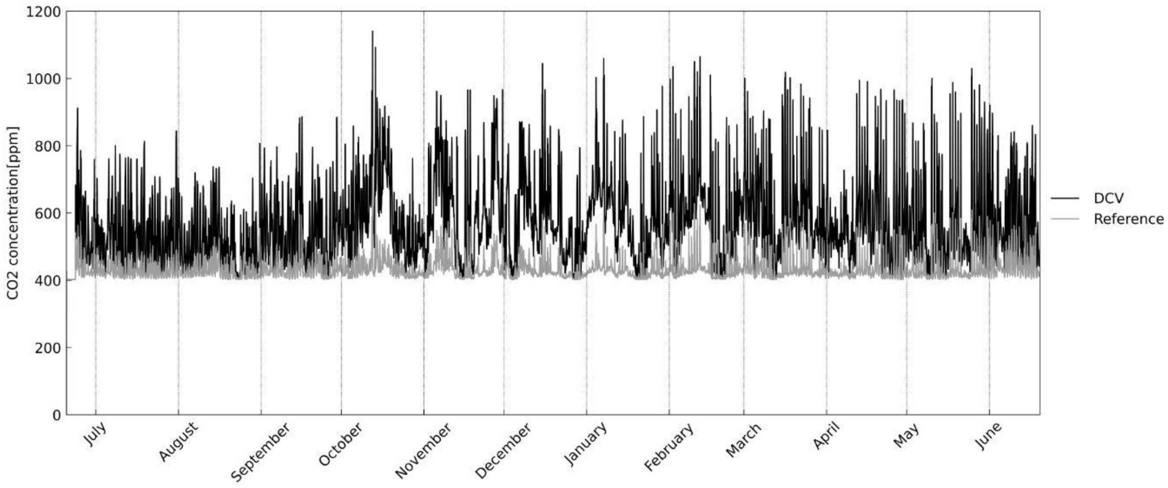

Figure 4-66 DCV strategy and reference CO_2 concentration of office room (UKA)

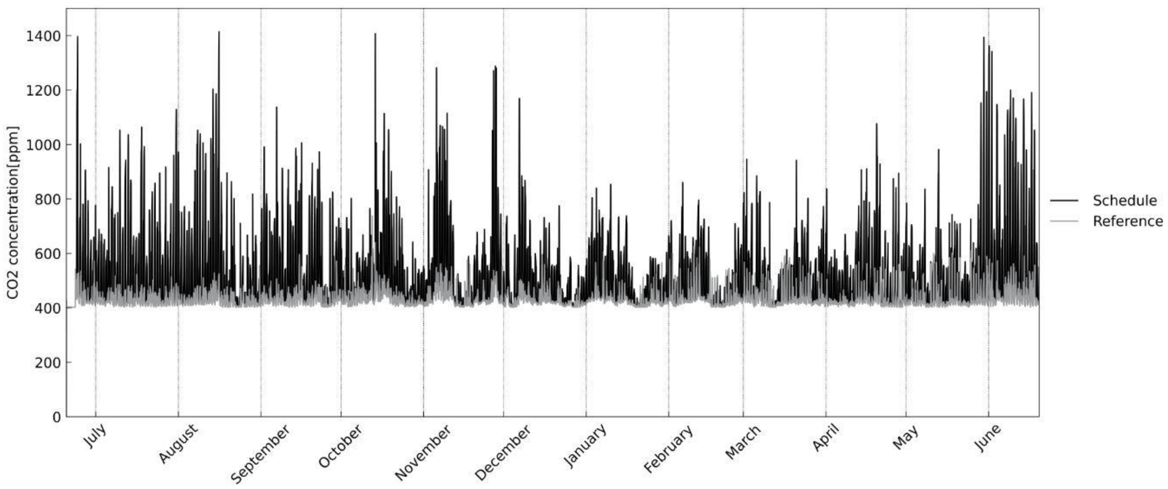

Figure 4-67 Schedule-based strategy and reference CO_2 concentration of office room (UKA)

High peaks in the CO_2 concentration plot of the schedule-based method are again by the reason of the presence of some people during a period of time out of working hours which is considered for the operation schedule of the air handling unit.

4.2.8 Consulting and treatment room

Before going to the energy consumption indication of consulting and treatment room, it should be mentioned that for the schedule-based simulation of this room usage type 16 hours of ventilation with reference supply volume flow is considered. Since the occupancy is distributed disorderly and there are many occupations recorded out of working hours during a year.

The following figures represent the energy consumption of different strategies for this room.

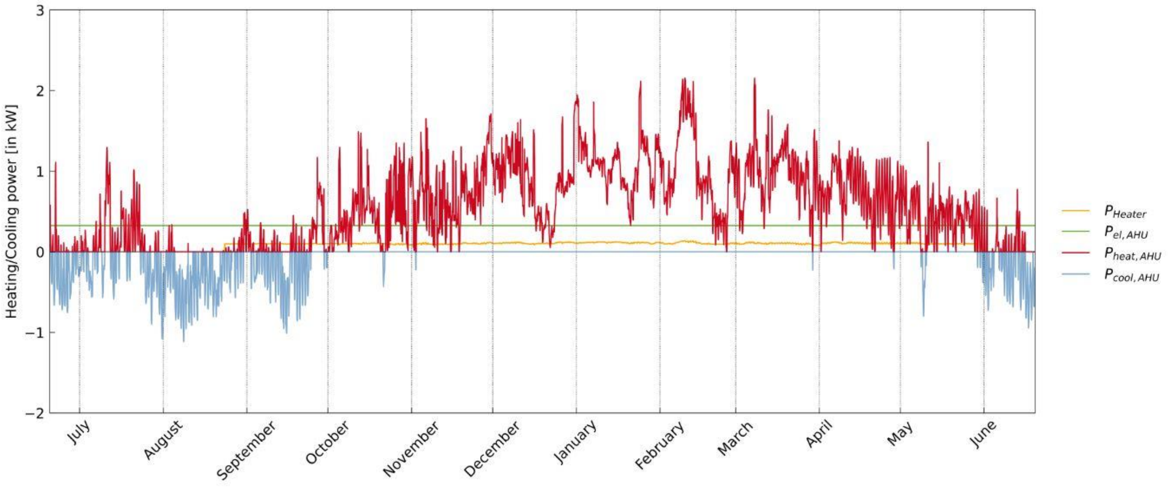

Figure 4-68 Reference energy consumption of consulting and treatment room (UKA)

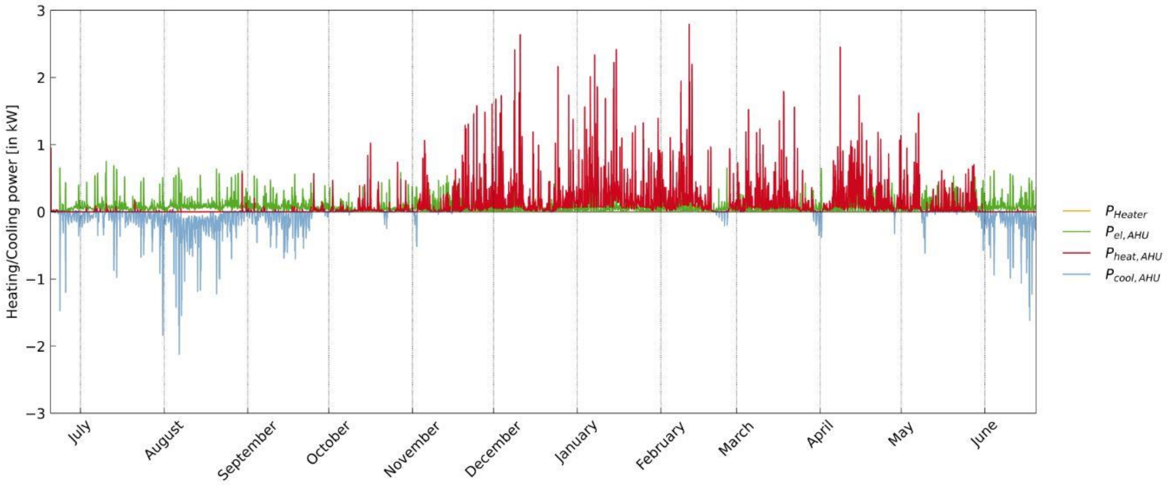

Figure 4-69 DCV strategy energy consumption of consulting and treatment room (UKA)

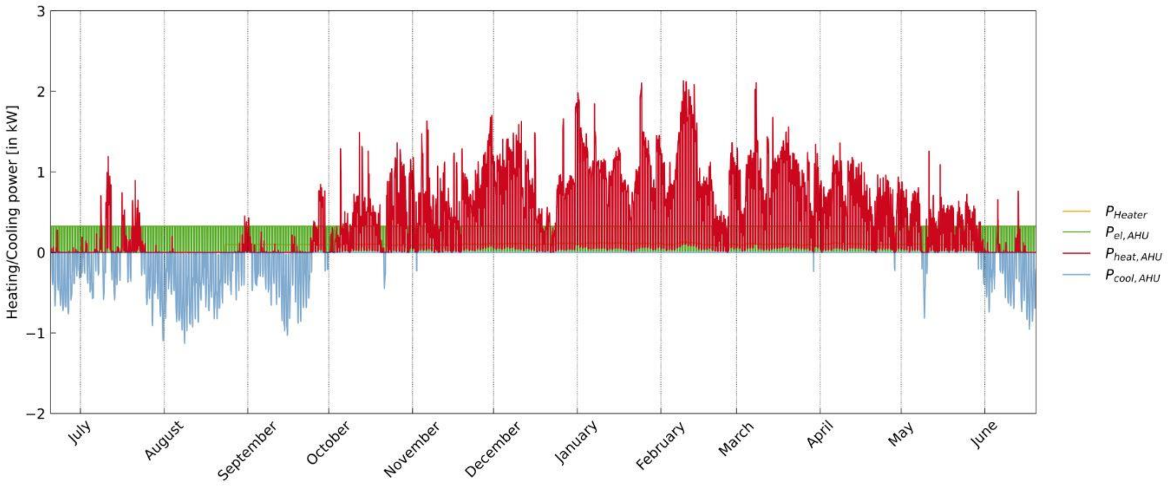

Figure 4-70 Schedule-based strategy energy consumption of consulting and treatment room (UKA)

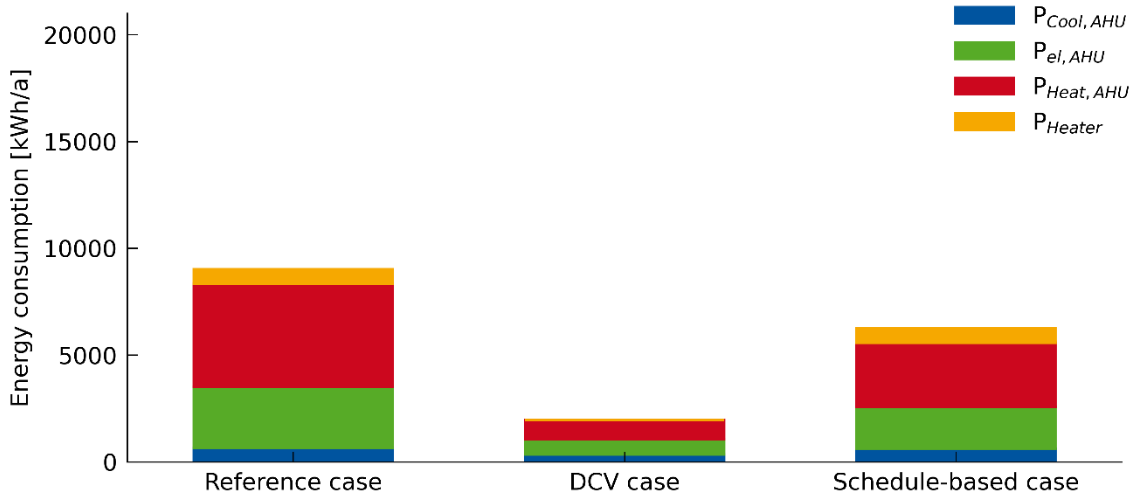

Figure 4-71 Energy consumption comparison of 3 strategies for consulting and treatment room (UKA)

Table 4-8 Consulting and treatment room energy consumption and saving (UKA)

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case	654.33	4815.14	2855.44	696.55	9021.46
DCV case	347.35	888.73	711.5	8.27	1955.85
Schedule based	614.74	3010.05	1950.57	679.83	6255.19
Saving for DCV %	46.92%	81.54%	75.08%	98.81%	78.32%
Saving for schedule-based%	6.05%	37.49%	31.69%	2.40%	30.66%

Like other simulations, the energy consumption of the air handling unit and decentral heater reduces rapidly by adjusting DCV. The schedule-based strategy does not show as much saving as other cases due to a longer period of ventilation with reference supply air volume flow rate.

Despite unreliable supply air temperature as the reference, applying the DCV method with controlling supply air temperature and volume flow we could easily keep the room air temperature in a thermal comfort zone. Also, we are capable of saving a remarkable amount of energy. However, it is taken into account to use reference temperature for supply air in the schedule-based strategy. There is also simulation done for the office and consulting and treatment room of UKA with supply air temperature controller adjusted in order to compare it with this case and also DCV strategy. The detail of the simulation is provided in plots in Appendix C.

The supply air temperature allocated to each strategy would clarify how the energy consumption of the AHU and room air temperature would change.

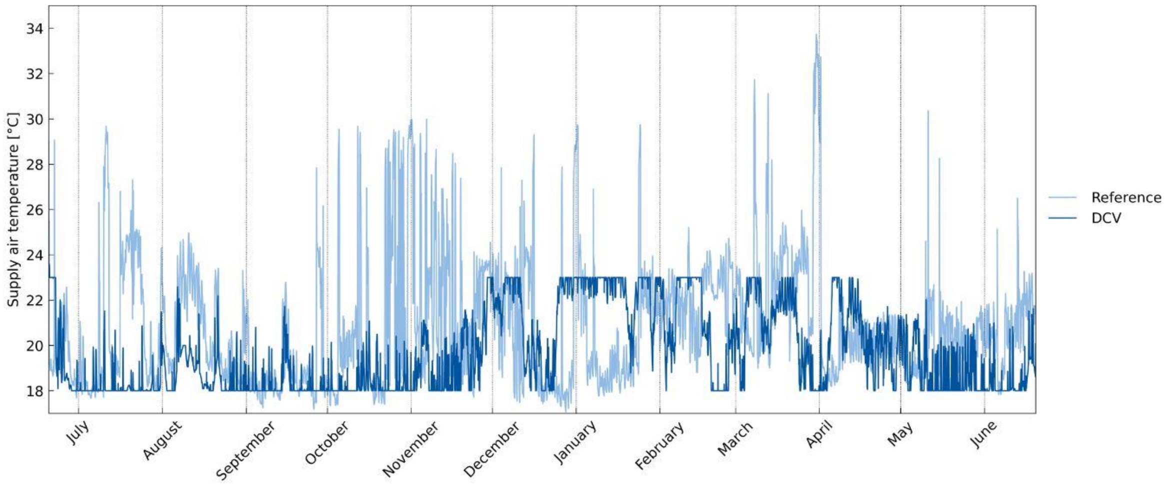

Figure 4-72 DCV strategy and reference supply air temperature of consulting and treatment room (UKA)

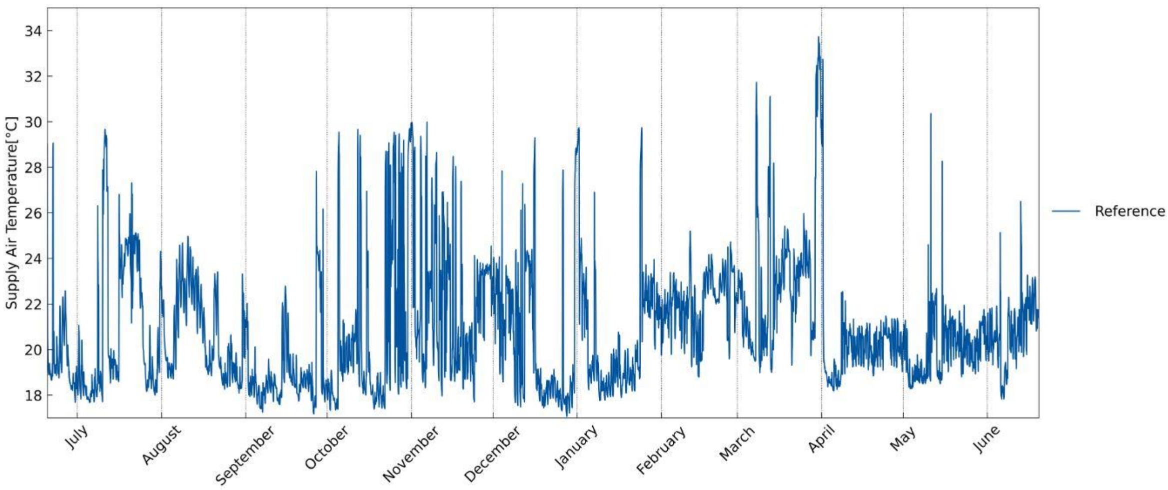

Figure 4-73 Schedule-based strategy and reference supply air temperature of consulting and treatment room (UKA)

In Figure 4-74 it is shown that sometimes the supply air volume flow rate reaches higher values than reference. It has two reasons. The first reason is that cooling provided by the AHU needs higher outdoor air volume flow to maintain thermal comfort since the supply air temperature could not reach values lower than the minimum considered value (18°C). The second reason is the number of people during the occupied times inside the room is high (Figure B-8) and therefore devoted volume flow rate will increase drastically. It should be mentioned that chosen volume flow rate from guidelines for consulting and treatment rooms is also high. But as is indicated in energy consumption plots, cumulatively the electrical energy consumption of the fans is lower than the reference case even though there are higher volume flow rates in the DCV method.

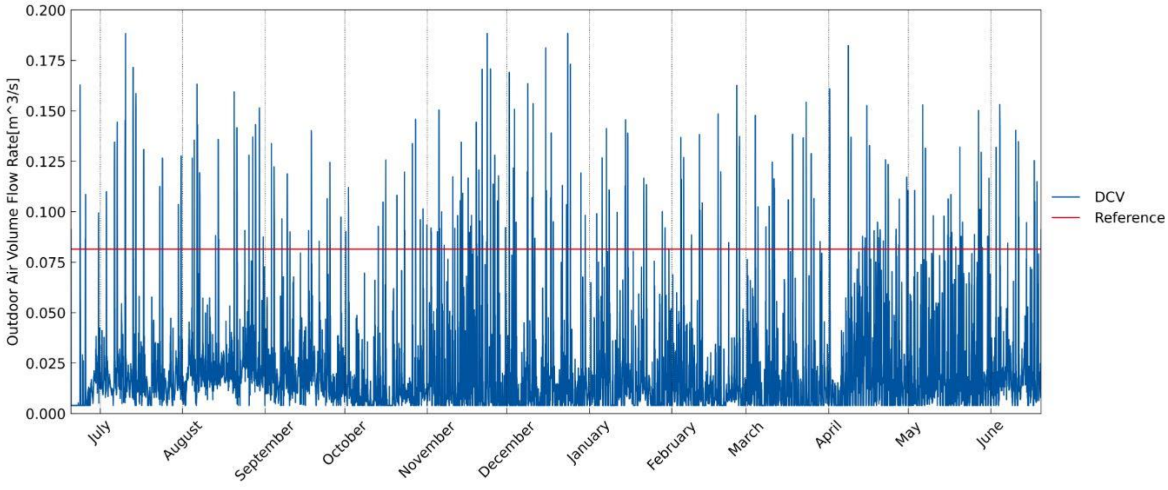

Figure 4-74 DCV strategy and reference outdoor air volume flow rate of consulting and treatment room (UKA)

On the other hand, for the schedule-based method as it is expected the supply air volume flow rate and consequently electrical energy consumption of fans follow the schedule allocated to this room. (Figure 4-75)

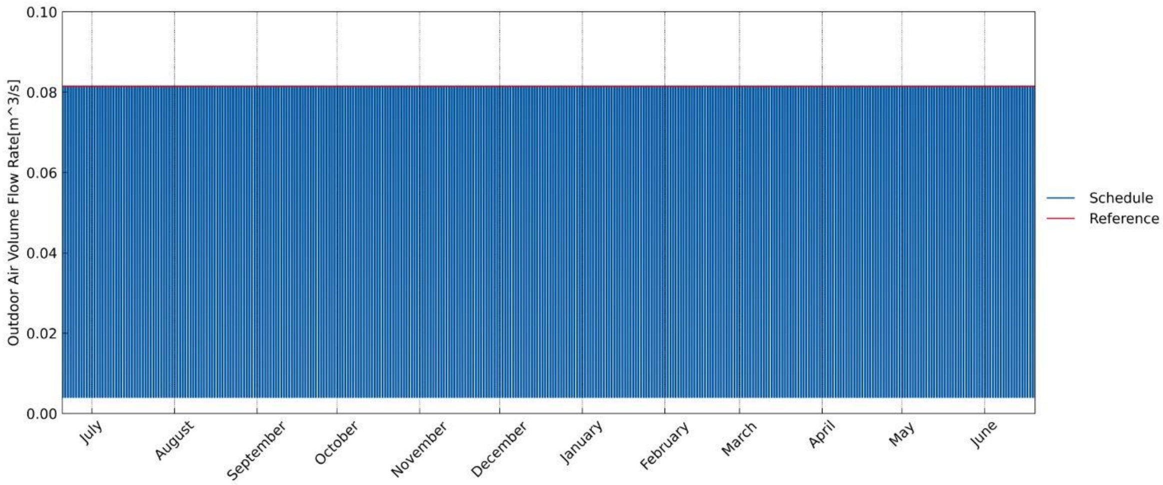

Figure 4-75 Schedule-based strategy and reference outdoor air volume flow rate of consulting and treatment room (HUS)

Lately, a comparison is done between simulated strategies and the reference room air temperature in Figure 4-76 and Figure 4-77. DCV strategy always maintains thermal comfort because it is a controlling boundary for the method. However, due to the fact that we use the reference supply air temperature in the schedule-based strategy, room air temperature is almost the same as the reference case with lower fluctuations which is because of the times in which the ventilation applied with minimum supply volume flow rate.

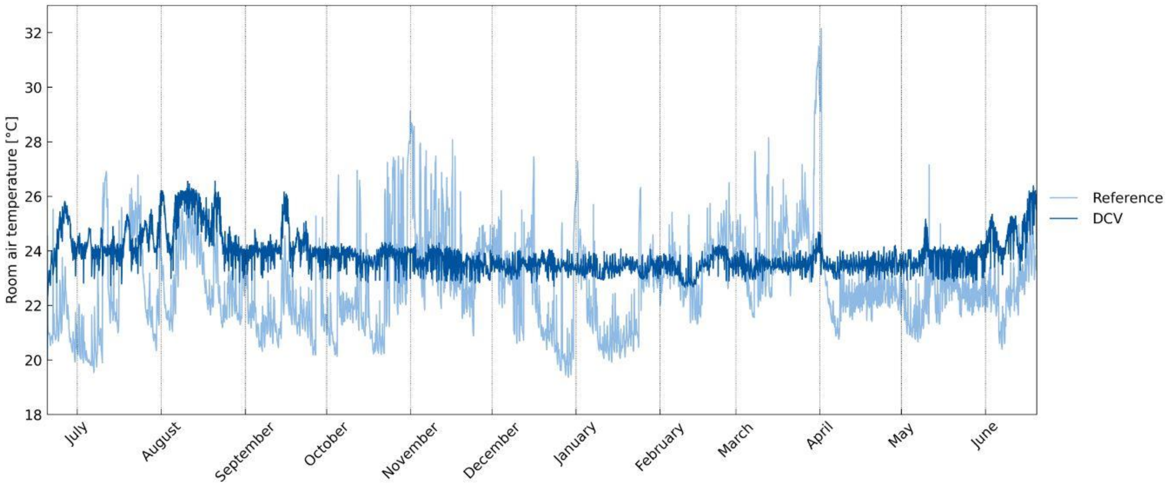

Figure 4-76 DCV strategy and reference room air temperature of consulting and treatment room (UKA)

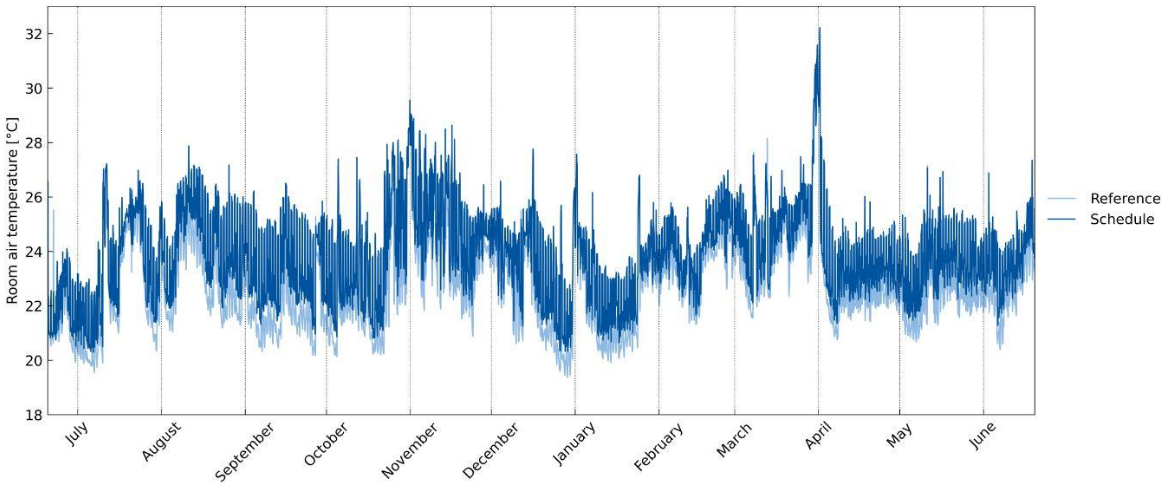

Figure 4-77 Schedule-based strategy and reference room air temperature of consulting and treatment room (UKA)

Values taken from standards and guidelines for supply volume flow rate per person always guarantee indoor air quality which is a notable point about the DCV strategy. Keeping CO_2 concentration lower than 2000 ppm inside the room makes indoor air quality acceptable, even though, there are quite a few times with high concentration of CO_2 in the schedule-based method which is again because of the unexpected and out-scheduled presence of occupancy.

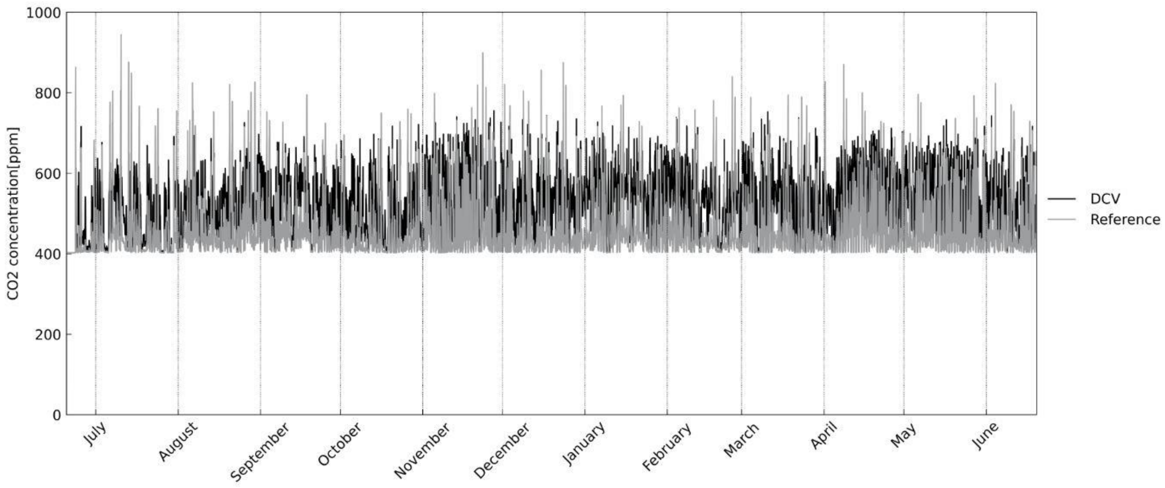

Figure 4-78 DCV strategy and reference CO_2 concentration of consulting and treatment room (UKA)

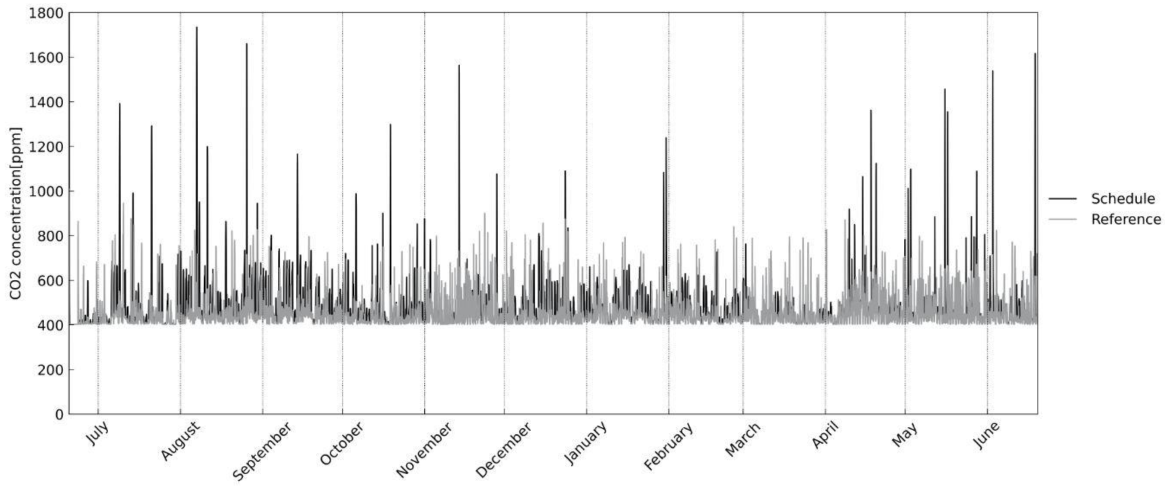

Figure 4-79 Schedule-based strategy and reference CO_2 concentration of consulting and treatment room (UKA)

4.3 Comparison and economic assessment

To compare the results, it is needed to be borne in mind that many aspects should be considered. First of all, results are provided for two different buildings in distinguished locations. Thus, the ambient condition of each location as well as building-related parameters like construction material, building orientation, HVAC operating system and etc., would influence on results.

Generally, comparing the two hospitals, it is expressed that the energy consumption of the HVAC system in UKA is much more than HUS. This could be due to the older construction of the building and operation of an aged and inefficient AHU which results in more energy dissipation and waste.

Moreover, developed strategies have almost the same basis to apply to each room usage type for both hospitals. Despite the possibility to control the supply air temperature in UKA and consider controlling boundaries with respect to national guidelines, the framework is similar for each usage type. Therefore, there are some other internal parameters related to the room itself which could make difference in the energy consumption of the HVAC system for each case. Location of the room inside the building, area of interior and exterior walls, thermal mass of the walls, area, and volume of the room, internal gains, and occupancy are some of these parameters. Later, in the next section, there is a simulation done for some rooms with different occupancy to observe the effect of this parameter on the energy consumption. Some of these parameters are reported in the table below for regular care in both hospitals and also an occupancy comparison is done in Figure 4-80.

Table 4-9 Room identification features

	Area $[m^2]$	Height $[m]$	Volume $[m^3]$	Occupation percentage %	Area of the exterior walls $[m^2]$	Area of the interior wall $[m^2]$
Regular care room (UKA)	38.5	2.8	107.8	78.37%	15	83.74
Regular care room (HUS)	30.8	2.5	77	86.4	14.2	53.6

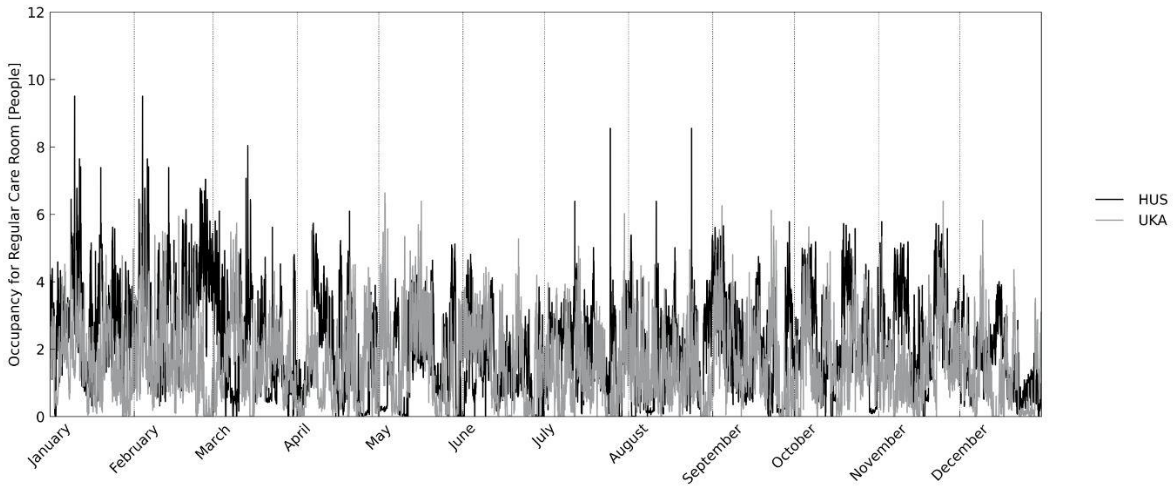

Figure 4-80 Occupancy difference in Regular care room

Lastly, there are some differences among strategies applied to each room usage type. There is a direct relation between supplied air volume flow provided to the room and its CO_2 concentration. Considering office and consulting room as two different room usage types with almost similar occupation trends, there is always more CO_2 concentration in the DCV strategy for office (Figure 4-25 and Figure 4-66) rather than consulting room (Figure 4-35 and Figure 4-78) in both hospitals. The reason is that the supply air volume flow rate devoted to consulting and treatment room in standards is more than three times of the one dedicated to the office. Consequently, the condition for regular care and isolation care room is equivalent. In both rooms where there may have a presence of the overnight patient, as the situation in isolation cares is more important, more supply air volume flow is considered for this usage type (Figure 4-15 and Figure 4-54). Thus, we can see CO_2 increase is way lesser than in regular care rooms (Figure 4-6 and Figure 4-43). Although there is a difference in CO_2 concentration increase for DCV strategy, it is always observed not to exceed the limitation amount for indoor air quality.

4.3.9 Economic assessment

In order to make an assessment economically on energy saving of each room, here 2 scenarios are presented. In the first scenario, we considered reported prices for electricity and heat from the UKA database as an available field source for the assessment of both hospitals. Scenario2 represents a price that is taken from an online source as the average price of electricity and natural gas per kilowatt-hours in each country [8],[7],[9]. Provided costs are considered directly for electric consumption and heating consumption in AHU and decentral heater. However, for cooling, since most of the consumption but not all is electrical, we considered a lower cost of 2/3 of the electricity price.

Selected values for each scenario are shown in Table 4-10.

Table 4-10 Selected values for two scenarios of economic assessment

Scenarios	Electricity price [€/KWh]		Heating price [€/KWh]	
	HUS	UKA	HUS	UKA
Scenario 1	0.14	0.14	0.038	0.038
Scenario 2	0.0695	0.1206	0.0513	0.0298

The following tables represent the cost assessment of all rooms in both hospitals.

Table 4-11 Regular care room economic assessment results (HUS)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	131.8	4409.44	752.91	1821.94	7116.09
DCV case consumptions [KWh/a]	246.47	545.44	189.28	455.36	1436.55
Benefits (scenario 1) [€/a]	-10.70	146.83	78.91	51.93	266.97
Benefits (scenario 2) [€/a]	-5.31	198.22	39.17	70.11	302.19

Table 4-12 Isolation care room economic assessment results (HUS)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	278.97	4232.24	880.75	1781.65	7173.61
DCV case consumptions [KWh/a]	392.63	630.5	247.73	239.27	1510.13
Occupancy state case consumption [KWh/a]	277.68	3339.21	671.72	528.77	4817.38
Benefits for DCV (scenario 1) [€/a]	-10.61	136.87	88.62	58.61	273.49
Benefits for DCV (scenario 2) [€/a]	-5.27	184.77	43.99	79.12	302.62
Benefits for OCC.State (scenario 1) [€/a]	0.12	33.94	29.26	47.61	110.93
Benefits for OCC.State (scenario 2) [€/a]	0.06	45.81	55.05	64.27	165.20

Table 4-13 Office room economic assessment results (HUS)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	51.15	2853.43	451.75	640.95	3997.28
DCV case consumptions [KWh/a]	52.4	202.6	63.3	4.55	322.85
Schedule-based case consumption [KWh/a]	55.02	1397.3	236.79	27.67	1716.78
Benefits for DCV (scenario 1) [€/a]	-0.12	100.73	54.38	24.18	179.18
Benefits for DCV (scenario 2) [€/a]	-0.06	135.99	27.00	32.65	195.57
Benefits for schedule-based (scenario 1) [€/a]	-0.36	55.33	30.09	23.30	108.37
Benefits for schedule-based (scenario 2) [€/a]	-0.18	74.70	27.62	31.46	133.60

Table 4-14 Consulting and treatment room economic assessment results (HUS)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	81.16	3173.39	534.57	1663.97	5453.09
DCV case consumptions [KWh/a]	121.36	150.51	65.47	353.85	691.19
Schedule-based case consumption [KWh/a]	84.05	1912.68	305.68	422.54	2724.95
Benefits for DCV (scenario 1) [€/a]	-3.75	114.87	65.67	49.78	226.58
Benefits for DCV (scenario 2) [€/a]	-1.86	155.07	32.60	67.21	253.02
Benefits for schedule-based (scenario 1) [€/a]	-0.27	47.91	32.04	47.17	126.86
Benefits for schedule-based (scenario 2) [€/a]	-0.13	64.67	32.59	63.69	160.81

Table 4-15 Regular care economic assessment results (UKA)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	765.15	9574.15	3714.27	6586.87	20640.44
DCV case consumptions [KWh/a]	906.07	4102.94	1480.66	5320.97	11810.64
Benefits for DCV (scenario 1) [€/a]	-13.15	207.91	312.71	48.10	555.56
Benefits for DCV (scenario 2) [€/a]	-11.33	158.12	269.37	36.58	452.75

Table 4-16 Isolation care room economic assessment results (UKA)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	283.48	5972.78	2778.08	4633.86	13668.2
DCV case consumptions [KWh/a]	575.45	2864.74	1331.3	3610.32	8381.81
Occupancy state case consumption [KWh/a]	568.54	1059.96	615.99	3764.52	6009.01
Benefits for DCV (scenario 1) [€/a]	-27.25	118.11	202.55	38.89	332.30
Benefits for DCV (scenario 2) [€/a]	-23.47	89.82	174.48	29.58	270.41
Benefits for OCC.State (scenario 1) [€/a]	-26.61	186.69	302.69	33.03	495.81
Benefits for OCC.State (scenario 2) [€/a]a]	-22.92	141.98	310.61	25.12	454.79

Table 4-17 Office room economic assessment results (UKA)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	799.31	4564.5	2855.11	951.11	9170.03
DCV case consumptions [KWh/a]	232.24	213.53	258.51	89.76	794.04
Schedule-based case consumption [KWh/a]	661.78	2023.02	1473.67	911.84	5070.31
Benefits for DCV (scenario 1) [€/a]	52.93	165.34	363.52	32.73	614.52
Benefits for DCV (scenario 2) [€/a]	45.59	125.74	313.15	24.89	509.38
Benefits for schedule-based (scenario 1) [€/a]	12.84	96.58	193.40	1.49	304.31
Benefits for schedule-based (scenario 2) [€/a]	11.06	73.45	300.49	1.13	386.13

Table 4-18 Consulting and treatment room economic assessment results (UKA)

	$P_{coolAHU}$	$P_{heatAHU}$	P_{el}	P_{heater}	Total
Reference case consumption [KWh/a]	654.33	4815.14	2855.44	696.55	9021.46
DCV case consumptions [KWh/a]	347.35	888.73	711.5	8.27	1955.85
Schedule-based case consumption [KWh/a]	614.74	3010.05	1950.57	679.83	6255.19
Benefits for DCV (scenario 1) [€/a]	28.65	149.20	300.15	26.15	504.16
Benefits for DCV (scenario 2) [€/a]	24.68	113.47	258.56	19.89	416.60
Benefits for schedule-based (scenario 1) [€/a]	3.70	68.59	126.68	0.64	199.61
Benefits for schedule-based (scenario 2) [€/a]	3.18	52.17	308.17	0.48	364.00

Generally, the benefits of applying the DCV strategy are higher than other strategies. It is due to more energy-saving occurred by applying the same strategy. Considering different aspects of the energy consumption in the HVAC system, saving on the electrical consumption is the most beneficial as the price for this sector is higher than others. Although saving in heating consumption is more compared to electrical savings in most of the rooms, economic benefits are higher for electrical savings since its price is higher comparably.

The reason that the cooling energy consumption is much lower than other sectors, the saving is also low in the cooling. Therefore, despite the conditions where we have more cooling in our developed strategies, we have just a few financial benefits in this part.

4.4 New occupancy and results

Occupancy data is measurement data that is calculated through detected CO_2 concentration by sensors inside each room. Therefore, we only have one unique occupancy data for the periods under consideration for every single room.

But the occupation is one of the major parameters in simulation which the DCV method is completely based on. So, it brings a question to mind how will the results change if the occupancy of a considered room changes?

To answer this question, it is needed to be taken into account that by recording data from a room with detection sensors, there is one and only one possible occupancy data available. Thus, it is needed to generate new data for occupancy.

The other challenging part is how to generate this data to have validity for simulation and make a comparison with real data. Occupancy data like any other data is provided for each hour during a year. So, it is not possible to check each of the data in order to modify it for generating a new one.

Therefore, a deeper study on occupancy trends on a daily basis is done. Then, we decided to keep the total occupancy trend of the rooms and only change the percentage of occupation of the room during a year. In this way, it is possible to prolong a period of non-occupancy in order to decrease the percentage of occupation of the room whereas we used the same pattern of the high occupied period to change them with lower occupied times in order to increase the percentage.

For investigating the effect of occupancy on previous cases, 2rooms are selected to apply new occupancy for them. One is the regular care room in HUS in which the percentage of occupation is changed from 86.1% to 71.8%. The other chosen room is the HUS office, where the occupation percentage is increased from 21.2% to 28.6% for this room.

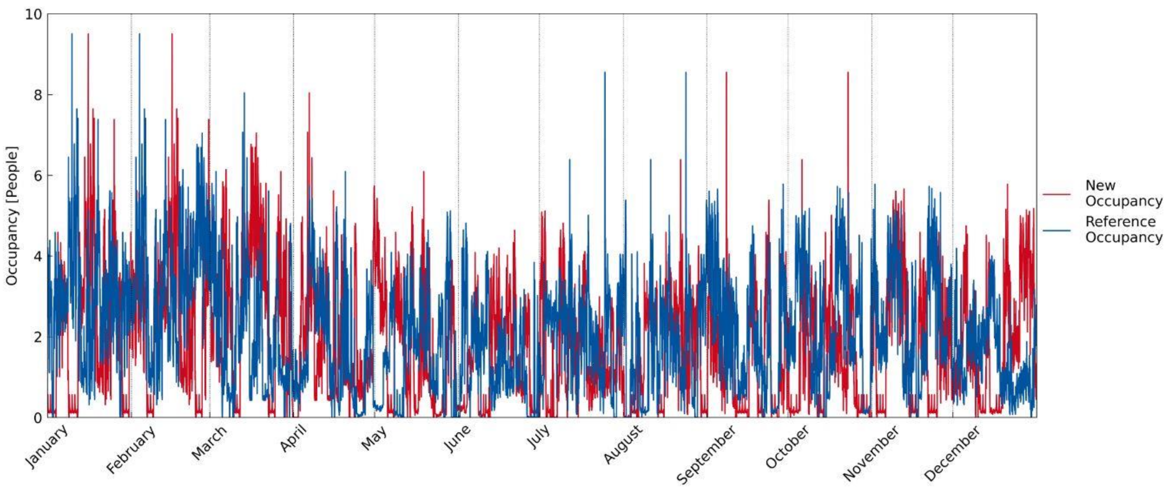

Figure 4-81 Room occupancy data for the HUS regular care room (generated and reference)

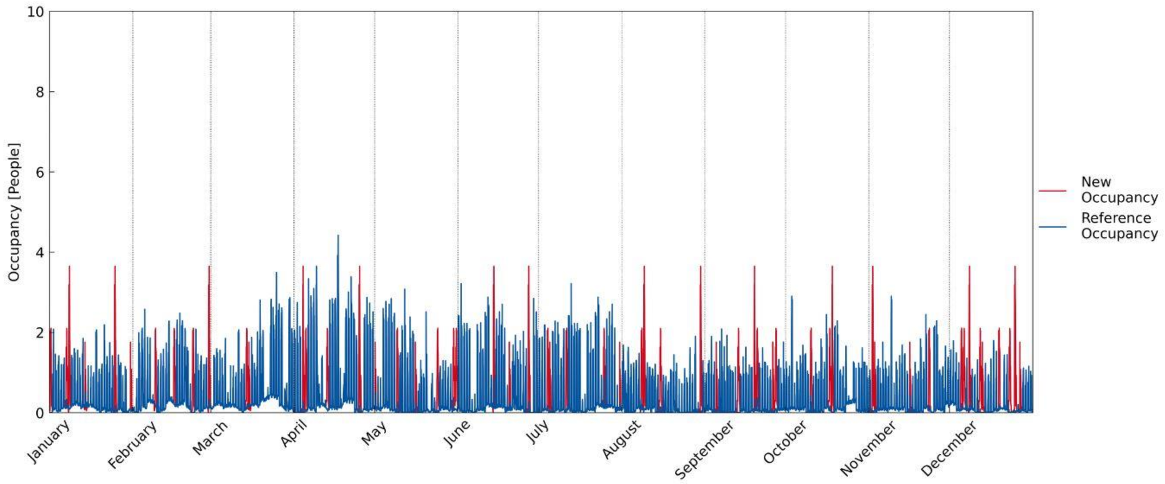

Figure 4-82 Room occupancy data for the HUS office room (generated and reference)

Later on, the strategies simulated previously are placed for newly generated occupancy.

In Table 4-19 below the result of simulation for different strategies is given compared with previous results.

Table 4-19 Energy consumption results for new occupancy of regular care room (HUS) in comparison to reference occupation

	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case (refernce occupancy)	131.8	4409.44	752.91	1821.94	7116.09
DCV case (refernce occupancy)	246.47	545.44	189.28	455.36	1436.55
Reference case (new occupancy)	133.3	4503.05	752.91	1862.18	7251.44
DCV case (new occupancy)	247.64	506.59	171.16	534.97	1460.36
Comparison of Reference case (new to reference occupancy)%	1.13%	2.08%	0.00%	2.16%	1.87%
Comparison of DCV case (new to reference occupancy)%	0.47%	-7.67%	-10.59%	14.88%	1.63%

Comparing the results for two occupation patterns, as the new occupancy generated is lower than the reference case, the internal gains of the room decrease in parallel. By reduction of internal gains, it is expected that heat demand would increase correspondingly. Therefore, energy consumption for heating in the air handling unit, as well as the decentral heater, raises. However, it was expected to see a reduction in the cooling sector of AHU due to the same reason, here the energy consumption of cooling is increased. The reason is, although the whole occupation is decreased over a year, the occupancy of the warm season is more than the reference case which concludes in more energy consumption for cooling (Figure 4-81). Since in reference strategy the volume flow rate of the supply air does not change for different occupancies, there is no difference in electric consumption of fans.

For DCV strategy the situation is a little more complicated. Lowering the occupancy would generally mean a lower supply volume flow rate devoted to the room. But it should always be considered that less internal gain due to lower occupancy results in more heat demand while lower energy consumption of the AHU can be inferred from less supply volume flow rate. Additionally, there is a controller dedicated to this strategy which will change the supply volume flow rate in case of need to maintain the thermal comfort of the room. Thus, for reasoning the energy consumption difference of two occupancies in this method, there are some factors that contribute together.

Results for the new increased occupancy of the office room are also indicated in the table below.

Table 4-20 Energy consumption results for new occupancy of office room (HUS) in comparison to reference occupation

`	$P_{coolAHU}$ [KWh/a]	$P_{heatAHU}$ [KWh/a]	P_{el} [KWh/a]	P_{heater} [KWh/a]	Total [KWh/a]
Reference case (reference occupancy)	51.15	2853.43	451.75	640.95	3997.28
DCV case (refernce occupancy)	52.4	202.6	63.3	4.55	322.85
Schedule-based case (reference occupancy)	55.02	1397.3	236.79	27.67	1716.78
Reference case (new occupancy)	54.29	2820.53	451.75	627.84	3954.41
DCV case (new occupancy)	62.3	236.99	73.51	5.84	378.64
Schedule-based case (new occupancy)	57.89	1370.75	236.79	17.27	1682.7
Comparison of Reference case (new to reference occupancy)%	5.78%	-1.17%	0.00%	-2.09%	-1.08%
Comparison of DCV case (new to reference occupancy)%	15.89%	14.51%	13.89%	22.09%	14.73%
Comparison of Schedule-based case (new to reference occupancy)%	4.96%	-1.94%	0.00%	-60.22%	-2.03%

As it is shown in the table, considering the reference case, due to the occupancy increase in the new occupancy generated, the internal gains would be higher in the room. Therefore, heat demand would decrease, and it is indicated the same result where heating consumption of the AHU, as well as the decentral heater, decreased for the new occupation. On the other hand, cooling demand is raised which results in new occupancy generated shows the same manner. Considering that heating is the most dominant energy consumption, in this case, there would be a decrease in total energy consumption.

In parallel to the previous case, reasoning about the DCV strategy difference between the two occupations is more complicated. Although it is expected to have similar changes to the reference case while the occupancy is changed, it should be taken into consideration that the volume flow rate is also changing for the DCV strategy. This change is regarding the adaptation of the system with occupancy and adjustment of the supply air volume flow controller.

For instance, during the cold season the upper boundary limit for room air temperature is 22.5°C which is taken from Figure 3-4. By increasing occupancy, internal gains would also increase which could result in exceeding room air temperature from the considered limit. Thus, a cooling process will occur to keep the temperature below the boundary. Since the supply air temperature is fixed to 18°C, a volume flow rate of more than the devoted one will be supplied to cool the room air temperature. However, the aim of controlling is to cool down the room air temperature, we need to be aware of the operating process. Since the cold season is taken into account, the ambient temperature would be in a range below the supply air temperature. For maintaining the supply air temperature, it needs to heat up the outdoor air temperature even though the supply air is going to be utilized for cooling. Thus, there would be more heating consumption of the AHU to cool down the room air temperature.

To make a comparison between two dedicated occupancies for the schedule-based strategy, Since the supply volume flow would not change in both cases, the electric consumption difference is zero. Energy consumption behavior for the schedule-based method is almost the same as the reference case as the supply air volume flow is kept constant for both considered methods. Therefore, the results are quite similar. The only distinguishing parameter is, that when the percentage difference is taken into account for the decentral heater it seems huge. But if considering the real value of heater consumption, we can get that the high percentage difference is due to very low energy consumption in both cases.

Generally talking about the effect of occupancy over energy consumption of the HVAC system, it can be argued that when occupancy increases (or decreases) the internal gains would increase (or decrease). Therefore, opposite to the cooling, the heating demand would also decrease (or increase) correspondingly. But the general approach is valid while the supply air volume flow is kept constant in both cases and there is no controlling method applied.

Chapter 5
Conclusion and Outlook

The presented work focuses on the development and simulation of different demand-controlled ventilation strategies. Demand-controlled ventilation (DCV) is a strategy in which dedicated volume flows taken from standards and guidelines are applied with respect to the number of people present in the room. Additionally, the schedule-based control ventilation developed and studied for applicable cases as another strategy is represented.

The ventilation strategies were compared in simulations with a reference case based on measured data. By implementing the demand-control, the supply air volume flow was reduced according to the need of the space. Therefore, the energy requirements decreased. Results of this study show a great and considerable saving in energy consumption of the HVAC system. Simulations provide overconsumption and waste of energy by devoting constant ventilation in hospitals as one of the high energy-consuming commercial buildings.

Also considering revenues calculated for saving in each room, there is a huge economic benefit in applying DCV in hospitals. However, the investment costs for sensors, development, and production of the controlling system and in some cases constructional changes should be taken into account.

For further research, a development of the control system is conceivable. This can be done by optimizing the temperature control. For longer periods without the use of the room, a deviation from the specifications for the room air temperature is a possible approach. Integration of the relative room humidity is also recommended. The consideration of more complex systems with several rooms allows for studying the interactions between them as well. In the future, better CO_2 sensors can improve the application for higher air volume flows and increase the accuracy in all rooms. However, validation of the minimum air volume flows required by DIN and ASHRAE is also central, as these should not be undercut in the demand-controlled ventilation strategy. They determine how far the air volume flow can be reduced. They, therefore, have a significant influence on the energy requirement.

Appendix A.

Room Air Temperature Calibration Results

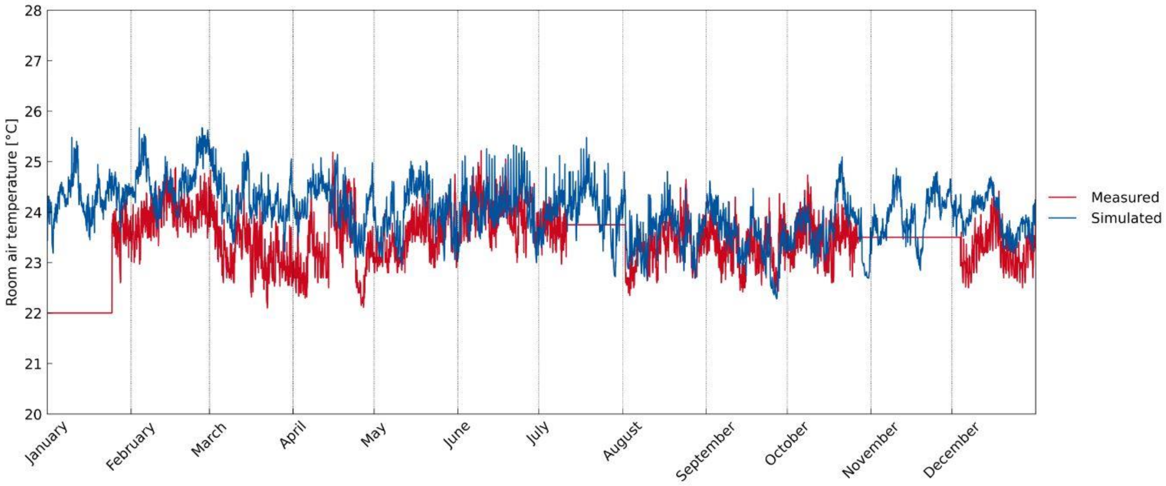

Figure A-1 Room air temperature comparison for calibration (HUS Regular care room)

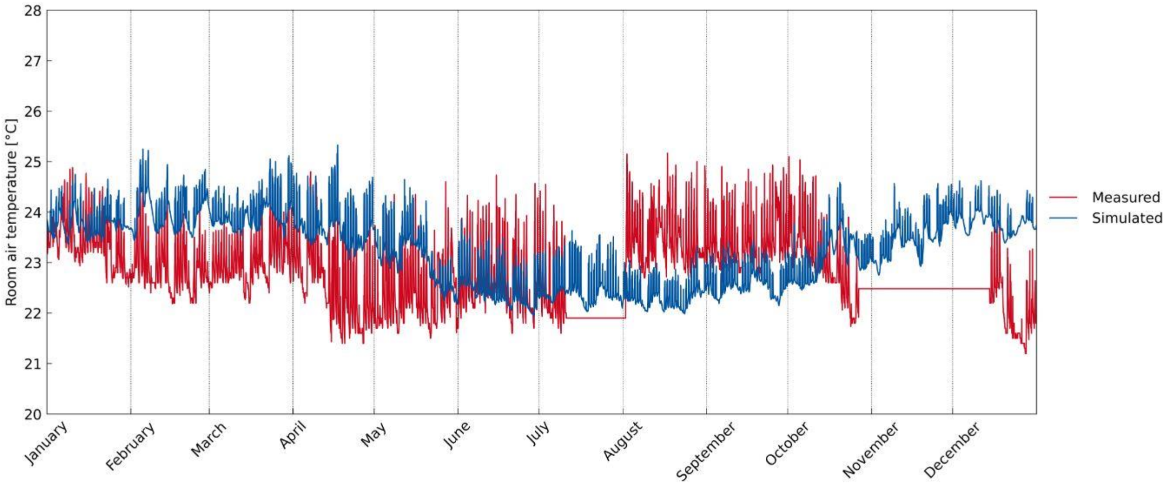

Figure A-2 Room air temperature comparison for calibration (HUS Office room)

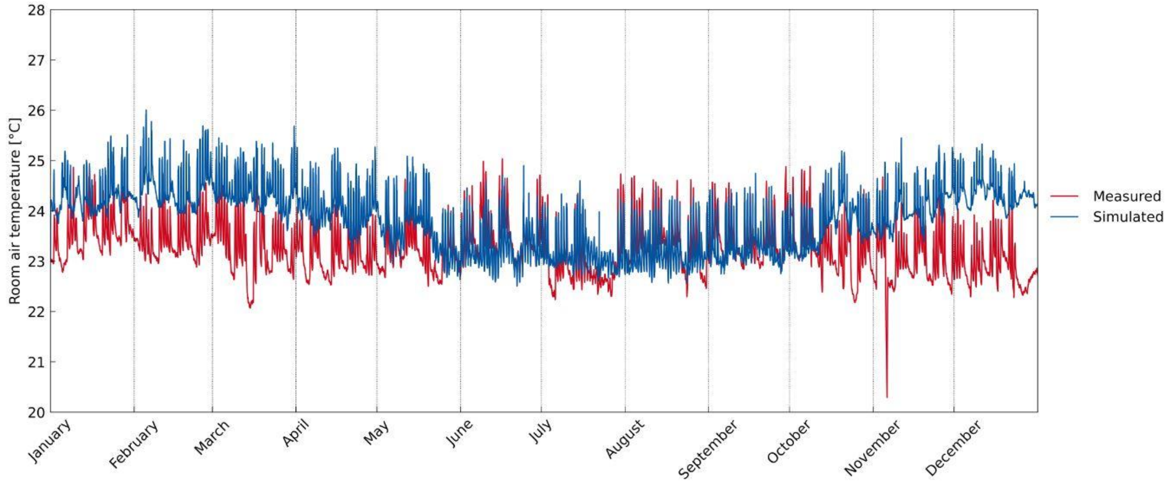

Figure A-3 Room air temperature comparison for calibration (HUS Consulting and treatment room)

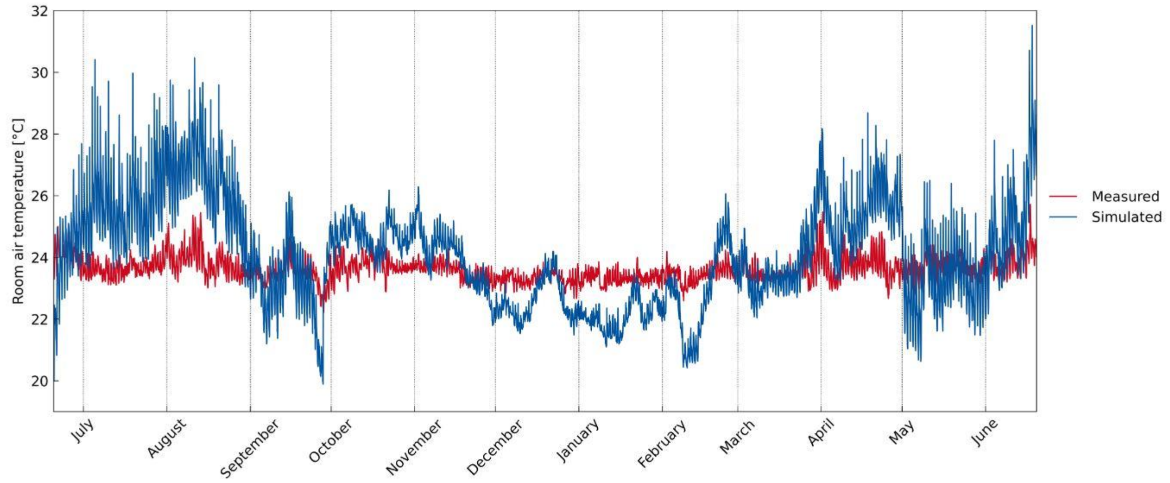

Figure A-4 Room air temperature comparison for calibration (UKA Isolation care room)

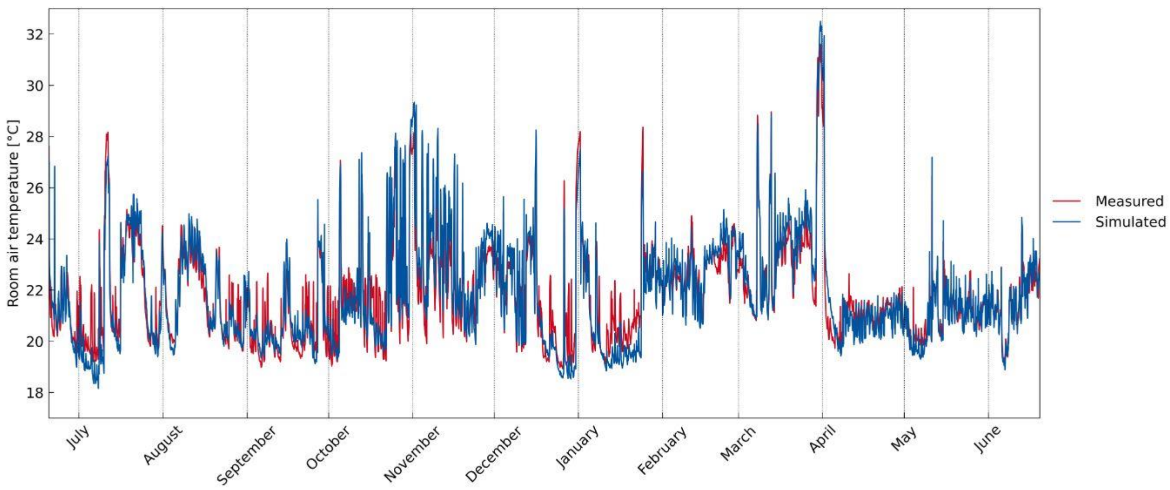

Figure A-5 Room air temperature comparison for calibration (UKA Office room)

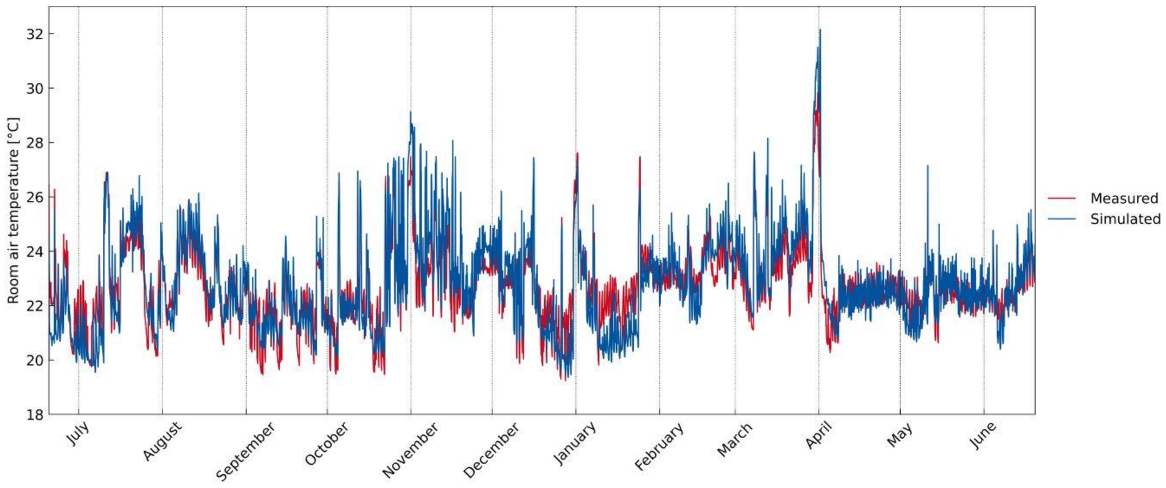

Figure A-6 Room air temperature comparison for calibration (UKA Consulting and treatment room)

Appendix B.

Room Occupancy Data

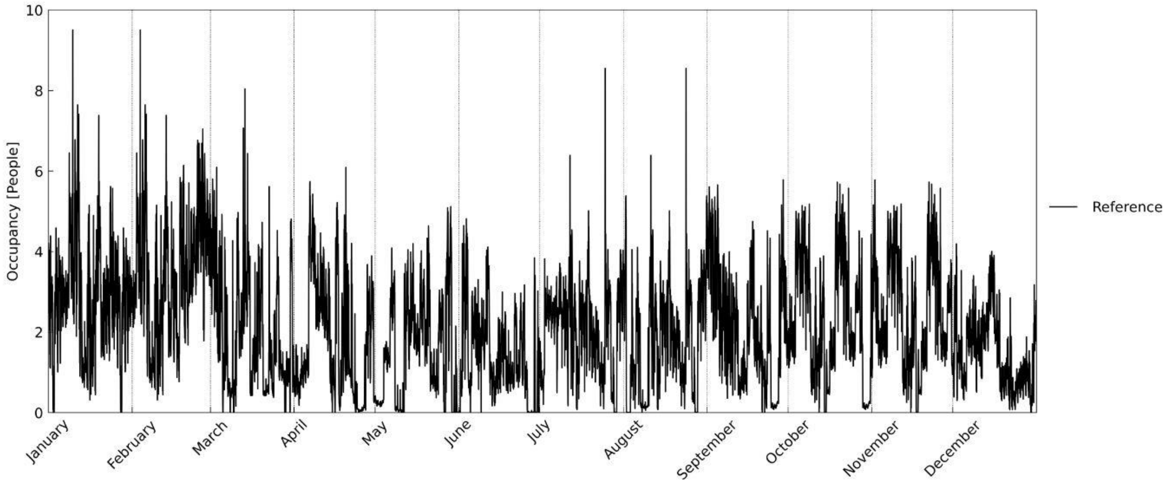

Figure B-1 Room occupancy data (HUS regular care room)

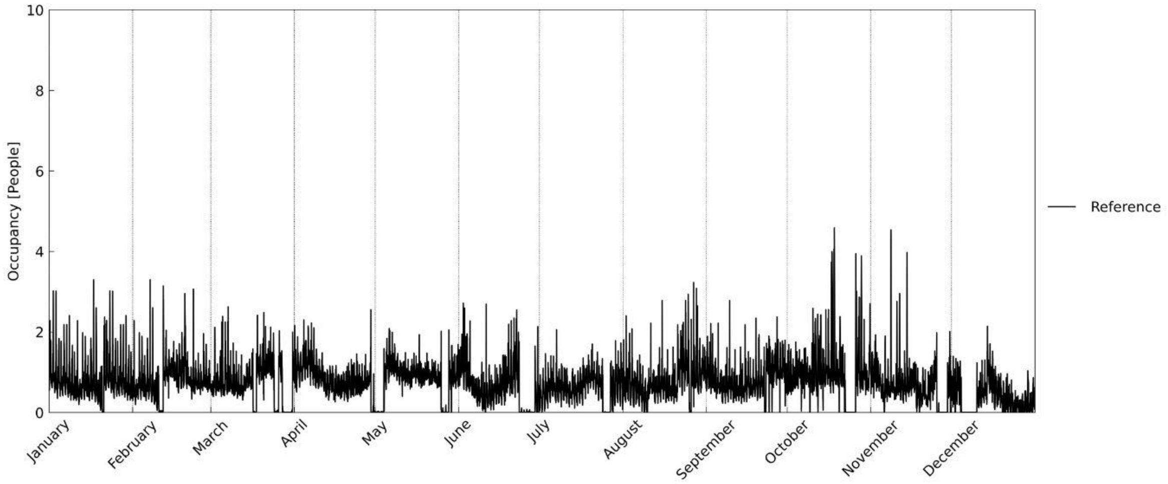

Figure B-2 Room occupancy data (HUS isolation care room)

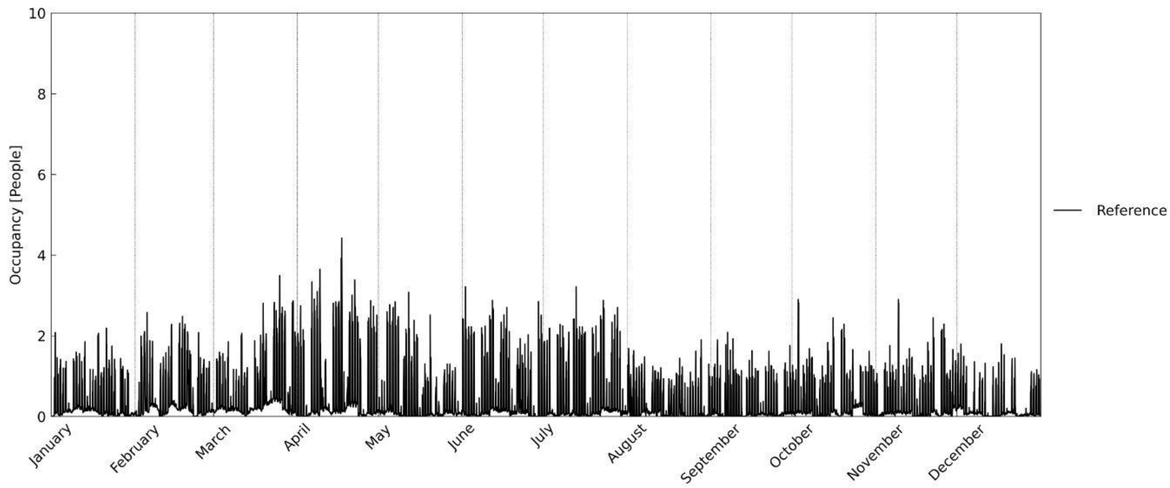

Figure B-3 Room occupancy data (HUS office room)

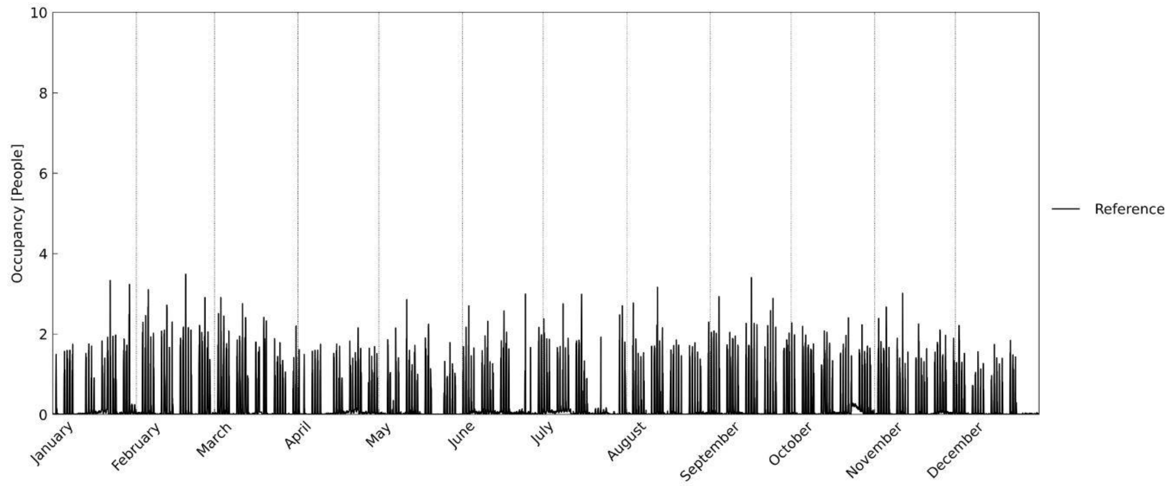

Figure B-4 Room occupancy data (HUS consulting and treatment room)

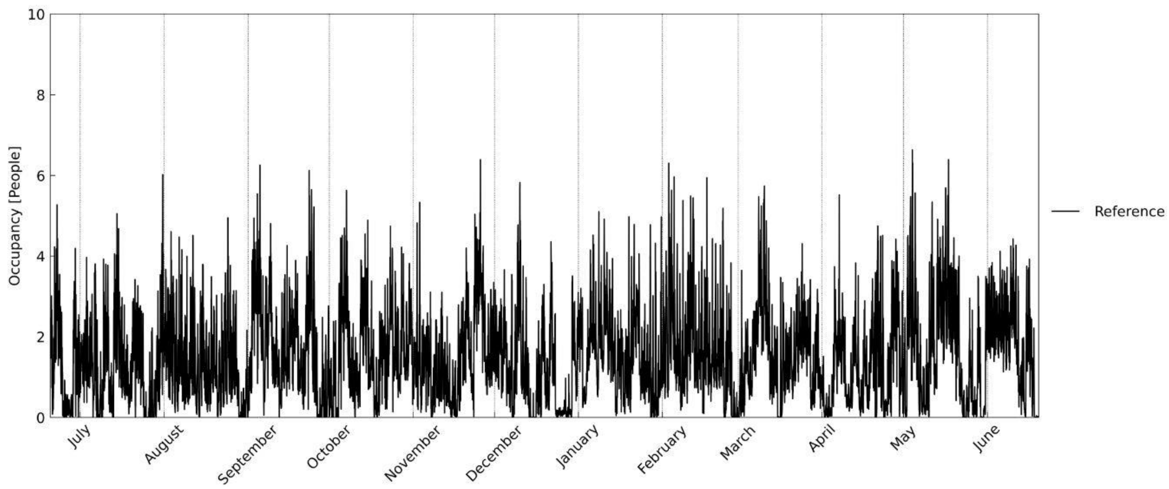

Figure B-5 Room occupancy data (UKA regular care room)

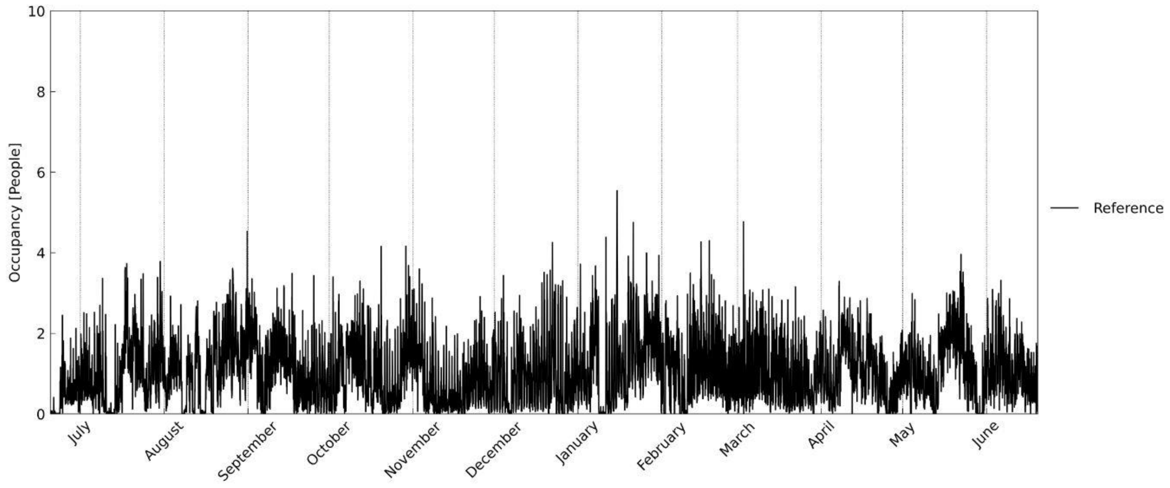

Figure B-6 Room occupancy data (UKA isolation care room)

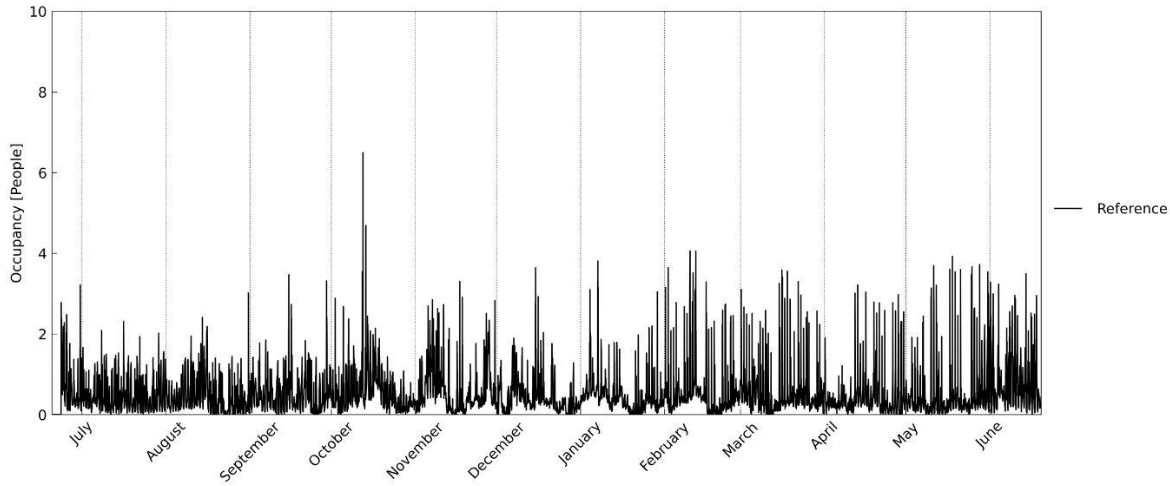

Figure B-7 Room occupancy data (UKA office room)

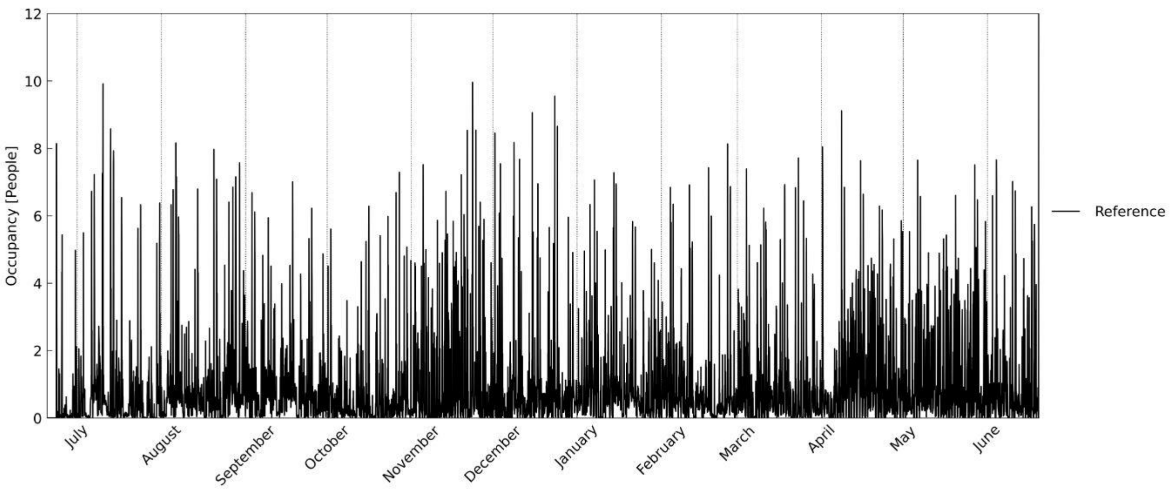

Figure B-8 Room occupancy data (UKA consulting and treatment room)

Appendix C.

Results for Office Room and Consulting and Treatment Room (UKA) with Supply Air Temperature Control

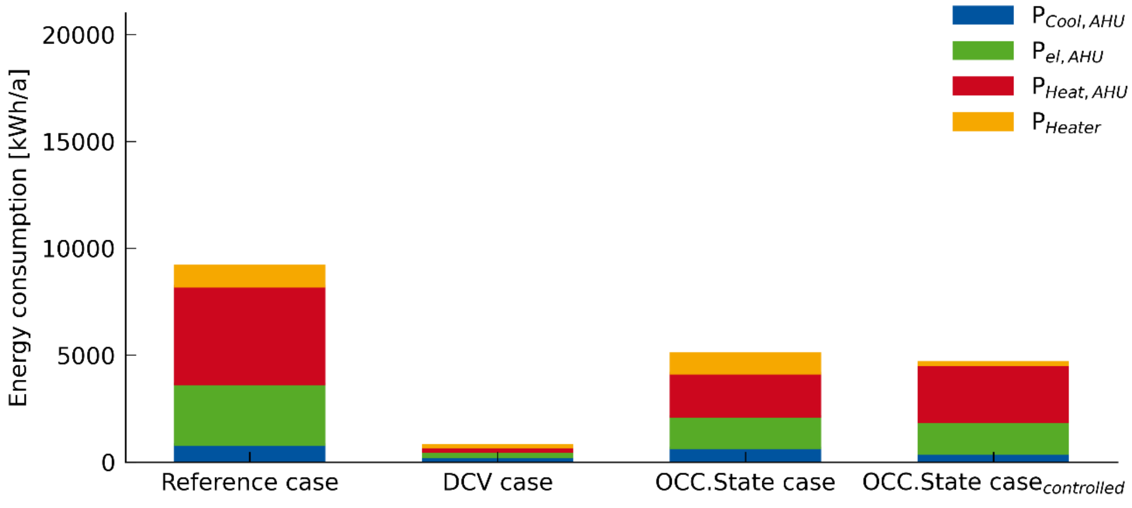

Figure C-1 Cumulative energy consumption comparison of 4 strategies for office (UKA)

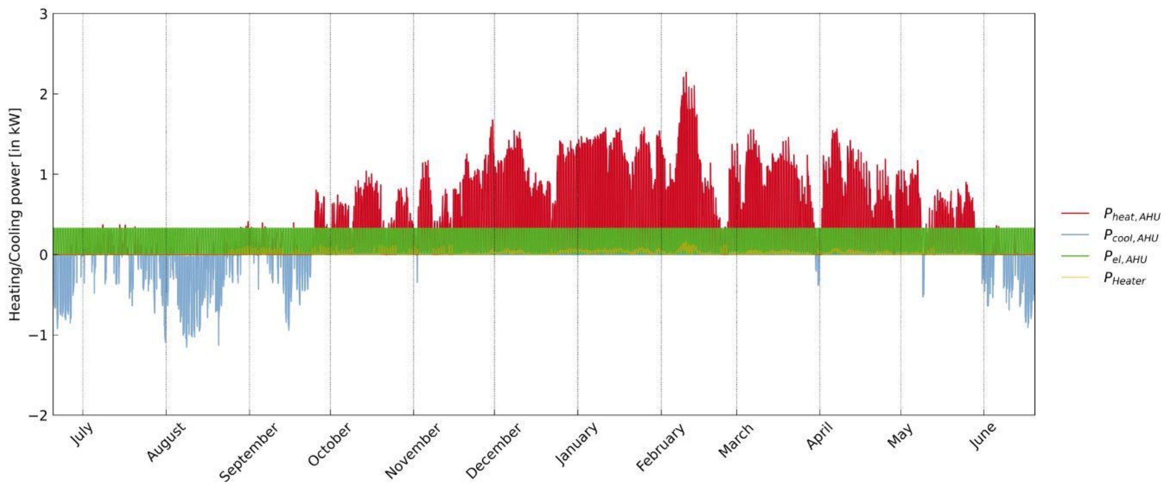

Figure C-2 Schedule-based energy consumption of office room (UKA)

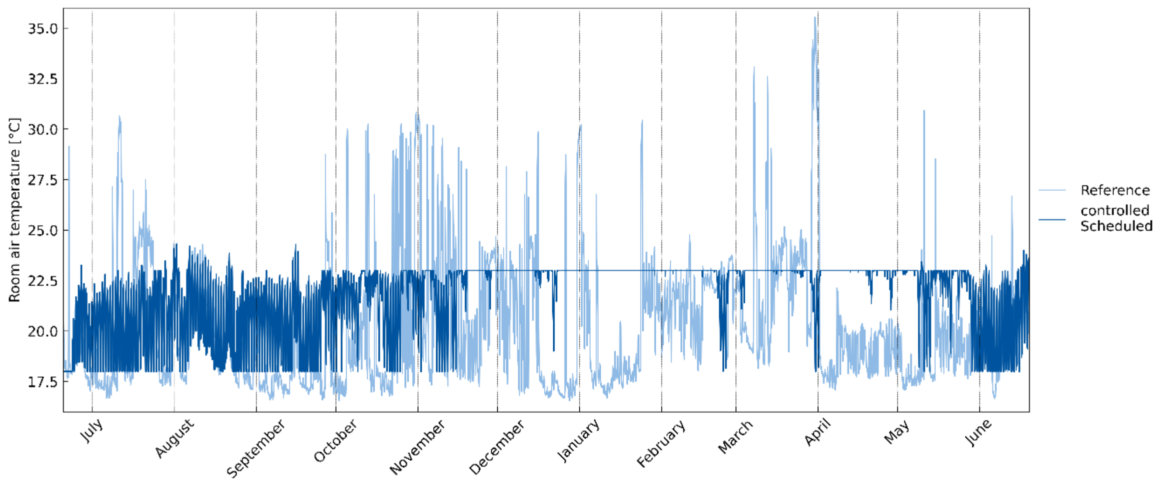

Figure C-3 Schedule-based strategy and reference supply air temperature of office (UKA)

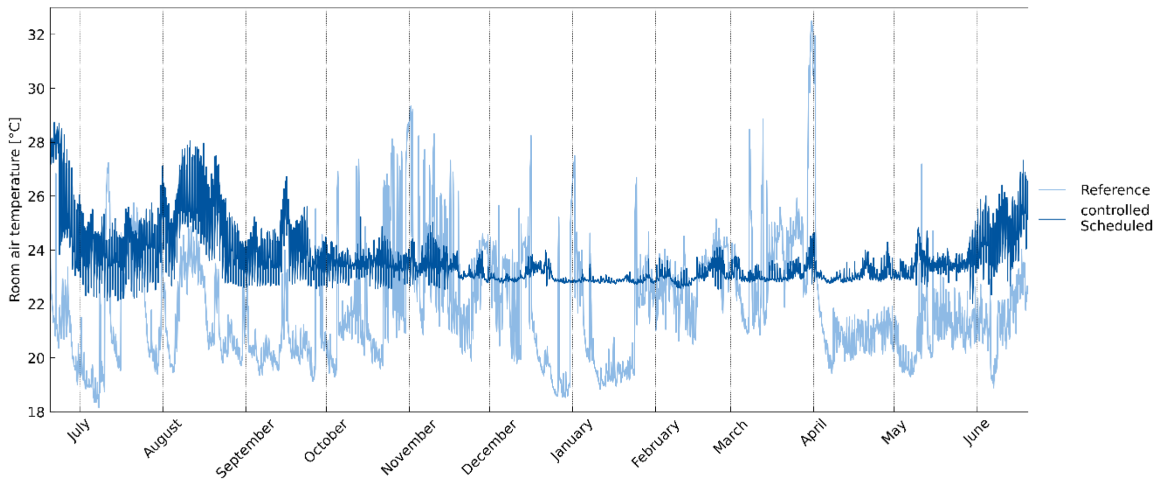

Figure C-4 Schedule-based strategy and reference room air temperature of office (UKA)

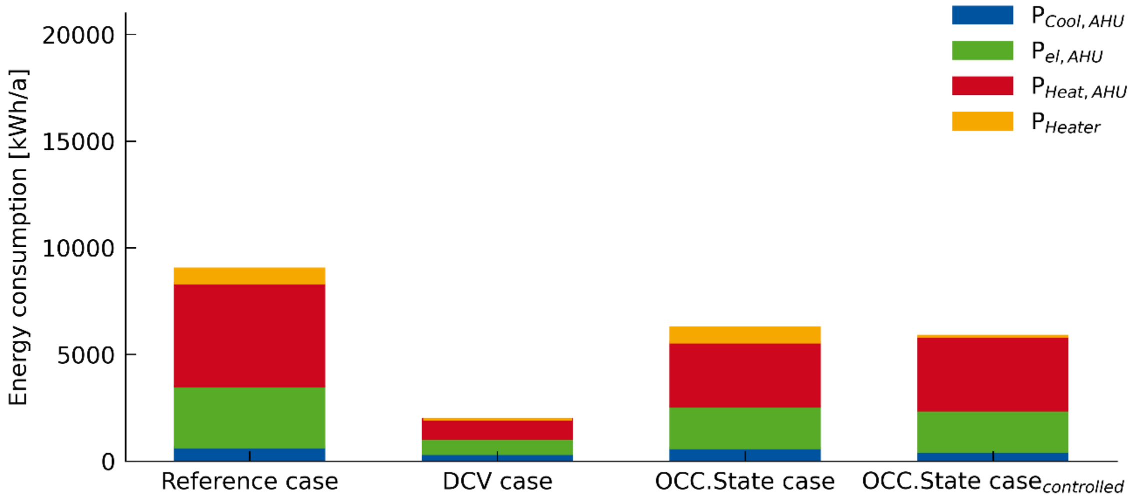

Figure C-5 Cumulative energy consumption comparison of 4 strategies for consulting and treatment (UKA)

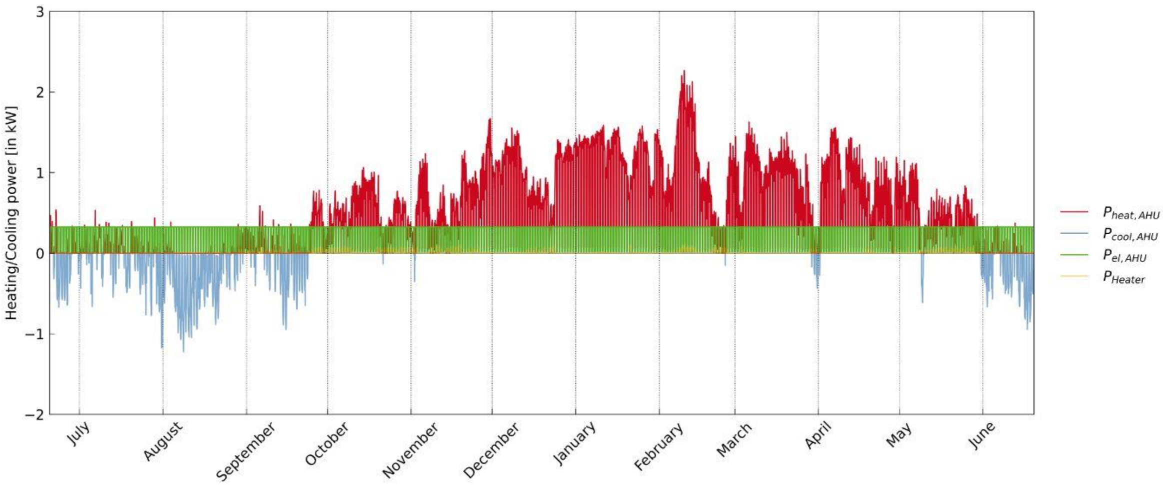

Figure C-6 Schedule-based energy consumption of consulting and treatment room (UKA)

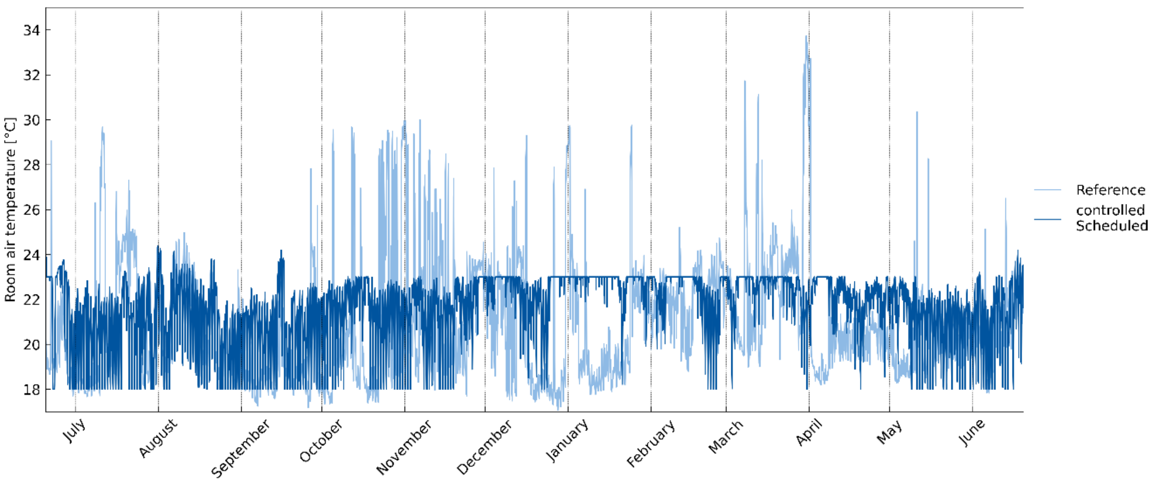

Figure C-7 Schedule-based strategy and reference supply air temperature of consulting and treatment(UKA)

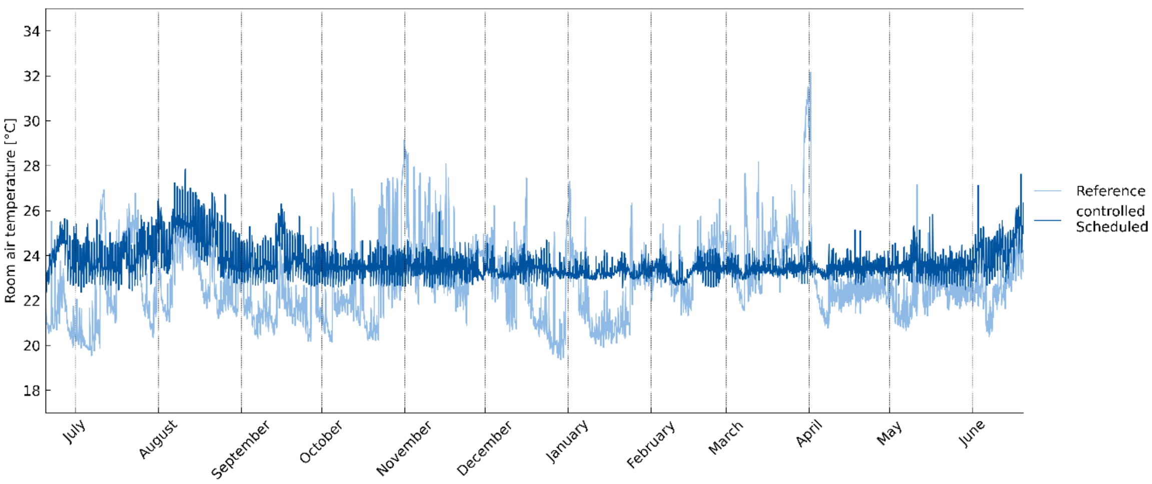

Figure C-8 Schedule-based strategy and reference room air temperature of consulting and treatment (UKA)

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