KTH Industrial Engineering and Management

Natural ventilation strategies for nearly-Zero Energy Sports Halls

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Master of Science Thesis
KTH School of Industrial Engineering and Management
Energy Technology EGI-2016-097 MSC
Division of Applied Thermodynamics and Refrigeration
SE-100 44 STOCKHOLM

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Approved	Examiner	Supervisor
6^{th} of October 2016	Jaime Arias Hurtado	Jaime Arias Hurtado
	Commissioner	Contact person

Abstract

In line with the article 9 of the EPDB, member states shall ensure that all new public properties are nearly zero energy buildings (n-ZEB) by December 31, 2018. Sports buildings account for a significant share of the European building stock consumption. More than half of their current energy needs are related to lighting, and a relevant energy use is due to domestic hot water. This work aims to test different energy measures to design nearly zero energy sports halls in Mediterranean climates. Under a holistic approach, the design of the base case sports hall includes the implementation of passive strategies in combination with renewable energy and energy efficient systems in order to meet the n-ZEB conditions. However, a special focus is put on the study of the sports hall ventilation requirements. A natural ventilation system is proposed as an alternative to a traditional mechanical one. The effectiveness of the analyzed ventilation strategies is validated using TRNSYS, a dynamic simulation tool. Therefore, natural ventilation impact on thermal comfort, air quality and energy needs is estimated. A cost effective evaluation is done following the methodology proposed by the European Directive. Additionally, the study is complemented with a short period of measurements in a selected existing facility according to which poor indoor air quality is the main cause of users discomfort during period of maximum occupancy. The obtained results show that the combination of reduction of thermal transmittance of the envelope, optimization of the windows surfaces, façades orientation, introduction of shading devices, installation of energy efficiency systems as LED lamps and use of natural and night ventilation, are advantageous for the reduction of heating, cooling and artificial lighting demand. Overall, consisted primary energy savings are achieved. Moreover, the described strategies ensure indoor thermal comfort, minimizing the period of overcooling and overheating, and provide good air quality conditions for most of the occupied time along one year simulation. Finally, it is verified that the PV system integration positively affects the sports hall performance toward n-ZEB standards.

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Sammanfattning

EUs direktiv om byggnaders energiprestanda (EPBD - 2002/91/EC) uppdaterades 2010 och har som mål att minska energianvändning i Europas fastighetsbestånd. Efter den 31 december 2018, ska alla nya byggnader som används av offentliga myndigheter vara nära-nollenergibyggnader.

Idrottshallar står för en betydande andel av den totala energianvändningen i EU. Denna rapport syftar till att studera olika energieffektiviseringsåtgärder, förnybara energikällor och passiva strategier för att utforma n-ZEB idrottshallar i medelhavsklimat.

Ett särskilt fokus läggs på att studera ventilationskraven i idrottshallar och användning av naturlig ventilation. Energiprestanda av de analyserade ventilation strategierna har studerats i programmet TRNSYS som är ett verktyg för dynamisk simulering av byggnader. Under projektet har mätningar genomförts i en idrottshall i Barcelona för att analysera de olika parametrarna som påverkar energianvändning i dessa byggnader.

En ekonomisk analys att de olika energieffektiviseringsåtgärderna har utförts.

Resultaten från projektet visar att lämplig naturlig ventilation i idrottshallar, kan säkerställa god luftkvalitet inomhus och termisk komfort. Dessutom kan naturlig ventilation minska energianvändningen och de totala kostnaderna.

Acknowledgment

My deepest gratitude goes to my supervisors in IREC, Dr. Jaume Salom and Joana Ortiz for their constant support and guidance in all phases of the realization of this project.

I would like also to thank all the Thermal Energy and Building Performance Group of IREC. I have learned an incredible amount of valuable skills in the last six months spent with you.

Fins ara!

Nomenclature

Abbreviations

Abbreviation	Meaning
BBCC	Bioclimatic Chart
BIPV	PV Building Integration
BMS	Building Management System
CB	Condensing Boiler
CEC5	Central Europe Cooperation programme
CTE	Código Técnico de la Edificación
CFD	Computation Fluid Dynamics
DHW	Domestic Hot Water
DVC	Demand Controlled Ventilation
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Coefficient
EU	European Union
HP	Heat Pump
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
ICAEN	Institut Catala d'Energia
IEQ	Indoor Environmental Quality
IREC	Catalonia Institute for Energy Research
MS	Member State
MV	Mechanical ventilation without control strategy
MV + DV	Mechanical ventilation with variable speed fan
MV +CTL	Mechanical ventilation with control strategy
NPL	Neutral Pressure Level
NPV	Net Present Value
NV	Natural Ventilation
n-ZEB	Nearly Zero Energy Building
PAV3	Triple sports hall
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SBS	Sick Building Syndrome

Symbols

Symbol	Unit	Meaning
$\dot{m}$	kg/h	Net mass flow
$\dot{Q}$	kJ/h	Heating rate
ΔP	Pa	Pressure difference
A	m^2	Area
ACH	h^{-1}	Air Change Rate
A_r/A_{DU}	-	Skin portion involved in the radiative heat exchange
C	W/m^2	Rate of convective heat loss
C+R	W/m^2	Sensible heat loss from skin
C_d	-	Discharge coefficient
CLO	clo	Clothing insulation
C_p	-	Static pressure coefficient
c_p	KJ/kgK	Specific heat
Cs	kg/s	Air mass flow coefficient
DLE	minutes	Duration Limited Exposure
D_{max}	Wh/m^2	Maximum value of water loss
E	W/m^2	Rate of convective heat loss
E_{req}	W/m^2	Required Evaportation Rate
f_{cl}	-	Ratio of clothed surface area to nude surface area
FLNEL	kg/h	Net mass flow per link (TRNFLOW output)
g	m/s^2	Gravitational acceleration
g-value (T-SET)	-	Total Solar Energy Transmittance
H	m	High difference
h	W/m^2K	Heat transfer coefficient
K	-	Flow coefficient
M	W/m^2	Rate of metabolic heat production
MET	met	Metabolic activity
n	-	Flow exponent
N	rpm	Fan speed
n_{50}	h^{-1}	External envelope airtightness. Air permeability at 50 Pascal.
p	Pa	Pressure
P	W	Power
p_a	Pa	Partial water vapor pressure

Q	m^3/s	Flow rate
Q_{max}	Wh/m^2	Maximum value of body heat storage
R	%	Market Interest Rate
R_D	%	Discount Rate
R_E	-	Energy Evolution Rate
RI	%	Inflation Rate
R_R	-	Real Interest Rate
RX_E	-	Energy Cost Evolution
S	W/m^2	Rate of heat storage
SW_{req}	W/m^2	Required Sweat Rate
T or t or θ	°C or K	Temperature
U	W/m^2K	Thermal transmittance
V or v	m/s	Velocity
Vol	m^3	Volume
W	W/m^2	Rate of metabolic work accomplished
W_{max}	-	Skin weatness
z	m	High
α	-	Wind velocity profile exponent
ρ	kg/m^3	Density

Subscripts

Subscript	Description
0	standard condition for dry air
a or air	air
c	convective
cl	clothing
cr	core
da	daily average
ea	exponential average
ext	exterior
f	final energy
g	globe
hr	hour
int	interior
m	mean
max	maximum
min	minimum
NW	North-West
op	operative
opt	optimal
out	exterior
p	primary energy
r	radiant
ref	reference
res	respiration
s	static
SE	South-East
sk	skin
w	wind

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1 Introduction

As reported in the article 2 of the European Union Directive 2010/31 (EPDB recast 2010) a "nearly zero energy building" (n-ZEB), due to its very high efficiency, is characterized by very low energy requirements, satisfied by significant extent through renewable sources available on-site or nearby. In Spain energy requirements for new and refurbished buildings are set up, depending on building use and climate zone, in the "*energy savings*" chapter of the Technical Building Code (Código Técnico de la Edificación - CTE, 2013). Each Member State (MS) is following a different path toward a more exhaustive definition of n-ZEB, including for example specific building subcategories in their national energy plans. More than half of the MS is managing sports facilities as a precise subcategory (D'Agostino 2015).

Energy performance improvements of sports facilities can significantly contribute to the fulfillment of the article 9 of the EPDB, stating that MS shall ensure that all new public properties are n-ZEBs by December 31, 2018 (EPDB recast 2010). Sports facilities have a relevant impact on the European energy context. The European Union Sport and Recreational Building Stock is on average 30 years old and characterized by a low efficiency level. It accounts for 1 million and half buildings, namely 8% on the entire EU-48 Building sector. Specifically, 15'000 of the sports buildings are indoor sports halls. Those numbers are bound to increase in the future, considering the yearly actual growth rate of 0.5 - 1.1% and the constantly larger interest in sports and wellbeing (Sport*e*^{2} 2013). However, new sports buildings risk suffering the same processes that has already involved other building categories: became hermetically closed and controlled at constant temperature in all climates (Santamouris and Wouters, 2006). Aiming to reduce the energy consumption due to unnecessary infiltration and exfiltration, it has become increasingly common improve the air tightness of the building envelope. As consequence, today mechanical ventilation is considered a basic element buildings equipment. Moreover, the development of building management systems (BMS) emphasizes and promotes the control of indoor environments within narrow limits. This is very energy-intensive approach, with negative impact on energy utilization and, consequently, on the environment (Kwon et al., 2013). In this regard, Aflaki et al. (2015) claim that the amount of energy needed for cooling and heating buildings, due to the contribution of modern houses, has grown to 6.7% of the total world energy consumption, with air conditioners consuming a major part of this.

Currently, up to 10% of the worldwide annual energy consumption is due to sports installations, which represent 8% of the total consumption due to the building sector in some regions (Sport*e*^{2} 2013). Some countries have introduced performance-based requirements for new sports buildings: as examples, the Norwegian overall net energy demand limit is 170 kWh/m^2, while the Portuguese regulation sets to 233 kWh/m^2 the maximum amount of consumed primary energy (Economidou 2013).

More than 200 net zero energy balance projects have been realized during the last 20 years (Musall et al., 2010). However, most of them are located in North West countries and climates, where the availability of economic resources, the degree of development of the technological sector, the knowledge of the specific local energy and climate problems have facilitated the building renovation process. Spain occupies one of the lowest position regarding the number of identified n-ZEBs, despite the suitable climate conditions.

Architects, engineers and policymakers all around the world have explored several solutions to realize n-ZEBs. However, widen the range in which the buildings can ran freely, in practice without the activation of mechanical systems, is an option still relatively unexplored, but that can produce important energy savings (Santamouris and Wouters, 2006).

As stated by Allard (2002), to design an energy *conscious building*, it is fundamental to balance between envelope performance, selection of appropriate heating, cooling and daylight systems and the attention toward the preservation of acceptable indoor conditions, as ventilation effectiveness, air quality and thermal comfort. Allard suggests that natural ventilation can play an important role in this context, and it is especially suitable in recreational buildings in moderate or mild climate. In this regard, Florentzou (2015) shows as the adoption of natural ventilation brings several benefits in large sports spaces, usually mechanically ventilated. Through his studies, he verified that natural ventilation is a cheap, ecological, simple and no space consuming solution that ensure optimal temperature in winter and preserves air quality in summer.

1.1 Scope

The approach proposed in the thesis supports the design of a nearly zero energy sports hall in Mediterranean climates, through the implementation of specific energy strategies. The goal is to guarantee healthy environment to the final users of the building. For this reason, indoor thermal comfort condition are evaluated in the different scenarios.

In line with the *Trias Energetica* principles (Brouwers and Entrop, 2005), the n-ZEB concept is achieved implementing passive design and energy efficient measures in combination with renewable energy systems. The work is focused on the study of an appropriate and effective natural ventilation system. The advantages of the implementation of this technique are presented in relation to energy saving and cost-effectiveness considerations. Moreover, taking into account that natural ventilation efficiency is strongly dependent on high variable parameters, as wind characteristic and thermal state of the building, part of this research is devoted to the identification of an adequate control strategy to ensure the optimal functioning of the selected case-study sports facility.

1.2 Report structure

To improve the readability of this report, its structure is briefly explained. The present section aims to introduce the work, including a brief description of the research context and of the problems correlated to the Master thesis topic. The specific objectives and focal points of the thesis have been clarified.

The organization of the following parts of the thesis is presented:

- Chapter 2: sets the basis of the developed research. The findings of a literature review investigation are reported. It is presented an overview on real sports halls status, regarding their distinctive energy needs as well as the already implemented n-ZEB strategies.
- Chapter 3: illustrates the theoretical framework of the thesis. The attention is focused on the description of the natural ventilation history, working principles and applications. The models adopted in the research to perform the thermal comfort and air quality analysis are also described.
- Chapters 4 – 10: chapter 4 deals with the methodology applied for the development of the thesis. The successive chapters explore in detail the different aspects and steps of the research. The objectives, the execution and the collected data of the measurements campaign are described in chapter 5. The selected n-ZEB strategies are presented and categorized in chapter 6. In chapter 7 the base case buildings characteristics are finally introduced, the studied sports hall is graphically represented and the site-specific parameters are reported. Chapter 8 is fully devoted to the explanation of the TRNSYS (SEL 2012) simulation. Ample space is assigned to the TRNFLOW ventilation model, involving natural and mechanical ventilation. The natural ventilation modelling phase is accurately illustrated (chapter 8.3), as well as the corresponding tested control strategy (section 8.3.1). How the PV configuration analysis is performed through the software Skelion (Skelion v5.1.9 2015) and the TRNSYS type 94 is described in chapter 9. The economic part of

the thesis is enclosed in chapter 10, where the cost-optimal methodology is defined and the economical assumption made for the systems analysis are summarized.

- Chapter 11: in chapter 11 is possible to find the outcomes of the different sections previously described. The presented results are moreover discussed. Furthermore, an energy study of the results is performed and elaborated in the energy balance available in section 11.3.1.
- The report concludes with chapter 12, which includes the conclusion and suggestions for further researches.

2 State of the art

The findings of a literature review investigation and an overview on real sports halls status are presented in the following subchapters.

2.1 Sports Hall energy consumption

According to the findings of the European project Step2Sport, within which 26 pilot sports buildings from seven EU countries have been subjected to energy audit, indoor swimming pools are the most energy demanding sports installation. Spanish swimming pools on average consume 1'012 kWh/m²yr (Radulov et al., 2014). The same research shows that sports halls are responsible annually for 13% of the total energy consumed by sports facilities.

Sport halls are very large spaces with a specific energy demand profile, characterized by high level of heat and electricity demand. Sports halls consumptions are closely related to the sport activity, the timetable of the sports center, the public attendance during the matches and the site-specific climate conditions (Artuso and Santangeli 2008). For instance, sports halls in the continental European zone require double amount of energy (about 490 kWh/m²) than the Mediterranean ones (Trianti-Stourna et al., 1998).

Aelenei et al. (2015) analyzed the primary energy consumption share per building category at country level, in Europe. As it possible to see in figure 1, their results show that sports facilities are responsible for a significant part of Spanish total primary energy consumption.

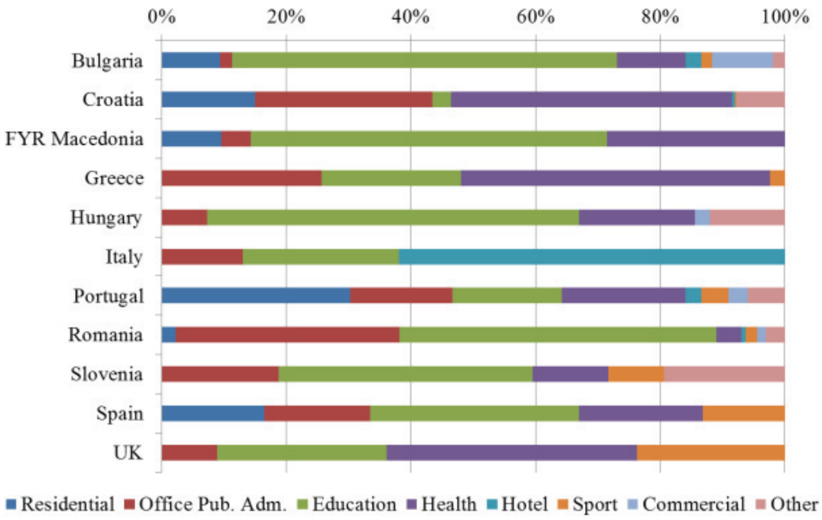


Figure 1. Analysis of primary energy consumption share per building category at country level. ***Source: Aelenei et al. (2015)***

More in detail, the Catalan region of Spain alone accounts for 2'417 public buildings identified as sports facilities, covering 1'338'104 m² of total built-up floor area (6'061'595 m²) and responsible for 14% of the total primary energy consumption of the public building stock. Specifically, sports pavilions use 238 kWh/m² every year (Radulov et al., 2014) and only around 1.3% of the sports facilities have the energy performance certification, that according to the Spanish regulation is based on computer simulation (six official software tools allow to compare the building with a reference building, considered as an average building over more than 100.000 computer simulation) (Gunnarsson et al., 2015).

The results of the investigation conducted by ICAEN (2012) suggest that more than half of the current Catalan sports halls energy consumptions are related to lighting (56%), a relevant energy use is due to domestic hot water (28%.), while heating and ventilation demand accounts for 4% of the total (other consumptions are estimated about 12%). Predicting that through the implementation of energy efficiency

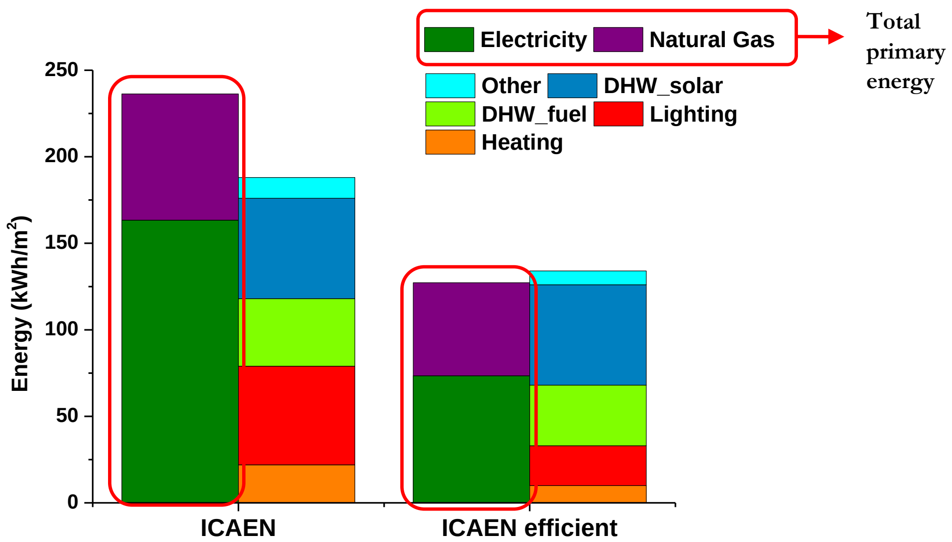


Figure 2. Catalan Sports Hall primary energy consumption (kWh/m²). Heating includes ventilation. ***Source: self-elaboration based on data ICAEN (2012)***

improvements a significant reduction in primary energy use can be achieved, an energy efficient scenario is also proposed. In this case, the primary energy consumption reaches the value of 128 kWh/m². The available data are elaborated in figure 2. From figure 2 it results evident that significant energy savings are expected from lighting, DHW and heating (including ventilation) demand reduction.

Finally, it is reaffirmed that sports hall energy consumptions are strongly linked to the number of users of the installation. In this regards, it is possible to examine the data made available by the Barcelona Provincial Council (Diputació de Barcelona 2016) referred to the Catalan sports facilities and summarized in table 1.

Table 1. Sports Halls consumption ratios (Barcelona Provincial Council)

Surface (m²)	Liter of water/user	Electricity (kWh/user)	Fuel (natural gas) (kWh/user)	Euro/user
1’600-2’300	20-40	0.15-0.5	1-2	0.2-0.6
2’100-3’000	20-40	1-2	1-2	

2.2 Nearly Zero Energy Sports Halls

The previous section dealt with the estimation of the specific energy consumptions of Catalan sports halls. Generally, few researches have been conducted regarding the energy behaviour of sports buildings. An example is the energy audit performed by Trianti-Stourna et al. (1998) for a representative number of Hellenic indoor sports facilities built between 1970 and 1980. The authors proposed passive solar retrofitting interventions. The result of the study shows that, for small and medium-sized sports centers, annually from 55% to 95% of heating consumption can be covered implementing architectural solutions as insulation of the external walls, creation of South-facing clerestories, and supplementary sun spaces, installation of shading devices and appropriate ventilation systems. Additionally, according to their research, a reduction of the electricity demand, along with the improvement of the indoor thermal comfort conditions, can be achieved taking advantage of natural light and ventilation, and installing heat recovery systems in traditional heating and ventilation mechanisms.

Following, real cases study regarding the implementation of energy saving measures in existing sports facilities are presented.

The research project developed by the Institute of Power Engineering at TU Dresden, the Fraunhofer Institute for Solar Energy Systems and "Am Königswald" Planungsgesellschaft mbH, is focused on the building operation analysis and on the optimization of the Gerhard Grafe Sports Hall (EnOB 2009) situated in Dresden and built in 2006 (Felsmann et al., 2015). In this case study, the energy efficiency and thermal comfort targets are achieved implementing building and energy concepts. The adopted building concepts are summarized in table 2 while the main characteristics of the energy system optimization strategies are reported in the table 3.

Table 2. Building concepts implemented in the Gerhard Grafe Sports Hall in Dresden-Weixdorf

	Building concept	*features*	*function*
Opaque components	Concrete perimeter wall	*thermal activated component* • high thermal mass • high inertia	✓ constant indoor temperature ✓ passive cooling
	Monolithic structure	• compactness	✓ reduction of transmission heat losses
	Rainscreen cladding		✓ weather protection
Transparent components	Windows surface	• South-East elevation 20% less than North and West	
	Windows	• vertically angled ribbon	✓ homogenous lighting ✓ glare free
	Glass	• low solar energy transmittance factor	✓ glare reduction

Table 3. Energy concepts implemented in the Gerhard Grafe Sports Hall in Dresden-Weixdorf

	Energy concept	*features*	*function*
Energy savings measures	Ventilation system	• moisture-led ventilation in the sanitary and changing rooms • CO_2-led ventilation in the hall	✓ reduction of ventilation need
		• high energy efficiency heat recovery • ground-air heat exchanger	✓ reduction of the heat supplied at the external air
Heat	Absorption natural gas heat pump		✓ heat generation
	Boreholes in the ground		✓ heat source for the heat pump ✓ heat sink for cooling
	Collector and distribution centre	• steel distributors/collectors • 5 thermally separated temperature chambers	✓ specific temperature for different heat zones ✓ no mixed temperatures
	Solar thermal system	• provides 70% of the heat along all the year	✓ DHW
	Condensing boiler	• modulated peak load	✓ backup system
	Buffer storage tanks	• 1'200 litres	✓ storing surplus solar thermal ✓ balance

Overall, the system achieved 35% reduction of gas consumption, good indoor thermal comfort and reduction in heating and primary energy requirements.

The sports hall of the Cracow University of Agriculture is an additional example of sports facility designed according to the German passive house standard (tab.4) (Kisilewicz and Dudzińska, 2015).

Table 4. Construction features of the Sports Hall of the Cracow University of Agriculture. ***Source: based on Kisilewicz 2015***

Thermal transmittance of the external walls	0.1 W/m^{2}K
Triple glazed windows	0.8 W/m^{2}K Total solar transmittance g = 0.6
Mechanical exhaust-supply ventilation + air heater + recuperator	Heat recovery efficiency = 75%
Electrical external blinds	Shading South and North orientated windows
West and East façades	Glazed
Building orientation	Large East and West windows
Insulated green roof	
Radiant water floor heating system	
Final energy for heating **<15 kWh/m^2 ;** air tightness, n_{50}[1]= **0.2 h^{-1}**	

However, the focus of the research conducted by Kisilewicz and Dudzińska (2015) is the investigation of the summer overheating phenomenon occurring in the passive building. The authors measured the internal microclimate parameters during two summer days, when there was no occupancy, the mechanical ventilation system was not operating and the windows were closed. The collected results suggest that 33% (90% in extreme conditions) of the sports hall users would be dissatisfied with the recorded thermal conditions, due to the excessive increase of indoor temperature. The study indicates that the costs of a mechanical cooling system can be avoided implementing accessible measures against overheating, as windows blinds. Moreover, considering the favourable condition of significant lower outside air temperature respect to the internal one, the researchers propose an intensive adoption of night cooling, aimed at discharging the internal thermal capacity of the building.

Tsoka (2015) simulated (through Pleiades-Comfie software developed by the Center of Energy and Processes of Mines-ParisTech) and analysed different design strategies for the Michel Walter stadium in Strasbourg. The objective is to achieve the highest possible energy efficiency and simultaneously to avoid thermal discomfort in summer periods. The studied building is designed to reduce the annual heating energy demand: the interior concrete wall provides additional thermal mass, the heat transfer coefficients of the buildings components are between 0.13 and 0.18 W/m^{2}K, the windows are doubled glazed with aluminum thermal brake frame and a U-value of 1.40 W/m^{2}K, the large openings harvest solar gains. However, the high inertia of the building increases the risk of summer overheating. The research shows that vertical solar shading devices can decrease electricity consumption for air conditioning and improve indoor conditions, achieving a reduction of the ratio of the occupied time during which the internal zone temperature exceeds 27°C to the total occupied period, between 42.83% and 55%. In addition, a solution including shading deciduous trees 6.5 meters high and the activation of natural ventilation in the offices adjacent to the sports halls (only during occupied time and in case of indoor air temperature 2°C above outdoor air temperature), has been evaluated. It has been proved that this configuration reduces the number of occupied hours during which the indoor air temperature exceeds the maximum acceptable comfortable temperature of 27°C, between 30.6% and 35.1% compared to the previous case. The most

[1] n_{50} is the parameter that indicates how often the air volume of the building is exchanged per hour at a pressure difference of 50 Pa (AENOR 2002a)

effective measure to reduce summer overheating results the implementation of nocturnal mechanical ventilation (from 23:00 pm to 9:00 am, when interior temperature is 2°C higher than exterior temperature). According to this simulation scenario, during summertime air temperature does not exceedes the limit of 27°C for more than 50 hours.

The study conducted by Flourentzou et al. (2015) investigates the performance of another construction designed as a typical passive building, including 10 classrooms and a gym, in Switzerland (Commune de Savièse) (fig.3). The high volume of the gym has been analysed in detail. The aim of the research is to provide a stack effect of 6000 m^3/h without extra costs. The performance of a natural ventilation system are assessed. The designed natural ventilation configuration requires two opening of 4 m^2 on the top and on the bottom of the space (the same used to comply with the fire regulation) and 2 additional lateral 1 m^2 openings for better air distribution. Overall, natural ventilation results to be more efficient than mechanical ventilation with heat recovery: the height of the building creates a high stack effect while the large volume creates a large reservoir of fresh air, making possible the exploitation of infiltration for ventilation. The energy consumption for fans is completely avoided. In this particular case study, air path and light path are dissociated. Moreover, during summer ventilation is controlled by the difference between indoor and outdoor temperatures (fig.4); during winter natural ventilation activation is related to the indoor air quality, expressed in CO_2 concentration (fig.5).

Figure 4. Sports Hall in Commune de Savièse in Switzerland. ***Source: Flourentzou et al. (2015)***

Figure 3. Summer ventilation. Night ventilation: the fresh air enters on the basement and goes out from the top openings. ***Source: Flourentzou et al. (2015)***

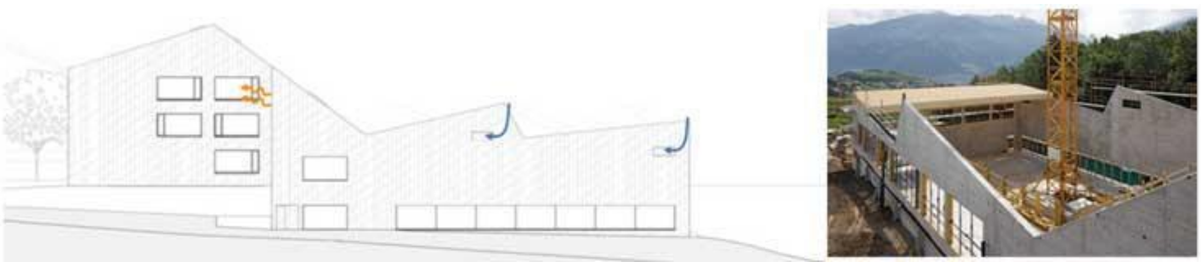


Figure 5. Winter ventilation. Air enters from the top lateral openings and goes out from the top front opening in order to avoid cold draughts. ***Source: Flourentzou et al. (2015)***

The Nanyang Technological University in Singapore (The Singapore Engeneering 2015) designed a new sports hall with the intention to achieve 35% reduction in water and energy consumption and waste production by 2020. The adopted sustainable measures are summarized in the tables below (tab.5 and tab.6) and graphically represented in figure 6 and figure.7.

Table 5. Building concepts implemented in the Sports Hall of Nanyang Technological University in Singapore. ***Source: self-elaboration based on The Singapore Engeneering (2015)***

	Building concept	*features*	*function*
Opaque components	Engineered wood system:	• glued laminated timber with panels linearly aligned • cross-laminated timber	✓ heat insulation

Table 6. Energy concepts implemented in the Sports Hall of Nanyang Technological University in Singapore. ***Source: self-elaboration based on The Singapore Engeneering (2015)***

	Energy concept	*features*	*function*
Energy savings measures	Natural ventilation	• designed analysing wind and sun patterns on site • operable louvers	✓ reduction of the need of mechanical ventilation
Cooling	Passive induction air conditioning	• provides cold air at the floor level • chilled water coil cool the warm air at the high level (fig.7)	✓ temperature stratification: only the occupied zone is cooled ✓ avoid the need of a fan: convective force provided by the heat source in the space ✓ avoid the need of metal ducting ✓ avoid condensation and draughts
	Chiller	• auto condenser-tube cleaning system	✓ prevent fouling and scaling ✓ maintain good heat transfer
Lighting	Maximising natural light	• daylight sensors • East and West walls with top light shelf • double skin wall in the West	✓ reduction of artificial light requirements ✓ diffusion of the light in the Sports Hall ✓ reduce sun radiation intensity
	Artificial lighting	• LED lamps • zoning • motion sensor	✓ reduction of the operating wattage ✓ variable lighting to suit the needs
Water	Water sub-meters for the cooling tower		✓ monitoring water usage
	Heat recovery system	• provide hot water for shower	✓ avoid use of conventional electric heater

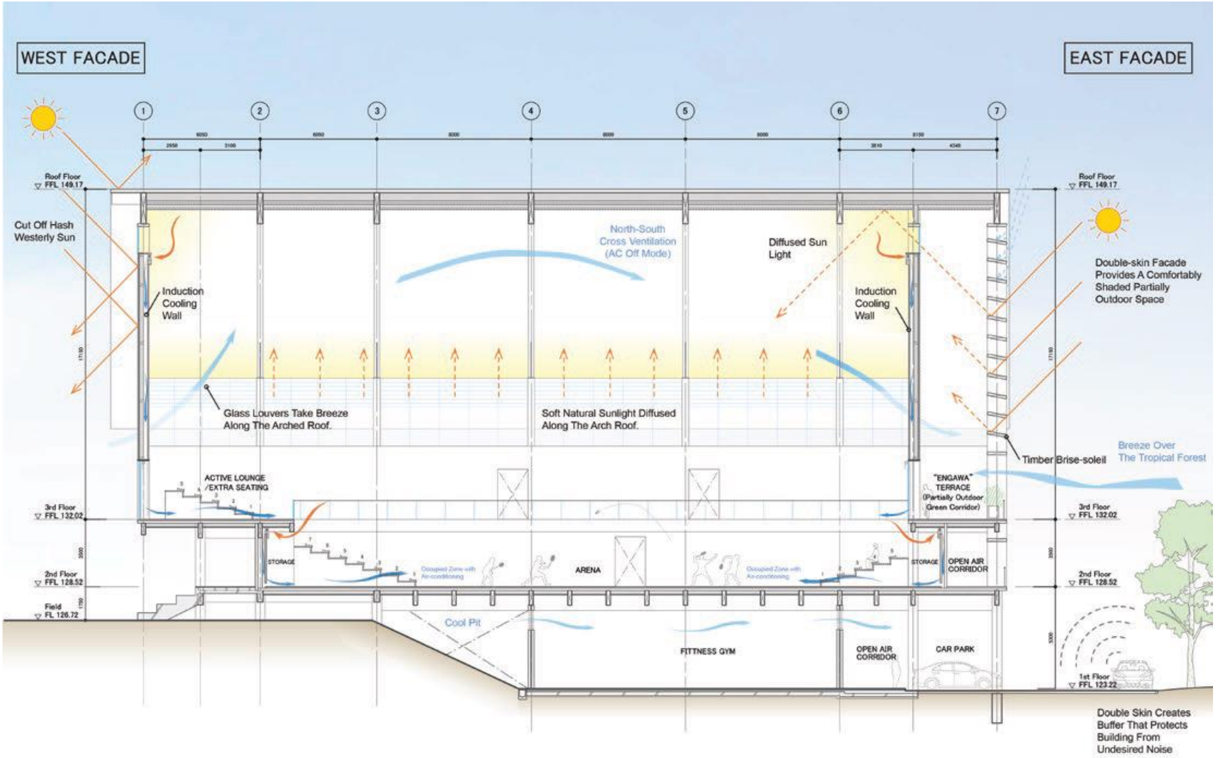


Figure 6. Energy efficiency strategies implemented in the Sports Hall of Nanyang Technological University in Singapore.
Source: The Singapore Engeneering (2015)

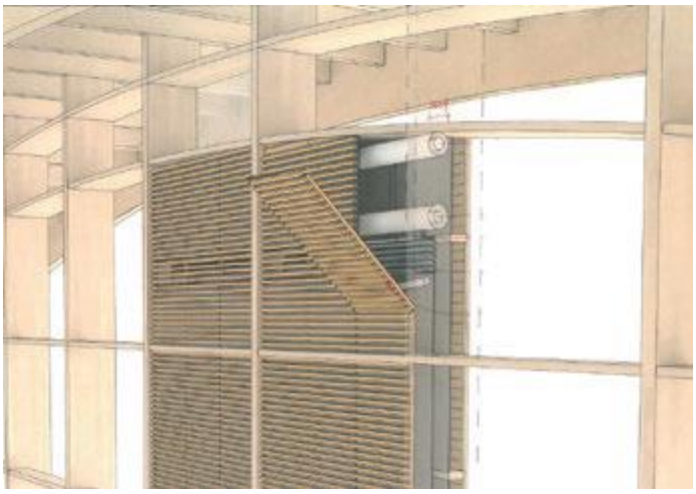


Figure 7. Chilled water coils, at a high level, used to cool down warm air. ***Source: The Singapore Engeneering (2015)***

Rajagopalan and Luther (2013) analysed the indoor enviromental conditions (thermal comfort, CO_2 concentration and temperature stratification) of a sports hall in an aquatic center in Australia (temperate climate), to then identify potential strategies for low energy conditioning. Also exterior weather data have been collected during their research. The studied sports hall was not equipped with a cooling system; there were three exahust fans in the ceiling to assist the ventilation. Evaluating the current building conditions, the researchers verified that the users of the sports hall experiece periods of great discomfort due to high indoor temperature. Conversely, the CO_2 and the relative humidity levels resulted good. The authors proposed a set of strategies to improve thermal comfort and reduce energy consumption of the sport facility:

- direct evaporative cooling: to take advantage of periods when exterior temperature is high and its moisture content is low;
- shading: to reduce discomfort in hot days, blocking part of the solar radiation to reach the glass;
- control and monitoring: to shut down the ventilation during several hours, depending on the indoor air quality conditions;
- night purging: to cool down the indoor space, preparing the room for the hot day ahead;
- optimization of the exhaust fans and openings position: through a CFD simulation, it has been verified that more air movement occurs when the exhaust fans are at lower level. Moreover, it resulted that the air movement profile could be further improved replacing the exhausts fans with opening, as in natural ventilation mode.

The passive sports hall of Slomniki, Poland, is presented as a successful example within the CEC5 project- *Demonstration of energy efficiency and utilisation of renewable energy sources through public buildings* (fig.8) (CEC5 2014). The sports hall is the first Polish passive public building with a quality certificate awarded by the Passive House Institute. The solutions implemented in the building achieved 87% energy use reduction and 90% CO_2 emissions reduction. Wood-derived materials have been used as construction elements. A mechanical ventilation system with heat recovery has been installed. The orientation of the building and the position of the windows have been designed to acquire most of the sunlight during winter. Conversely, the position of the windows has been also assessed to minimize the sunlight during summer and a roller shutter system has been adopted to prevent overheating.

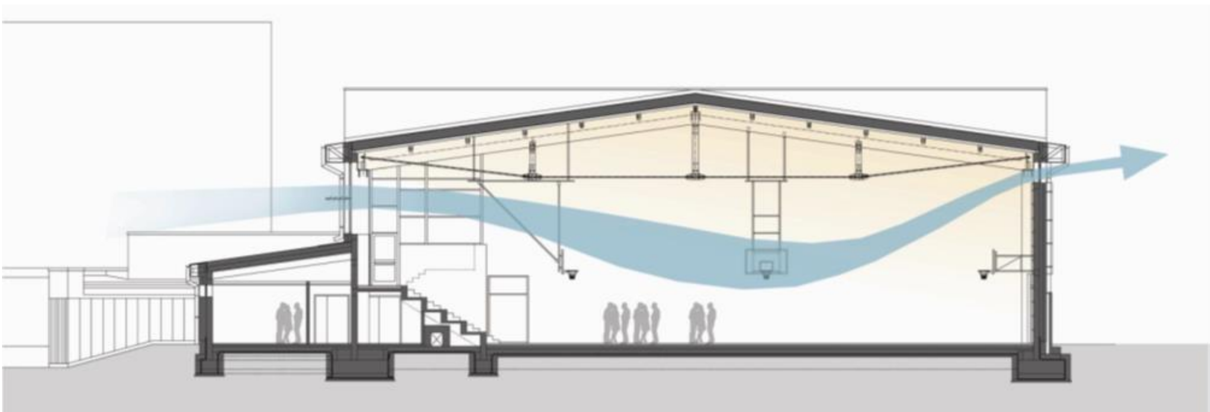


Figure 8. Summer ventilation in the Passive Sports Hall of Slomniki. ***Source: CEC5 (2014)***

Within the framework of the European Union Green Building project (European Commission, Joint research centre – Energy Efficiency, 2016a), a voluntary programme started in 2005 that aims to improve energy efficiency of non-residential buildings in Europe, the German Grammar school Königsbrunn - school sports centre (European Commission, Joint research centre – Energy Efficiency, 2016b) is a successful example of building refurbishment. The energy efficiency strategies implemented in the sports center achieved 44.81% energy savings. Specifically, consumptions decreases from 648.93 kWh/m²yr, registered before the renovation, to 358.14 kWh/m²yr.

Table 7 reports a summary of the thecniques adopted to contain energy consumptions and, consequentely, the high operating costs of the sports facility (IBOS-TGA).

Table 7. Energy efficiency strategies implemented in the German Grammar school Konigsbrunn. ***Source: self elaboration based on IBOS-TGA***

<table>
<tr><td rowspan="12">Building envelope</td><td rowspan="6">Heat insulation: mineral rock wool rear ventilated</td><td rowspan="2">Walls</td><td colspan="2">Exterior</td><td>25 cm</td></tr>
<tr><td colspan="2">Facing the inner courtyard</td><td>12 cm</td></tr>
<tr><td rowspan="3">Basements</td><td colspan="2">Walls or ceilings to rooms</td><td>12 cm</td></tr>
<tr><td rowspan="2">Walls or floor slabs in contact with the ground</td><td>On the outside walls</td><td>12 cm</td></tr>
<tr><td>On top of the floor</td><td>14 cm</td></tr>
<tr><td colspan="2">Roof</td><td colspan="2">40 cm</td></tr>
<tr><td rowspan="2">Transparent components</td><td colspan="3">Glazing</td><td>Coated double glazing</td></tr>
<tr><td colspan="3">Window frame</td><td>Wood</td></tr>
<tr><td rowspan="4">Miscellaneous</td><td colspan="2">Ratio area/volume and compactness</td><td colspan="2">Atria covered with a glass roof</td></tr>
<tr><td colspan="2">Exterior mobile shading on the roof</td><td colspan="2">Automatic positioning according to the sun altitude</td></tr>
<tr><td colspan="4">Vertical façade under the roof ridge that can be open completely to remove warm air</td></tr>
<tr><td colspan="4">Floor ducts to direct cool air into the courtyards</td></tr>
<tr><td rowspan="9">HVAC-system</td><td rowspan="2">Supply systems</td><td colspan="2">Heating and sanitary water production</td><td colspan="2">District heating
(184 kW)</td></tr>
<tr><td colspan="2">Electricity</td><td colspan="2">PV on the roof
(1’140.9 m^2; 155’478 kWh/yr)</td></tr>
<tr><td rowspan="7">Ventilation concept</td><td colspan="2" rowspan="3">Supply air</td><td rowspan="2">Well water</td><td>Cooling: 10-15 °C</td></tr>
<tr><td>Heating: 9-4 °C</td></tr>
<tr><td colspan="2">Filtering</td></tr>
<tr><td colspan="2" rowspan="3">Heat recovery</td><td colspan="2">Rotary heat exchanger (81%)</td></tr>
<tr><td colspan="2">Freewheel regulated by frequency converter</td></tr>
<tr><td colspan="2">Pressure control to regulate the flow rate</td></tr>
<tr><td colspan="4">Radiators</td></tr>
<tr><td rowspan="3">Lighting</td><td rowspan="3">T5 lamps</td><td colspan="2" rowspan="3">Control</td><td colspan="2">Light sensor</td></tr>
<tr><td colspan="2">Local and central switches</td></tr>
<tr><td colspan="2">Presence detectors</td></tr>
</table>

In the town of Unterschleißheim (Germany), it has been realized a passive sports hall to serve the needs of the adjacent school and to be used by private sports clubs and by the local community for local events. The technical features of the building are reported in the figure 9 (SEAI 2010). It is important to highlight other interesting design aspects of the sports facility, which contribute to the achieved energy use minimization, high comfort levels and optimal indoor air quality. To balance between providing sufficient light for the users of the sports hall, whilst also minimising use of artificial lighting, the transparent components have been carefully dimensioned and roof windows equipped with louvers, installed to provide additional day lighting and to prevent overheating. The choice of the ventilation system capacity has been a crucial aspect of the project. Avoiding to size the system for the larger, but less frequent, occupational patterns, large operable windows have been installed. Basically, an hybrid system of mechanical and natural ventilation has been implemented.

Project Description	
Project type	Gymnasium
Treated floor area in PHPP	1,000m²
Annual heat requirement (delivered energy)	PHPP = 14 kWh/(m²a)
Year of construction	2003
Project Team	
Architects	P S A Pfletscher und Steffan
Mechanical Engineers / Building Services Planning	Ingenieurbüro Bauer, Herr Veeh
Other important design team members (eg. Passivhaus Institut or others?)	Passivhaus Institut
Construction Details	
Construction type	Timber frame
Exterior wall U value insulation thickness and type	0.088 W/(m²K), 400mm of mineral wool insulation
Roof U value insulation thickness and type	0.094 W/(m²K), 400mm of mineral wool insulation
Floor U value insulation thickness and type	0.155 W/(m²K), 240mm of perimeter insulation
Window frame details	U_f = 0.91 W/(m²K)
Glazing details	U_g = 0.6 W/(m²K) g-value = 50%
Ventilation Details	
Air-tightness	n_{50} = 0.20/h
Ventilation equipment used	Menerga Resolair machine, delivering 3,000m³/h
Average air change rate	Different ventilation rates used for showering area (high air change rate) and for the sports hall (moderate)
Means of controlling ventilation rate	Manual setting and time clock
Design Heating (and Cooling) System and Renewable Energy	
Heat load per m²	11W/m²
Type of back-up heating system used	Hybrid system of geothermal heat pumps and district heating
Cooling load per m²	Not required
Method of cooling used	Not required
Domestic hot water production	District heating provided via a geothermic renewable energy source
Renewable energy production	Not applicable
Construction and Energy Costs	
Cost of construction (not including cost of land)	€2,400 / m² net
Estimate on additional ('extra') costs over conventional cost for construction	Unknown
Typical annual energy costs (only for space heating and / or cooling)	Unknown

Figure 9. Building features of the Sports Hall in Unterschleißheim. ***Source: SEAI (2010)***

Also the refurbishment of the sports hall located in Lorch (Germany) (fig.10), operating since 1976, has been realized according to energy efficiency principles (BEHNISCH ARCHITEKTEN 2015). Similarly to the previous cases, the technical solutions implemented to avoid summer overheating and glare problems include the installation of plastic skylights and of movable external solar shading on all the transparent façades, except for the Northern one. The ventilation functions have been separated from the heating ones. The ventilation system is based on the displacement principle, to avoid draft and noise extraction of pollutants. It operates in combination with the natural ventilation contribution of openable windows.

Additionally it is equipped with high efficient heat recovery system. The external fresh air is pre-heated in winter, and pre-cooled in summer, passing through an underground duct; than, it goes to the equipment storage room, the hall, the changing room and finally it is extracted through the toilets and shower rooms. The users have the possibility to control the system and adjust it according to their needs. Finally, process water is heated by a solar heating system and thermal energy is supplied through the local biomass heating network.

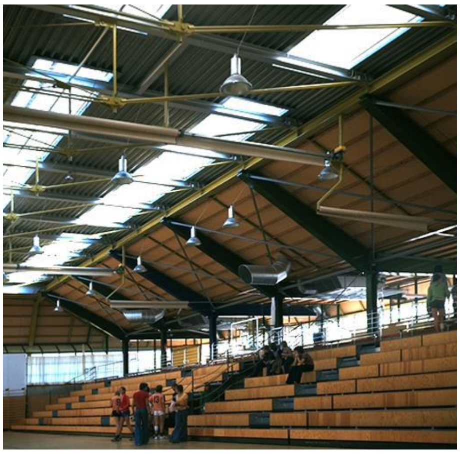


Figure 10. Sports Hall in Loch. ***Source: BEHNISCH ARCHITEKTEN (2015)***

The designer of the sports centre in Wageningen, Netherdlands (Reijenga 2005), aimed to realize a bioclimatic sports building implementing sustainable and low energy strategies. The project regards two sports halls (used by high-school students during the week and for competitions at weekends), an office tower, a canteen, an indoor climbing wall and a fitness area, all situated around a central unheated outdoor area called "the Plaza". The areas of the building are used for both energy concepts and sports functionalities, according to integral design techniques. The most innovative aspect of the construction is the optimization of the energy-saving natural ventilation system, which includes different components:

- Solar chimney: it consists of a high wall of offices with a glass cavity in front that is smaller nearer the top. At the top of the ventilation tower there are a wind vent cowl, that ensures that the opening is always on lee-side, and a ventilator, characterized by a low resistance when is not turning, to allow the ventilation air to pass naturally. Moreover, at the top of the solar chimney a heat pump recovers the heat from the ventilation air and returns it via the heating and domestic hot water system, as in balanced ventilation systems (fig.11, fig.12);
- Glass-covered area (the Plaza);
- Self-regulating grills in the sport halls.

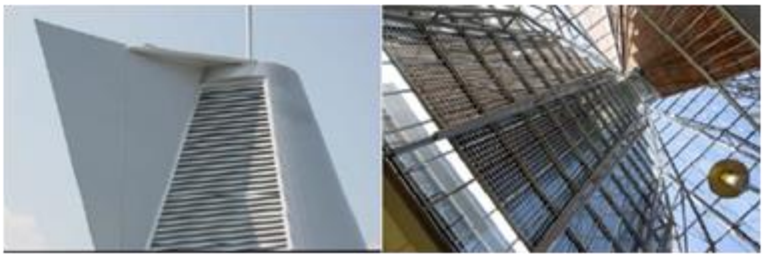


Figure 11. Left: the wind cap. Right: interior view of the solar chimney.
Source: Reijenga (2005)

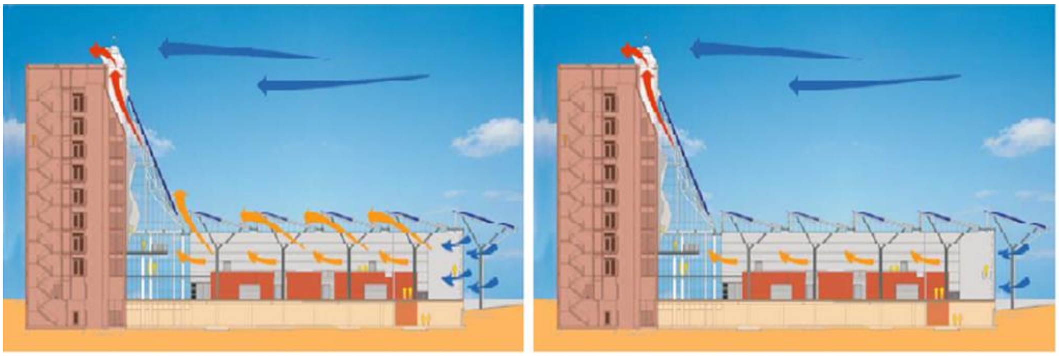


Figure 12. Ventilation tower: summer ventilation (left); winter ventilation (right). ***Source: Reijenga (2005)***

The energy generation installations, in addition to the heat pump, include high-efficiency boiler (cascade format), a solar boiler with 60 m² of collectors on the Plaza roof and a PV system. The PV system covers 2448 m², includes transparent and solid panels and has a total output power of 281.8 kWp. The solar panels in the roof can reduce the amount of direct sunlight entering the building of 30%, contributing to avoid the risk of overheating. Overall, it results that for the entire structure the calculated energy consumption is about 60% lower than usual and the energy performance coefficient (EPC) is about 0.37.

As mentioned in section 2.1, lighting system in sports facilities is responsible for a large amount of electricity consumption. In this regard, a further case study is presented. In the Universida Autonoma Metropolitana (UAM) in Mexico City (Castorena et al., 2011) the current needs of light appliances, composed of 50 Lithonian 400 Watts high pressure sodium lamps (ModelTH-A16), correspond to 240 kWh per day, 1680 kWh per week and 7200 kWh per month. Aiming to reduce this significant electricity consumption and the related high economic load, the researcher evaluated the possibility to install sunducts in the facility. Sunducts are lighting systems that, through a collection system with mirrors, enable natural light to reach zones which would be dark under normal conditions. The results of the study show that the installation of these devices can achieve important improvements in the illuminance levels of the sports hall. Considering the regular schedule of the activity (from 10 am to 10 pm), for 50% of the use time, 380 lux can be provided indoor in condition of overcast sky and 1600 lux in condition of clear sky. Currently, the registered daylight illuminace level with artificial light system off is on average around 50 lux. The installation of sunducts results to be an energy saving alternative that contribute to the traditional lighting system of the sports hall taking advantage of the natural light.

Finally, according to the reports published as part of the Step2Sport European project (Torrentellé and Escamilla, 2015) (LEITAT & SEA 2015) and aimed to support the refurbishment of existing sports buildings through step by step renovation towards n-ZEB standards, sports facilities across European countries have common energy efficiency problems. The proposed improvements are summarized in table 8. It is expected that the implementation of these measures achieves on average 60% reduction of energy use per gross floor area in typical sports halls.

Table 8. Energy efficiency strategies for Sports Hall proposed by the Step2Sport European project

	Enegy efficiency measures	Function	Saving potential
Building components	External wall insulation	Prevents heat gains and losses	10%-15% of heating and cooling demand
	Cavity wall insulation	Reduction of heat losses	10%-25% of heating demand
	Thermal roof insulation	Prevents heat gains and losses	33% of heating and cooling demand
	Double and triple glazing windows	Prevent bi-directional heat transfer	2%-22% of heating and cooling demand
	Shading solution	Prevents heat gain and glare	10%-25% of cooling load
Storage solutions	Stratified buffer thank for hot water	Increase heat storage efficiency	20-35%
Lighting	LED lighting	Provides cost cut and improved light quality	15-60% of lighting energy consumption
	Lighting control system	Provides the righ amount of ligh when and where it is necessary	20-50% lighting energy consumption
	Natural daylight system - Sunpipe	Directing sunlight into a room from roof level	75% during day time
Ventilation	Ventilation units with heat exchanger	Up to 85% efficiency in recovery heat from exahaust air	50%-85% of thermal energy for heating of supply air
	Optimization system for ventilation units	• Reduce the number of operational hours • Reduce airflow	10%-80%
Control strategies	Building energy management system	To suit the use and the occupancy level of the Sports Hall	Up to 25%
	Digital time switches	Turn off the equipments when they are not used	1%-7% of the total energy consumption
Energy production	Photovoltaic system	Electricity production	40-65%
	Solar thermal system	Hot water production	60%
	Geothermal heat pump	• Heating and cooling • Production of hot water	25%-65%
	Biomass boiler	Heating	2%-5%
	Cogeneration – Combined heat and power	Provides heat and electricity	20%-35%
	Efficient condensing boiler	Recovery of the latent heat – incresed efficiency	5%-20%

3 Theoretical framework

The following subchapters illustrate the theoretical framework of the thesis research. The theoretical aspects regard the natural ventilation working principles as well as the description of the adopted comfort models.

3.1 Natural ventilation

The term ventilation refers to the practice of replace stale indoor air with fresh external air (Chenari et al, 2016). Why is it necessary to ventilate a building? Ventilation functions are briefly listed below.

- Supply oxygen for respiration
- Dilution of indoor contaminants
- Control of indoor aerosol concentration
- Control of indoor relative humidity
- Optimization of air distribution.

Natural ventilation achieves the mentioned objectives without the support of a mechanical system.

Natural ventilation has been used since ancient time to ensure acceptable condition in inhabited spaces. Several technical solutions have been implemented along the human history to take advantage of the natural ventilation phenomenon. Allard (2002) mentions the Native America *tipi*, the Mongolian *yurt* and the Iraqui *ma'dam* as examples of traditional buildings located in hot and temperate climate that adopted wind-driven ventilation techniques. Further examples of wind-stack driven ventilation devices are provided by the Iranian traditional architecture that used curved-roof air vent, wind tower (dating back to 300 BC), cistern and ice maker systems (appeared about 900 AD). It is proved that wind catches, or *malkaf*, appeared in the ancient Egyptians houses since 1300 BC. While ventilated atria and courtyards, attached to vernacular buildings to promote natural ventilation effects, were used in Greek and Roman architecture, in Mesopotamia, in Cina, in the Indus and in the Nile valley (Santamouris and Wouters, 2006). Furthermore, a ground-cooling ventilation system, called *covoli*, was mentioned in an Italian architecture book for the first time in 1570 (Allard 2002).

In this section functioning principles and preeminent characteristics of natural ventilation are presented.

3.1.1 Natural ventilation driving forces

Generally, a natural ventilated building is one for which ventilation occurs trough openings in the envelope (Etheridge 2015), as effect of pressure difference established across them. Santamouris and Wouters (2006) describe the physical principles which natural ventilation in based on. Specifically, airflow is generated through wind velocity and thermal buoyancy effects.

The time mean pressure induced when wind flow comes into contact with an object can be expressed as:

$$p_w = C_{p\,w} * \rho_w * v_w{}^2 /2 \qquad \textit{(eq. 1)}$$

where C_p is the static pressure coefficient and v is the time mean wind speed at given level, usually at the high of the building or openings. Referring to the convention according to which the pressure difference between the interior of the building and the exterior environment is positive when the building is pressurized respect to outdoors, the wind force make that the air is driven into the building entering from the openings in the windward side. Conversely, the air is driven out passing through the openings located in leeward side of the envelope.

Wind and buoyancy work in combination to determine airflow. To define the buoyancy effect it is necessary to introduce the static pressure, presented here in its derivate form:

$$dp_s = -\rho_a(z) * g * dz \qquad \textit{(eq. 2)}$$

Looking at equation 2, it must be taken into account that air density depends on temperature and that the order of magnitude of pressure differences in ventilation systems is significantly lower than the atmospheric pressure (p_o= 1.325 Pa). Therefore, considering the gas law in isobaric transformation and the temperature constant on vertical direction, the following equation can be applied:

$$p_s = p_{ref} - \rho_0 * g * \frac{T_0}{T_{z_0}} * H \quad \textit{(eq. 3)}$$

where subscript 0 indicates the standard conditions for the dry air, p_{ref} is the reference pressure at the height z_0 and h the established high difference. Essentially, equation 3 describes the natural phenomenon according to which warmer air, with lower density, is forced to move upward by colder air, with higher density.

Moreover, it is introduced the expression that allows to evaluate the airflow through an opening. Equation 4 derives from the Navier-Stock equation:

$$\Delta P = 0.5 * \rho_a * Q^2/(C_d * A)^2 \qquad \textit{(eq. 4)}$$

C_d is a dimensionless parameter depending on opening geometry and Reynolds number; A is the opening area and Q is the mean air flow rate expressed in m^3/s.. However, the reported expression is applicable to small orifices through which air infiltrates and it is obtained for fully developed flow. This last condition generally is not verified in real building, where the openings have not a uniform geometry. Therefore, in real case studies, when the behavior of small and large openings must be analyzed, it is necessary to apply empirical lows. Generally, the power law expressions have the form (Allard 2002):

$$Q = K * (\Delta P)^n \qquad \textit{(eq. 5)}$$

where K is the flow coefficient that varies according to the building geometry; n is the flow exponent, determined from experiments and without a physical meaning, it specifies if the flow is turbulent or laminar.

The equations from 1 to 5 are extrapolated from Santamouris and Wouters (2006).

3.1.2 Natural ventilation strategies

To take advantage of natural ventilation principles, different ventilation strategies can be implemented, determining the patterns according to which the air enters and exits from the building (Santamouris and Wouters 2006).

Single side ventilation

It is the most localized technique, realized installing opening only in one side of the ventilated space. The air enters and exits alternatively from the upper and lower part of the opening. The fluctuation component of the wind is the main drive force of the air movement. The range of effectiveness of this solution is limited to a maximum room depth of 2.5 times the ceiling height that has to be about 2.5m. Moreover, to maximize the single side ventilation effect, window should measures 1/20 of the floor area.

Cross-ventilation

Cross-ventilation is achieved through the installation of openings in opposite side of the building envelope. It occurs when air enters into the building from one side, traverse the entire indoor space, and leaves from another side. Therefore, this technique is able to provide ventilation for a whole building floor.

Stack ventilation

The air movement generated by thermal buoyancy is known also as *stack effect* and it is typical of tall buildings where the pressure difference generated by the density difference, mainly during summer, forces interior warm air to rise. An over-pressure is created at the top of the building and consequently air flows out. The outdoor cooler air, entering from lower inlets, will replace it. The level at which the indoor and the outdoor pressures are equal is called neutral pressure level (NPL), and it correspond to the absence of air movements.

The three main ventilation strategies can be also implemented simultaneously, as shown in figure 13 (Axley 2001). Other measures can be considered in the building design to improve natural ventilation effectiveness. In figure 13 an inslab is represented. Its function is to increase the control on air distribution and temperature.

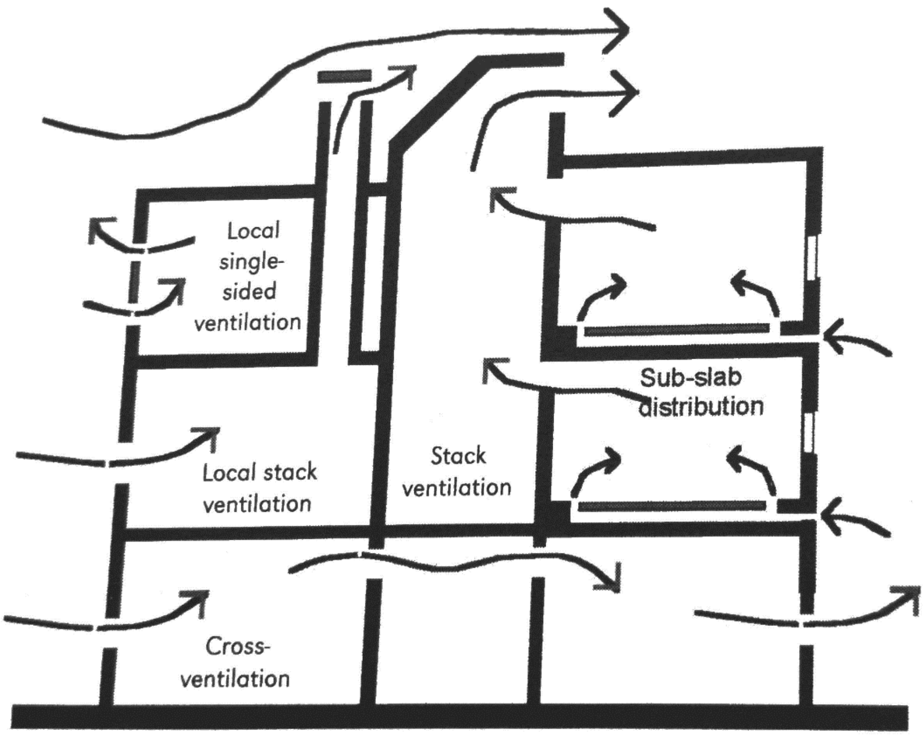


Figure 13. Schematic of mixed local/global and stack/wind ventilation strategy. Source*: Axley (2001)*

3.1.3 Natural ventilation technical solutions

According to the classification proposed by Chenari et al. (2016), the technical solutions so far available to take advantage of the natural ventilation principles, can be summarized as in table 9:

Table 9. Characteristic elements of natural ventilation. ***Source: self-elaboration based on Chenari et al. (2016)***

Element/features	Natural ventilation principles	Supply or Exhausted
Atrium	Single-sided, Cross and Stack	Supply and Exhaust
Wind scoop	Cross and Stack	Supply
Wind tower	Cross and Stack	Exhaust
Wind catcher	Cross and Stack	Supply and Exhaust
Ventilation shaft	Single-sided, Cross and Stack	Supply and Exhaust
Solar Chimney	Cross and Stack	Exhaust
Ventilation openings on façade	Single-sided, Cross and Stack	Supply and Exhaust
Double-skin façade	Single-sided, Cross and Stack	Supply and Exhaust

Aflaki et al. (2015) present other architectural elements able to promote natural ventilation effects, as balconies, wall grooves and corridors, which helps to create cross ventilation by channeling and delivering air flow from outdoor into different parts of a building.

Some of the mentioned technical solutions are described more in details.

Wind towers provide natural ventilation maximizing the pressure difference between inlet (positive pressure on the wind ward side that drives the fresh air into the room) and outlet (negative pressure on the leeward side to extracts the stale and warm air) of the building. A wind tower takes advantage of different physical principles according to the interior and exterior climatic conditions, as summarized in table 10 (Allard 2002):

Table 10. Wind tower operating principles

	Mechanisms	Effect
No wind during the day	*Downdraught*	The air, cooled through the tower wall, sinks down
Wind	*Wind effect*	The air flow faster and is cooled more effectively
No wind at night	*Updraught (stack effect)*	The air, warmed up through the tower walls with enough thermal inertia (the tower releases at night the heat absorbed during the day), moves up

Traditional wind towers can be classified in four main categories (Dehghani-sanij et al., 2015):

- one-sided wind tower: there is only one opening in the dominant direction of the wind;
- two-sided wind tower: it is designed to blow and suck the airflow into the building;
- four, six, eight-sided wind towers: the dimensions are related to the local climate conditions;
- cylindrical wind towers.

The construction elements that characterize wind towers have evolved along the history of architecture to adapt to different climate needs and aiming to improve efficiency. The main limitations related to wind tower implementations have been the difficulty of rotating in the direction of maximum ambient air, the poor interior recirculation and the need for an outward wind characterized by sufficient speed.

Researchers investigated the integration of wind towers in modern buildings. The wind tower design proposed by Bahadori et al. (2008) takes advantage of the evaporative cooling potential of the air. It includes wetted columns, realized through unglazed ceramic conduits uniformly sprayed of water, or wetted surfaces, consisting of straws or cellulose called pads, usually used in evaporative coolers, and placed at the top of the device. Dehghani-sanij et al. (2015) designed a wind tower model to be adopted in residential buildings, closed arenas, and commercial and administrative buildings as passive ventilation strategies. The main features of the proposed wind tower is the possibility of rotating in the direction of maximum wind speed, detected through a wind vane. The considered wind tower is meant to be used in combination with one or more windows, a solar chimney or another wind tower installed in the opposite direction.

The use of the wind tower devices in cold climate is related to the integration of heat recovery systems. In this regarding, Calautit et al. (2016) studied the performance of a natural ventilation system realized with heat pipes and heat sinks integrated in a multidirectional wind tower channel. The researchers achieved an increment of the supply air temperature by up to 4.5 K.

Traditional wind towers can be installed in connection with an additional channel positioned at 5-7 meters underground and called *naghb* in Persian (Jafarian et al. 2010). It uses the ground humidity to cool the air, operating as a ground-air heat exchanger. The system is effective also when there is no wind, because the ambient air that enters the *naghb*, passing through the openings on the wind tower sides, is cooled through an evaporative processes. Consequently, the cool heavier air replace the interior warm air resulting in a natural ventilation air movement. When the wind is blowing, the air passes through the underground channel, enters in the building and goes outside from windows and doors. By analogy, the benefits related to the high inertia of the soil, namely the ability to keep the surrounding air temperature almost constant along the year, are the key functioning aspects of the *covoli*, the ground cooling ventilation system implemented in a group of sixteenth century villas in Italy (Allard 2002). The system is based on interconnected sloped caverns, located underground and used as cool reservoirs. The *covoli* are linked to the outside, to create a downdraught of cooler air during the summer and an updraught during the winter, and to the villas, placed at lower level. The Canadian or Provencal well are modern examples of ground-cooling ventilation principles application (Touzani and Jellal, 2015). This kind of installations are passive thermal solutions that use soil as seasonal dumper. Specifically, the Canadian well is intended to warm the fresh air in the winter and the Provencal well to cool it in summer.

A similar design has been studied in a university campus in Malaysia. Sanusi et al. (2013) present an underground cooling system as a passive cooling alternative to the air-conditioning. The investigated technology includes polyethylene underground-buried pipes. Ambient air is conveyed to the pipes to use the soil as heat sink. The results of the investigation show that the air passing through the pipes experiences a relevant temperature drop, up to 6.4 °C and 6.9 °C depending on the season of the year.

Alba et al. (2013) provide an additional example performance study of a ground cooling combined with natural ventilation system. Their research regards an industrial building located in the city of Cali, Colombia, a typical hot humid location. In the studied building, the natural ventilation strategy is implemented through the installation of louvers at the bottom of the façade and a ventilated skylight at the roof, while the interior temperature is controlled through shading devices and a good thermal insulation. The simulation of the integration of an earth-air heat exchanger in the described system shows that, without extra energy consumption, an ambient internal temperature of 28.5°C can be achieved, namely 3°C lower than the case with natural ventilation alone.

There are several possibilities to promote natural ventilation in modern buildings through the implementation of passive solar strategies. Considering architectural roof and façade elements, two typical passive designs are briefly presented (Chan et al., 2010).

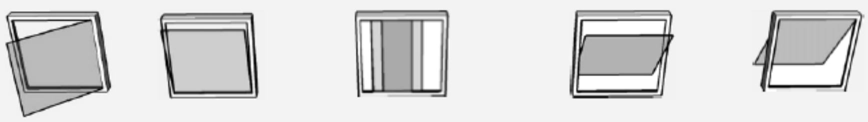
- *Trombe wall (double-skin façade)*:
  it is a massive wall covered by an exterior glazing with an air channel in between. The function of the glass is to trap solar radiation, while the wall absorbs and stores the solar energy and partially transfers it to the interior room. The interior denser air enters the channel through a lower vent in the wall; it is heated up, flows upward due to buoyancy effect and returns in the room through an upper vent.

- *Solar chimney*:
  it is a thermo-syphoning air channel designed to improve ventilation stack effect by maximizing solar gain, consequently increasing the difference between indoor and outdoor air temperature (Khanal and Lei, 2011). In a cold or moderate climate, when the outdoor temperature is lower than the indoor temperature, a solar chimney converts thermal energy in kinetic energy of air movements. The thermal buoyancy driving mechanism is influenced by the geometry and the tilt angle of the device.

This thesis deals mainly with the study of cross-ventilation effects. As mentioned, this technique is implemented through the installation of ventilation openings on opposite building façades. In this regard, a very recent study is cited. The research of Cheng et al. (2016) investigates the consequences of the implementation of a natural cross-ventilation system in a large gymnasium (63.2m in depth, 147.8m in length, maximum height 14.3m), currently equipped with an hybrid ventilation system. IES-VE is the simulation software used for the thermal and airflow modelling. The study concludes that the net opening size is a crucial factor that determines the airflow rate available for natural ventilation scopes. Moreover, they verified that uniformity of the opening distribution positively affects the cross-ventilation efficiency in a building with multiple inlets and outlets in opposite façades. Additionally, the study recognizes that an appropriate design of the opening control strategy reduce building overheating and overcooling problems more effectively than changes in building architecture.

Cross ventilation is a simple solution. However, windows selection is a fundamental and studied aspect of the natural ventilation design process (Gao and Lee, 2010). Considering the site-specific climatic limitations, window choice must be carefully evaluated. Roetzel et al. (2010) provide an overview on the proprieties of different window opening types (fig. 14).

Evaluation of different window opening types regarding properties affecting the effectiveness of ventilation in offices for typical opening angles. Description of symbols: –, poor; O, medium; +, good.



Properties of different window types when opened at a typical angle	Side hung, opening to inside	Bottom hung, opening to inside	Sliding, opened pane always covers part of window	Horizontal pivoted, lower part opening to outside	Top hung, opening to outside
Weather protection	–	+	–	O	O
Max. achievable ventilation rate	+	–	O	+	O
Adjustability of opening size	+	–	+	+	+
Flexibility for placement of furniture	–	+	+	O	+

Figure 14. Window opening types. ***Source: Roetzel et al. (2010)***

3.2 Thermal comfort

The tendency of the HVAC industry is to maintain constant indoor temperature inside buildins, aiming to satisfy the largest number of people. However, there are many factors that concur in the comfort definition and there is not a temperature that will content all the occupants of a certain space (Santamouris and Wouters 2006).

A person that function without involuntary stress from feeling too warm or too cold, from smelling objectionable odours, or from having irritated eyes, nose, or throat is experiencing a condition of general comfort. The comfort determinants include thermal, atmospheric, visual and acoustical aspects (Cain 2002). The different features of the indoor environment are interrelated and building occupants, to a certain extent, are able to balance the good elements against the bad ones to perform a global evaluation (Centnerová and Boerstra, 2010).

Specifically, according to the standard ASHRAE 55-2010 (ASHRAE 55, 2010), thermal comfort is defined as the state of mind that expresses satisfaction with the thermal environment and is assessed by a subjective evaluation. Therefore, thermal sensation is a crucial aspect of the comfort perception and depends on different parameters (Allard 2002):

- physical, as air temperature, air relative humidity and local air velocity;
- physiological, as age, sex and particular characteristic of the occupants;
- external, as human activity, clothing and social conditions.

Moreover, building users have different expectations and different abilities to adjust to the surrounding thermal environment; their recent thermal history has an impact on their comfort perception; their cultural background governs their reaction to the perceived discomfort and affects the evaluation of the importance of thermal comfort itself (Harriman and Lstiburek, 2009).

Overall, the conditions that define an environment as satisfactory are dependent on several physiological and psychological factors, which influence people differently.

Standards and models have been statistically elaborated to evaluate the thermal comfort of existing buildings or to support the design stage of new ones. They are based on laboratory and field data. In this study, the sports hall thermal environment has been assessed through the standards UNE-EN ISO 7730 (AENOR 2006), UNE-EN 15251 (AENOR 2008a), UNE-EN ISO 7933 (AENOR 2005), UNE-EN 12515 (AENOR 1997) and ASHRAE 55-2010.

Standards provide also recommendations about local thermal discomfort phenomena as asymmetrical thermal radiation, draft, vertical air temperature difference and warm or cold floor.

The following sections are devoted to the description of the adopted models.

3.2.1 Predicted mean vote

The Predicted Mean Vote (PMV) is one of the most recognized thermal comfort model. It is related to the Fanger's model, based on thermoregulation and heat balance theories, according to which the human body balances between the heat lost through the skin and respiration, and the heat produced by the metabolism, implementing physiological processes (Orosa Garcia 2010).

The heat balance of the human body can be expressed through the following equation (eq. 6):

$$M - W = (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \quad \textit{(eq. 6)}$$

Where:

M - rate of metabolic heat production
W - rate of mechanical work accomplished
C+R - sensible heat loss from skin
C_{res} - rate of convective heat loss from respiration
E_{res} - rate of evaporative heat loss from respiration
S_{sk} - rate of heat storage in skin compartment
S_{cr} - rate of heat storage in core compartment

The analysis of the terms that compose the heat balance equation allows to identify the six parameters that define the thermal status of human body, classifiable in personal and environmental factors:

- activity
- clothing

} personal factors

- air temperature
- air velocity
- relative humidity
- mean radiant temperature

} environmental factors (microclimate parameters)

According to Fanger's approach, thermal sensation can be defined determining the deviation between the actual condition of the body and the optimum comfort level (condition of neutrality). The PMV index is the tool necessary to perform this comparison. Fanger developed it to study the results of a set of experiments conducted with 1300 subjects in stable conditions in climate chambers. It has been then normalized in the UNE-EN ISO 7730 standard. Fanger's theory assumptions are reported below:

a) the "*hot*" or "*cold*" sensations are proportional to the thermal load ($M - W$), namely the difference between thermal the power generated inside the human body and the thermal power dispersed by the subject who is in well-being condition (considering the skin temperature and the sweat rate) performing a specific activity;

b) there is a relation between the PMV index, the thermal sensation felt by an average individual and expressed as a vote on a 7-point scale, and the thermal load.

The 7-point bipolar scale according which the PMV is defined is reported in table 11.

Table 11. Thermal sensation scale. ***Source: self-elaboration based on Orosa Garcia (2010)***

PMV	Thermal sensation
-3	Hot
-2	Warm
-1	Slightly warm
0	Neutral
+1	Slightly cool
+2	Cold
+3	Very cold

The PMV index can be evaluated according to the equation 7, which involves the 6 personal and environmental variables listed above (Orosa Garcia 2010).

$$PMV = (0.303exp^{-0.0036\,M} + 0.028) * \{(M - W) - 3.05 * 10^{-3} * [5733 - 6.99(M - W) - p_a] - 0.42[(M - W) - 58.15] * 1.7 * 10^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) - 3.96 * 10^{-8}f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} * h_c * (t_{cl} \pm t_a)\} \qquad \textit{(eq. 7)}$$

Where:

p_a - partial vapour water pressure
t_r - mean radiant temperature
f_{cl} - ratio of clothed surface area to nude surface area
h_c - convective heat transfer coefficient
t_{cl} - clothing surface temperature

In other words, the PMV index coincide to the vote of an average individual (precisely the average of the votes expressed by a large number of people placed in predetermined temperature and humidity conditions) expressed to evaluate the perceived subjective thermal sensation.

The condition of thermal neutrality corresponds to -0.5 < PMV < 0.5. However, even if PMV results null, the votes of individuals considered separately have a certain dispersion around zero. For this reason, the Predicted Percent of Dissatisfied (PPD) index is introduced. The PPD is calculated from PMV (eq. 8 and fig.15) and predicts the percentage of people who are likely to be dissatisfied with a given thermal environment, namely the percentage of the people who felt more slightly warm or slightly cold (Djongyang et al., 2010).

$$PPD = 100 - 95e^{-n} \qquad \textit{(eq. 8)}$$

where

$$n = 0.03353PMV^4 + 0.2179PMV^2 \qquad \textit{(eq. 8.1)}$$

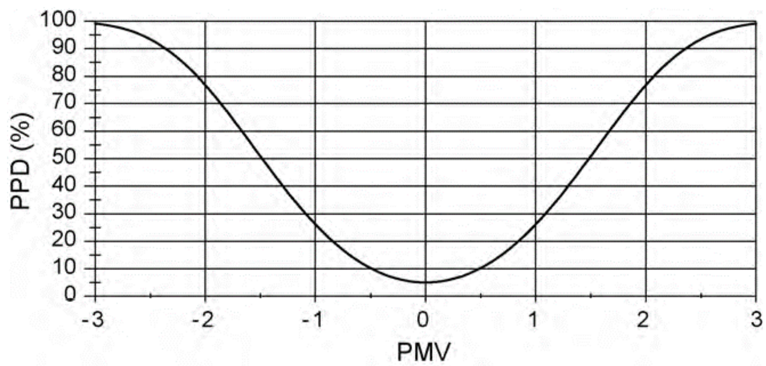


Figure 15. Relationship PMV versus PPD. ***Source: Djongyang et al. (2010)***

3.2.2 Adaptive model

The adaptive model has been elaborated to take into account the natural process of adaptation that users perform assessing the thermal perception of an occupied building (Djongyang et al., 2010).

Thermal adaptive model derives from field studies. The term adaptation is referred to behavioural, physiological and psychological mechanisms implemented to fit the indoor climate to personal requirements (de Dear et al., 1997) (fig.16). It has been found that the evaluation of physical and personal factors is not sufficient to accurately predict thermal sensation. This is especially true in context where people can interact with the surrounding environment. Several studies show that in natural ventilated buildings the occupants prefer a wider range of thermal conditions and variable indoor air temperature, according to the outdoor climate parameters and to daily and seasonal climate changes. Conversely, Fordham (2000) points out that the massive introduction of air conditioning systems reduces people's awareness and, enabling any temperature to be chosen, removes the need to understand what, for example, can be defined *"too hot"*.

According to the adaptive principle, building users are considered active subjects. This means that when a discomfort condition occurs, they are able to react and restore their comfort status undertaking a series of actions (Rupp et al., 2015). From the adaptive point of view, comfort should be intended as a measure of how successful those actions have been (Nicol et al., 2007).

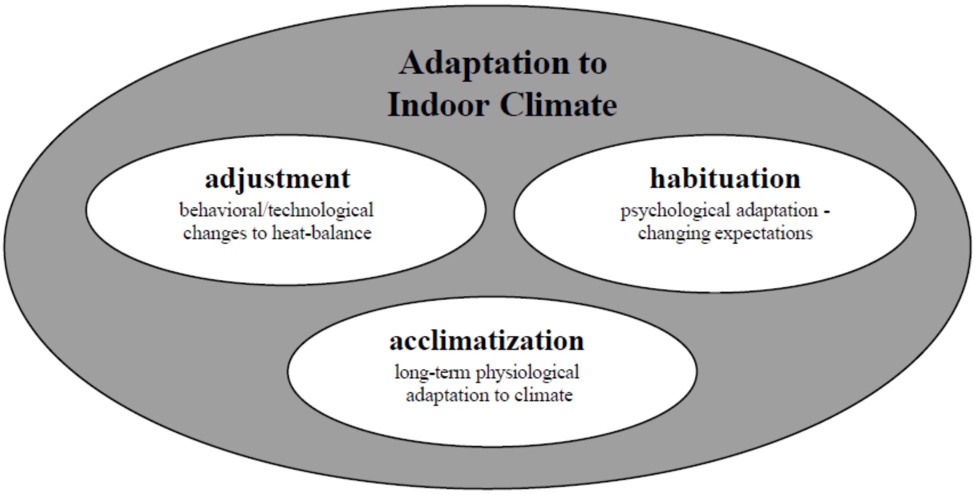


Figure 16. Thermal adaptive process. The components of adaptation to indoor climate. *Source: de Dear et al. (1997)*

The ASHRAE 55-2010 and UNE-EN 15251 standards recognize the thermal adaptation phenomenon and provide a methodology to be applied in the study of naturally ventilated environment.

The application of the proposed thermal adaptive comfort procedure requires the introduction of an additional parameter: the operative temperature (T_{op}) defined as "*a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non uniform environment*" (Kazkaz and Pavelek, 2013). T_{op} correlates air temperature, mean radiant temperature and air velocity according to the expression reported in the UNE-EN ISO 7730 standard (eq. 9):

$$T_{op} = T_a * A' + T_{rm} * B \qquad \textit{(eq. 9)}$$

where A' and B are function of the air velocity, as in table 12.

Table 12. Coefficients for the calculation of Top depended on air velocity

	$V_a < 0.2$ m/s	$0.2 < V_a < 0.6$ m/s	$V_a > 0.6$ m/s
A'	0.5	0.6	0.7
B	0.5	0.4	0.3

The adaptive model allows the definition of an acceptable indoor temperature range. A relationship between the optimal thermal indoor conditions and the exterior climate is established. This is a key aspect that clearly differentiate the adaptive approach from the PMV model. In this regard, it should be make a clarification. As it is possible to observe in the figure 17, the mean monthly outdoor air temperature is used as reference exterior temperature. Its value, according to the ASHRAE 55-2010 standard, is calculated as the arithmetic average of mean daily minimum and mean daily maximum outdoor temperatures:

$$T_{a(out)} = \frac{T_{max} + T_{min}}{2} \qquad \textit{(eq. 10)}$$

The same parameter in the UNE-EN 15251 standard is calculated as an exponentially-weighted running mean temperature:

$$\theta_{ea} = \frac{\theta da_{-1}+0.8*\theta da_{-2}+0.6*\theta da_{-3}+0.5*\theta da_{-4}+0.3*\theta da_{-6}+0.2*\theta da_{-7}}{3.8} \qquad \textit{(eq. 11)}$$

where

$\theta da = \sum_{n=24}^{1} t_{mhr} /24$, the daily average exterior temperature; it is an average of the hourly average outside temperature for one day (24h).

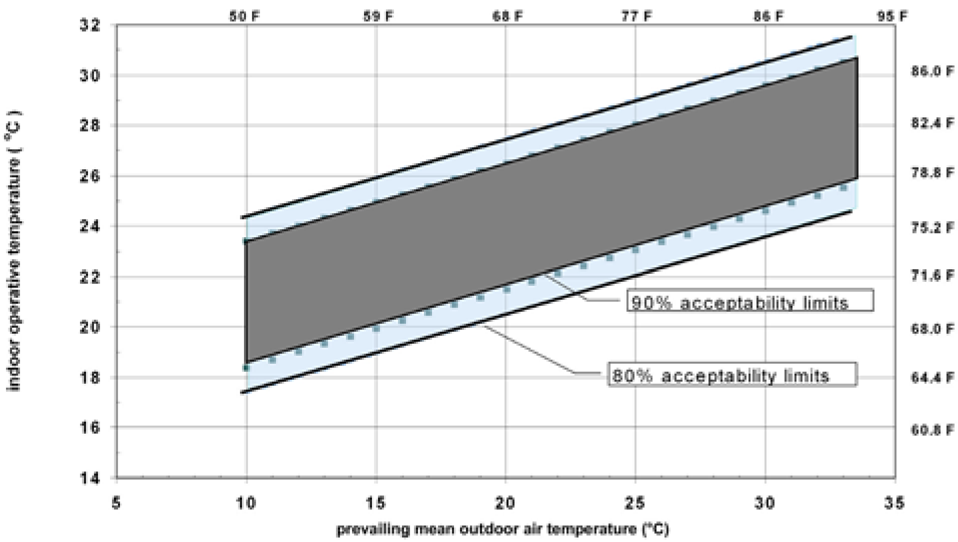


Figure 17. Acceptable operative temperature ranges. 90% acceptability limits = 90% of the occupants experience a comfort condition; 80% acceptability limits = 80% of the occupants experience a comfort condition. ***Source: ASHRAE 55-2010 (2010)***

Consequently, there are two different expressions to define the optimal operative temperature and the correspondent indoor temperature acceptability range:

Table 13. Adaptive model parameters according to the ASHRAE-55 and EN UNE 15251 standards

	ASHRAE 55-2010		**EN-UNE 15251**		
$T_{opOPTIMAL}$	$t_{op\ opt} = 0.31 * t_{a\ out} + 17.8$		$\theta_{op\ opt} = 0.33 * \theta_{ea} + 18.8$		
Acceptability	90%	80%	Category		
			I	II	III
	$t_{op\ opt} \pm 5$	$t_{op\ opt} \pm 7$	$\theta_{op\ opt} \pm 2$	$\theta_{op\ opt} \pm 3$	$\theta_{op\ opt} \pm 4$

3.2.3 Required sweat rate

For the analytic determination of the thermal stress, the UNE-EN ISO 7933 and the UNE-EN 12515 standards are applied. The adopted model is based on the calculation of the heat exchanged between a standard person and the environment. It is assumed that the heat is transferred through convection, radiation and respiratory heat loss. The model is related to a rational/analytic index defined as Required Sweat Rate (SW_{req}). The SW_{req}, derived from the heat balance equation, predicts the sweat rate necessary to facilitate the evaporation required to maintain null the heat storage in the body (Bethea and Parsons, 2002). The methodology suggested in the standards is graphically summarized (fig.18)

As it is possible to see in figure 18, different parameters, regarding interior microclimate conditions as well as personal factors, have to be implemented in the model. The interpretation of the results (outputs) aims to determine the Duration Limited Exposure (DLE), namely the acceptable period of work that can be performed in the evaluated environment. The DLE is function of maximum values of body heat storage (Q_{max}) and water loss (D_{max}). The DLE calculation considers as well the limits imposed for skin wettedness (W_{max}). Specifically, the results are interpreted according to two subcategories (Malchaire et al., 2000):

- warning level: there is no risk for any subject in good health performing the considered activity;
- danger level: there could be risk for certain subjects, although in good health, performing the considered activity.

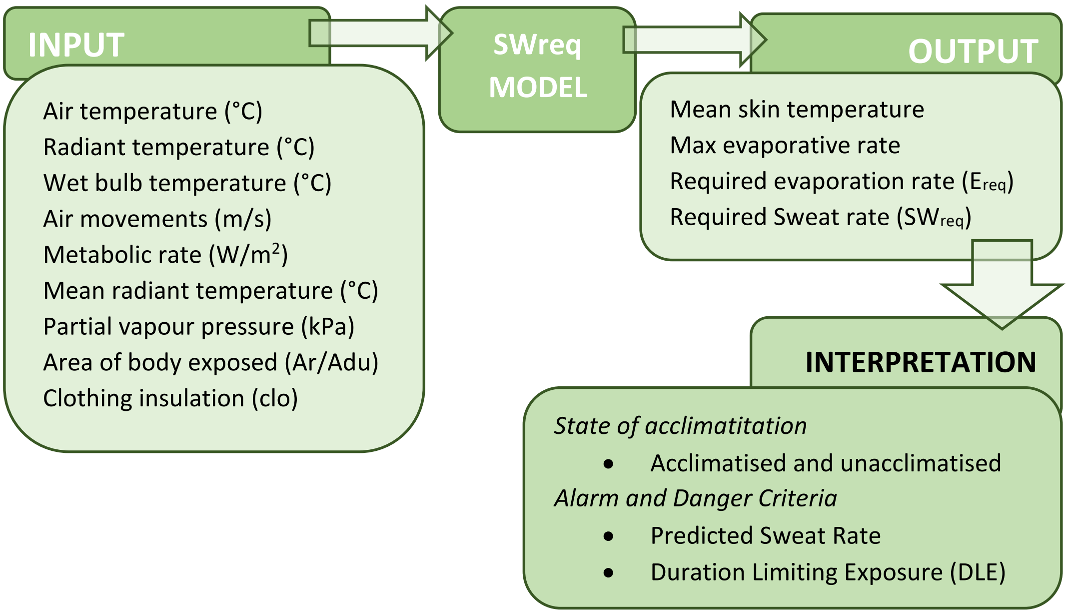


Figure 18. Graphical description of the Required Sweat Rate model. ***Source: self-elaboration based on Luna Mendaza (1994)***

3.2.4 Givoni diagram

The bioclimatic diagram proposed by Givoni predicts the indoor thermal-hygrometric comfort state according to the external prevailing climatic conditions. Bioclimatic charts are useful tools to identified the best building passive thermal design strategies for a specific location. The definition of the Givoni building bioclimatic chart (BBCC) is based on the linear relationship between the temperature amplitude and vapor pressure of the outdoor air (Al-Azri et al. 2012). In the Givoni chart interior and exterior parameters are introduced in a psychometric diagram, that graphically representing the relation between temperature and air moisture content, allows to easily identify the comfort zone and its extension (La Roche 2011). The diagram is organized in five different zones. The winter comfort zone results wider than the summer one, assuming that the clothing and the metabolic activity that describe the building users are higher during the coold season.

The Givoni diagram elaborated for the comfort analysis of the sports hall where the measurements campaign has been performed, is reported in section 11.1.2

3.3 Indoor Air quality

Since ancient times natural ventilation contributed to satisfy building occupants demand of control on acceptable indoor temperature and humidity levels. This aspect has been briefly discussed in section 3.1 of this work.

However, other complementary needs arose along the human history, as the desire to eliminate disagreeable contaminants from the occupied spaces. The ancient Egyptians realized that stones carvers working inside were more subject to respiratory distress than people working outdoor and attributed the phenomenon to the indoor high level of dust. In the Middle Ages people stated to link the transmission of diseases to the density of occupation of common areas. In 1777, Lavoisier concluded that excess of CO_2 causes sensation of stuffiness and so called *bad air*. In 1836, Thomas Tredgold published the first estimation of the minimum quantity of ventilating air needed to ensure comfort (Janssen 1999).

Considering the fact that humans spend more than 80% of their lifetime inside close environments (Norhidayah et al., 2013), it is undeniable that indoor comfort deserves thorough investigation. Many studies have been focused on indoor pollutant measurements in residences, offices, restaurants and shopping malls. While few researches can be found in literature regarding the evaluation of indoor contaminants in large enclosures as sports halls. (Junker et al., 2000; Alves et al., 2013)

A poor indoor air quality can affect dramatically building habitability. Today it is increasingly frequent that occupants exhibit symptoms of sick building syndrome (SBS) that lead to experience irritation, discomfort or ill health (Allard 2002). It results that, in general, naturally ventilated buildings have fewer symptomatic occupants than air-conditioned ones (Burge 2004). Health issues have increased in parallel with the wide use of HVAC systems. This phenomenon often is related to the fact that ventilation ducts are dirty and filters not changed, increasing contaminants that are recirculated into the occupied spaces (Clausen 2004).

The expression indoor air quality (IAQ) refers to the amounts of contaminants present in the indoor air. Undesired emissions are caused by different sources. The users produce bio-effluents; the furniture, the equipment, the internal partitions, surface paint and decorative pieces release chemical particles in the air. Other common pollutants are fungi and micro-organisms (Chenari et al., 2016).

According to the UNE-EN 15251 standard, air quality can be evaluated referring to CO_2 indoor concentration. Normally, for ordinary building, the reached CO_2 concentration levels are not harmful for humans. However, CO_2 concentration is a useful indicator of the contaminants produced by the human body (Kleiven 2003). All people are CO_2 sources, as a results of their metabolism. The CO_2 emission rate is not constant: depends on the type of person and on the performed activity level. Pre-defining a maximum acceptable concentration level of a certain pollutant and identifying the dominant contaminant source, it is possible to evaluate the require ventilation rate. Practically, the pollution decreases exponentially increasing the air flow rate (fig.19) (Allard 2002).

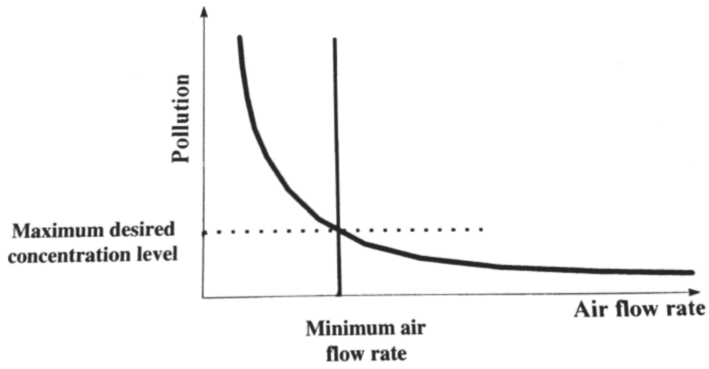


Figure 19. Ventilation and air quality. ***Source: Allard (2002)***

4 Methodology

The methodology according to which this research has been realized, includes different steps.

First, in order to complement the available environmental comfort performance data about typical Spanish sports halls (section 2.1), a field measurements campaign has been conducted in an existing sports facility. Information regarding occupation patterns and environmental indoor quality have been collected through field measurements. Thermal microclimate parameters, as indoor air temperature at different heights, radiant temperature, air velocity, relative humidity and air quality indicators, as CO_2 concentration, have been measured during different usage conditions of the sports hall. Additionally, the appropriate clothing insulation and metabolic activity profiles of the users have been estimated. At the same time of the measurements campaign, the subjective perception of the occupants has been investigated through a questionnaire survey. Following the procedures described in ASHRAE 55-2010 and UNE-EN 15251, the adaptive and Fanger thermal comfort models have been applied to evaluate the internal comfort conditions. Secondly, a selection of energy efficiency and renewable energy integration strategies is introduced. The base case sports hall is identified following the technical indications provided by the Catalan sports council (Consell Català de l'Esport 2005) concerning a so-called *triple sports hall* (PAV3). A triple sports halls is a sports facility equipped with a playing field that can be divided in three transversal spaces, increasing its versatility. When the base case sports hall 3D geometry is modelled in Google Sketch Up, it is introduced in the simulation by a 3D model, realized through the plugin Trnsys3D. The energy efficiency measures are then tested using the dynamic simulation tool TRNSYS. Within the proposed n-ZEB strategies, natural ventilation is studied more in detail in order to estimate its impact on thermal comfort, air quality and energy needs. The contribution of the designed natural ventilation system is assessed through TRNFLOW, the extension realized to integrate the airflow and pollutant transport model COMIS into the multizone building thermal model of TRNSYS and based on air mass conservation laws (Weber et al. 2003). Therefore, the ventilation behaviour and the ventilation effects on the building indoor conditions are investigated. The implementation of renewable energy systems, specifically the potential contribution of the installation of a photovoltaic system, is estimated through the Google Sketch Up plug-in Skelion and the type 94 of TRNSYS. Finally, the economic evaluation of the studied cases is realized implementing the cost-optimal methodology, consistence with the guidelines provided by the European Union (IEA 2014).

The detailed description of each phase of the research is reported in the following sections. Moreover, a scheme of the implemented methodology is reported in figure 20.

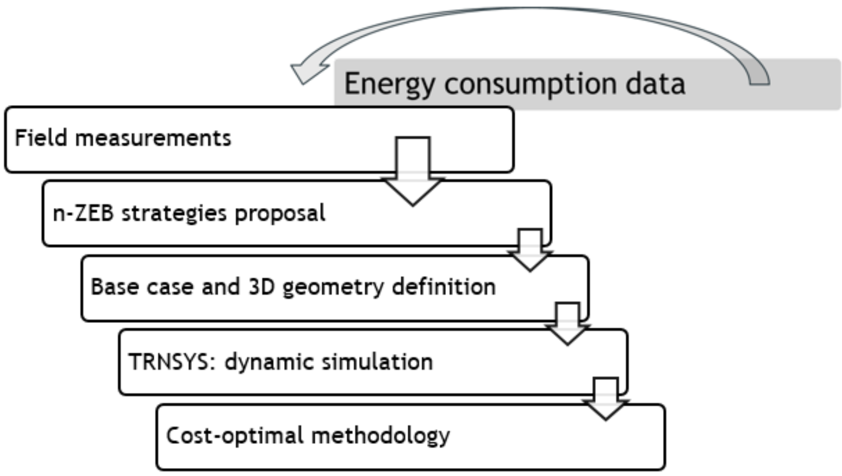


Figure 20. Research methodology

5 Measurement campaign

The field measurement campaign has been realized in the "Poliesportiu Pla Del Bon Aire" located in Terrassa (Barcelona) and currently not equipped with a ventilation system neither a heating system. The main goal is to evaluate the indoor environmental quality (IEQ), the thermal condition and the perception of the users, players and audience, of the sports facility. Therefore, thermal microclimate parameters and air quality indicators have been monitored.

The measurements has been performed along two days, 12/03/2016 and 13/03/2016. The first day, the instrumentation were installed, compromising between quality of measurements, equipment safety and reduction of the interaction of the building users. The measurements equipment named *Tower 1* and *Tower 2* include different sensors, while the equipment named *Sensor 1* and *Sensor 2* are more compact devices (fig.20).

Figure 21. Measurements devices: left, *Tower 1* and *Tower 2*; right, *Sensor 1* and *Sensor 2*

Measuring devices were placed on the playing field floor (*Tower 1* and *Tower 2*) and on higher level (*Sensor 1* and *Sensor 2*), in different locations of the sports hall, as shown in figure 21 and in figure 22.

The environmental parameters assessed during the measurements campaign are summarized in table 14. All the data have been recorded with 3 minutes interval. Measurements were carried out when sports hall was empty as well as fully occupied. The matches took place during the second day of measurements between 09:30 and 13:45 in the morning and between 16:00 and 21:30 in the evening. The different occupation condition were registered. Table 15 summarizes the occupation pattern registered in the sports hall during the day of measurements.

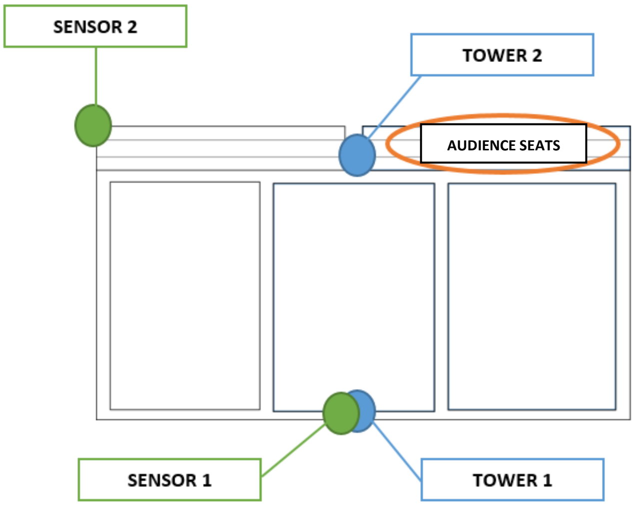


Figure 22. Placement of the measurements devices in the sports hall

Table 14. Measurements configuration

Measurements and position		**Tower 1**	**Sensor 1**	**Tower 2**	**Sensor 2**
Air temperature	0.1 m	x		x	
	0.6 m	x		x	
	1.1 m	x		x	
	1.4 m	x		x	
	1.7 m	x		x	
	2.8 m		x		x
Globe temperature	1.4 m	x		x	
Relative humidity	1.4 m	x		x	
	2.8 m		x		x
Air velocity	1.4 m	x			
CO_2 concentration	1.4 m	x		x	
	2.8 m		x		x
Dew point temperature	2.8 m		x		x
Hours:	*12/03/2016*	*20:15-00:00*	*20:11-00:00*	*20:36-00:00*	*20:45-00:00*
(3 minutes steps)	*13/03/2016*	*00:00-21:51*	*00:00-21:47*	*00:00-21:39*	*00:00-21:39*

Table 15. Occupation of the sports hall

Hours	07:30	08:30	10:30	12:30	16:30	18:30	19:30	21:30
Occupation	10	90	100	180	75	115	330	330

To have a complete description of the actual thermal performance of the sports hall, a survey related to indoor air perception was conducted among the audience (Annex 1). The survey has been performed at different hours of the day. The aim of the survey was to collect information about the thermal sensations experienced by the audience, to then compare them to the measurements results.

5.1 Assumptions and parameters

In order to calculate the thermal comfort index PMV, as well as to apply the adaptive comfort model, some parameters have to be defined:

- metabolic rate (Met): according to the standard ASHRAE 55-2010, different values have been identified for the players and the audience:

Table 16. Metabolic rate

	Activity	Met
Players	Basketball	6.3
Audience	Seated, heavy limb movement	2.2

- clothing insulation (CLO): as reported in the standard ASHRAE 55-2010:

Table 17. Clothing insulation

		Garments	CLO
Players		Walking shorts, short sleeve shirt	0.36
Audience	Morning	Trousers, long-sleeve shirt plus long-sleeve sweater	1.01
	Evening	Trousers, long-sleeve shirt plus long-sleeve sweater	1.01

The value of clothing insulation relative to the audience has been determined taking into account the answers received in the proposed survey, as shown in table 18.

Table 18. Survey answers. Clothing description

Thermal comfort survey answers		
	Morning	Evening
1. Shorts and short-sleeved shirt	3	
2. Throusers and short-sleeved shirt	2	4
3. Throusers and long-sleeved shirt	11	5
4. Throusers and jersey	**13**	**7**
5. (3) + jacket	3	2
6. (3) + jersey and interior shirt	1	2
7. Knee-length skirt and short-sleeved shirt		
8. Knee-length skirt and long-sleeved shirt		1
9. Knee-length skirt and jersey		
10. (7) + jersey		
11. (7) + jacket		
12. Ankle-length skirt, long-sleeved shirt and jacket		

- mean radiant temperature: the method provided by the UNE-EN ISO 7726 (AENOR 2002b) standard has been used to calculate this parameter that cannot be directly measured. The method is briefly explained. The desired parameter must be extrapolated from another variable, the globe temperature. The used global thermometer is normalized (diameter of 0.15 m and balloon emissivity of 0.95). The relative equations are:

- natural convection:

$$T_{rm} = \left[\left(T_g + 273\right)^4 + 0.4 * 10^8 * \left|T_g - T_a\right|^{\frac{1}{4}} * \left(T_g - T_a\right)\right]^{1/4} - 273 \qquad \textit{(eq. 12)}$$

- forced convection:

$$T_{rm} = \left[\left(T_g + 273\right)^4 + 2.5 * 10^8 * {V_a}^{0.6} * \left(T_g - T_a\right)\right]^{1/4} - 273 \qquad \textit{(eq. 13)}$$

The convection regime is determined by the highest value of the heat transfer coefficients calculated as follow:

- natural convection

$$h = 1.4 * \left(\frac{\Delta T}{D}\right)^{1/4} \qquad \textit{(eq. 14)}$$

- forced convection

$$h = 6.3 * \left(\frac{{V_a}^{0.6}}{D^{0.4}}\right) \qquad \textit{(eq. 15)}$$

where $\Delta T = T_a - T_g$ and D is the global thermometer diameter.

The mean radiant temperature is needed for the PMV index calculation (section 3.2.1).

The sports hall comfort study required additional assumptions:

- only one air velocity sensor was available, therefore the air velocity measured through *Tower 1* is assumed to be equal in all the measurements areas;
- only the equipment installed in *Tower 2* for the air quality evaluation worked properly, therefore the CO_2 concentration relative to *Tower 1* is assumed to be equal to the value measured through *Tower 2*;
- the comfort investigation is performed only regarding the occupation periods, namely between 9:30 and 21:30 of 13/03/2016;
- the exterior CO_2 concentration is assumed to be equal to the lower concentration registered through the indoor sensors during the night (451 ppm at 05:36).

It was not possible to install a weather station to collect data regarding the exterior weather conditions. The needed external parameters, as air temperature and humidity, have been extrapolated from the database provided by the Meteorological Service of Catalonia (Generalitat de Catalunya 2016) regarding the observation conducted every half an hour in the meteorological station of Sabadell - Parc Agrari, located at 10 km from the studied sports hall. The information about the evolution of the average monthly temperature along the years in Terrassa, that as explained in section 3.2.2 are needed in the implementation of the adaptive model, have been provided by InfoMet (Universitat de Barcelona - Departament d'Astronomia i Meteorologia 2016), a database realized by Department of Astronomy and

Meteorology at the University of Barcelona with the support of the Catalan Foundation for Research. The average values relative to the two days of measurements are reported in table 19.

Table 19. Exterior weather parameters

		12/03/2016	13/03/2016
Temperature	*Average*	8°C	7.7°C
	Maximum	14.8°C	14.5°C
	Minimum	2.7°C	0.2°C
Average relative humidity		63%	64%
Precipitation		0 mm	0 mm
Maximum wind gust		25.9 km/h	32.8 km/h
Average atmospheric pressure		1’020.5 hPa	1’019.8 hPa
Global solar irradiation		18.9 MJ/m^2	18 MJ/m^2

Finally, the infiltration of the building has been evaluated applying the CO_2 tracer gas concentration decay method described by Cui et al. (2015). It results that the building infiltration correspond to an ACH value of 0.27h^{-1}.

5.2 Data elaboration

After the data acquisition phase, the measured internal conditions have been analyzed in combination with the weather variable, the results of the survey and the assumed parameters.

The graphic elaboration of the collected data, regarding the microclimate indoor parameters recorded during the measurements campaign, are reported below.

The indoor temperatures start to increase around 9:00 in the morning, following the behaviour of the external temperature. Observing the interior temperatures recorded by *Tower 1*, it is possible to notice that the maximum value of 24.5°C is registered by the sensor at 1.4 m at 16:15. Similarly, the sensors of *Tower 2* registered the maximum temperature of 23.9°C at 16:18, but at higher altitude (1.7 m) (fig.23).

In relation to the indoor relative humidity, the registered values and the correspondent exterior measurements are presented in figure 22. The maximum relative humidity value is registered through *Tower 1* during the day at 14:09 (43.6%) and in the evening at 21:30 (62.5%). *Tower 1* measured also a minimum value of 33.7% at 15.24, when the sports hall was not occupied (fig.24).

Figure 25 represents the evolution of the air velocity, measured through a specific sensor located on *Tower 2*. The minimum registered air velocity value corresponds to 0.08 m/s, the maximum is 0.28 m/s. On average, the air velocity during the measurements campaign was of 0.17 m/s. However, considering the high sensitivity of the measurements instrument, likely the collected data have been affected by the proximity of the audience, especially during the hours of maximum occupancy.

The last graph (fig.26) reports the measured interior CO_2 concentration. The maximum CO_2 concentration regarding the morning measurements was registered through *Tower 2* at 13:39 (1268 ppm); while at the 21:30 the concentration reached the value of 2127 ppm. It is possible to notice that a significant decrease of CO_2 concentration occurs around 15:00 (the daily minimum concentration is 706 ppm, registered at 15:15), when the sports hall was empty and the matches suspended.

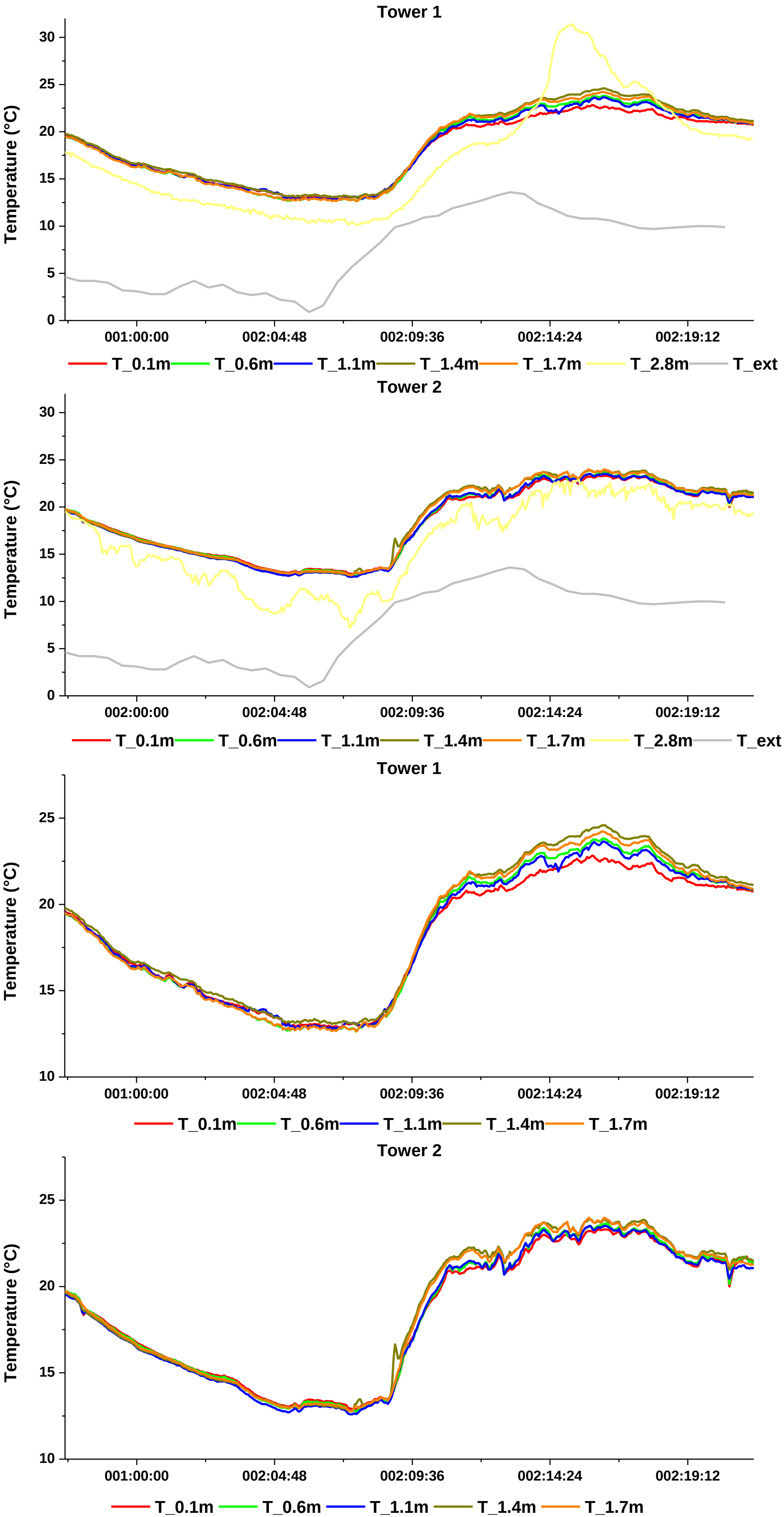


Figure 23. Air temperature measurements

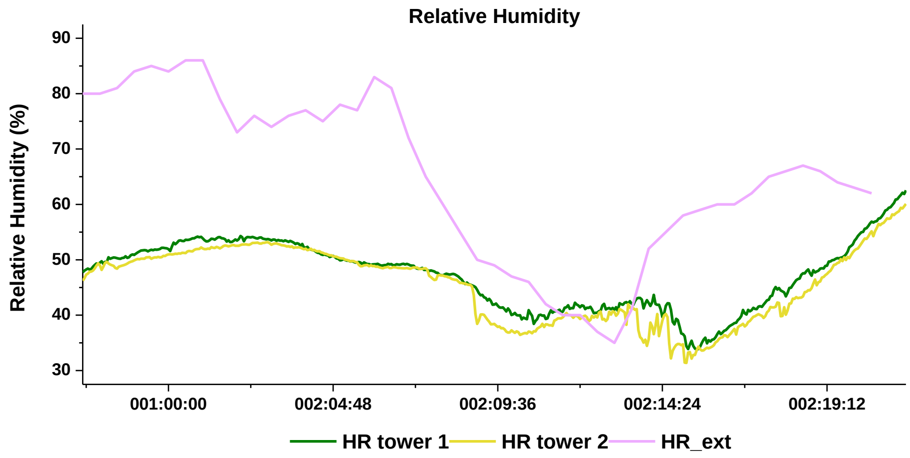


Figure 24. Relative Humidity measurements

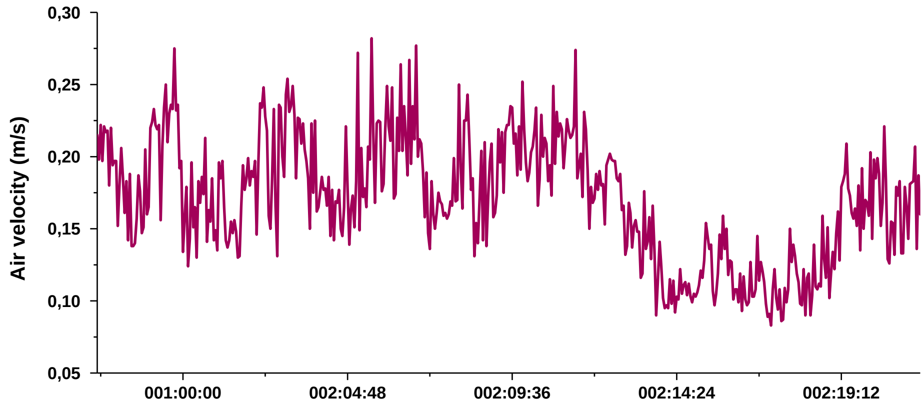


Figure 25. Air velocity measurements

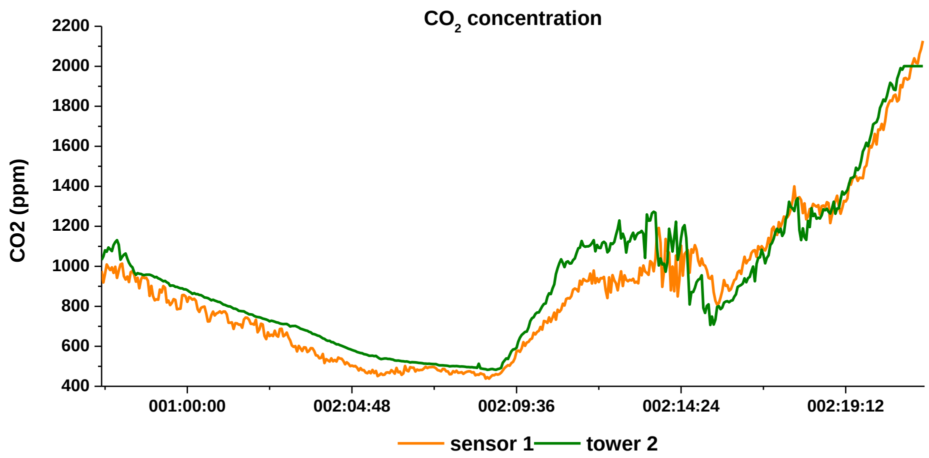


Figure 26. CO_2 concentration measurements

6 Proposed n-ZEB strategies

As described in section 2.1, sports halls are characterized by very specific energy needs. With the goal of fulfill the energy needs of this particular kind of installation satisfying the users comfort requirements and achieving a significant reduction of the primary energy use, appropriate n-ZEB strategies have been selected. The selection occurred in the light of the climatic conditions of the site and of the type of use that characterize the investigated sports facility. Consequently, considering the solutions presented in section 2.2, implemented in the already existing net zero energy sports buildings, the data collected during the measurements campaign and the guideline available regarding energy efficient sports halls, (ICAEN 2012, Guía de Eficiencia Energética en Instalaciones Deportivas 2008), a suitable set of passive approaches, energy efficiency measures and renewable energy systems have been identified (tab.20).

Table 20. Proposed n-ZEB strategies

	Measures		Implementation	Objective
Passive strategies and control	Thermal behavior		• Selection of building materials to ensure low thermal transmittance of the envelope • Optimization of the ratio opaque components/ windows of the façade according to the building orientation • Installation of shading device in the South-East façade, dimensioned to take advantage of natural light during winter and to reduce solar radiation during summer	✓ ensure good thermal insulation ✓ use solar gains ✓ avoid risk of overheating
	Natural light		• Design of the South-East façade to maximize the contribution of natural light • Installation of diffuses light sources • Installation of skylight devices	✓ ensure visual comfort ✓ avoid glare
	Natural ventilation		• Definition of control system • Design independently from the natural light system • Nigh ventilation	✓ ensure thermal comfort of the users ✓ ensure good air quality
Renewable energy system	PV installation		• Design of the façades and the roof to allow the installation of PV panels • Study of the optimal roof slope and orientation to maximize the energy production	✓ reduce energy costs ✓ reduce CO_2 emissions
Active system	Systems efficiency	Artificial light	• Installation of LED lamps • Regulation with control system	✓ reduction of energy costs
		Heating system	• Sizing according to the heating demand • Evaluation of heat pump/condensing boiler installation	

Overall, the presented building concepts and energy approaches aim to achieve a significant reduction in the energy demand due to the mechanical systems typically installed in a sports hall (lighting, ventilation, heating and cooling), without compromising indoor comfort and air quality conditions. Specifically, this study, within the set of measures presented in the table 20, evaluates in details which is the effect of the implementation of natural ventilation on the sports hall energy performance toward n-ZEB standards. a natural ventilation system has been designed and its effectiveness has been energetically and economically assessed.

7 Base case description

The indoor comfort condition of a building derives from the interaction of different aspects: environmental factors, as the external climate; building factors, as shape and construction materials; occupants related factor, as internal gains (Huang et al., 2015)

This section describes in detail the base case study and the related aspects listed above.

7.1 The triple sports hall

The starting point of the base case building definition is, as introduced in section 4, the technical document provided by the Catalan sports council regarding the triple sports halls characterization and intended as a guide for the building designer (Consell Català de l'Esport 2005). It results that 133 on 564 Catalan sports installations are triple sports halls. Therefore, PAV3 is a representative building typology.

The main features of a triple sports halls (fig.27), as reported in the technical report, are:

- dimension of the playing field: 45 m x 27 m
- minimum height: 8.5 m
- maximum capacity: 300 people of audience and 168 players
- minimum interior temperature: 14°C
- minimum lighting: 200-400 lux
- minimum ventilation rate: 2.5 dm^3/sm^2
- orientation: the longitudinal axis should be oriented to the East-West direction; Southern openings should be equipped with protection from direct incidence of sunlight

The document elaborated by the Catalan sports council does not mention specific requirements about energy usage.

It must be taken into account that the mentioned report includes structural, hygienic and of maintenance indications regarding all the spaces forming part of the sports hall, as locker rooms, bathrooms and warehouses. However, in this thesis only the space relative to the playing field and the seats where the audience is allocated, are examined. Therefore, the calculation regarding DHW consumption and the specific comfort condition that must be guaranteed in the locker rooms are not performed.

Moreover, it is important to highlight that the entire research is based on a real project developed, in collaboration with IREC, by the municipality of Sant Andreu de Llavaneres (Ajuntament de SANT ANDREU DE LLAVANERES 2015a, 2015b), 40 km away from Barcelona. The project regards the construction of a new triple sports hall. The design includes eco design elements and aims to minimize the building energy consumption. This clarification implies that this thesis has been developed respecting some boundary conditions and does not involve the study of those parameter assumed as default, for example building orientation.

Neither in the technical report redacted by the Sport Council nor in the original project, there are recommendations about building airtightness. This means that there are not information regarding desired building infiltration. It is defined infiltration the ventilation that occurs through adventitious openings (Etheridge 2015). In buildings, some infiltration will always be present and an accurate evaluation of its contribution is fundamental during the ventilation system design process to avoid risk of oversizing (d'Ambrosio Alfano et al., 2012).

To define this important parameter, it is adopted the approach proposed by Florentzou et al. (2015). The researchers suggest that "*a reasonable and controlled infiltration is not the enemy of building energy performance*". The results of their study confirm that in large spaces infiltration is almost sufficient to provide good air quality. Consequently, the air tightness of the studied sports hall is considered equal to n_{50} = 2.6 h^{-1} According to UNE-EN 15242 (AENOR 2007), the considered value corresponds to a level of airtightness medium. This choice is in sharp contrast with the trends occurring in the high efficiency building sector and with the Passivehouse (Passive House Institute 2015) standard requirements that set a maximum of n_{50} = 0.6 h^{-1}. However, it is expected that the defined infiltration will not affect negatively the sports hall thermal behavior. In this regard, the comparison can be made with the German and Norwegian regulations, that specify a minimum airtightness requirement of n_{50} = 3 h^{-1} for non-residential natural ventilated building (Erhorn-Kluttig et al., 2009). Taking into account that the abovementioned countries are characterized by cold climate, the impact of the infiltration losses on heating energy use should result very low in the Spanish context.

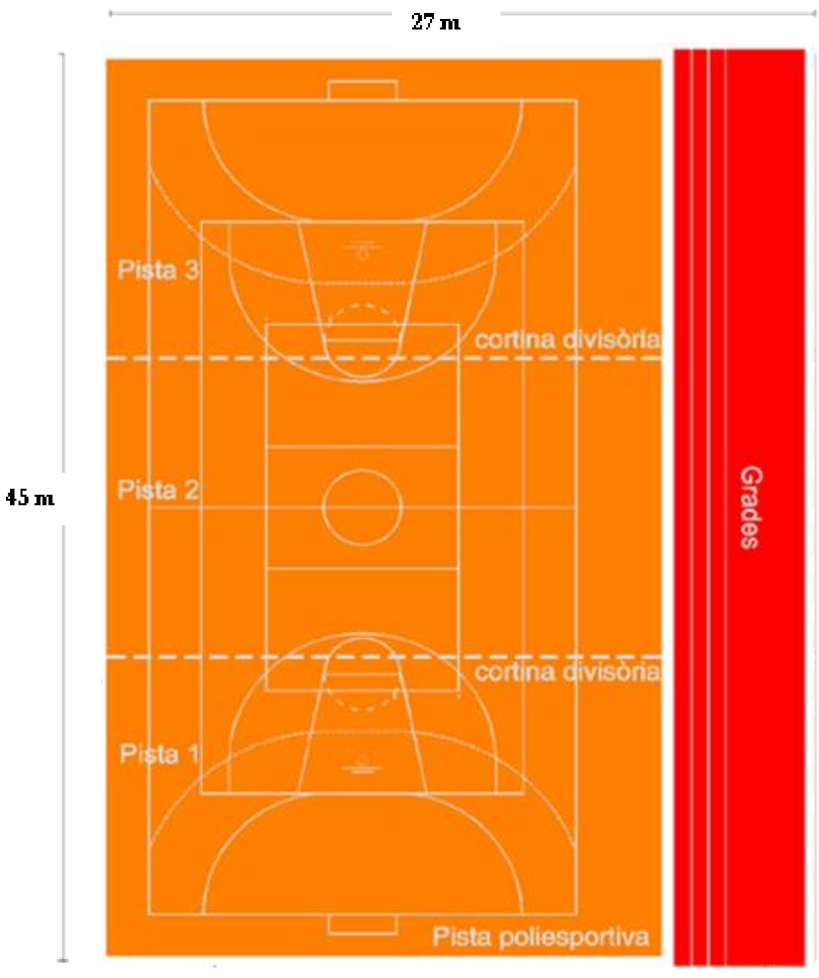


Figure 27. The triple Sports Hall. ***Source: Consell Català de l'Esport (2005)***

7.2 Occupation patterns

Sports hall energy consumptions are closely related to the number of users of the installation (section 2.1). For this reason, with the contribution of the data collected during the measurements campaign, realistic profiles of the sports hall occupancy have been defined. Two main occupancy patterns are identified, corresponding to weekdays and weekend. The information regarding the occupancy schedule are reported in table 21.

Table 21. Sports hall occupation. (1° = Saturday; 2° = Sunday)

	occupation														
	weekdays	weekends													
schedule	17-22	7-9		9-11		11-14		14-16		16-19		19-20		20-22	
		1°	2°	1°	2°	1°	2°	1°	2°	1°	2°	1°	2°	1°	2°
players	45	0	0	40	40	40	40	0	0	35	35	35	35	35	35
audience	20	8	10	40	50	48	60	8	10	40	50	64	80	200	300
total	65	8	10	80	90	88	100	8	10	75	85	99	115	235	335

7.3 Weather data

As outlined in the theoretical framework section (section 3), weather conditions have a fundamental impact on the building thermal behavior and consequently on the selection of appropriate energy saving strategies.

It is assumed that the studied sports hall is located in Spain, specifically in the Catalan city of Barcelona. According to the Köppen Climate Classification system, Barcelona is characterized by a Subtropical-Mediterranean climate (AEMET 2011). The climatograph elaborated from the information provided by AEMET (2016) (extracted from the publication *Guía resumida del clima en España 1981-2010*), is reported in figure 28. It results that annually the average temperature is 15.5°C, the maximum 19.2°C and the minimum 11.7°C, while the average relative humidity is 70%.

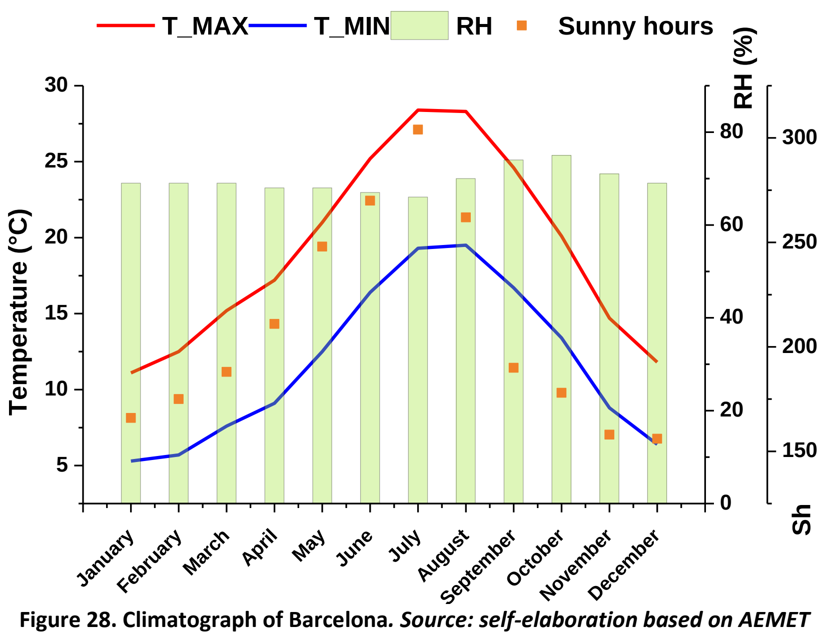


Figure 28. Climatograph of Barcelona. ***Source: self-elaboration based on AEMET (2011)***

The information on the wind characterization regard year 2015 and have been provided by "*Servicio Meteorológico de Cataluña* (Generalitat de Catalunya 2016b)". The prevalent wind direction results North-West while the percentage of calm is 11.9% (fig. 29).

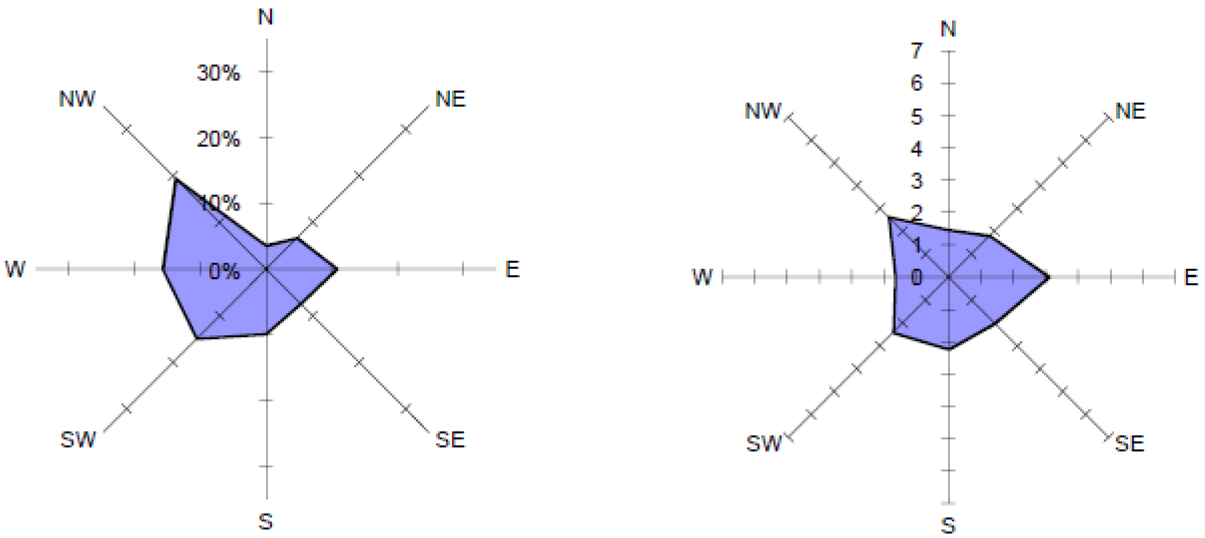


Figure 29. Left: wind rose. Right: average wind velocity for each direction (m/s). ***Source: Servicio Meteorológico de Cataluña***

The weather condition of the chosen site are introduced in the building simulation through a data file in typical meteorological year (TMY2s (NREL 2016)) format. The TMY2s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. They represent typical rather than extreme conditions.

7.4 3D geometry definition

The base case sports hall 3D geometry is defined through the modelling software Google Sketch Up, respecting the technical requirements reported above.

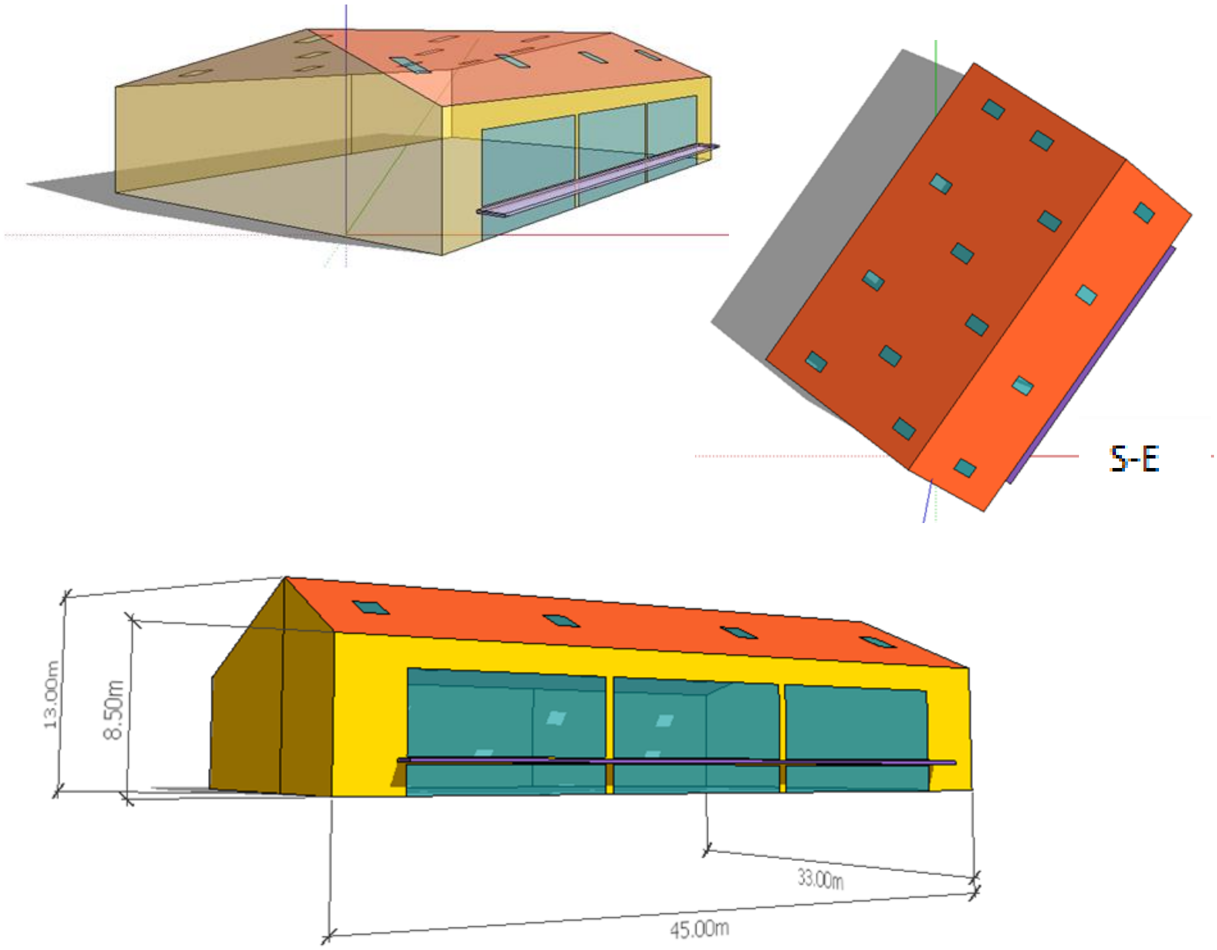


Figure 30. Sports Hall 3D model

The dimensions of the building are summarized in table 22.

Table 22. Sports Hall dimensions

	Volume [m³]	Area [m²]
Sports hall	13’618	1’485

8 TRNSYS: building simulation

TRNSYS is the calculus tool used to perform the building simulation. TRNSYS is a transient resolution software with a modular structure. It allows solving complex energy system problems subdividing them in a series of smaller component (Kim et al., 2009). The sports hall geometry presented in the previous section (section 7.4) is introduced in the simulation by a 3D model, using the plugin Trnsys3D for Google SketchUp. Specifically, the thermal behavior of the building is modelled through type 56 component (TRNSYS 17).

Natural ventilation is high dependent on climate and site specific characteristics. Therefore, there is not "*one set of determined criteria*" applicable to every naturally ventilated building. In this context the modelling tool as TRNSYS are extremely useful to predict and optimize the natural ventilation system performance (Stephan et al., 2009).

8.1 Thermal behavior

The thermal characteristics of the selected opaque components of the envelope are reported in table 23, while the thermal performance of the windows in table 24. The complete description of the opaque components, as well as the windows description, are reported in Annex 2.

Table 23. Thermal performance of the construction elements

	***U* – value (W/m²K)**
Façade NE and SW	0.284
Façade SE and NW	0.296
Interior wall	0.304
Roof	0.284
Floor	1.366

Table 24. Thermal performance of the windows

	Windows_lower level		**Windows_higher level**		**Window 3_skylight**	
	Frame	Glazing	Frame	Glazing	Frame	Glazing
Composition	Aluminium with thermal break	Clear double glazing 6/16/6	Aluminium with thermal break	OKAPANE (OKALUX GmbH 2016) with glass fibre tissue, 16 mm, air 40 mm	Aluminium with thermal break	Double glazing with prismatic lens
U–value (W/m²K)	2.27	1.26	2.27	1.24	2.27	1.4
g – value (-)		0.368		0.335		0.589
Area frame glazing (%)	15	85	5	95	5	95

It is important to draw attention to the fact that, as specified in table 20, the ventilation requirements of the building are satisfied through a system designed independently from the natural light one. This means that the windows and the skylight are not operable (they cannot be opened). They are designed to take advantage of the illuminance and of the heat gains freely made available by the sun. They are conform to esthetic needs and allow to establish a dialogue between the external and the internal environment.

U-value is a measure of thermal insulation performance of construction materials and building elements. The thermal transmittance values considered in this study (except for the one relative to the ground floor that must meet specific construction requirements considering the peculiar function of the building) are significantly lower than the ones proposed by the Spanish Building regulation (CTE, Código Técnico de la Edificación, 2013). The CTE sets in fact for the climatic zone of Barcelona (named C2) limits U-values of 0.73 W/m^2K and 0.5 W/m^2K, respectively for buildings façades and roof.

All the parameters summarized in the above mentioned tables are introduced in the TRNSYS simulation (fig.31). The façades and the windows are in contact to the exterior environment.

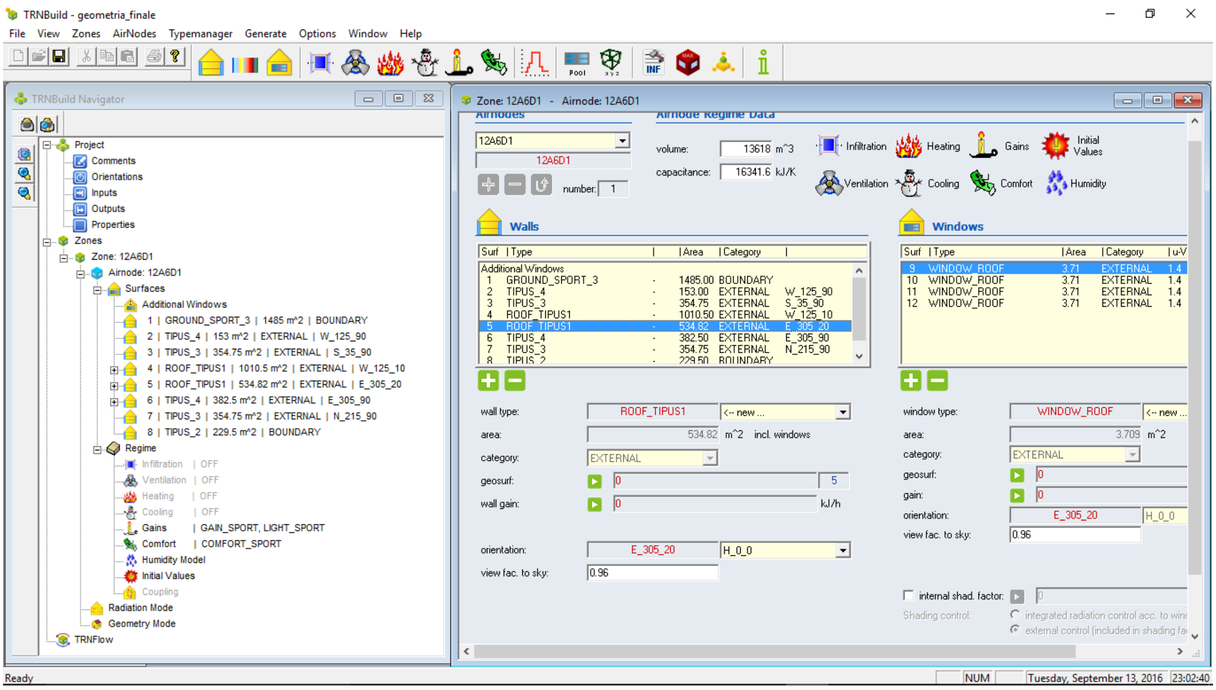


Figure 31. TRNSYS building simulation. Building envelope characteristics

In the simulated building, there is only an interior wall. The interior wall, mentioned in table 23, is located in the North West direction and it is assumed to be in contact to the lockers room. The boundary temperature for this partition wall is considered of 23°C or 18°C, respectively during the warm and cold occupied period. While, the unoccupied periods are characterized by a boundary parameter evaluated as average of the previous values and the exterior registered temperature. The ground temperature is introduced according to the indication reported in the *Guía técnica de condiciones climáticas exteriores de proyecto* redacted by ATECYR (2010) ($T_{ground} = 0.0068 * T_{air}{}^2 + 0.963 * T_{air} + 0.6865$ [$°C$]).

As it possible to see in figure 30, 14 skylights are placed on the building roof. The skylights contribution is simulated according to the technical specification of Sunoptics ® - Lledó (2011).

Additionally, it is clarified that the second row of windows represented in figure 30 are made of OKAPANE, namely light diffusing insulation panels, introduced to reduce heat losses and take advantage of daylight availability.

The thermal behavior of the building is also affected by the installation of a fix horizontal overhang (length 38m and width 2m) that aims to prevent temperature increase during the warm season.

8.2 Internal gains

The internal gains of a building are formed by the release of sensible and latent heat from the indoor heat sources. This study considers the contribution of the building occupants and of the lights appliances. The internal gains are implemented in the simulation through the TRNSYS *Gain Type Manager*.

The total heat gain due to people occupancy is evaluated considering the performed activity (tab.16; applied conversion factor 1 met= 58 W/m^2) and taking into account the mean surface area of the human body (approximately 1.8 m^2 (ASHRAE 1994)). The sensible heat produced by the occupants depends on their metabolic activity and on the indoor air temperature, according to the equation (Michaelsen and Eiden, 2009):

$$\dot{Q}_{sensible\_occupant} = 6.461927 + 0.946892 * MET + 0.0000255737 * MET^2 + 7.139322 * T_{air} - 0.0627909 * T_{air} * MET - 0.19855 * {T_{air}}^2 + 0.000940018 * {T_{air}}^2 * MET - 0.00000149532 * MET^2 * {T_{air}}^2 \quad \text{(eq. 16)}$$

The total sensible heat produced by the users of the sports hall is considered 30% convective and the remaining 70% radiative (ASHRAE 1993). Knowing the generated sensible heat, the latent contribution can be extrapolated.

The artificial lights system is mounted at 13 meters high. It is composed of 30 led lamps consuming 276 W each, with luminous efficiency of 80% (Ortiz et al. 2015). The installed systems is designed to ensure 300 lux of indoor illuminance, following the recommendation of UNE-EN 12193 (AENOR 2012) for sports activities as basket. Therefore, the contribution of the lights equipment to the internal heat load is calculated in function on the natural light availability. Artificial lights are assumed to be *ON* when the natural light provided by the 14 skylights placed on the building roof is lower than the required illuminance level and the sports hall is occupied. The data, on monthly bases, regarding the daily average sunlight availability are provided by an external collaborator and introduced as input in TRNSYS. The resulting schedule of the assumed artificial light use is reported in figure 32.

hours of the day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
january	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1
february	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1
march	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
april	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
may	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
june	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
july	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
august	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
september	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
october	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
november	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1
december	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1

Figure 32. Use of artificial lights schedule. 1 = lights ON if the sports hall is occupied (natural light <300 lux); 0 = lights OFF (natural light>300 lux). ***Source: self-elaboration based on data provided by an external collaborator***

8.3 Natural ventilation

Natural ventilation has been investigated in detail. It is chosen as the main strategy to ensure optimal indoor air quality condition and thermal comfort, avoiding the energy consumption due to mechanical systems.

The thermal comfort is evaluate applying the adaptive comfort model. The comfort conditions are set according to the limits defined in the standard UNE-EN 15251 and observing the requirements reported in the document redact by the Catalan sports council. The interior optimal operative temperature (θop_{opt}) is calculated following the procedure proposed by the standard. In the TRNSYS *Comfort Type Manager* tool the value of the audience metabolic rate (2.2), the audience clothing factor (considered 0.36 during the warm season and 1.01 during the winter time) and the assumed relative air velocity are introduced as inputs. The mean radiant temperature is a TRNSYS output as well as the indoor operative temperature. CO_2 indoor concentration (given as TRNFLOW output) is the parameter used to evaluate the indoor air quality (table 25). The exterior CO_2 concentration is considered 450 ppm.

Table 25. Building simulation: comfort parameters

	Lower limit	Upper limit	Source
Operative temperature (°C)	$\theta op_{opt} - 3$	$\theta op_{opt} + 3$	UNE-EN 15251
Indoor temperature (°C)	14°C	-	*Catalan sports council*
CO_2 concentration (ppm)	-	$CO_{2exterior} + 750$	UNE-EN 15251

As mentioned, cross-natural ventilation is modelled through TRNFLOW. Two identical openings (called *airlinks*) are introduced in the opposite façades of the building, taking into account the prevalent wind direction of the site (section 7.3). A large opening by definition is an internal or external opening that can be characterized by two-way flow (Allard 2002). The characteristic of the openings are reported in table 26 (fig. 33).

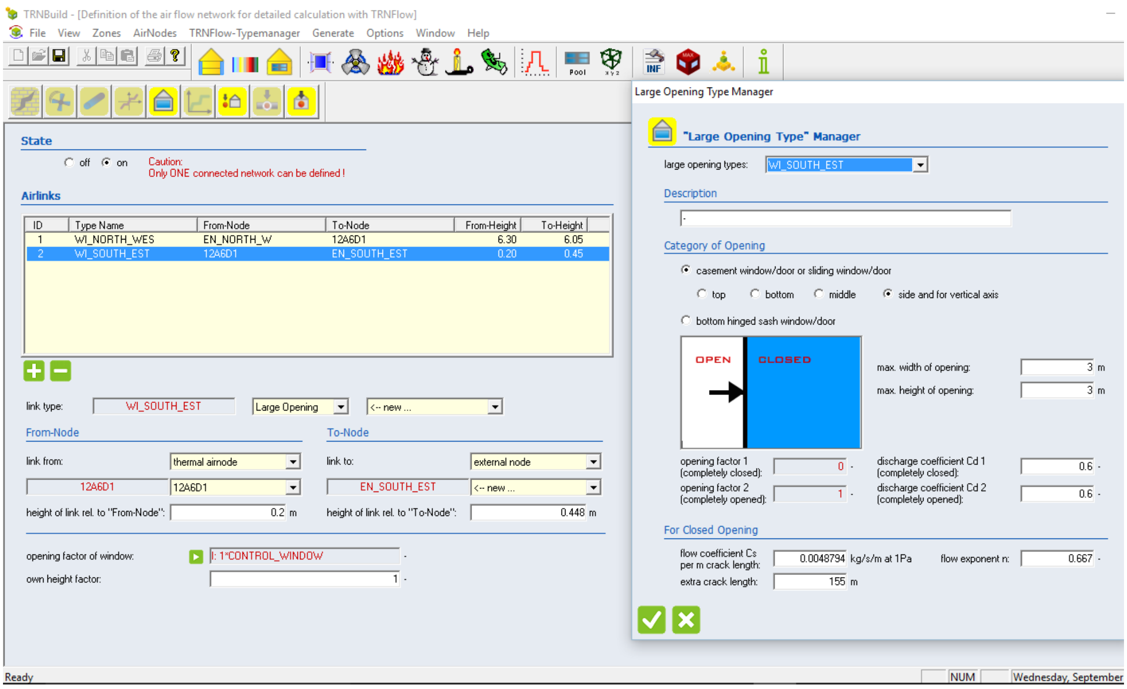


Figure 33. TRNFLOW natural ventilation simulation

Table 26. Components of the simulated natural ventilation system

Opening	Description	Dimension [m²]	Position: high [m]
North-West façade	Horizontal sliding	9	6.30
South-East façade	Horizontal sliding	9	0.45

The TRNFLOW airflow model is based on a network model of the building (TRNFLOW 2009), according to which the different nodes are linked by non linear conductances that model the airpath. For the studied case this means that the North-West opening (*airlink 1*) relates (*From-Node*) the outdoor conditions (*external node*) to (*To-Node*) the sports hall internal space (*thermal airnode*). While the opening in the South-East façade (*airlink 2*) links (*From-Node*) the interior of the building (*thermal airnode*) to (*To-Node*) the exterior environment (*external node*). The external nodes are defined introducing the wind pressure coefficient values for each wind direction angle. The thermal node description consists in the airnode dimensioning.

The wind pressure coefficient, the discharge coefficient and the wind velocity profile are introduced according to the parameters reported in literature and in the TRNFLOW manual. The wind velocity profile exponent is assumed $\alpha = 0.3$; this values, equal to all directions, corresponds to a roughness class 3, referred to a terrain located in "small city, suburb" (TRNFLOW 2009), suitable for the considered study case assuming that a large installation, as the simulated sports hall, is not designed for a city center. The wind pressure coefficient is a fundamental parameter to calculate ventilation rates in buildings *(eq. 1)*. However, as wind velocity is dependent upon the geographic region, terrain category, shielding and the topographic location, wind pressure coefficients are dependent upon the building geometry and roof pitch. In this study wall averaged C_p-values for low rise semi-shielded buildings (up to 3 storeys), with a length to width ratio 2:1, are used. The reference values are provided by Orme et al. (1998). The discharge coefficient is a parameters that refers to the configuration of the opening itself. Namely, it accounts for the fact that different air flow characteristics could be obtained from different opening type (Vitooraporn and Walaikanok, 2002). The discharge coefficient value for large opening is the ratio between the real flow rate through the opening and the theoretical flow rate calculated with the Bernoulli equation (TRNFLOW 2009). In the sports hall simulation the default value for sliding window, $C_d = 0.6$, is implemented.

The desired infiltration (section 7.1) is simulated introducing *cracks* in the building envelope. Typically, *cracks* are defined as openings with dimensions smaller than 10 mm (Allard 2002). The air leakages associated to the two large openings and to the not operable windows in the façade (air leakages through the skylights are neglected) are modelled defining the *cracks* length, equals to the entire perimeter of the listed construction elements (179 m). The flow coefficient of the *cracks* must be defined as well. At this scope, the conversion formula reported in UNE-EN 15242 is used:

$$\frac{Q_{50}}{Q_1} = 13.59 \qquad \textit{(eq. 17)}$$

Equation 17 is valid for flow coefficient exponent $n = 0.667$. Q indicates the air flow in [m³/s] at 50Pa (Q_{50}) and at 1Pa (Q_1). Taking into account that

$$Q_{50} = \frac{n_{50} * Vol_{building}}{3600} \qquad \textit{(eq. 18)}$$

the resultant flow coefficient value per meter of crack length is 0.0048794 [kg/s/m at 1Pa].

The only examined pollutant inside the zone is CO_2. The outside concentration is set to 450 ppm and assumed constant for all the external nodes and directions. The occupants of the sports halls are considered as CO_2 source in proportion to their metabolic activity. Therefore, in the simulation the contaminant exhalations from the audience accounts for 21.5 l/s per person while players are responsible for 62.5 l/h per person (Demianiuk et al., 2010). The air velocity in the building is assumed equal to 0.25 m/s when the natural ventilation is not operating and of 0.5 m/s when the openings are open. The selected values are in the range of acceptability considering that the recommended upper limit of indoor air movement is usually 0.8 m/s (Allard 2002).

8.3.1 Control strategy

As mentioned, natural ventilation working principles depend on variable parameters as wind pressure and temperature difference. Internal building requirements and occupation pattern are not constant as well. Therefore, a control strategy is fundamental to ensure desired indoor conditions and natural ventilation efficiency. The importance of control in reducing energy consumption has become evident also for energy demanding solution as mechanical ventilation systems (Raja et al. 2001).

As reported in the section 3.2.2, users tend to accept wider comfort ranges when they can exert control on the surrounding environment. However, manual control is not the most efficient solution for public building occupied by more than one person (Allard 2002). Automatic control is considered more effective for the studied sports hall. Automatic control systems for natural ventilation usually include sensors, actuators, controllers and a supervisor.

Literature provides several examples of control strategies applied to natural ventilated building. The research conducted by Schulze and Eicker (2013) shows that in moderate climate good indoor air quality can be easily maintained through natural ventilation. However, uncontrolled activation often results in too low indoor temperature. To deal with this problem, the researchers have developed a control strategy focusing on three objectives. The preservation of indoor air quality, achieved planning 5 minutes openings at 50% of the effective opening areas when the indoor CO_2 level exceed the outdoor one of a certain concentration. The thermal comfort is ensured including specific algorithms that avoid overcooling during heating and intermediate seasons. The risk of local thermal discomfort, as air drafts, is avoided modulating the opening area as function of the difference between indoor and ambient air temperature. Paoletti et al. (2014) designed an n-ZEB natural ventilated office in Italy. The implemented control aims to establish optimum interior thermal comfort conditions. It includes activation thresholds related to exterior, interior and dew point minimum temperature. A relative humidity control is also integrated. Allard (2002) and Nicol et al. (2007) highlight the importance of planning a *dead band*, an area within which there is not need for the opening state to change. The scope is the promotion of the stability of the system. Dell'Osso et al. (2015) calibrated the natural ventilation system of a designed residential building on a variable set-point. The set-point is based on the optimal indoor temperature, evaluated according to the adaptive comfort theory. A similar approach is adopted in this thesis.

The control strategy developed for the specific need of the studied sports halls is now described. The control of the simulated natural ventilation depends on the occupancy, the internal operative temperature and the CO_2 concentration. During daylight hours, natural ventilation is activated only when the building is occupied. Natural ventilation activation implies that the openings are opened if the operative temperature exceeds the upper limit of the selected thermal category (category II, which should be adopted as reference for the design of new building according to UNE-EN 15251) or if the indoor CO_2 concentration is outside the acceptability range. Specifically, the interval of indoor tolerable concentration is restricted respect to the recommendations of the standard. This configuration is introduced to give stability to the system, avoid frequent *ON/OFF* cycles and allow the removal of the excess CO_2 while there is continuous emission from the occupants. In fact, in analogy with the explanation reported in Nicol et al. (2007), model that suggests a particular CO_2 concentration at which windows are opened are unstable, since the window opening can itself cause a drop of CO_2 concentration resulting in a window closure, which will in turn cause a rise CO_2 concentration and a window opening and so on. The operation of the control system is implemented in TRNSYS through type 2 (*ON/OFF Differential Controller*). The activation (or deactivation) of the ventilation system depends on its actual state.

The control strategy is schematized in figure 34, representing the set points and the dead band configurations.

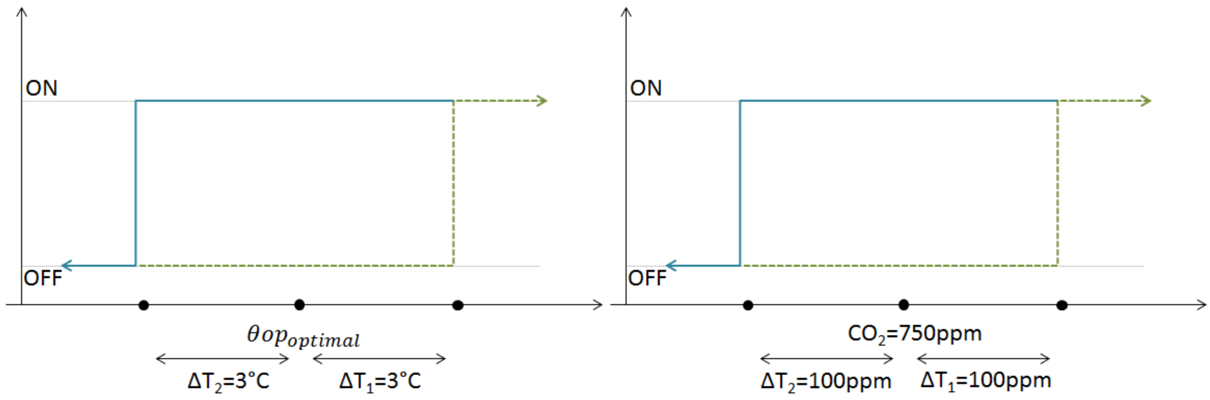


Figure 34. Control strategy. Left: thermal comfort control; right: air quality control. ***Blue line: openings behavior when the actual state of the natural ventilation system is ON. Green dashed line: openings behavior when the actual state of the natural ventilation system is OFF***

As it possible to see in figure 33, the TRNFLOW simulation requires the definition of another parameter: the opening factor of the windows. In this study, the opening factor have been adjusted to avoid the risk of overcooling and air draft. At this scope, the opening are more or less opened depending on the difference between the interior and exterior temperature during the cold season and on the wind velocity during the warm season (tab.27). Moreover, during the weekend, when the CO_2 production is significant considering the expected greater occupation, the system is forced to work with an opening factor equal to 1, unless the wind velocity is granter than 6 m/s. Again, this condition is suggested to maintain the stability of the system, namely to avoid that a substantial flow of air can rapidly reduce the pollutant concentration causing the closure of the openings. Indeed, it is desirable that the natural ventilation system works constantly during the period of high occupancy.

Table 27. Control strategy. Opening factor variation

Opening factor	Summer Wind velocity (m/s)	Winter $T_{interior} - T_{exterior}$ (°C)
0.2	>15	> 9
0.4	15 – 11.25	9 – 7.5
0.6	11.25 – 7.5	7.5 – 5
0.8	7.5 – 3.75	5 – 4
1	< 3.75	< 4
1	if Occ = max and wind velocity < 6m/s	

To verify its effect on overheating risk reduction, night ventilation is also tested. Therefore, in summer, natural ventilation is activated after that the users leave the sports hall if the exterior air temperature is lower than the interior air temperature. In general terms, set this conditions, natural ventilation stays on until the morning hours.

8.4 Mechanical ventilation

To compare the performance of the tested natural ventilation strategy to the energy and economical expenditure due to a more conventional installation, TRNSYS is used to model a simple mechanical ventilation system.

According to the PAV3 document, the forced air renovation requirements for the specific studied case account for 13’365 m³/h, namely ACH = 0.98 h⁻¹.

To provide the desired external air supply, the installation of an axial flow fan is simulated through the TRNSYS *Fan Type manager* (fig.35). The technical features of the selected fan and the relative characteristic curve are reported in Annex 3. The fan is coupled with a large opening, as reported in table 28. The contribution of the infiltration is also taken into account. In this regard, when the fan is turned off the air mass flow coefficient is set to value C_s = 0.0504 kg/s at 1Pa; the flow coefficient per meter crack length is set to C_s = 0.00504 kg/s/m at 1Pa.

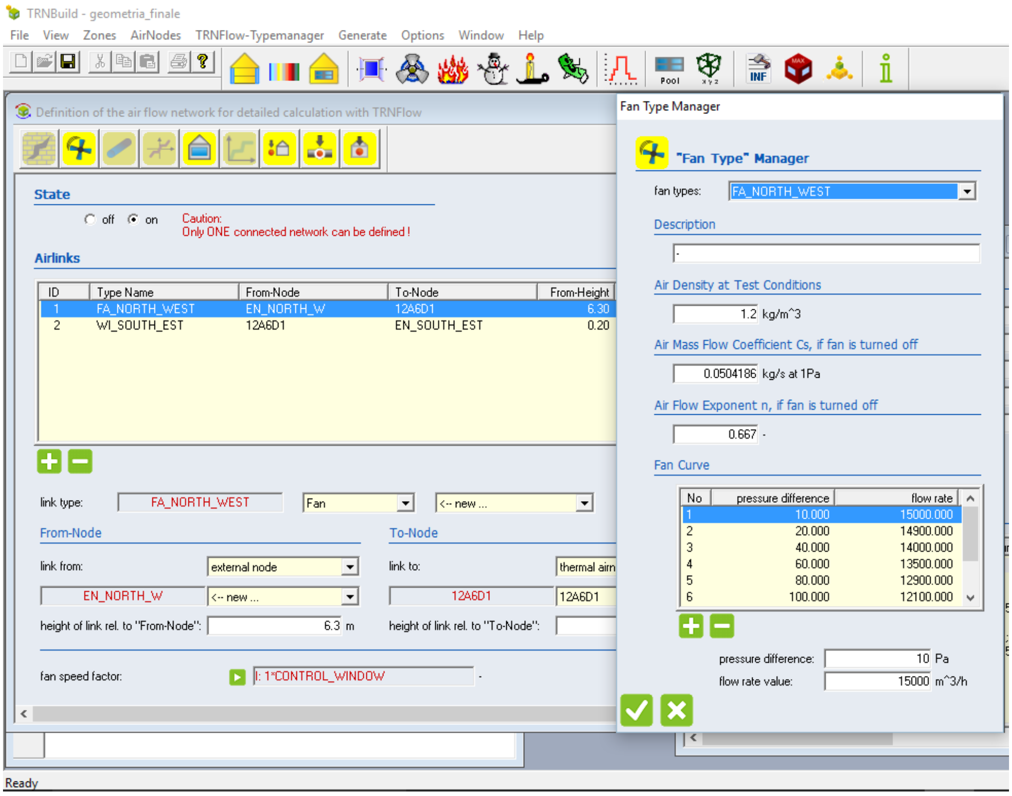


Figure 35. TRNFLOW mechanical ventilation simulation

Table 28. Description of the mechanical ventilation system

	Description	Dimension [m²]	Maximum air flow [m³/h]	Position: high [m]
North-West façade	Fan *(airlink 1)*	-	15’350	6.30
South-East façade	Opening-Horizontal sliding *(airlink 2)*	5	-	0.45

Regarding the operation of the mechanical ventilation system, the effectiveness of three different control strategies is evaluated:

- NO CONTROL (*MV*): the mechanical ventilation system works at its maximum capacity when the sports hall is occupied. The opening factor of the opening results always 1, as well as the *fan speed factor*, a parameter that, as it possible to see in figure 35, must be defined in TRNFLOW in case of mechanical ventilation simulation.

- CONTROL (*MV+CTL*): the activation of the mechanical system is regulated by the same control implemented for the natural ventilation installation. However, the speed of the fan and the opening factor of the opening is fixed to 1.

- VARIABLE (*MV+DC*): the mechanical ventilation system is activated only when the building is occupied. The speed of the fan and the opening factor are function of the CO_2 concentration inside the building, correlated to the occupancy level (fig.36). In other words, the performance of a demand controlled ventilation (DCV) system is simulated (Lawrence 2004). A DCV system adjusts outside ventilation air based on the number of occupants and the ventilation demands that those occupants create. The aim is to reduce energy penalty due to over ventilation during period of low occupancy (Emmerich and Persily, 1997).

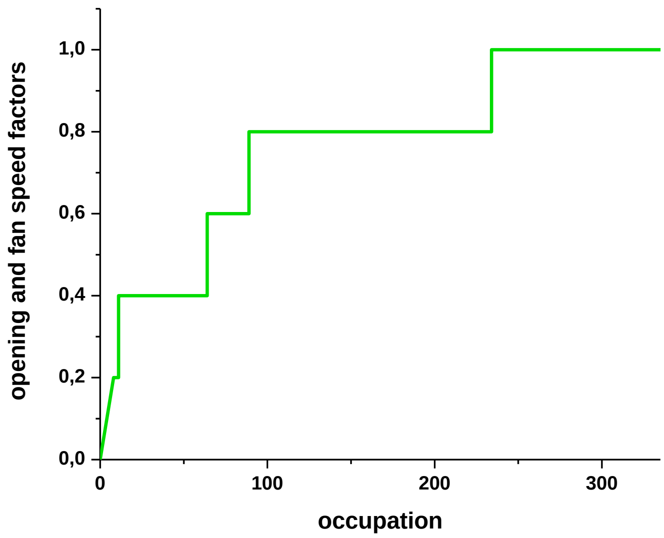


Figure 36. Demand controlled ventilation

The affinity laws of fans allow to calculate the delivered airflow and the relative absorbed power (Vogt 2012) (eq. 19 and eq. 20) in case of variable speed installation.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad \textit{(eq. 19)}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \qquad \textit{(eq. 20)}$$

Where Q is the air flow rate expressed in m^3/s, N the fan speed in rpm and P refers to the fan power in W.

The heating demand that emerges in case of operation of the mechanical ventilation system is satisfied through the installation of an electric heaters battery that preheats the external air before it is introduced into the sports hall by the fan. The type 6 (*HVAC\Auxiliary Heaters*) is used in TRNSYS to simulate the electric heater battery behavior (TRNSYS 2010). The maximum heating rate is calculated according to the equation:

$$\dot{Q}_{max} = \dot{m} * c_p * \Delta T = m * \ c_p * \left(T_{setpoint} - T_{ext}\right) \qquad \textit{(eq. 21)}$$

Where $\dot{m}$ [kg/h] is assumed equal to the average net mass flow through the operating fan; c_p is the specific heat of the air (1.005 kJ/kgK)); T_{ext} is considered as the minimum exterior temperature registered along the year (0.2°C); $T_{setpoint}$ is evaluated taking into account the amount of exterior air introduced in the sports hall. The introduced exterior air is less than the entire indoor air volume, therefore it must be heated up to a temperature higher than the desired comfort temperature of 14°C. The resultant heating rate, required to heat up the fluid (exterior air) to a certain $T_{setpoint}$ temperature, is added as an additional heat gain in the simulation. The scope is to evaluate the impact of a potential heating system on the thermal behavior of the building, as well as to calculate its energetic and economic costs. Finally, it is specified that the control of the heating system forces the heaters to work only when the sports hall is occupied and the exterior temperature goes below a certain limit value (between 8°C and 11°C, depending on the different operation modes of the mechanical ventilation system).

9 PV system design

PV Building Integration (BIPV) is a practice that refers to the use of PV modules as architectural elements, being a collaborative part of the design of the building envelope and having an architectural function in symbiosis with functional properties and economic regenerative energy conversion (Achenza and Desogus, 2013). Part of this research has dealt with the test of different PV system configurations designed to contribute to the energy needs of the investigated sports facility. The analysis is performed through the Google Sketchup plug in Skelion (Skelion v5.1.9 2015). The software Skelion allows to insert solar panels in any surface of the building, previously modelled in Google Sketchup and geolocalized through Google Hearth. It is possible to modify, within other features, position, azimuth and tilt of the panels. The software, taking into consideration the shading that solar obstructions project on the panels in different period of the year, supports the design of the PV system minimizing the shading losses. In the specific analyzed case study, this feature has been useful, for instance, to consider the effect of the installation of skylights on the roof and to evaluate the no shaded surface available for the PV modules. Connected to the simulation software packages PVsyst (PVsyst SA 2012) and PVwatt (Alliance for Sustainable Energy, LLC, 2016) Skelion is able to evaluate the annual and average monthly electricity production of the modelled PV systems, its yield as well as its shading losses.

The findings of the Skelion simulation are shown in the corresponding results section 11.3.

Within the 16 tested PV system configurations, 4 have been selected for a further study. The selection has been made taking into account the economic convenience (case 2 and case 6) or the peculiar architectonical integration into the studied building (in case 12 the PV panels are integrated into the building façade, while in case 15 the PV panels are installed on the shading device). The selected configurations have been simulated in TRNSYS through type 94 (*Photovoltaic Array*). This additional analysis has been necessary to evaluate the PV system production on 6 minutes basis. This means, to have results comparable to the building TRNSYS simulation outputs that include the time steps of functioning (and consequently of consuming) of the ventilation system (the activation of the fan, for the mechanical ventilation scenario, or of the engines that turn on the opening, for natural ventilation scenario), of the heating and of the artificial lighting systems. Also the consumptions indicated as *others* (considered electric consumptions) are time-depending: occur only when the building is occupied. The final objective is to perform, for any time step along the one-year simulation, an energy balance between the electricity demand and the electricity production. Therefore, overall, it has been possible for the different scenarios to calculate the self-consumption of site and the amount of exported energy.

It is anticipated that the two used programs return different results. The observed discrepancy is due to various reasons:

- TRNSYS PV array simulation does not account for performance losses. Conversely, Skelion resulting electricity generation is discounted of system losses, according to default values (tab.29), as well as of estimated shading losses.
- Skelion photovoltaic system performance predictions do not reflect variations between PV technologies. PV modules with better performance are not differentiated from lesser performing ones. The program specifies that Shell Solar S115 commercial modules are installed. However, the only information implemented in the simulation regards the dimension of the module (outside dimension (mm) = 1220x850), necessary to identify the most convenient array configuration for the available surface. On the contrary, type 94 requires the introduction of several module specific parameters. The characteristics of the simulated module (Shell Solar S115) used as TRNSYS inputs are reported Annex 4.

Table 29. Default values for the system loss categories (Dobos 2014)

Category	Default Value (%)
Soiling	2
Shading	3
Snow	0
Mismatch	2
Wiring	2
Connections	0.5
Light-Induced Degradation	1.5
Nameplate Rating	1
Age	0
Availability	3

Therefore, taking into account the reported considerations, it has been deemed appropriate elaborate the TRNSYS outputs, subtracting from the resultant PV generation the losses reported in table 29 as well as the shading losses calculated by Skelion for each configuration on monthly bases (Annex 5).

10 Cost-optimality methodology

In line with the European Union building policies tendency to move toward an integrated approach that takes into account simultaneously energy, environmental, financial and comfort related aspect, the results of a cost-optimality analysis are elected as an additional indicator for the comparison of the proposed sports hall systems configurations (BPIE 2013).

Cost optimal level is the energy performance level which leads to the lower costs during the estimated building economic lifecycle (Official Journal of the European Union 2012). A set of actions is cost optimal when maximize the net present value (NPV, calculated according to UNE-EN 15459 (AENOR 2008b)) of cost effective measures, namely measures characterized by benefits higher than the cost of their implementation over the expected lifetime (BPIE 2013).

The implementation of the cost-optimality methodology provides a useful comparative framework to study cost optimal and n-ZEB solutions, in terms of costs, primary energy consumption and CO_2 emissions savings. The energy performance is measured in *kWh/m²* of primary energy. The calculation of primary energy, performed taking into account the national primary energy conversion factors, includes the energy consumption due to space heating, cooling, ventilation, domestic hot water and lighting systems. The total primary energy demand must be discounted of the renewable energy produced on-site (European Commission 2016c).

Given a specific set of measures, the cost-optimal approach aims to evaluate its global cost. Global cost is defined as the results of the calculation of the present value of all the costs during a long period, taking into account the residual values of components with longer lifetimes (fig.37). Conforming to the cost-optimality procedure, cost calculation must include operational, maintenance, disposal and investments costs. Energy costs regard consumed energy-related costs and exported energy-related costs. Environmental costs due to the CO_2 emissions are not considered in this study, which adopts a financial prospective (building owner and investor perspective). On the contrary, taxes (VAT) are included. All the costs have been introduced in the calculation according to the corresponding evolution rates (tab.30). Discount rates reflects national financing environment and mortgage conditions.

Table 30. Description of the evolutions rates implemented in the cost-optimal calculations. ***Source: Ortiz et al. (2016a)***

Economic term	Evolution rate calculation	
Replacement cost Disposal cost Maintenance cost Additional values for purchase/sale energy	Discount rate (R_D) Market interest rate (R) Inflation rate (RI) Real interest rate (R_R)	$R_R = -\frac{R-RI}{1+(RI/100)}$ [%] *(eq. 22)* $R_D = -\frac{1}{1+(R_R/100)^t}$ [-] *(eq. 23)*
Energy cost	Energy evolution rate (R_E) Energy cost evolution (RX_E)	$R_E = (1 + RX_E/100)^{t-1}$ [-] *(eq. 24)*
t, the year of calculation		

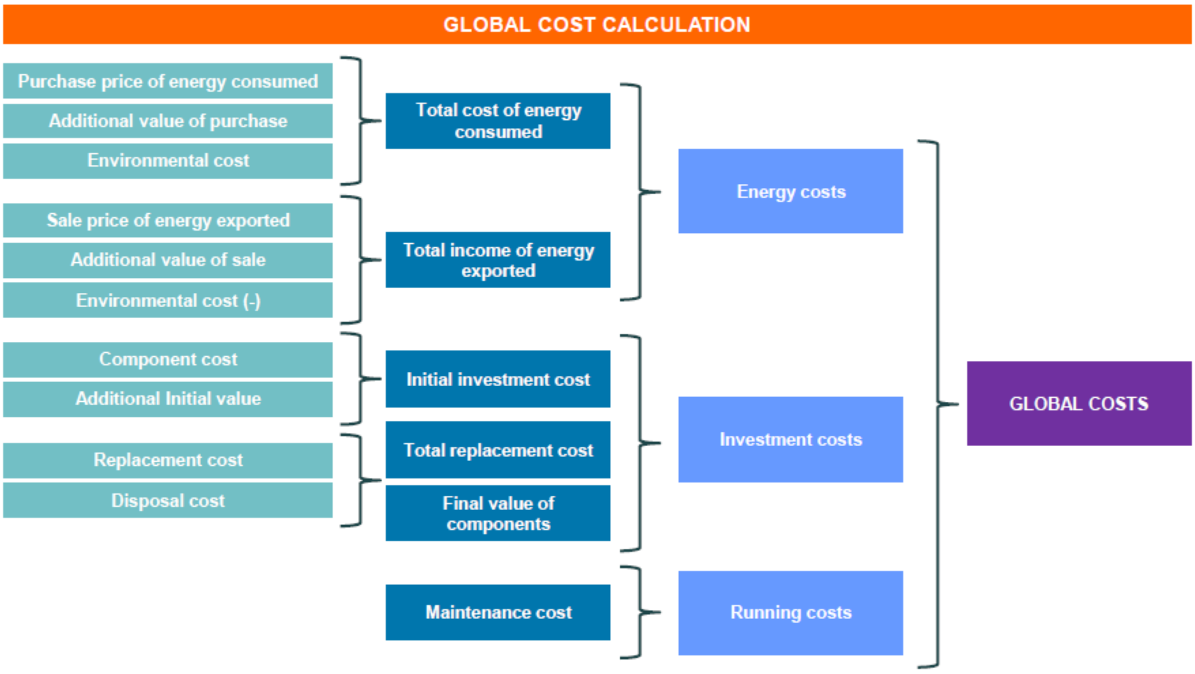


Figure 37. Global cost calculation. ***Source: Ortiz et al. (2016a)***

10.1 Calculation hypothesis

As described in the previous section, to perform a cost-optimality evaluation it is fundamental the availability of energetic, economic and system components data.

Table 31 reports the energy costs hypothesis, while table 32 shows the assumed economic parameters.

Table 31. Energy and environmental hypothesis for the cost-optimality analysis

Parameter		Electricity		Natural gas
		Consumed	Exported	
Energy cost (€/kWh)	*(Ortiz et al., 2016a)*	0.1315	0.06575	0.0527
Additional values for purchase (€/y)	*(Ortiz et al., 2016a)*	178.552	0	106.56
Energy cost evolution, RX_E (%)	*(Ortiz et al., 2016a)*	2.5	2.5	2
Conversion factor from final energy to total Non-renewable primary energy (kWh_p/kWh_f)	*(RITE 2014)*	1.954	0 (Musall and Voss, 2014)	1.190
Conversion factor from final energy to CO_2 emissions (gCO_2/kWh_f)	*(RITE 2014)*	331	0	252

Table 32. Economic hypothesis for the cost-optimality analysis

Parameter *(Ortiz et al. 2016a)*	**%**
Inflation Rate (RI)	2
Market interest rate (R)	4.5
VAT	21

Overall, this study evaluates the cost optimality level of 24 scenarios that result from the combination of the different simulated ventilation modes, control strategies, PV system configurations and heating systems, chosen, as mentioned in table 20, within energy efficient alternatives as heat pump and condensing boiler.

In the simulation of the natural ventilation cases, the heating load of the studied sports hall is evaluated through the TRNSYS *Heating Type Manager* tool. The heating system is sized to ensure a minimum indoor temperature of 14°C during the occupation periods. Regarding the case of mechanical ventilation, it is assumed that the heating requirements are met through the installation of electric heater batteries. The heating system is sized according to the maximum heating requirements resulting from the calculation reported in section 8.1. The heating demand is available as a TRNSYS simulation output. To evaluate the final energy consumption due to heating purpose, TRNSYS results are elaborated taking into account the efficiency of the heating devices, as well as the efficiency of the emission and distribution systems.

The characteristics of the systems components are reported in table 34. The information regarding the maintenance costs and the lifetime are consistent with the indication reported in the standard UNE-EN 15459. Systems components costs are extrapolated form a Spanish construction price database (CYPE Ingenieros, S.A. 2016). The costs of the ventilation equipment come from the Soler y Palau (S&P 2016) price list. The costs of the devices involved in the implementation of the ventilation control, as wind speed, CO_2 concentration and temperature sensors, are considered negligible.

Some additional assumptions are made:

- the replacement cost of the automatic opening accounts only for the replacement of the mechanical part of the component, assuming that the lifespan of the opening itself is considerably longer than the engine one;
- the control system implemented in case 1 manages only the building ventilation while the one implemented in case 4 manages only the heating devices. Therefore, their costs are lower respect to the costs considered for the other analyzed cases.

The sports hall falls in the category of non-residential building. Therefore, its life cycle is considered to be 20 years (Official Journal of the European Union 2012).

The costs of the PV systems are also included in the cost-optimal calculation:

Table 33. PV system costs. ***Source: Huld et al. (2014)***

Investment costs (€/kWp)	**Replacement costs (€/kWp)**	**Maintenance costs (€/y)**	**Lifespan (y)**
1’400	1’400	28	20

Table 34. System components costs

	Case	Systems components	Investment costs (€)	Replacement costs (€)	Maintenance costs (€/y)	Lifespan (y)	η
1	Natural ventilation	Automatic Openings 9 m^2 (2x)	5’364	1’259	119	20	
		Control system	662	662	23	20	
2	Natural ventilation + heat pump	Automatic Openings 9 m^2 (2x)	5’364	1’259	119	20	
		Heat pump (33.5 kW)	17’758	17’758	621	17	4.27 (Ortiz et al., 2016b)
		Distribution and emission system (4x11.4 kW)	6’017	6’017	168	20	0.89
		Control system	1’018	1’018	35	20	
3	Natural ventilation + condensing boiler	Automatic Openings 9 m^2 (2x)	5’364	1’259	119	20	
		Condensing boiler (50kW)	4’364	4’366	412	20	1.09 (Ortiz et al., 2016b)
		Radiant panels (24x6m)	5’286	5’286	89	50	0.89 (Q^{rad} 2016)
		Control system	1’018	1’018	35	20	
4	Mechanical ventilation + no control	Automatic Opening 5 m^2	2’161	564	49	20	
		Fan	1’145	1’145	108	17	
		Electric heater (50 kW)	2’340	2’340	35	17	0.9
		Heaters control	355	355	10	20	
5	Mechanical ventilation + control	Automatic Opening 5 m^2	2’161	564	49	20	
		Fan	1’145	1’145	108	17	
		Electric heater (50 kW)	2’340	2’340	35	17	0.9
		Control system	1’018	1’018	35	20	
6	Mechanical ventilation + variable speed	Automatic Opening 5 m^2	2’161	564	49	20	
		Fan	1’145	1’145	108	15	
		Electric heater (16.5 kW)	1’094	1’094	16	17	0.9
		Speed control	937	937	40	20	
		Control system	1’018	1’018	35	20	

11 Results and discussion

The following subchapters present the outcomes of the different sections previously reported. The results are moreover discussed and an energy balance is performed.

11.1 Measurement campaign

The data collected through the measurement campaign have been elaborated according to the comfort models described in section 3.2. The objective is to analyze the comfort conditions of the selected sports hall. Some aspects of the adopted models must be clarified.

The Fanger model, as well as the adaptive approach, have been developed for building environment significantly different from the case study investigated in this thesis. Similarly, the used standards do not contain specific indication for sports buildings.

Regarding the critical issues related to the Fanger model, it is highlighted that such approach has been elaborated for mechanical ventilated spaces and validated mainly for office and residential buildings (Pagliano et al., 2012; Gilani et al., 2015). Moreover, the PMV theory is based on steady-state parameters, while usually a sports hall is an environment characterized by non-homogenous users profile and where transient conditions occur, as the changing of the metabolic rate and the evaporative heat loss (Revel and Arnesano, 2014b).

In detail, to implement the proposed adaptive methodology, the studied space should comply with different requirements (Emmerich et al. 2011):

- presence of windows that open to the outside
- no mechanical cooling system
- metabolic activity of the occupants between 1.0 and 1.3 MET
- possibility of clothing adaptation for the users
- monthly outdoor temperatures below 33.5°C and above 10°C

The users of the Terrassa sports building perform activities characterized by a MET outside the applicability range (tab.16). Additionally, the players are not completely free of changing their clothes according to the perceived thermal sensation. Revel and Arnesano (2014a) point out that another limitation of the adaptive thermal model in case of sports facilities thermal comfort evaluation, is related to the fact that the model is not able to consider the effect of skin wetness.

11.1.1 Survey results

The comfort surveys have been conducted during the period of data acquisition and have been directed to the occupants of the monitored area. The completed surveys have been in total 54. However, only 19 answers have been given to the question regarding the air perception

According to the results of the survey (fig.38), 84% of the audience was experiencing a thermal discomfort, mainly due to overheating: 33% affirmed that the environment was slightly warm, 28% that it was warm and 17% that it was very warm (only 3 people considered it slightly cold.). Regarding the humidity, the majority of the audience (65%) considered the environment neutral, while the air movement was perceived mainly as inadequate (slightly low for 33% and very low for 37%). The lighting was evaluated neutral by 54% of the audience.

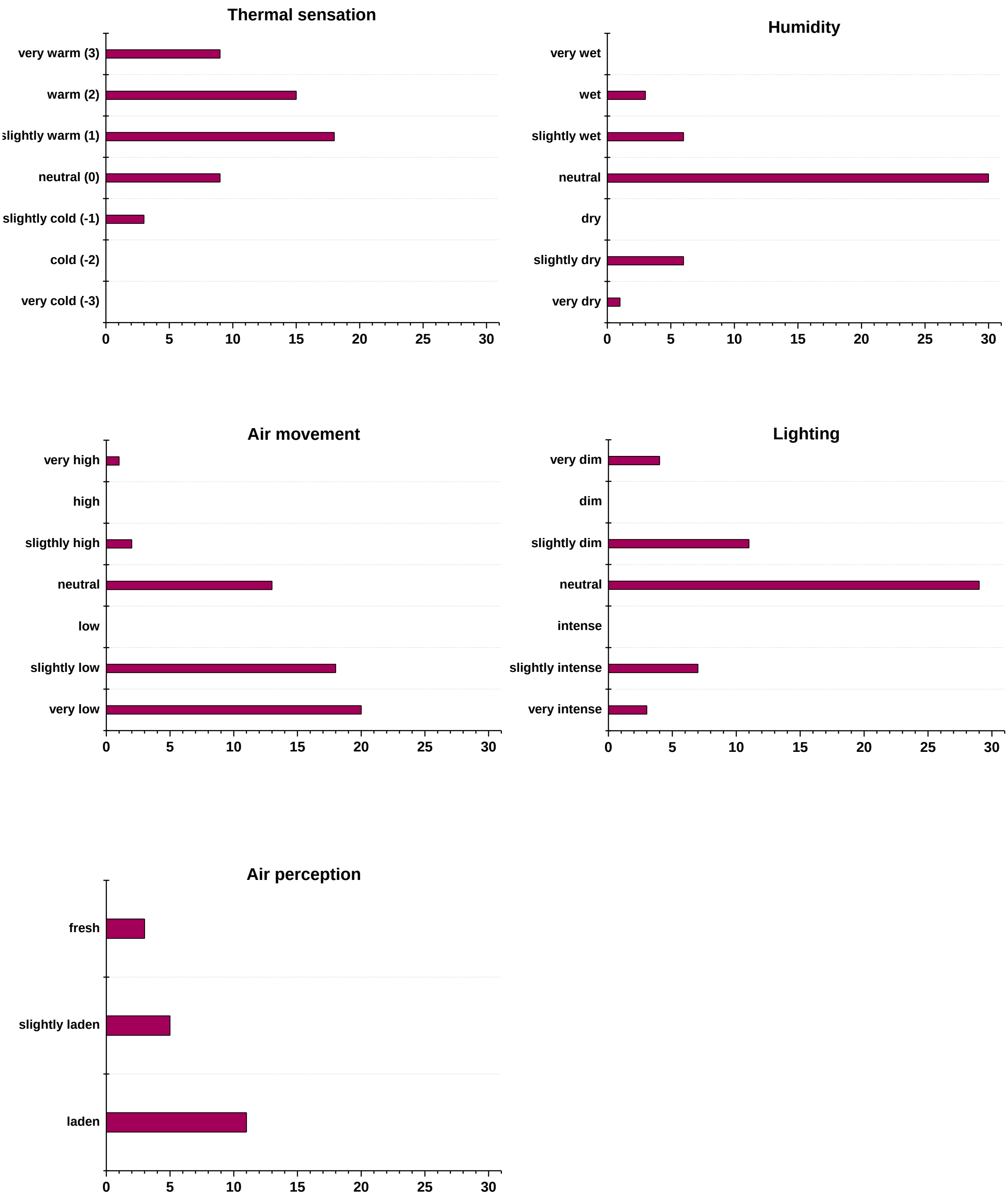


Figure 38. Comfort survey results

11.1.2 Thermal comfort analysis

This section reports the results obtained from the comfort evaluation of the "Poliesportiu Pla Del Bon Aire" of Terrassa. The interior thermal comfort of the sports hall has been assessed using the PMV Fanger model, the adaptive model, according to the UNE-EN 15251 and ASHRAE 55-2010 standards, the Givoni diagram and the heat stress methodology previously described (section 3.2).

The air temperature used for the calculation is the one registered at 1.4 meters height.

PMV - Fanger model

Firstly, the thermal sensation evaluated by the audience through the survey is compared to the results of the PMV calculation (fig.39). The survey answers have been averaged for each considered time period.

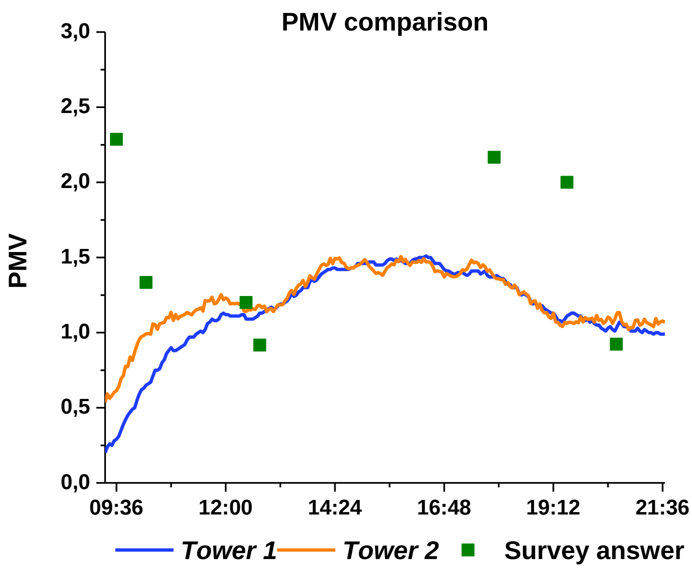


Figure 39. PMV index comparison. *Tower 1* and *Tower 2* indicate the results of the calculation implemented following the Fanger model

Observing figure 39, it is possible to notice that in a few cases the thermal sensation perceived by the audience does not correspond to the calculated PMV. During the hours of maximum occupation (from 18:30 to 21:30), it occurs that the divergence is more evident. Overall, the survey and the calculation confirm that generally the PMV index deviates from the condition of neutrality (PMV = 0). Mostly, the thermal environment results to be slightly warm or warm. It is perceived very warm by some users.

From the analysis of the PVM indices and according to the classification introduced by UNE-EN 15251 (tab.35), the comfort categories that characterize the existing sports hall are determined. (fig.40).

Table 35. Building category according to UNE-EN 15251

Category	PPD %		
I	<6	-0.2<**PMV**<+0.2	High level of expectation, recommended for spaces occupied by people with special requirements
II	<10	-0.5<**PMV**<+0.5	Normal level of expectation; for new and renovated buildings
III	<15	-0.7<**PMV**<+0.7	Acceptable and moderate level of expectation; for existing buildings
IV	>15	**PMV**<-0.7;or +0.7<**PMV**	Acceptable only for a limited part of the year

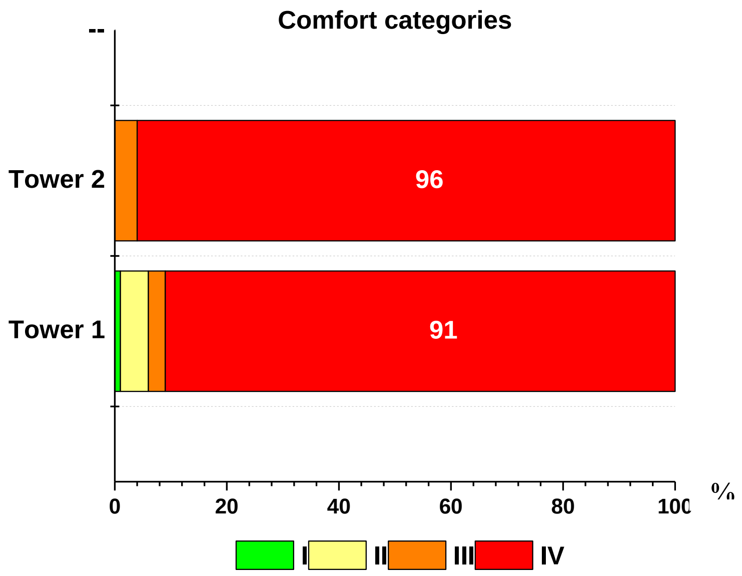


Figure 40. Thermal comfort classification according to the calculated PMV index

Figure 40 shows clearly that, during almost all the occupied period (more than 90% of the time), the audience is in condition of thermal discomfort. The situation is slightly better in the case of *Tower 1*, located farther from the audience seats and from windows than *Tower 2*.

The reasons that determine the reported thermal discomfort are investigated analyzing Category IV more in detail (tab.36).

Table 36. PMV index classification for Category IV

Category IV	PMV≤ -0.7	0.7≤PMV<1	PMV≥1
Tower 1	0%	13%	87%
Tower 2	0%	5%	95%

The values reported in table 36 confirm that the thermal discomfort is related to the perception of an excessive increase of the indoor air temperature.

Regarding the thermal comfort analysis of the players, the application of the Fanger model results in a condition of thermal discomfort due to overheating for the entire interval of measurements, as consequence of players high metabolic activity. For this reason, the players comfort is additionally assessed through the Required Sweat Rate methodology (section 3.2.3)

Required Sweat Rate

Table 37 reports the UNE-EN ISO 7933 reference values adopted for the evaluation of the thermal stress conditions of the players in the sports hall.

Table 37. UNE-EN ISO 7933 reference values for thermal stress and strain evaluation

	NON ACCLIMATISED		**ACCLIMATISED**		**DLE**
Criteria for MET≥65W/m²	Warning	Danger	Warning	Danger	DLE1 = 60 Q_{max} / (E_{req} -E_p) DLE2 = 60 D_{max} / SWp where E_p - predicted evaporating rate SW_p - predicted sweat rate The shortest DLE shall be used for limiting the duration of work.
W_{max}	0.85	0.85	1	1	
Q_{max} (Wh/m²)	50	60	50	60	
D_{max} (Wh/m²)	1’000	1’250	1’500	2’000	
SW_{max} (W/m²)	200	250	300	400	

The DLE sets the acceptable work period advisable to avoid dehydration, excessive heat storage and skin wettedness. The DLE values calculated according the UNE-EN ISO 7933 procedure and determined for the warning and danger categories, are summarized in table 38.

Table 38. Duration Limited Exposure

DLE (minutes)			
NON ACCLIMATISED		***ACCLIMATISED***	
Warning	Danger	Warning	Danger
28.87	41.58	74.41	219.00

Considering the duration of an average basket match (4 periods of 10 minutes each), the thermal environment results appropriate for players activity.

Adaptive comfort model

As anticipated, the sports hall indoor thermal comfort is investigated according to the thermal adaptive model. The standards ASHRAE 55-2010 and UNE-EN 15251 are applied.

The UNE-EN 15251 approach (section 3.2.2) is based on the average exponential daily temperature. In this report only the results related to day 13/03 are presented (tab.39, fig.41).

Table 39. Thermal comfort categories. Adaptive model UNE-EN 15251

Category	MAX operative temperature (°C)	MIN operative temperature (°C)
I	23.72	19.72
II	24.72	18.72
III	25.72	17.72

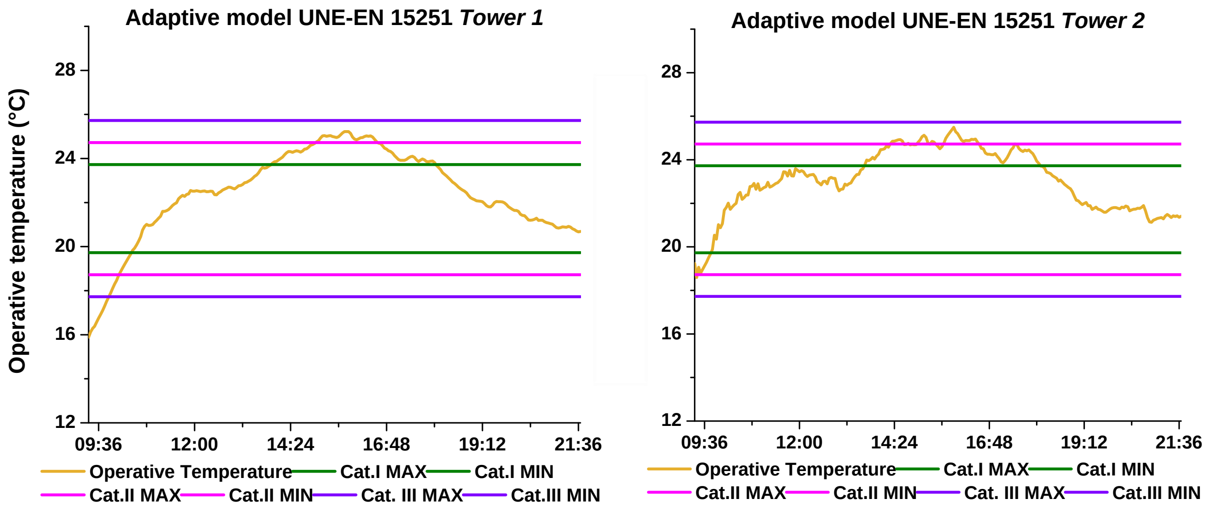


Figure 41. Indoor operative temperature and comfort categories according to the UNE-EN 15251 standard

The indoor operative temperature, for *Tower 1* and *Tower 2*, remains into the range of Category I for most of the occupied period. However, between 13:30 and 18:00, when the interior air temperature reaches its maximum (fig.23), the operative temperature curve lies in Category II and even in Category III.

Following the ASHRAE 55-2010 standard, the resultant comfort acceptability ranges, calculated referring to the average monthly exterior temperature (section 3.2.2), are (tab.40):

Table 40. Thermal comfort categories. Adaptive model ASHRAE 55-2010

Acceptability	MAX operative temperature (°C)	MIN operative temperature (°C)
90%	26.59	28.59
80%	16.59	14.59

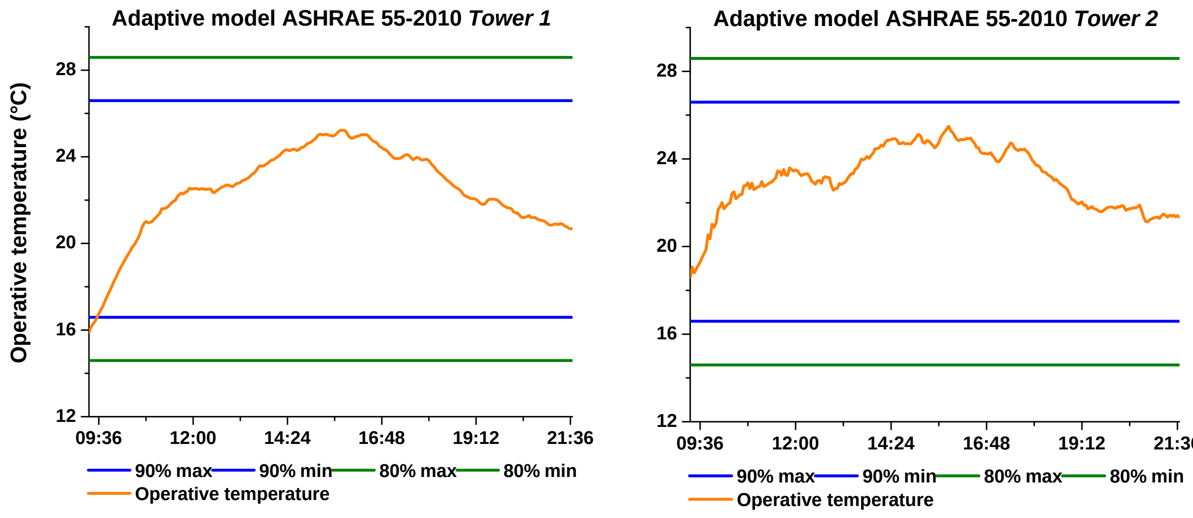


Figure 42. Indoor operative temperature and comfort categories according to the ASHRAE 55-2010 standard

The operative temperature registered in the sports hall is inside *90% acceptability range* for the entire occupied period (fig.42).

Taking into account the considerations reported at the beginning of this section (section 11.1), figure 41 and figure 42 show that the comfort parameters registered in the sports hall are inside the acceptability ranges defined by the ASHRAE 55-2010 and UNE-EN 15251 standards.

Givoni diagram

The Givoni diagram (fig.43) reports the interior and exterior information about temperature and relative humdity in a psychometric chart. The represented data corresponds to the measurements carried out during the occupation hours (09:30 - 21:30). The diagram is divided in five areas, depending on the action required to ensure indoor thermal comfort:

- heating zone (blue)
- cooling and dehumidification zone (red)
- cooling and humidifying zone(yellow)
- comfort zone (green)
- comfort zone with natural ventilationand air velocity of 1m/s (green dottet line)

Figure 43 shows that almost all the measurements realized during the occupation period comply with the comfort requirements.

As mentioned before, the studied sports facility is not equipped with a mechanical ventilation system, therefore the comfort zone referred to natural ventilated building should be considered. However, as reported in figure 25, the indoor air velocity values recorded during the measurement campaign are lower than the reference value of 1 m/s.

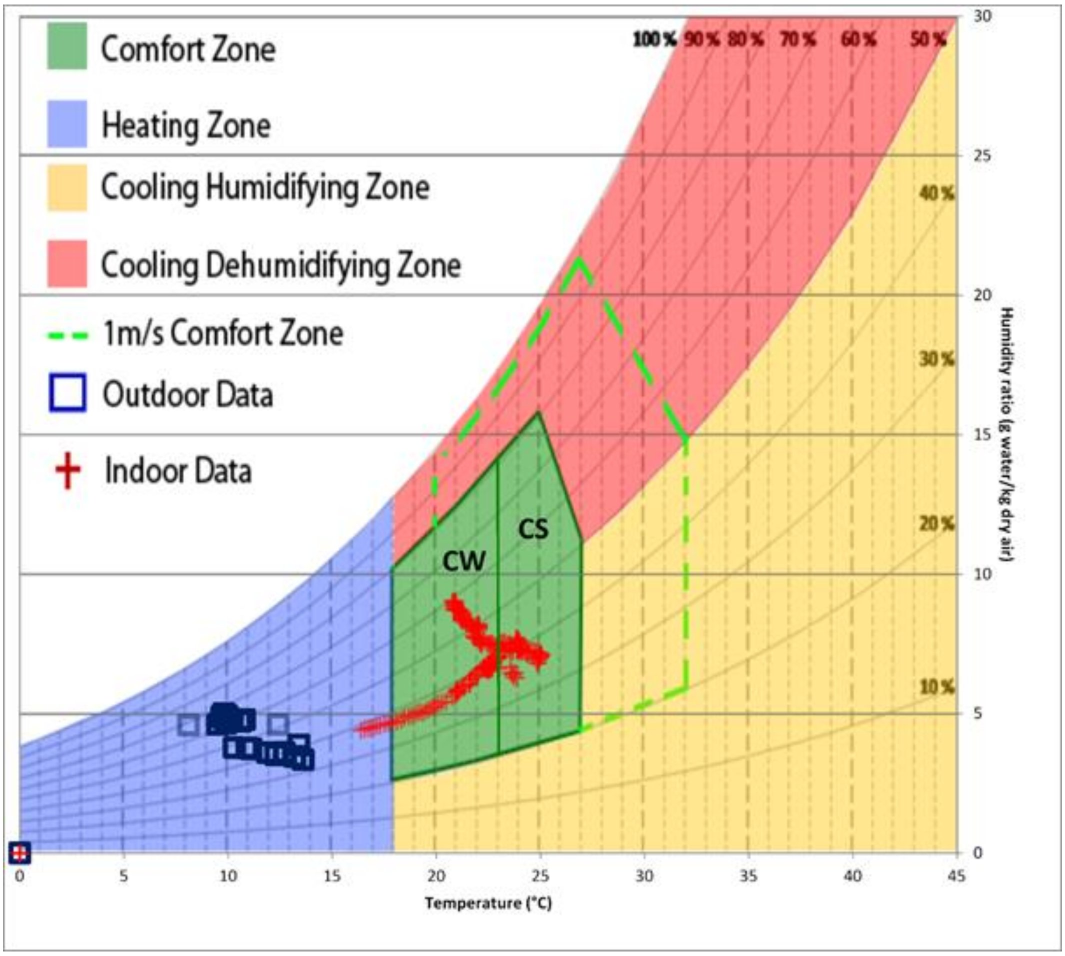


Figure 43. Givoni diagram. ***Source: self-elaboration based on Al-Azri et al. (2012)***

Relative Humidity

UNE-EN 15251 standard establishes relative humidity comfort criteria for building characterized by human occupation (tab.41).

Table 41. Relative humidity categories according to the UNE-EN 15251 standard

Category	Maximum %	Minimum %
I	50	30
II	60	25
III	70	20
IV	>70	<20

The sports hall relative humidity falls in Category I for most of the investigated time (fig.44). Relative humidity percentage reaches Category II during the night and in condition of maximum occupation. The values registered by *Tower 2* lays also in Category III. It is evident the relationship occurring between the occupation level and the indoor relative humidity. Relative humidity, in fact, decreases significantly during the break (14:00) and then increases sharply again following the increment of the sports hall occupation.

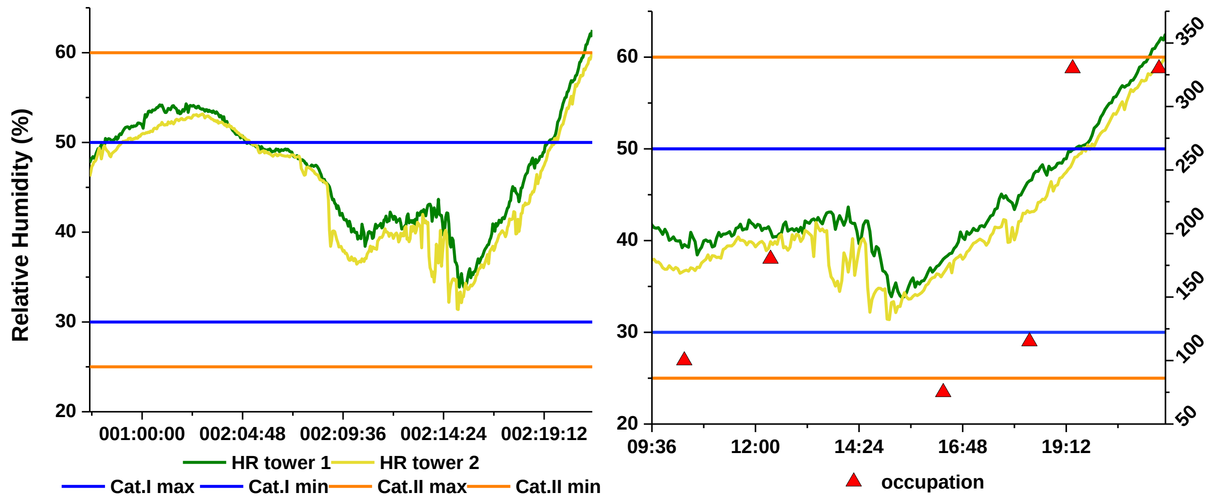


Figure 44. Relative humidity comfort categories. Left: relative humidity registered along the two days of measurements. Right: relative humidity and sports hall occupation

11.1.3 Air quality: indoor CO_2 concentration

Through the elaboration of the field measurements results, it is possible have information regarding the air quality inside the studied sports facility. The air quality categories are identified according to the UNE-EN 15251 standard requirements and taking into account the exterior CO_2 concentration (450 ppm) (tab.42).

Table 42. CO_2 concentration categories according to the UNE-EN 15251 standard

Category	Allowed CO_2 concentration (*ppm*) above the exterior value
I	350
II	500
III	800
IV	>800

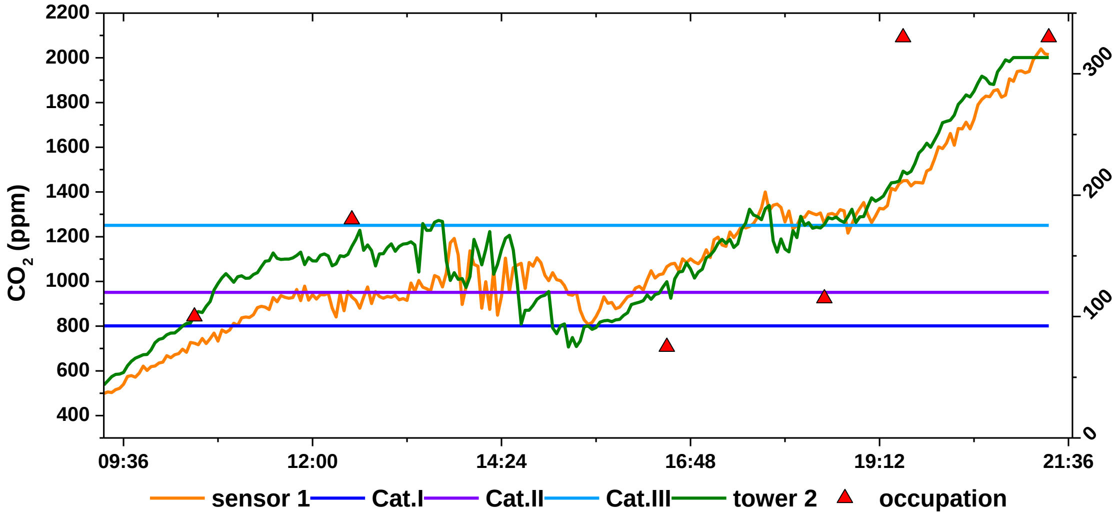


Figure 45. CO_2 concentration measurements and comfort categories

It can be observed that the quality of the air inside the sports hall is good during the night (fig.26), worsen rapidly when the building starts to be occupied and is very poor in condition of maximum occupation (fig.45). In analogy with the presented relative humidity behaviour (fig.44), CO_2 indoor concentration increases significantly during the evening. It results that the comfort condition recommended by the UNE-EN 15251 standard are not met starting from 19:00 until the end of the measurements period, when the CO_2 concentration value reaches Category IV.

The main findings of the measurements campaign are briefly summarized.

- Taking into account that the adopted standards are not specifically elaborated for sports facilities and for the consequent high level of metabolic activity of the users (the reasons of the inadequacy are explained in detail at the beginning of this section), the results of the thermal comfort analysis show that the adaptive comfort requirements (indoor operative temperature ranges) reported in the ASHRAE 55-2010 and in the UNE-EN 15251 standards are mostly complied.
- The relative humidity, according to the standard UNE-EN 15251, is acceptable.
- The thermal stress is acceptable as well.
- Conversely, looking at the level reached by the interior CO_2 concentration and following the recommendation proposed by the UNE-EN 15251, it has been verified that the users of the sports hall experience periods of discomfort due to poor air quality (when the occupation is maximum).
- The results of the survey regarding the audience thermal sensation and the calculated comfort parameters don't coincide. A possible reason could be that the comfort index does not evaluate the relative humidity and the CO_2 concentration. The excessive CO_2 concentration during the hours of maximum occupation and, to a certain extent, the simultaneous sharp increase of the indoor relative humidity appear as the possible main causes of the perceived discomfort emerged through the survey.

11.2 Ventilation strategies

The objective of the building simulation is to verify to which extend the selected n-ZEB strategies are able to reduce the primary energy consumption of a typical sports hall without causing discomfort to the users.

11.2.1 Natural ventilation results

Observing figure 46, showing the TRNSYS simulation outputs for selected summer and winter control weeks, it results that the designed control system works correctly. Figure 46 shows, in fact, that the openings are opened when the CO_2 concentration increase excessively during period of sports hall occupation. However, it occurs that during the weekend, when the occupation is maximum, if there is not enough exterior wind, the CO_2 concentration exceeds the limits set to 1200 ppm (as it is possible to notice in figure 46, July week case, blue circle). On the other hand, the thermal comfort requirements are fulfilled most of the simulation time. However, the indoor temperature is close to the lower temperature limit of 14°C when, during the weekend, the openings are completely opened for air quality reason but the exterior temperature is significantly low (as it is possible to notice in figure 46, February week case, green circle).

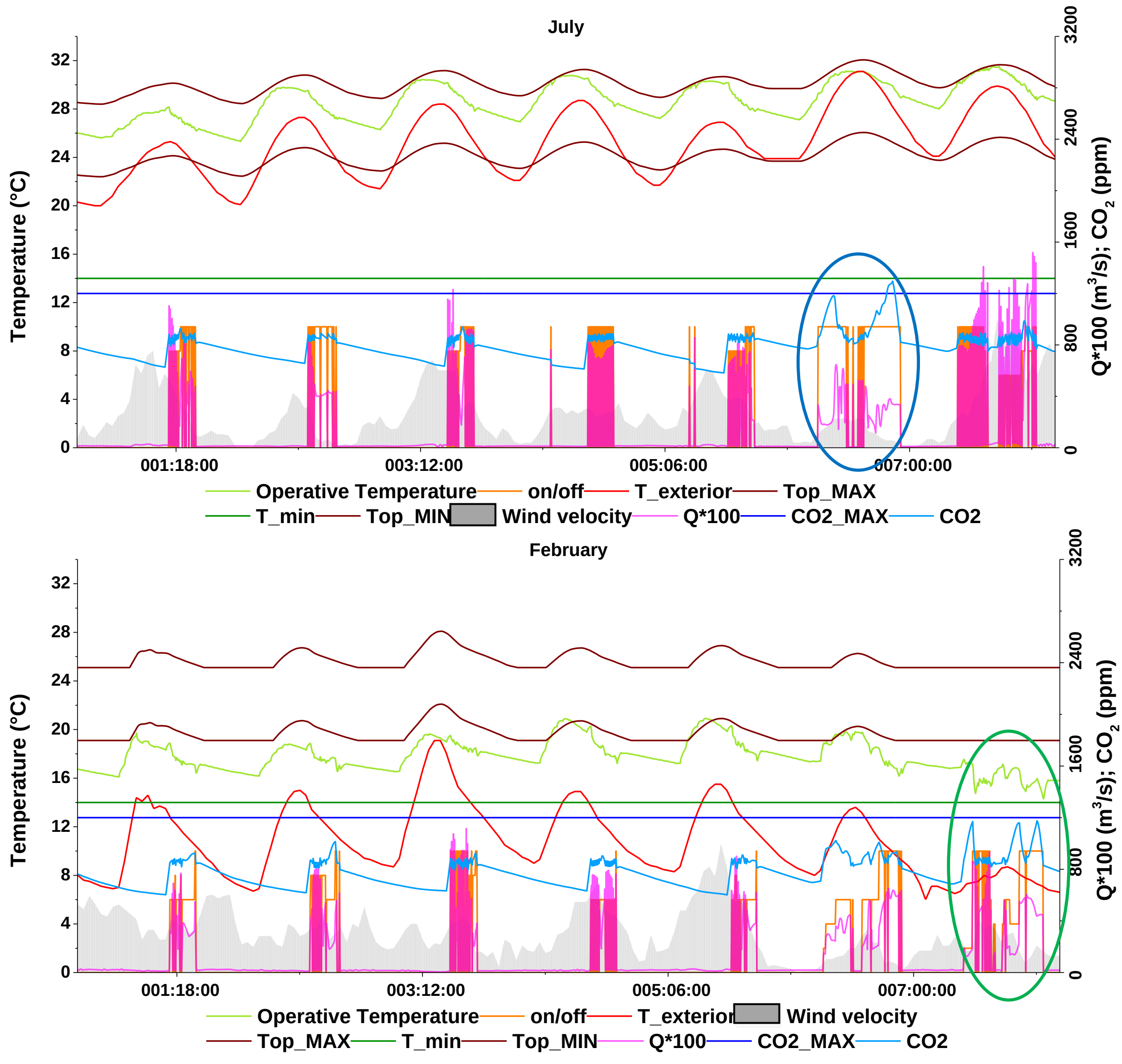


Figure 46. System behavior during selected winter and summer control weeks

The maximum registered ACH is 9.97 h^{-1}. The average ACH with natural ventilation *ON* is 1.57 h^{-1}, while the infiltration on average equals to 0.05 h^{-1}. The presented results are achieved without the introduction natural night ventilation.

The following figure (fig.47) presents more in detail the airflow behavior (*FLNEL, net mass flow through the opening*). According to the control strategy, the openings are activated when the indoor CO_2 concentration increases as much as it reaches values above the comfort limit. Therefore, external air can enter into the building. Positive air flow corresponds to air movement from *From-Node* to *To-Node* (section 8.3) according to the TRNLOW convention. For the studied case, it results that when the airflow is positive, the external air enters from the North-West opening, goes through the sports hall and exits from the opening located in the South-East façade. Conversely, when the air flow results negative, the airflow follows the opposite pathway, namely it enters from the South-East façade and exits from the opening located in the North-West façade. TRNFLOW takes into account the contribution of the two physical principles that govern natural ventilation (section 3.1.1), the wind pressure acting on the building façade (defined as the difference between the local pressure on the surface and the static pressure of the undisturbed wind at the same height) and the buoyancy resulting from temperature and air composition differences. In the graphs (fig.46 and fig.47), it is not easy to distinguish the effect of each driving force, considering that generally they occur at the same time. However, typically thermal buoyancy dominates during cold periods with almost no wind. During those time steps, air displacement involves the cold and dense air entering from the bottom opening and the buoyant air leaving from the one installed at the top of the sports hall façade. During windy days, it is the wind direction that determines the airflow direction.

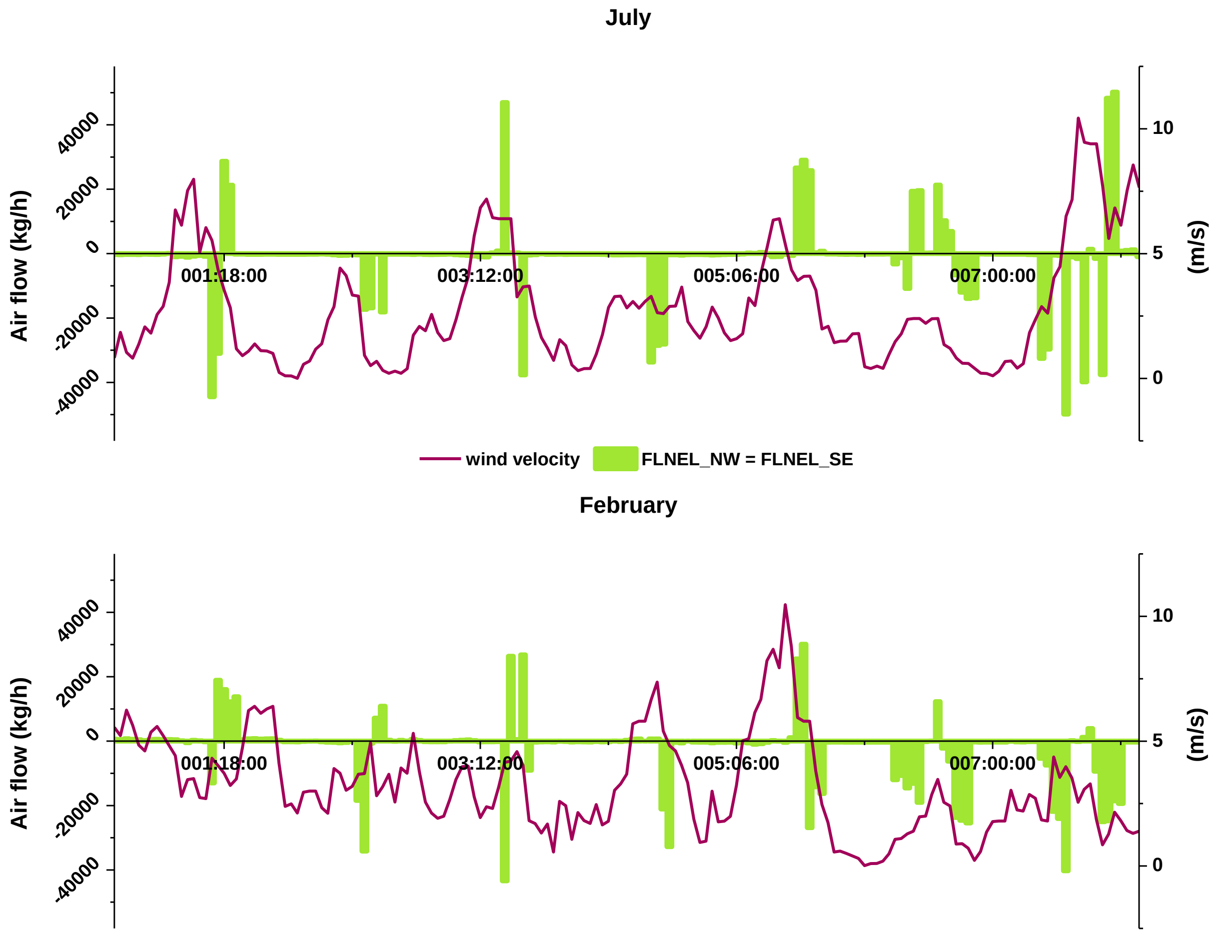


Figure 47. Air flow in the natural ventilated sports hall. FLNEL: net mass flow per link, TRNFLOW output. FLNEL_NW: net mass flow through North-West opening; FLNEL_SE: net mass flow through South-East opening

Different criteria have been used to evaluate the achieved comfort conditions:

- yearly exceedance: on yearly base, the number of time steps during which the considered parameters are outside the set comfort ranges;
- hours of daily exceedance: the maximum number of discomfort hours registered during one day;
- degree of exceedance: to which extent the limits are exceeded.

Thermal discomfort and air quality condition are assessed only during the occupied hours. It is assumed that the overheating phenomenon occurs if $Top_{int} > Top_{opt} + 3$, as the technical indications provided by the Catalan sports council do not set a maximum indoor temperature requirement. The building is overcooled if the condition $Tair_{int} < 14°C$ is verified.

The TRNSYS results relevant for the comfort evaluation of the building are organized in table 43 and reported in function of the natural ventilation state, being the only variable parameter.

Table 43. Natural ventilated building: discomfort results

	% of the occupied time	
	winter	summer
Natural ventilation ON	54.76	50.09
Overcooling	1.69	-
Overheating	-	0.36
CO_2 > 1200 ppm	1.20	0.71

Discomfort occurs mainly during winter. As expected, the excess of CO_2 concentration is more significant during this season, considering that the opening factor has been defined as a trade-off between air quality needs and the reduction of cold airflow from the outside.

Closely analyzing the discomfort events, it results that for 2 days overcooling occurs during 2.75 hours that is the maximum consecutive period of overcooling thermal discomfort. The maximum consecutive period of discomfort due to excessive CO_2 concentration is 3 hours and it occurs one day along the annual simulation. Overall, considering thermal and air quality parameters, good indoor conditions are ensured for most of the occupied time along the yearly simulation. It is expected that annually the users of the natural ventilated sports hall would experience only 16 days of discomfort with the distribution shown in figure 48. The results deviates from the limit values for maximum 329 ppm, 4.61°C in case of overcooling and 0.48°C in case of overheating (tab.44).

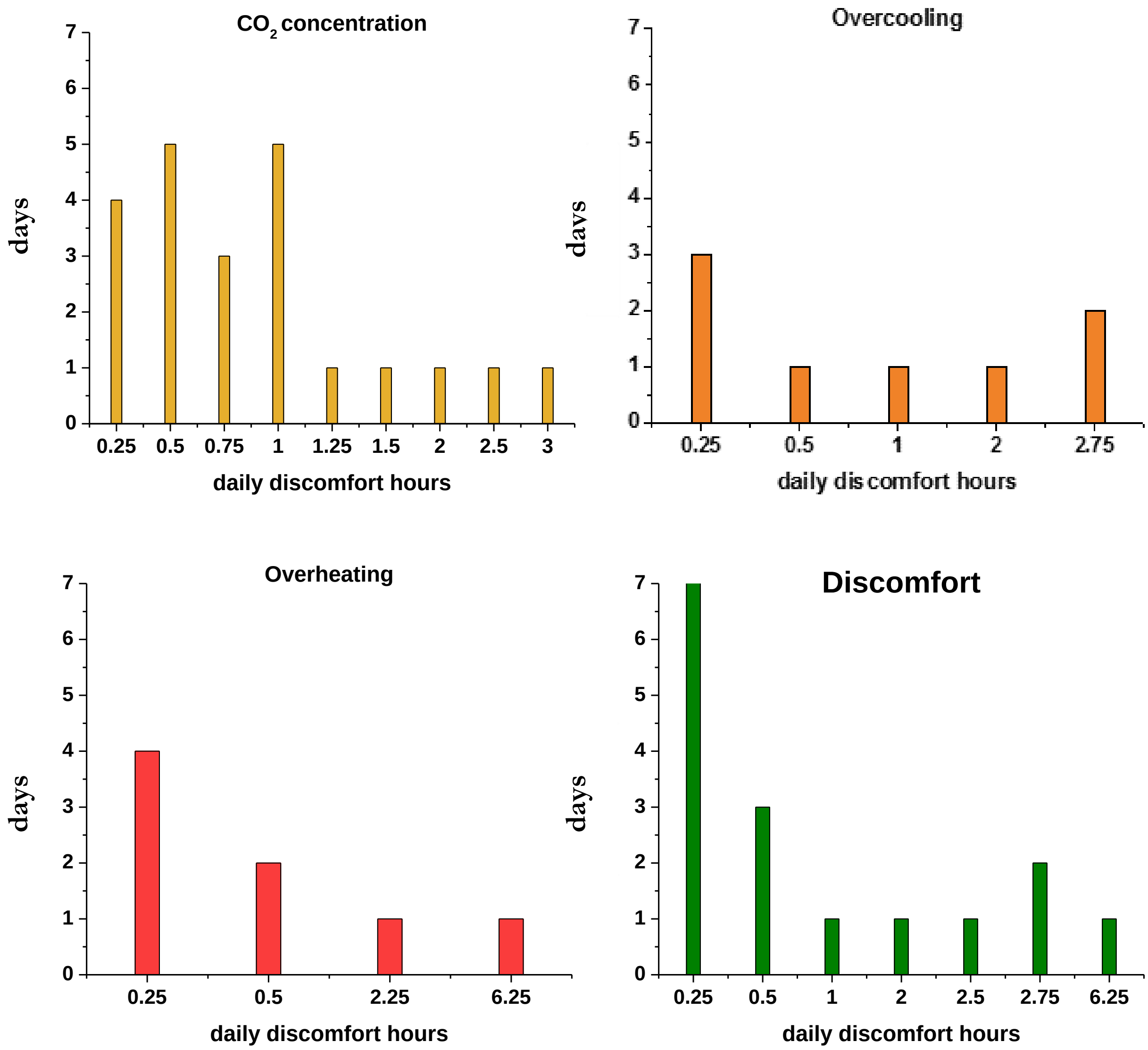


Figure 48. Discomfort hours. X-axis=discomfort hours; Y-axis=number of days

Table 44. Natural ventilation. Deviation from the comfort limit values

	MAX	MIN	Average
Overcooling	-4.61 °C	-0.0025 °C	-0.53 °C
Overheating	0.48 °C	0.0005 °C	0.08 °C
CO_2 > 1200 ppm	328.96 ppm	0.28 ppm	86.73 ppm

The additional night ventilation further reduces the overheating phenomenon to 0.1% of the occupied summer time. Therefore, the implementation of night ventilation technique results to have a limited impact on thermal comfort improvements of this study case building situated in a moderate climate. However, it is expected that night cooling would be considerably beneficial in extreme climate conditions and even in moderate climate if phenomenon as heat wave occurs.

11.2.2 Mechanical ventilation results

The mechanical ventilation systems, differing for the implemented control strategy, have been simulated in combination to *HVAC\Auxiliary Heaters*, as explained in section 8.4. Therefore, for these cases overcooling events are completely avoided. Regarding the indoor CO_2 concentration, although the fan has been sized according to the indication reported in the PAV3 document, air quality discomfort occur, except when the fan works without a control strategy. Overheating occurs as well. (tab.45)

Table 45. Mechanical ventilation. Discomfort results

		MV	MV+CTL	MV+DC
		% of the occupied period		
Ventilation ON	winter	100	71.95	100
	summer	100	69.80	100
Overheating	winter	-	-	-
	summer	0.19	0.51	1.01
CO_2 > 1200 ppm	winter	-	0.94	1.15
	summer	-	1.05	1.48

It results that overheating phenomenon, as in the natural ventilated case, rarely occurs during the year. However, it slightly increase in case of mechanical ventilated building respect to the natural ventilated one. At this regards, it is specified that in case of simulation of mechanical ventilation system with variable speed fan (*MV+DC*), the summer indoor temperature deviates from the upper limit on average of 0.57°C, reaching a maximum of 2.02°C.

11.2.3 Energy consumption comparison

The next graph (fig.49) aims to briefly compare the different operations mode of the tested ventilation mechanisms and control principles. At this scope, the correspondent electric consumptions (including lighting and ventilation electric needs), are represented for a typical summer day. It results that the daylight availability strongly influence the energy needs of the simulated building. It is evident that at 20:00 artificial light system is switched ON, according to daylight availability reported in figure 32. Moreover, the potential energy savings achievable through the implementation of the natural ventilation strategy clearly emerges. Implementing natural ventilation, during a typical summer day, it is possible to reduce the electricity consumption of 21% respect to a mechanical ventilation system without a control strategy. The energy savings correspond to 17% electricity needs reduction respect to the *MV+CTL* case and 5% respect to *MV+DC* scenario, according with the control strategies explained in chapter 8.3.

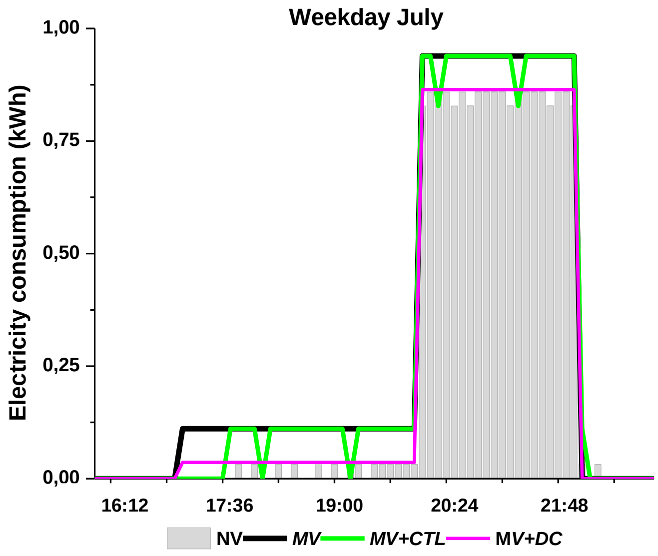
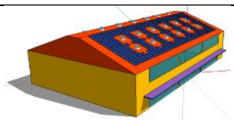
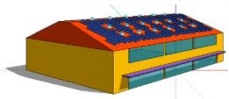
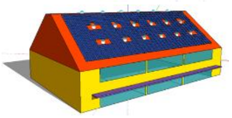
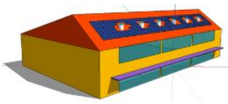
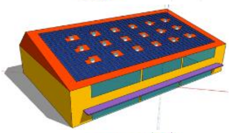
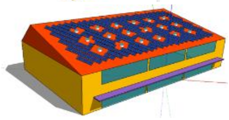
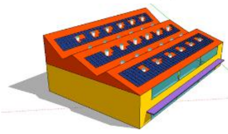
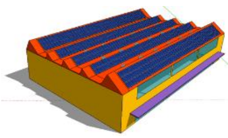
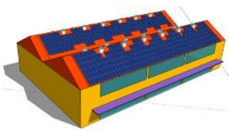
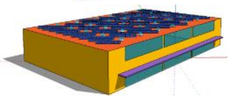


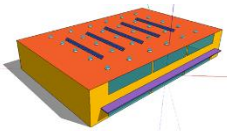
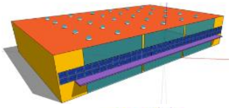
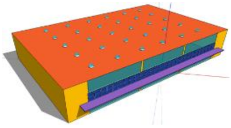
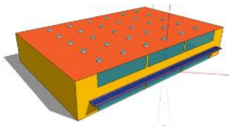
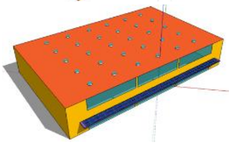
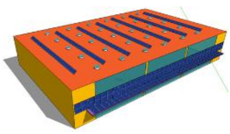
Figure 49. Energy consumption of occupied period in a summer weekday

11.3 PV system configurations

Table 46 summarizes the results of the PV designs analysis. As mentioned (section 10.1), the economic data are extrapolated from Hulb el al. (2014). The comparison of the different PV system configurations suggests that, considering the available surface for PV modules integration and the weather condition of the site, the most advantageous solution is the one tested in case 10. In a range of acceptability of 5% specific cost difference, case 2 and case 6 have similar performance. The mentioned cases are characterized by the installation of the panels with a slope of 38° and an orientation toward South direction (182°). The integration of the PV panels in the façade and on the shading device of the building results less convenient.

Table 46. Tested PV system configurations

		Azimuth	Slope	Panels	kWp	Specific generation (kWh/kWp)	Total generation (kWh)	Specific cost (€/kWh)
1		135	20	367	42	1255	52385	1.11
2		182	38	190	22	1364	29807	1.02
3		135	38	568	365	1267	82746	1.10
4		135	37	162	19	1266	23589	1.10
5		135	14	719	83	1230	101718	1.13
6		182	38	302	35	1371	47623	1.02
7		135	17 23 37	441	51	1245 1256 1265	63583	1.11
8		135	37	600	69	1263 1256 1254 1268 1213	86494	1.11
9		135	34	470	54	1269 1258	68374	1.10
10		182	38	294	34	1381	46680	1.01

11		225	38	60	7	1297	8352	1.15
12		135	90	68	12	876	10606	1.59
13		135	90	56	10	876	8734	1.59
14		180	0	51	6	975	5718	1.43
15		180	0	70	8	979	7882	1.42
16		180 225 134.66	0 37.6 0	265	35	979 1297 876	37442	1.29

11.4 Energy balance of n-ZEB strategy

As introduced in section 9, within the PV configurations proposed in table 46, case 2, 6, 12 and 15 have been selected and analyzed in TRNSYS through type 94. For those cases, it has been possible to calculate the covering factor of the PV electricity production respect to the total electricity consumption of the natural ventilated sports building. The results referring to the natural ventilated sports building not equipped with a heating system (case 1 of table 34) are shown in table 47. The total electricity consumption is 32'297 kWh/yr. The lighting consumption accounts for 13'968 kWh/yr. The electricity demand due to the automation of the natural ventilation systems is estimated at 509 kWh/yr. *Other* electricity consumption have been assumed 12 kWh/m^2 (ICAEN 2012), resulting in 17'820 kWh/yr.

Table 47. n-ZEB energy balance. Terminology according to Sartori et al. (2012)

Electricity (kWh/yr)	PV 2	PV 6	PV 12	PV 15
Total load	32'297			
Total generation	35'425	56'639	8'514	9'492
Total delivered *(by the grid)*	25'072	23'803	29'759	29'224
Self-consumption	7'224	8'494	2'538	3'073
Total exportation	28'201	48'145	5'976	6'419
Covering factor	*22.3 %*	*26.3%*	*7.8%*	*9.5%*

As listed in table 20, the installation of a renewable energy system forms part of the package of measures implemented to realize the design of a low energy sports hall. Specifically, the optimal roof slope and PV panels orientation have been studied to maximize the energy production. Overall, considering the instantaneous balance between electricity demand and supply along one year of operation of the simulated sports building, the configuration 6 reported in table 46 results the most advantageous one. Characterized by the higher value of self-consumption (8'494 kWh/y), PV 6 potentially can give the higher contribution to the final objective of energy costs and CO_2 emissions reduction.

Moreover, it results that the thermal load necessary to comply with the minimum temperature requirements of 14°C is very low: it equals to 213 kWh/yr, namely 0.14 kWh/m².

Elaborating the data made available by ICAEN (2012), the obtained results are compared to the heating, lighting and ventilation performance of a standard triple sports hall and of an efficient one, concerning which energy efficacy measured are applied. The respective non renewable primary energy requirements are compared as well. The considered non renewable primary energy conversion factors are reported in table 31. It is assumed that the PV 6 configuration is installed and that the thermal demand of the simulated sports hall is covered by the installation of a condensing boiler (η=1.09 according to Ortiz et al. (2016b)) combined with an emission and distribution system consisting of radiant panels (η=0.9) (case 3 of table 34). The resultant consumption is 217 kWh/yr, generated using natural gas.

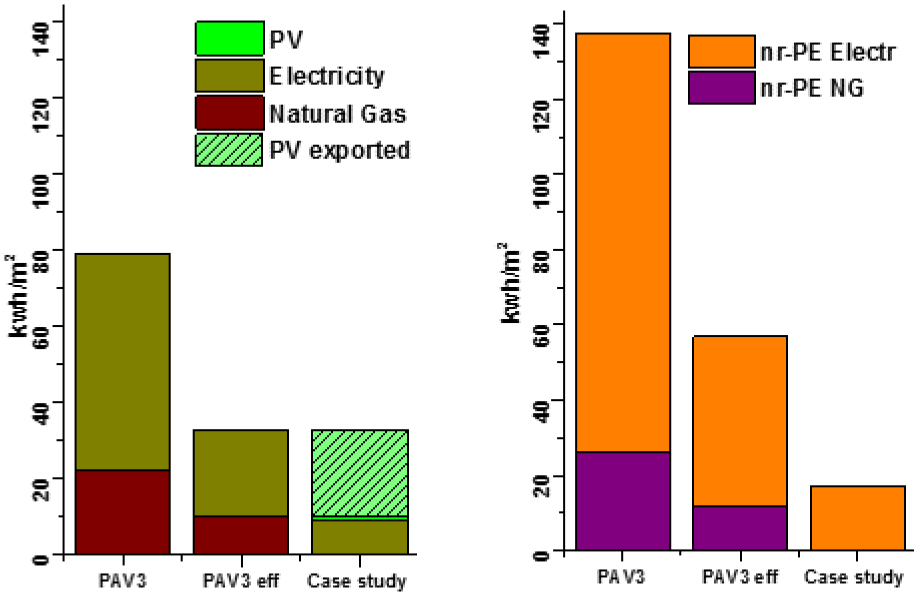


Figure 50. Left: final energy; right: not renewable primary energy. The data elaborated in the figures include heating, lighting and ventilation needs (*other* electricity consumption assumed equals to 12 kWh/m², are not represented)

From figure 50, it is evident that the selected n-ZEB strategies substantially contribute to the objective of primary energy consumption reduction.

11.5 Cost-optimal evaluation

Figure 51 and figure 52 present the findings of the cost-optimal analysis performed for 24 different scenarios, resulting from the combination of each tested ventilation strategy with a different heating system and PV configuration (section 10.1).

In figure 51, the global costs calculated through the cost-optimal methodology have been organized in a bar graph that reports as well for each solution the distribution of energy, investment, and maintenance costs (calculated according to the data reported in table 34). The main results are described.

As expected, the natural ventilation case (*NV*) combined with the PV configuration 6 (PV6) is the one characterized by the lower global costs over 20 years. The global cost for this solution is estimated in 60.78 €/m^2 (taking into account that the total surface of the simulated sports building is 1'485 m^2). Specifically, energy costs result considerably low (only 3.3% of the global costs). The non renewable primary energy accounts for 31 kWh/yrm^2. The PV covering factor, as reported in table 47, is 26.3%. A significant energy costs reduction is verified every time that the natural ventilation strategy is combined with PV 6, the configuration that maximize the electricity self-consumption (tab.47).

All the others scenarios include the evaluation of the contribution of a heating system, installed to cover the discomfort periods due to overcooling. The demand controlled mechanical ventilation system (*MV+DC*) combined with PV6 results the cost-effective solution. PV6 is able to cover 25.3% of the system electricity consumptions. The non renewable primary energy accounts for 34 kWh/yrm^2. The required global costs are 66.91 €/m^2. Energy costs account for 9.76% of the total. DCV investments costs results slightly lower than the ones for controlled mechanical ventilation system (*MV+CTL*). DCV systems are characterized by the fact that allow to modulate the amount of air flow entering into the ventilated space. As consequence, on one hand, investments costs are reduced because overcooling discomfort can be completely avoided mounting an electric heaters battery dimensioned for lower thermal load (16.5 kW instead of 50 kW). On the other hand, an extra expense for the additional fan speed control it must be taken into account.

The energy costs related to the case of natural ventilation system combined with a condensing boiler (*NV+CB*) are lower than in case of *MV+DC,* resulting 4.9% of the global costs (PV6 case; global costs are 75.60 €/m^2; covering factor of PV6 is 26.3%; non renewable primary energy accounts for 31 kWh/yrm^2). However, this solution requires higher investments and maintenance costs. Similarly, the case of a natural ventilation system coupled with a heat pump (*NV+HP*) and an electricity generation system as in PV6 case is characterized by low energy costs. The covering factor of PV6 is 26.25%. Non renewable primary energy accounts for 31 kWh/yrm^2. The installation of the high efficient heat pump ensures good energy performance of the system: the energy costs accounts only for 2.29% of the global costs (global costs result 93.04 €/m^2), the minimum value within the tested scenarios. However, again the high costs of the heating device and the reduced electricity demand of the building comport that energy savings do not balance the economic investments. Overall, the global costs of this solution results greater than for other scenarios.

Applying to the mechanical ventilation system (*MV+CTL*) the same control strategy implemented for the natural ventilation one, it results that the global costs are 74.18 €/m^2 (PV6, covering factor 23.58%). This value is very close to the one calculated for the condensing boiler case (PV6) of 75.60 €/m^2. However, there is a substantial difference in terms of energy costs contribution. For the considered mechanical ventilation system they account for 18% of the global costs. Non renewable primary energy accounts for 39 kWh/yrm^2.

It evident that the installation of a mechanical ventilation system that works at its maximum capacity during all the occupied period (*MV*) is the most expensive solution. The reduction of the investments and maintenance costs (resulting of 2.1% respect to the DCV and the *MC+CTL* cases combined to PV6) is significantly lower than the related increase of the energy costs. They account for 51.25% of the global costs in case of PV6 (global costs result 122.13 €/m^2). Specifically, energy costs are 92'966 €, more ten times higher than in case of mechanical ventilation with variable speed fan and five times more than the controlled mechanical ventilation case. PV6 is able to cover 14.66% of the system electricity consumptions. Non renewable primary energy accounts for 73 kWh/yrm^2.

Summarizing, the cases characterized by the lowest energy costs involve the installation of natural ventilation systems. The installation of the heat pump costs in terms of energy almost as much as the configuration that does not include a heating system. However, it is the most expensive solution at investments and maintenance costs level. Also the condensing boiler solution presents high maintenance costs. Therefore, to cover the heating needs of the simulated sports halls, the controlled mechanical ventilation systems result the most convenient ones.

The covering factors of the different evaluated PV system configuration are reported in table 48 for the different studied cases.

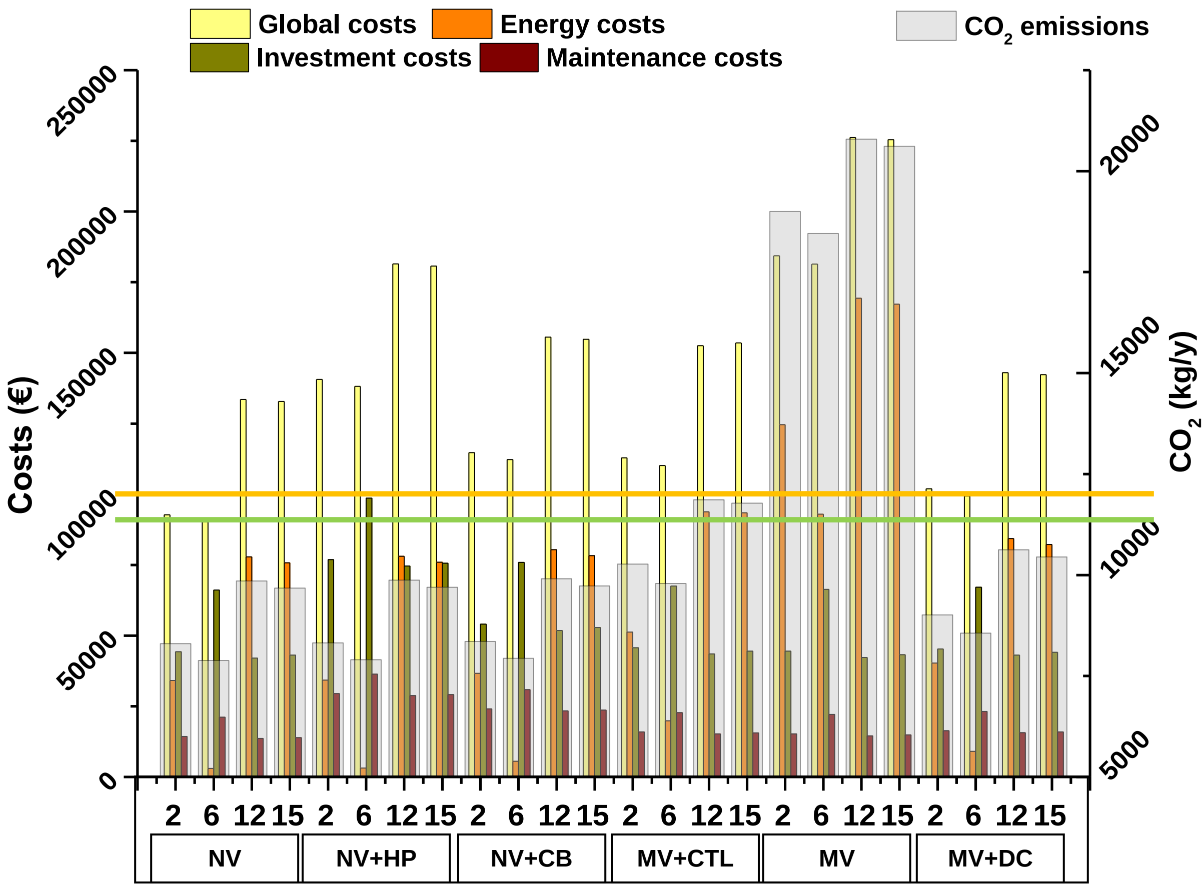


Figure 51. Cost-optimal analysis results. Orange line: lowest global costs level including heating system. Green line: lowest global cost level without heating system

As mentioned (section 10), this work adopts a financial perspective, therefore the CO_2 related cost have not been included in the cost-optimal evaluation. However, in figure 51 the estimated annual CO_2 emissions are also reported.

Table 48. Covering factors of the different evaluated PV system configurations

	NV	NV+HP	NV+CB	MV+CTL	MV	MV+DC
PV2	22.37%	22.33%	22.37%	19.83%	12.13%	21.38%
PV6	26.30%	26.25%	26.30%	23.58%	14.66%	25.30%
PV12	7.85%	7.84%	7.85%	7.39%	3.87%	7.30%
PV15	9.51%	9.49%	9.51%	8.04%	4.69%	8.85%

Figure 52 shows the cost-optimality results in terms of annual not renewable primary energy consumption (including lighting, heating, ventilation and *other* electrical needs) and global costs over 20 years. The results are grouped according to the implemented ventilation and heating strategies. It is easy to notice that the only configurations that require the consumption of more non renewable primary energy than the efficient PAV3 proposed by ICAEN (2012), used as reference case, regard the installation of mechanical ventilation without control. Similarly, it is easy to realize that all the tested solutions are significantly below the level of non renewable primary energy consumption of a standard PAV 3. The 8 points close to the graph origin in the left corner, refers to PV system configurations 2 and 6. Again, it is confirmed that natural ventilation implementation is associate to a significant reduction of primary energy load: not renewable primary energy consumed in the three natural ventilation scenarios results about 7-8% lower than in the cost-optimal case (mechanical ventilation with variable speed fan combined with PV6). However, the costs associated to condensing boiler and heat pump installation negatively influences global costs.

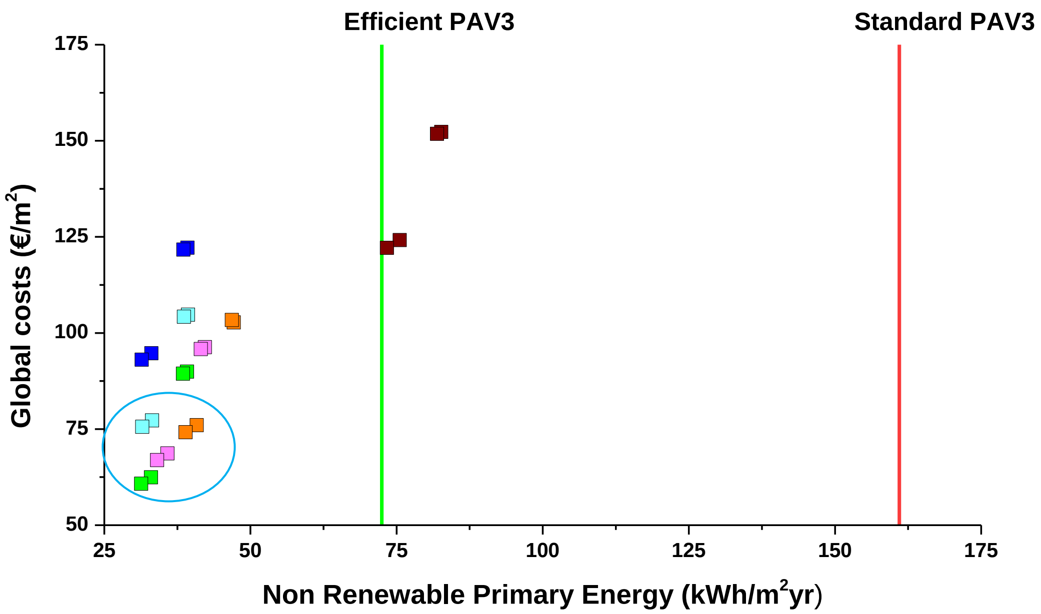


Figure 52. Cost-energy evaluation: not renewable primary energy consumption vs. global cost over 20 years. Color map: green: natural ventilation without heating system; light blue: natural ventilation with condensing boiler; blue: natural ventilation with heat pump; orange: mechanical ventilation with control; pink: mechanical ventilation with variable speed fan; dark red: mechanical ventilation without control. Light-blue circle: PV2 an PV6 configurations

The presented cost-optimality analysis must be completed with some consideration.

- Firstly, the simulation of the mechanical ventilation system and the evaluation of its correspondent costs have been extremely simplified, being this work more focused on the study of the role of natural ventilation as passive design strategy. Therefore, elements that usually forms part of a mechanical ventilation system, as ducts, with an impact on system performance as well as on system costs, have been neglected.
- Moreover, it must be taken into account that a further reduction of the investments costs due to natural ventilation is possible taking advantage of the combination of the ventilation system with other architectural elements, usually introduced into the design of the sports building for different purposes. The use of the openings required to comply with the fire regulation is one of the examples reported in literature (Flourentzou et al., 2015);

- According to Ortiz el al. (2016b), currently investments costs results 10-30% lower than the ones reported in the used price database. Therefore, a certain degree of uncertainty affects the economic analysis.
- From the cost-optimal analysis, it emerges that the introduction of a heating system has an economic impact on global costs that is greater when heat pump or condensing boiler are installed. Heat pump and condensing boiler, in fact, are more complex and expensive systems than simple electric heaters. However, taking into account the other zones that typically form part of a sports hall, the choice of a natural ventilation configuration that include a heating system able to cover simultaneously the heating and DHW needs of the lockers rooms (therefore a configuration that includes the installation of a heat pump or a condensing boiler) appears beneficial in terms of costs reduction.

Conclusion

Under a holistic approach, different energy measures for the design a nearly zero energy Sports Hall have been tested. A novel aspect of the study is its focus on the peculiarity of the Mediterranean climate context.

The first step of the research has involved a field measurement campaign in an existing facility. The obtained data suggest that in a standard sports hall comfort issues are closely linked to indoor air quality conditions. Excess of CO_2 concentration causes discomfort perception, even though the registered thermal parameters fall within the acceptability range. Secondly, TRNSYS simulation confirms that the combination of reduction of thermal transmittance of the envelope, optimization of the window surface, correct façades orientations, introduction of shading devices, installation of energy efficiency systems, and use of natural and night ventilation, is advantageous for the reduction of heating, cooling and artificial lighting demand, as well as building global costs. It is verified as well that PV system integration positively affects the sports hall performance toward n-ZEB standards. Overall, the simulated sports building is characterized by an energy demand of 22 kWh/m^{2}yr (assuming the installation of a condensing boiler and considering 12 kWh/m^2 of other electrical consumption (ICAEN 2012)), 76% less than a standard sports hall and 46% less than an efficient one. Considering the contribution of the electricity generation on-site, the annual total primary energy consumption is estimated in 44 kWh/m^2.

Moreover, the described strategies minimize the discomfort period due to overcooling and overheating, and provide good air quality conditions for most of the occupied time along one-year simulation. The design of the natural ventilation system and of the relative control strategy plays a relevant role in the energy performance improvements of the building. It is estimated that the natural ventilated sports hall, not equipped with a heating system, will be overcooled for 1.69% of the winter occupied time, while CO_2 concentration will exceed normative limits only during 0.95% of the year. As said, in this regard it must be taken into account that all the calculations are based on comfort and thermal standards not elaborated specifically for natural ventilated and sports building categories.

It is evident that a successful application of natural ventilation strategies requires to overcome several barriers. In cold or tropical climates, it is necessary to combine ventilation systems respectively to heating and cooling system. In moderate climates, using the Cook's (2014) definition, the wide adoption of natural ventilation principles is linked to the respect of the so-called *3C*: control, client understanding and commissioning. The first parameter has been largely discussed in this thesis and a proper strategy has been identified to ensure sufficient ventilation for good IAQ without unnecessary heating energy costs during the cold season and without cooling load during the summer. As regard the client-understanding obstacle, it is true that the users of a natural ventilated building can be concerned about the exterior environment, in relation to safety issues, noise level and outdoor air pollution. Moreover, fire and acoustic regulation can be restrictive regarding the free flow of air inside the building. Commissioning: designers are usually reluctant to accept the risks related to a certain degree of indoor conditions fluctuation implied in the use of natural ventilation (Allard 2012). While energy efficient consultants are discouraged by the fact that low fees are expected to support a more complex design analysis. Moreover, there are few standards supporting the planners in the openings design process and there is a lack of experience within the architects, engineering and consultants regarding natural ventilation implementation (Schulze and Eicker, 2013). According to Florentzous' (ESTIA) words: "*There is a need of accounting the energy savings in the national energy regulations. It is the only way to make this technique able to penetrate the market, because there is nothing to sell other than engineering fees*".

Finally, it is suggested that future development of the presented study can involve the evaluation of the sports hall DHW needs and the investigation of the potential contribution of a thermal solar system.

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Annex 1

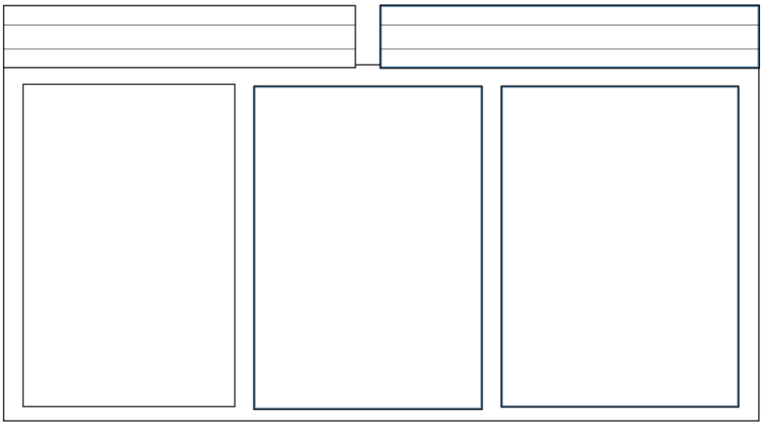
COMFORT SURVEY

This survey is part of a research project regarding thermal comfort in Sport Halls, performed by the Catalan Institute of Energy Research with the collaboration of the Club Natació Terrassa.

Please, answer the survey half an hour after reaching your sit.
Thank you in advance for your cooperation.

Hour:

Indicate your position in the scheme:



1. Which of the following option best indicate your clothing?

1. Shorts and short-sleeved shirt
2. Throusers and short-sleeved shirt
3. Throusers and long-sleeved shirt
4. Throusers and jersey
5. (3) + jacket
6. (3) + jersey and interior shirt
7. Knee-length skirt and short-sleeved shirt
8. Knee-length skirt and long-sleeved shirt
9. Knee-length skirt and jersey
10. (7) + jersey
11. (7) + jacket
12. Ankle-length skirt, long-sleeved shirt and jacket

2. How do you asses your thermal sensation?

- Hot (+3)
- Warm (+2)
- Slightly warm (+1)
- Neutral (0)
- Slightly cool (-1)
- Cool (-2)
- Cold (-3)

3. How do you perceive the room in the air?

- Wet
- Slightly wet
- Neutral
- Slightly dry
- Very dry

- Laden air
- Slightly laden air
- Fresh

4. How do you perceive the air movement in the room?

- Very low
- Slightly low
- Neutral
- Slightly high
- Very high

5. How do you perceive the illumination level of the room?

- Very intense
- Slightly intense
- Neutral
- Slightly dim
- Very dim

Annex 2

Description and thermal characteristics of the sports hall construction elements implemented in the TRNSYS simulation.

Table 49. Exterior façades composition

Façades NE and SW Layer	From the inside to the outside	Conductivity (kJ/hmK)	Heat Capacity (kJ/kgK)	Density (kg/m³)	Thickness (mm)
1	OSB panel	0.468	1.7	650	0.018
2	Fiberboard MDF - GUTEX	0.252	1.7	250	0.2
3	Larch wood	0.504	2.8	600	0.018
4	Air gap	Resistance = 0.05 m^2K/kJ			0.042
5	Ceramic	3.132	0.9	1250	0.04

Façades SE and NW Layer	From the inside to the outside	Conductivity (kJ/hmK)	Heat Capacity (kJ/kgK)	Density (kg/m³)	Thickness (mm)
1	OSB panel	0.468	1.7	650	0.018
2	Fiberboard MDF - GUTEX	0.252	1.7	250	0.2
3	Larch wood	0.504	2.8	600	0.04
4	Air gap	Resistance = 0.05 m^2K/kJ			0.02
5	Euromodul 44 – Metal profile	180	0.5	7800	0.001

Table 50. Partition (interior) wall composition

Partition wall NW Layer	From the inside to the outside	Conductivity (kJ/hmK)	Heat Capacity (kJ/kgK)	Density (kg/m³)	Thickness (mm)
1	OSB panel	0.468	1.7	650	0.018
2	Fiberboard MDF - GUTEX	0.252	1.7	250	0.2
3	Larch wood	0.504	2.8	600	0.018

Table 51. Roof composition

Roof Layer	From the inside to the outside	Conductivity (kJ/hmK)	Heat Capacity (kJ/kgK)	Density (kg/m³)	Thickness (mm)
1	Fiberboard MDF - Acoustic	0.504	1.7	600	0.025
2	OSB panel	0.468	1.7	650	0.015
3	Fiberboard MDF - GUTEX	0.252	1.7	250	0.2
4	OSB panel	0.468	1.7	650	0.015
5	Air gap	Resistance = 0.05 m^2K/kJ			0.05
6	Euromodul 44 – Metal profile	180	0.5	7800	0.001

Table 52. Ground floor composition

Ground floor Layer	From the inside to the outside	Conductivity (kJ/hmK)	Heat Capacity (kJ/kgK)	Density (kg/m^3)	Thickness (mm)
1	Concrete	4.86	1	2000	0.2
2	Wood - Parquet	0.756	2.8	800	0.004
3	Plywood panel	0.324	1.6	300	0.01
4	Plywood panel	0.324	1.6	300	0.012
5	Polyethylene	1.188	2.2	920	0.01
6	Linoleum	0.36	1.4	270	0.012

Table 53. Windows characteristics

	g Heat gain coefficient	T-sol Solar transmittance	Rf-sol Solar direct transmittance	T-vis Visible transmittance
Window 1_lower level	0.368	0.296	0.2	0.496
Window 2_higher level	0.335	0.294	0.325	0.388
Window 3_skylight	0.589	0.426	0.266	0.706

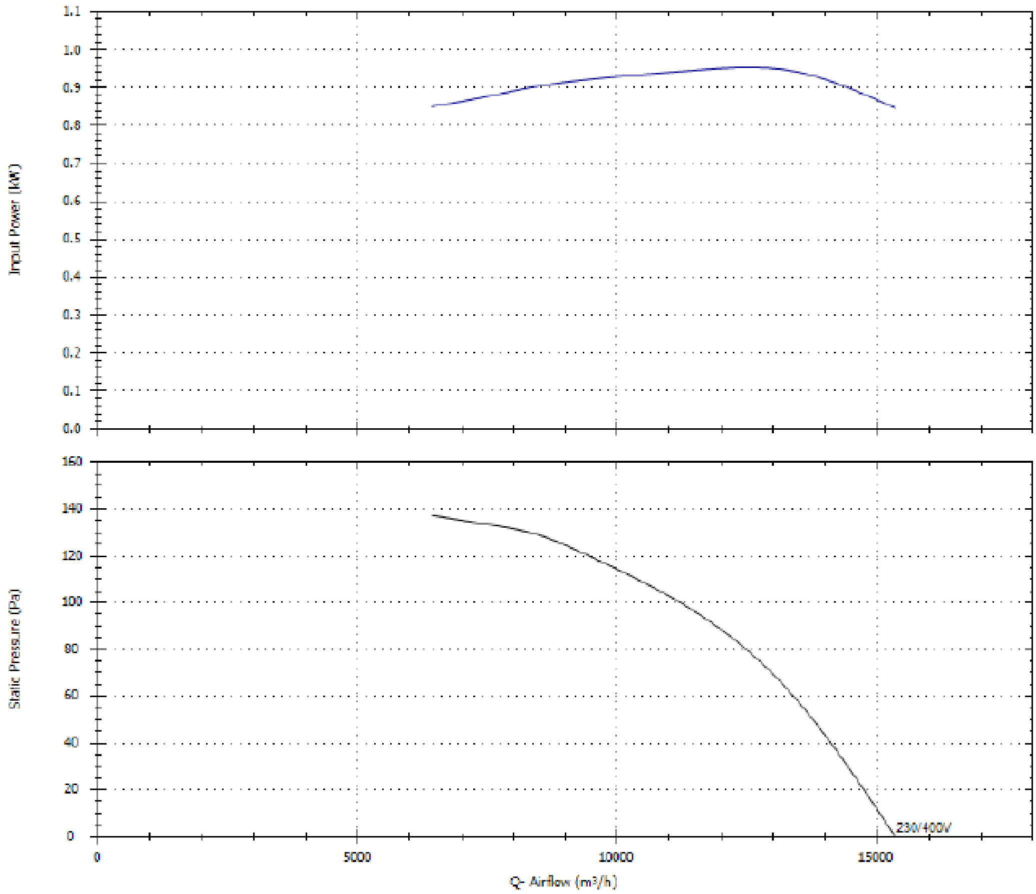
Annex 3

Plate mounted axial flow fans

COMPACT Series type HCBB / HCBT (Aluminium impellers)

HCBT/6-710/H- *230/400V50* V5

+ Curves



Model	Speed (r.p.m.)	Ø Valve (mm)	Maximum absorbed power (W)	Maximum current (A)		Sound pressure level* (dB(A))	Maximum airflow (m³/h)	Weight (kg)	Speed controller		Inverter control	
				230 V	400 V				REB	RMB/T**	VFTM**	VFKB**
HCBT/6-710/H	950	710	953	4,7	2,7	65	15.350	27	–	RMT-5	VFTM-Tri 1,5	VFKB-45

* Sound pressure level measured in free field conditions at a distance equivalent to three times the diameter of the impeller with a minimum of 1,5 meters.
** Three phase speed controllers (RMT) or inverter control (VFKB/VFTM): three phase 400V.

Annex 4

Shell S115 Photovoltaic Solar Module

Electrical Characteristics

Data at Standard Test Conditions (STC)

STC: irradiance level 1000W/m², spectrum AM 1.5 and cell temperature 25°C

Rated power	P_r	115W
Peak power*	P_{mpp}*	115W
Peak power voltage	V_{mpp}	26.8V
Open circuit voltage	V_{oc}	32.8V
Short circuit current	I_{sc}	4.7A
Minimum peak power	$P_{mpp\ min}$	109.25W
*Tolerance on Peak Power		±5%

The abbreviation 'mpp' stands for Maximum Power Point.

Typical data at Nominal Operating Cell Temperature (NOCT) conditions

NOCT: 800W/m² irradiance level, AM 1.5 spectrum, wind velocity 1m/s, T_{amb} 20°C

Temperature	T_{NOCT}	44°C
Mpp power	P_{mpp}	84W
Mpp voltage	V_{mpp}	24.4V
Open circuit voltage	V_{oc}	30.4V
Short circuit current	I_{sc}	3.8A

Typical data at low irradiance

The relative reduction of module efficiency at an irradiance of 200W/m² in relation to 1000W/m² both at 25°C cell temperature and AM 1.5 spectrum is 8%.

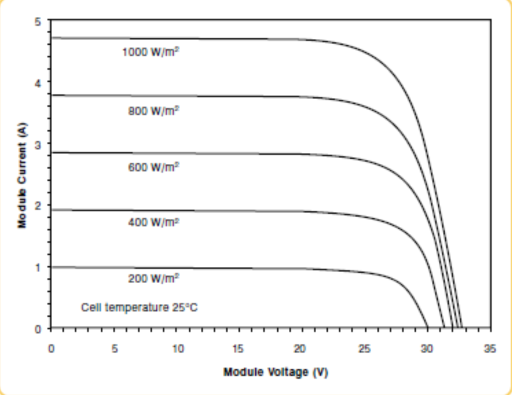
Temperature coefficients

$\alpha\ P_{mpp}$	−0.45 %/°C
$\alpha\ V_{mpp}$	−115 mV/°C
$\alpha\ I_{sc}$	+2 mA/°C
$\alpha\ V_{oc}$	−115 mV/°C

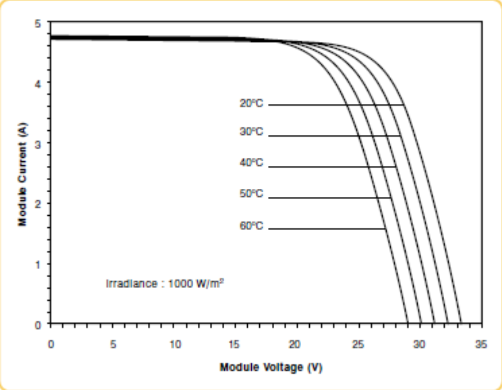
Maximum system voltage: 600Vdc

Typical I/V Characteristics

The I/V graph below shows the typical performance of the solar module at various levels of irradiance.



The I/V graph below shows the typical performance of the solar module at various cell temperatures.



Annex 5

Table 54. PV monthly shading losses (%). Skelion calculation

PV configuration	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.09	0.08	0.08	0.04	0.02	0.03	0.04	0.01	0.06	0.04	0.07	0.08
2	1.82	2.25	1	0.59	0.34	0.43	0.59	0.55	1.14	1.34	3.15	3.84
3	0.06	0.03	0.04	0.04	0.05	0.06	0.07	0.05	0.06	0.08	0.06	0.07
4	0.13	0.17	0.21	0.21	0.24	0.23	0.27	0.25	0.2	0.19	0.13	0.16
5	0.08	0.1	0.07	0.07	0.12	0.12	0.15	0.13	0.09	0.05	0.05	0.11
6	0.1	2.04	0.39	0.41	0.04	0.02	0.03	0.2	0.33	1.36	1.71	3.87
7	0.21	0.33	0.32	0.31	0.48	0.44	0.51	0.37	0.32	0.43	0.45	0.32
8	4.57	2.48	1.27	0.24	0.18	0.00	0.06	0.34	1.21	2.25	4.57	4.66
9	1.45	1.06	0.47	0.21	0.13	0.12	0.16	0.21	0.47	0.67	1.94	1.61
10	0.06	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.07	0.05
11	0.19	0.32	0.13	0.00	0.00	0.00	0.00	0.02	0.00	0.3	0.3	0.64
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	2.61	6.13	9.05	17.8	16.8	19.49	22.11	20.04	15.31	5.07	2.01	1.82
15	2.62	6.13	11.6	15.95	16.8	19.49	22.11	18.12	12.01	7.23	2.02	1.85
16	0.90	2.15	3.92	5.32	5.60	6.50	7.37	6.05	4.02	2.47	0.73	0.74