UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Concept, design and energy simulation of a Net Zero Energy Home for the Mediterranean climate

Mafalda Sofia Tavares Valente Correia

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Dissertação orientada por:
Marta João Nunes Oliveira Panão (FCUL)

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(This section is written in portuguese, my native language.)

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A todos,

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Abstract

A single-family single-floor detached NZEH was designed for the city of Nice, France, of Mediterranean climate. A horizontal overhang was projected analytically to completely shade the South glazing on summer and assure total exposure on winter. The thermal envelope was based on a nearby certified Passive House Premium, with some relaxation of the heat transfer coefficient, except for the roof (25 cm of cork insulation). An intermittent operation was used for the HVAC. A modern open concept of kitchen-dining-living room was applied, with separation of the untreated kitchen from the dining-living room (DLIV) by an always open door that covers the whole joint wall. A sunroom faces South, DLIV is in the middle (West glazing), the kitchen on the North with a wide window specifically to provide north winds for night flushing of DLIV. Thus, a multizone Airflow Network was created on EnergyPlus (E+). Both venting and movable shading devices' operation controls were customised using EMS. By writing simple codes inside E+, its limited control conditions were overridden, enabling a hybrid conditioning mode with HVAC and natural ventilation available at the same time but never overlapping, and a second shading device on windows, the external shutter, through a full window construction change. The shutters act as movable insulation, preventing overcooling and overheating when the house is unoccupied. The internal blinds, that block beam radiation when the occupants are home, were also optimised with EMS. All these controls resulted in thermal loads below 4 $kWh/m^2.y$ per Treated Floor Area for both cooling and heating, well below the Passive House 15 $kWh/m^2.y$ threshold for each. A theoretical heat pump was used, and a string of 7 PV modules was sufficient to supply the 1.99 MWh annual total electric consumption.

Keywords: NZEH, EnergyPlus, EMS, AFN, PV.

Resumo

Para reverter os efeitos das alterações climáticas e projetar um futuro sustentável, o setor da energia está a tomar três principais medidas: eletrificação, descarbonização e eficiência energética. Entre os três maiores consumidores de energia, logo maiores emissores de carbono, encontra-se o setor dos edifícios que, especialmente no sul da Europa, avança a passos lentos no sentido do edifício eficiente, estando em fase de desenvolvimento muito precoce da implantação do edifício de alta performance.

Prevê-se que os climas temperados de latitudes médias sejam dos mais afectados pelo aquecimento global, com aumento nomeadamente da frequência, duração e intensidade das ondas de calor, pelo que perceber e instalar estratégias passivas de arrefecimento é urgente. São elas: a ventilação nocturna, a obstrução solar (sombreamento), o isolamento – desde que não exceda a capacidade do espaço de evacuar calor, acumulando-o –, trocas radiativas com o céu, convectivas, evapo-transpiração, o uso da inércia para armazenamento e modelação das condições interiores em parceria com a ventilação natural para remoção do calor, etc.

Um desses climas com previsão de alargamento do verão é o clima Mediterrânico, que se traduz como um clima temparado quente – classe ‘C’ na classificação climática de Köppen-Geiger – de verão seco – subclasse ‘s’ – e quente ou ameno – subtipos ‘a’ e ‘b’, portanto Csa e Csb. Para uma recolha de 68 localidades do sul da Europa, com subtipos climáticos Csa e Csb, foi feita uma análise da temperatura ambiente e radiação global horizontal. A cidade que mais se aproximava da média da amostra em ambos os parâmetros era a de Nice, no sul de França, pelo que Nice foi escolhida como a cidade representativa da norma do clima Mediterrânico e o local de construção hipotética da casa projetada nesta dissertação. Nice apresenta clima Csa e verões quentes de Junho a Setembro.

A planta da moradia foi desenhada em SketchUp considerando uma família de 4 pessoas, um só piso, e uma otimização do uso dos espaços a Sul. Assim, os quartos das crianças, a sua casa-de-banho, e o solário/marquise junto à sala foram inseridos na fachada Sul. A suite dos pais foi posicionada virada a Este com o seu WC privativo no canto nordeste da casa, protegendo a envolvente da suite a Norte. Os quartos encontram-se todos na secção Este da casa. Do outro lado, a cozinha está virada a Norte, seguida da sala de jantar+sala de estar (zona DLIV) no meio da secção com janela a Oeste, e então o solário com portas de vidro amovíveis (viradas para a sala) orientado a Sul. Uma pála horizontal exterior foi dimensionada analiticamente para que sombreasse totalmente a janela do solário e quartos das crianças (têm a mesma altura) no verão, e garantisse exposição solar total no inverno. A zona térmica da cozinha teve que ser separada da da sala pois, ao contrário da última, não tem operação AVAC; no entanto, um conceito aberto moderno era desejado, pelo que se criou uma porta interior ocupando (praticamente) toda a parede de interseção entre as zonas, e definiu-se esta porta dentro do EnergyPlus, o software de simulação energética utilizado, como estando sempre aberta. A casa tem grande área envidraçada, pé-direito de 3 m, e áreas de chão bastante razoáveis.

A envolvente térmica que a compõe foi baseada na de uma casa certificada Passive House Premium localizada não muito longe de Nice (em *Solliès-Pont*). Os isolantes térmicos foram todos trocados por cortiça de condutividade 0.04 W/m.K, um material muito produzido no sul da Europa. A composição de cada fachada foi simplificada e os coeficientes de tranferência de calor (U-values) relaxados, excepto para o telhado plano que manteve 25 cm de isolamento. A janela escolhida foi dupla de baixa emitância térmica e preenchida com Árgon. Na construção do solo, uma simplificação foi utilizada que estabelece que as temperaturas do solo a 2 m de profundidade podem ser usadas no EnergyPlus como condição de fronteira do chão, se se projectar uma construção do pavimento com 2 m de espessura, tendo-se incluído o material ‘solo’ com a espessura em falta, 1.4 m.

Já no EnergyPlus, para que a janela larga da cozinha virada a Norte ventilasse a sala, motivo pelo qual ela foi traçada, foi criado um modelo de movimentação de ar multizona, o 'Airflow Network' (AFN). Mas tanto os controlos de abertura de janelas para ventilação natural do AFN, como de operação dos dispositivos de sombreamento amovíveis – estores exteriores e persianas interiores – foram personalizados com detalhe usando o 'Energy Management System' (EMS). Programando dentro do EnergyPlus, escrevendo códigos curtos e simples, as condições de controlo limitadas do software são ignoradas e sobrepostas. Assim, um modo de condicionamento híbrido de AVAC e ventilação natural foi criado, que tendo ambas as opções disponíveis ao mesmo tempo, garante que não há simultaneidade de operação entre elas, bem como um programa de controlo dos sombreamento amovível das janelas exteriores, que permite que haja um segundo dispositivo na mesma janela; tal foi feito impondo uma mudança da construção da janela para uma que inclui o estor na posição exterior, quando as suas condições de operação são satisfeitas. O estor funciona como isolamento amovível, prevenindo arrefecimento excessivo e sobraquecimento quando a casa está desocupada. As persianas interiores também são controladas no mesmo program de EMS para bloquearem a radiação directa quando: a família está em casa, a sala está perto do sobreaquecimento e a radiação incidente tem uma intensidade superior a 150 W/m^2.

Todos estes controlos resultaram em cargas térmicas anuais de 3.62 $kWh/m^2.a$ e 2.90 $kWh/m^2.a$ por Área Tratada (TFA, soma das áreas de todas as zonas condicionadas) para aquecimento e arrefecimento, respectivamente, portanto muito abaixo do requisito do standard Passive House de 15 $kWh/m^2.a$ para cada carga. Uma bomba de calor teórica de eficiência global de 20% foi usada como equipamento AVAC, e uma série de sete módulos fotovoltaicos foi suficiente para suprir o consumo anual total de electricidade da casa de 1.99 MWh. As horas de operação das janelas, estores e persianas foram constatadas como elevadas, evidenciando a eficiência da aplicação destas estratégias passivas – excepto para as persianas, como se previa, visto que estas bloqueiam radiação excessiva quando a casa está ocupada, e à semana a família só chega às 18:30, quando a radiação já não é elevada; estas persianas são úteis ao fim-de-semana. No entanto, verificou-se um consumo de arrefecimento elevado na sala, e taxas de desconforto por sobreaquecimento quando a casa está ocupada acima do desejado. O modo passivo revelou menor desconforto térmico, o que valida que o problema terá estado na operação do AVAC. O horário de operação intermitente deve ser demasiado reduzido, a meia hora que antecede a chegada da família a casa e em que o sistema liga será insuficiente para colmatar sobreaquecimentos. De qualquer forma, um edifício de baixíssimo consumo foi alcançado.

Palavras-Chave: NZEH, EnergyPlus, EMS, AFN, Fotovoltaico.

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List of Acronyms

AC	Air Conditioning unit
ach	air changes per hour
AFN	Airflow Network
BR1	Kids' central Bedroom thermal zone
BR2	Kids' corner Bedroom thermal zone
CCUS	Carbon Capture, Usage and Storage
CDD	Cooling Degree-Days
CLOS	Parent's walking Closet thermal zone
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CORR	Corridor thermal zone
DLIV	Dining and Living room thermal zone
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
Erl	*EnergyPlus Runtime Language*
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HALL	Entrance Hall thermal zone
HDD	Heating Degree-Days
HRV	Heat Recovery Ventilation system
HVAC	Heating, Ventilation and Air Conditioning
KIT	Kitchen thermal zone
LED	Light-Emitting Diode
LoE	low thermal emittance
NDC	Nationally Determined Contribution
NPS	New Policies Scenario
nZEB	nearly Zero Energy Building
NZEB	Net Zero Energy Building
NZEH	Net Zero Energy Home
PANT	Pantry thermal zone
PHI	*Passivhaus Institut*
PHPP	Passive House Planning Package
PV	solar Photovoltaic energy
SDS	Sustainable Development Scenario

SUIT	Parent's Suite thermal zone
SUNR	Sunroom thermal zone
TFA	Treated Floor Area
TFC	Total Final Consumption
toe	tonnes of oil equivalent
TPED	Total Primary Energy Demand
UHI	Urban Heat Island
WC12	Kids' bathroom thermal zone
WCSU	Parent's bathroom thermal zone
ZEB	Zero Energy Buildings

List of Symbols and Notations

ΔP_{infil}	pressure difference of the infiltration's flow rate (Pa)
Ω_o^{OFF}	profile angle of the overhang for the 'rad-off' period (°)
Ω_o^{ON}	profile angle of the overhang for the 'rad-on' period (°)
ρ_{air}^{NTP}	air density at NTP conditions (kg/m^3)
β	solar altitude (°)
γ_w	surface solar azimuth (°)
δ	solar declination (°)
η	Efficiency of heat pump's heating or cooling operation
Φ	solar azimuth (°)
Ψ_w	surface azimuth (°)
Ω_o	profile angle of the overhang (°)
$\dot{V}_{infil}$	volumetric flow of infiltration (m^3/s)
$\dot{m}_{infil}$	mass flow of infiltration (kg/s)
ACH_{infil}	flow rate of infiltration (h^{-1})
C_Q^{NTP}	air mass flow coefficient at NTP conditions (kg/s.Pa^n)
V_{build}	gross volume of the building (m^3)
l_o	length of the overhang (m)
COP_{Carnot}	COP of an ideal heat pump
$d_{w,w}$	distance between the window and the outer surface of the wall (m)
E	Electrical energy for heating or cooling (J)

G	Global horizontal solar radiation (Wh/m^2)
HA	solar hour angle (°)
h_o	height of the overhang above the window (m)
h_w	height of the window (m)
LAT	latitude of the location (°)
pw_o	partial width of the overhang on each side of the window (m)
Q	Thermal energy for heating or cooling (J)
RH	air Relative Humidity (%)
SH	solar hour (h)
T	dry bulb Temperature (℃)
T_{cond}	heat pump fluid's condensation temperature (K)
T_{evap}	heat pump fluid's evaporation temperature (K)
T_{flu}	heat pump fluid's temperature (K)
$T_{outdoor}$	site's outdoor air temperature (K)
U-value	Heat transfer coefficient ($W/m^2.K$)
w_o	width of the overhang (m)
w_w	width of the window (m)
n	air mass flow exponent
n	day of the year in the Julian calendar (days)

Chapter 1 – Introduction

1.1. Context

1.1.1. A review on global Energy Demand and CO_2 Emissions: recent data, projections, clean energy transition, and the Buildings sector

Three quarters of global anthropogenic Greenhouse Gas (GHG) emissions arise from the energy sector, consisting almost entirely of Carbon Dioxide (CO_2), followed by methane and nitrous oxide, as can be seen in Figure 1.1 (expressed in tonnes of CO_2 equivalent). Hence, representing two thirds of total GHG emissions, energy-related CO_2 remains the dominant contributor to climate change [1].

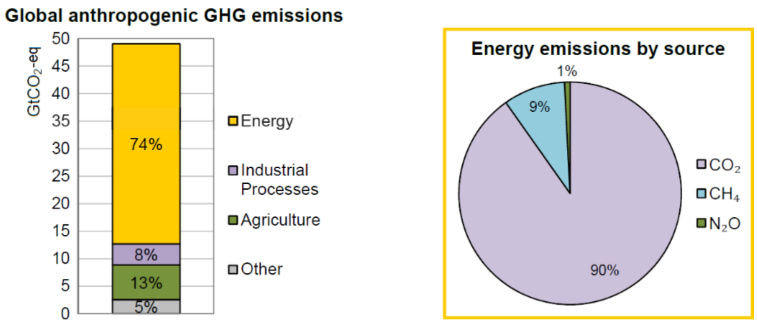

Figure 1.1 - Total and energy-related global anthropogenic GHG emissions by source, in 2015 (adapted from [1])

Energy consumption and consequent emissions are the product of demographic, economic, environmental and technological factors. The world population keeps growing at a steady (slightly slowing down) pace, having reached the 7.5 billion[a] mark in 2017, while the fluctuant growth rate of the Gross Domestic Product (GDP) found some stability in 2012 after the rebound effects of 2008-2009's recession, as shown in Figure 1.2. Between 2013 and 2016, Total Primary Energy Demand (TPED) (expressed in tonnes of oil equivalent [toe]) increased residually and CO_2 emissions stagnated, despite the solid economic expansion. This successful decoupling was primarily the result of strong energy efficiency improvements and low-carbon technology deployment [2].

However, the scenario regressed in 2017 and 2018, due to intensified economic progresses and more evident effects of climate change [2]. In 2017, global consumption and CO_2 emissions rose by more than twice and almost four times the respective average growth of the previous years, also as a result of weaker efficiency efforts and lower fossil fuel prices [3]. In some parts of the world, unusually drier, hotter or colder weather boosted emissions and electricity demand for air conditioning: Europe experienced a 16% increase in Cooling Degree-Days and a harsh drought, particularly Southern Europe, that sharply reduced hydropower output, imposing more fossil fuel-based power generation [4]. In 2018 the demand and emissions grew even more, into 14.3 Gtoe and 33.1 Gt respectively. Unfavourable

[a] This work was written using British spelling, thus large amounts' nomenclature complies with the short scale: 10^9 corresponds to "billion" and 10^{12} to "trillion", as is used in modern Britain and the United States (but not in most of continental Europe).

weather conditions were responsible for a fifth of the increases in electricity and total consumption: average winter and summer temperatures approached or exceeded historical records, with cold snaps but, more significantly, very high temperatures and prolonged heat waves skyrocketing air conditioning demand [2]. In Europe, the heat record was nearly broken in August as temperatures in parts of Spain and Portugal crept above 48°C [5]. Globally, 2018 ranked as the fourth hottest year on record [2].

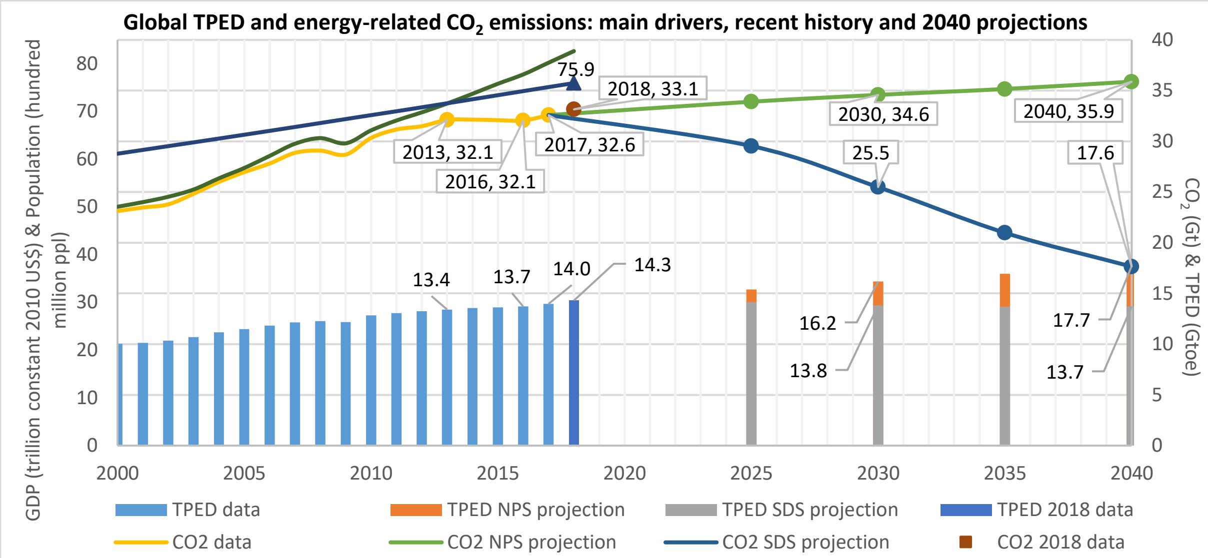

Figure 1.2 - Global TPED and energy-related CO_2 emissions: main drivers (Population and Real GDP[b]), recent history updated with 2018 data, and 2017 to 2040 projections under two scenarios (adapted from [2], [6], [7])

The Paris Agreement (December 2015, effective November 2016) comprises GHG mitigation actions for 2020 onward, and for the first time extends these obligations to all nations [8]. Its goals are ambitious: to limit temperature rise by 2100 to well below 2°C above pre-industrial levels and strive to curb it to 1.5°C. To do so, countries must reach global peaking of GHG emissions as soon as possible and then undertake rapid reductions, in order to attain a balance between anthropogenic emissions by sources and removals by sinks, i.e. net-zero emissions, in the second half of this century. The Agreement is founded on Nationally Determined Contributions (NDCs) outlining each country's highest possible ambition: these are to be revised and strengthened every five years, current NDCs (covering 2020 to 2030 or 2025) totalize 96% of world's CO_2 emissions, and most include quantitative reduction targets [8].

According to International Energy Agency's projections [6], by 2040 – in a world with 20% more people (mostly in urban areas of developing economies) and more than double the GDP – if there was no change in policies from today as in the Current Policies Scenario (mid-2018 legislation only), there would be severe strains on nearly all aspects of energy security (access and grid stability), with major rises of 39% in TPED and 30% in energy-related CO_2 emissions from 2017 levels – into roughly 19.4 Gtoe and 42.5 Gt [6]. Under current and planned policies (including the NDCs) of the more realistic New Policies Scenario (NPS), those growths are alleviated to 27% and 10%, denoting a combination of efficiency and decarbonisation actions – but energy and emissions still rise, linearly, as shown in Figure 1.2.

The Sustainable Development Scenario (SDS) outlines the fulfilment of the United Nations' Sustainable Development Goals on climate change (stipulated under the Paris Agreement), air quality and universal

[b] Real or Constant GDP refers to GDP adjusted for inflation (base year: 2010), its annual variation rate represents GDP Growth.

access to modern energy [6]. As part of its strategy: the power sector proceeds further and faster with the deployment of low-carbon generation, renewables pave the way to worldwide energy access, and all economically viable options to improve efficiency, using currently available technologies, are pursued. In a sustainable 2040, today's demand would be maintained while nearly halving energy-related GHG and CO_2 (Figure 1.2). Emissions would peak before 2020 and decline steeply after 2025 – on course towards reaching net-zero by 2070 and a global median temperature rise by 2100 of 1.7°C to 1.8°C above pre-industrial levels [6].

The rebounds of 2017 and 2018 reveal that the energy sector is off track, and in the projected 2040, only less than 30% of the required savings from Current Policies Scenario's levels (both in TPED and CO_2) derive from planned measures: NPS doubles the desired emissions, a worrying gap remains between where the world is heading and where it needs to go [6]. Nonetheless, the accelerated clean energy transition incorporated in the SDS highlights the sector's potential and paths to take. Worldwide efforts must target both supply and demand: progress in Electrification, Decarbonisation and Energy Efficiency (as well as an investment boost) must be substantial and simultaneous [9].

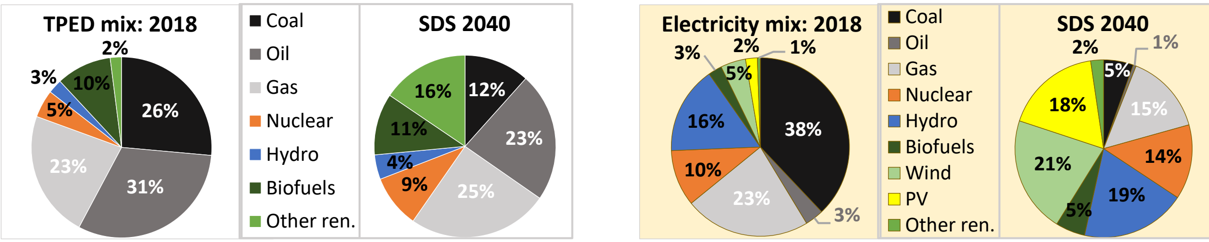

Figure 1.3 - Global energy demand (TPED) and electricity generation by source, in 2018 and the SDS (adapted from [2], [6])

The electricity share in Total Final Consumption (TFC) rose to almost 20% and is on course towards SDS's target of 28% by 2040 [9], with 'the fuel of the future' growing at nearly twice the rate of energy demand to over 23 PWh in 2018 [2]. The shift to powered technologies is happening through electric vehicles and freight in the transport sector, electric cooking, appliances, air and water heating in buildings, and changes in industry. However, the carbon intensities of both electricity and total energy have been significantly off track [9]. As shown in Figure 1.3, the combined share of fossil fuels in global TPED stayed at 81% in 2018, a level that has remained stable for more than three decades despite strong growth in renewables [2]. A substantial amount of new nuclear capacity saw its second full year of operation, accounting for 5%, while renewables supplied merely 14%. To fulfil SDS goals, by 2040 these shares must transform to 60%, 9% and 31% respectively, driven by wind and solar energies – and a slight singular rise in gas [6]. The latter derives from the fact that, while not all industrial processes can easily shift to power, on average fuel switching from coal to gas reduces both CO_2 and methane emissions by a third when providing heat (and a half when producing electricity), thus gas will continue to replace coal-fired industrial and residential boilers as it has been[c] [10].

As for electricity generation: in 2018, the fossil, nuclear and renewables shares were 64%, 10% and 26% [2] while the SDS intends for a complete reversal of sources – 21%, 14% and 66% – a rupture from thermal power, with coal and oil nearly disappearing from the mix, supported by a drastic expansion of wind (especially offshore) and solar Photovoltaic energy (PV) (especially decentralised) [6]. Although growing at double-digit in 2018, renewables pace of deployment still fell short to meet the rise in power

[c] Furthermore, gas grids can eventually also deliver decarbonised gases, like renewable methane and hydrogen [10].

demand and remains short of that needed [2]. A strong boost to the full range of low-carbon options, in combination with early retirement of coal-fired plants, coal-to-gas switching – as well as Carbon Capture, Usage and Storage (CCUS) technology – is necessary to reshape the supply side [9].

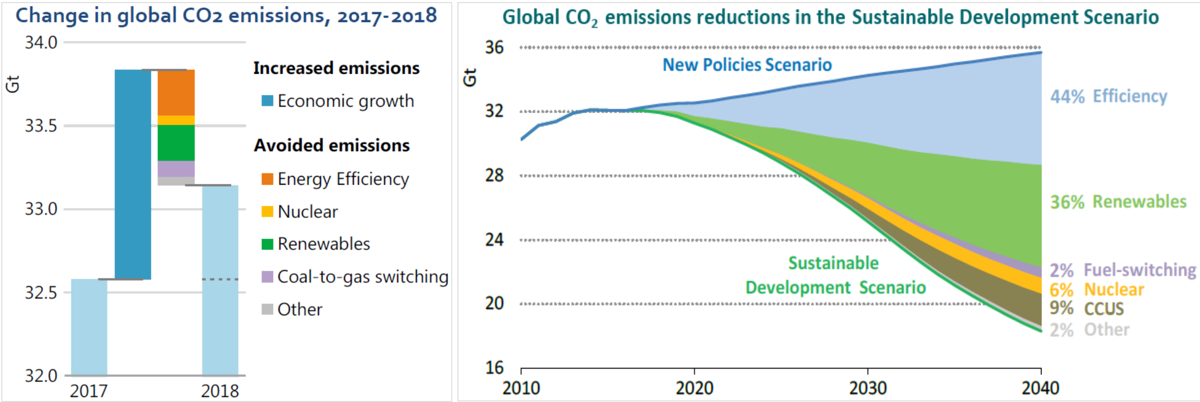

Figure 1.4 - Reduction of global energy-related CO_2 emissions by measure: in 2018 from economic growth's estimated impact (on the left), and by 2040 under the SDS from the NPS (on the right) (adapted from [2], [4])

If there weren't any measures in place to cap economic growth's impact, global energy-related CO_2 emissions' rise would have more than doubled in 2018, estimatedly, as shown in Figure 1.4. Renewables accounted for 31% and energy efficiency efforts for 40% of the avoided emissions [2]. The same applies when comparing 2040's projected emissions under the SDS and NPS: efficiency provides almost half of the abatement needed to veer from the future we're heading to the one we must grasp, more than any other technology. Fully realising existing cost-effective efficiency potential by 2040 would lower NPS's TPED by 23%, NPS's TFC and emissions by a similar stake, keep energy demand close to 2017's level while singularly cutting energy-related emissions by 12%, and key air pollutants (such as sulphur dioxide, nitrogen oxides and particulate matter) by one third [4].

Energy efficiency – 'the first fuel' – is the one energy resource that all countries possess in abundance [11] and has been the key decoupling driver [9]. Without efficiency progress across all sectors, increased economic activity would have had a greater impact on the energy system: since 2000, efficiency improved by an estimated 13% globally [9], without which both 2017's TFC and energy-related GHG emissions would have been 12% higher [4]; in the world's major economies, a 15% overall progress offset more than one-third of the GDP growth's impact, preventing over 14% more final energy use and 20% more fossil fuel imports in 2017 [4]; and in 2018 for most of these economies, improvements since 2000 avoided 20% more TFC and over 15% more financial energy expenditure [11]. Government policies have been pivotal in attaining these gains, but in recent years, a weakened progress in implementing new and increasing the coverage and stringency of existing policies has slowed down global improvements. As so, even though it remained the biggest source of emissions cut in the energy sector (Figure 1.4), efficiency offset 40% less CO_2 emissions in 2018 than in 2017 [2].

Energy efficiency is one of the most powerful and cost-effective ways to address climate change and air pollution, boost supply reliability and countries' security by reducing fuel imports, even save consumers money, while enabling a sustainable economic growth [4]. Yet, efficiency is off track, a sharp pick-up in improvements is urgent. Currently, only 35% of global TFC is covered by mandatory policies [11]. Governments need to anchor energy efficiency as the basis of clean transition plans, redouble efforts to design and enforce the correct balance of regulations, codes, standards and market-based policies [3].

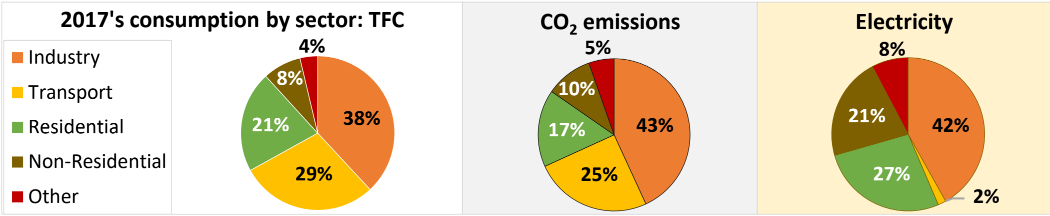

Figure 1.5 - 2017's global TFC, energy-related CO_2 emissions and electricity consumption by sector (adapted from [8], [12])

Figure 1.5 illustrates a breakdown of 2017's global total final energy (9.72 Gtoe [12]), total CO_2 emissions, and electricity consumption (1.84 Gtoe or 21.37 PWh) by the major end-use sectors: industry, transport and buildings (residential and non-residential [commercial and public]). Each of these amount to around one third of TFC, with industry taking the lead. While transport's and buildings' shares slightly drop to one quarter of emissions, industry's rises even more to almost one half. This is due to the fact that while most of transport's and buildings' consumption takes place in developed countries, most of industry's occurs in Asia, which is heavily reliant on coal-fired plants, so more carbon intensive [8]. As for power: buildings account for one half, industry slightly less and transport isn't visibly electrified yet.

Buildings is the largest consumer of electricity and the second biggest emitter of energy-related CO_2, with the residential consuming almost three times more final energy and consistently outweighing the non-residential sub-sector. When adding the construction industry (the portion of industry responsible for the manufacturing of construction materials), buildings become accountable for nearly 36% of TFC and 40% of emissions, instead of the 29% and 27% derived from operational energy use only.

Buildings demand continues to rise, driven by a rapid growth in global constructed floor area, improved access to energy in developing countries, and greater ownership and use of consuming devices. In 2018, buildings' TFC and total energy-related CO_2 emissions share grew to 3.1 Gtoe and 28%, respectively [5]. Buildings' CO_2 rose for the second year in a row to 9.6 Gt, as recently the demand for energy services – particularly electricity for cooling, appliances and other plug loads – is growing at a faster pace than decarbonised power availability. Enormous potential remains untapped due to the widespread use of less-efficient technologies, insufficient investment in sustainable buildings and a lack of effective policies – in 2018, only about 40% of buildings' TFC was covered by policies [5]. Overall according to the SDS, buildings by 2040 could be 40% more efficient than today (use 40% less energy per floor area), and global buildings demand could stay at current levels despite a 60% growth in total floor area [4].

Appliances, the second fastest-growing end-use in buildings, shows no signs of decelerating. Household appliances alone reached more than 3 PWh in 2018, so over 50%, nearly 30% and 15% of residential's, buildings' and overall final power demand respectively, with major appliances consuming only one third [5]. Consumer electronics, connected devices and other small plug-loads are proliferating rapidly, their energy use, unregulated in most countries, has grown twice as fast as major appliances' over the past decade. Inversely, lighting, previously a major consumer, now accounts for only 7% of buildings power consumption, thanks to technology breakthroughs and good policies. The phase-down of conventional incandescent lamps, although leading halogens (marginally more efficient) to grow, prompted a shift towards fluorescents (four times more efficient) and Light-Emitting Diodes (LEDs) – almost twice as efficient as fluorescents. With performances continuously significantly rising, LED uptake has expanded greatly in recent years and is expected to continue towards becoming the global norm, as intended [5].

Space cooling is the fastest-growing end-use and the leading driver of new power demand in buildings [13], due to an increased penetration of cooling equipments – Air Conditioning units (ACs) and electric fans – led by higher temperatures, populational and economic growth [4]. Cooling's global demand and CO_2 emissions have tripled since 1990 to over 2 PWh and 1.1 Gt in 2018, despite progress in average AC performance and power's carbon intensity, and already accounts for 20% and 10% of buildings' and overall electric consumption [5]. Harsh weather was one of the reasons behind recent emissions growth: 2018 was an exceptionally hot year, extreme heat set records in many sites, and energy used for cooling worldwide was an estimated 5% higher than in 2017, which had already been a hot year. A rapid growth in ownership in emerging economies also contributed to a 15% rise in sales, making it to over 1.6 billion ACs currently around the world. Naturally, local air pollutant emissions are on the rise as well [5].

ACs use is becoming increasingly common, but their efficiency can vary widely[d] and be underwhelming. Most units purchased are often half as efficient, if not less, than the best available technologies; in fact, the typical efficiency of ACs being sold in major cooling markets is not much better than the available product minimum. Consequently, cooling's rising demand is putting a huge strain on the power system, impacting distribution and generation, imposing capacity additions, especially during peak consumption periods and severe heat events [5]. Globally, today less than a third of households owns an AC, by 2050 that could grow to two thirds, which amounts to ten ACs sold every second until then. AC use is expected to become the strongest driver for buildings and the second strongest for overall power demand (after industry) so, without any action, cooling's TFC could more than triple by 2050, largely surpassing SDS targets [13]. Averting this 'cold crunch' entails major efficiency efforts (mandatory minimum energy performance standards): the average efficiency of ACs sold needs to jump by over 50% by 2030, which already exists on the market. Those should be paired with demand-side management tools, like smart thermostats and other improved controls that optimise the load distribution, reducing peak's impact [5].

On the other hand, global energy use and emissions from space and water heating have remained stable since 2010, and space heating is still the largest end-use, with 36% of buildings TFC. Despite efficiency improvements in markets, fossil fuel-based and conventional electric, like electric resistance and electric water heaters, continue to represent over 80% of heating equipments worldwide (excluding traditional use of biomass). Sales of heat pumps – high-performance electric apparatus – are on the rise, particularly as a side effect of cooling's increasing demand on the purchasing of air-source reversible units (reversible ACs, e.g. mini-split). Nonetheless, heat pumps and solar thermal technology supplied a residual share of 2018's heating needs: aligning with the SDS implies a drastic shift, tripling their sales share by 2030, and a switch to high-performance fossil fuel-based solutions (like condensing gas boilers with efficiencies typically above 90%) at the very least. District heating continues to meet a large portion of (especially space) heating demand in China, Russia and other parts of Europe; yet, significant effort is needed as well to cut its global carbon intensity (which is mainly due to China's reliance on coal) [5].

But, a building's demand for mechanical space cooling or heating is primarily, intrinsically linked to its own energy efficiency, its design, characteristics and features, its thermal envelope, construction materials and techniques, the passive solutions initially encased and the ones operationally employed. An optimised envelope is of extreme importance to avoid and diminish air conditioning needs, however, global buildings sector continues to lag behind [5]. Most nations have not made envelope performance improvements an explicit policy priority: many lack a building energy code, while code stringency

[d] E.g., ACs sold in the European Union and Japan are typically 25% more efficient than in the United States and China [13].

remains limited or voluntary in most codes in place. In 2018, two thirds of countries lacked mandatory codes, which translated to 45% of floor space built without compulsory performance requirements [5].

Highly efficient buildings that promote passive thermal comfort and require extremely low active conditioning – like nearly Zero Energy Buildings (nZEBs) – constituted only 4% of the global floor area built in 2018, and make up a similar share across most markets [5]. However, there are bright spots: France is a market leader, with a code that forces all new constructions to fall under its nZEB definition, and e.g., in Austria, Belgium and Italy, over 20% of 2018's new residential builds were nZEBs. Beyond new constructions, it is imperative to remind that buildings already standing will amount to a considerable portion of 2050's total stock. Energy renovation's typical annual rate is 1% to 2% of the stock, with an average energy intensity (energy use per floor area) improvement below 15% [5].

Action to establish, upgrade and enforce building energy codes is urgent, these will need to impose high performance envelopes as the new construction norm; deep large-scale refurbishments must be a policy priority as well. In sum, to achieve long-term sustainability, by 2030: all nations must move towards obligatory codes, dropping the non-mandatory code share in global construction to 17%; nZEBs must soar, escalating by more than thirteen times (in new floor area) into a 51% share; energy renovations must double their depth to at least a 30% to 50% energy intensity improvement [5]. Ideally, considering also renewable production on-site for all new builds, policies instating Net Zero Energy Buildings (NZEBs) – high-performance buildings that produce the same energy they consume in typically a yearly amount – should be in force by 2020 in advanced and 2030 in emerging economies [4].

The European Union (EU) is a leader in regulatory policies towards nZEBs, having published the first version of the Energy Performance of Buildings Directive (EPBD) in 2002, recast it in 2010 (Directive 2010/31/EU) [14], and amend in 2018 (Directive 2018/844/EU) [15]. The latter increases the stringency, encourages the cost-effective renovation of existing buildings into a highly efficient and decarbonised stock by 2050, promotes smart technologies and electric vehicles recharging in buildings. In 2019, the European Commission published its second Recommendation, explaining in more detail the amend, to ensure a uniform understanding across Member States in the preparation of their transposition measures.

The EPBD imposes that since 31 December 2018 all new public buildings and after 31 December 2020 all new buildings must be nZEB; Member States shall draft national plans, also regarding current stock's renovation into nZEB. Article 2 Point 2 reads: «'nearly zero energy building' means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby» [14]. The amended Annex I states that «The energy performance of a building shall be determined on the basis of calculated or actual energy use and shall reflect typical energy use for space heating, space cooling, domestic hot water, ventilation, built-in lighting and other technical building systems. The energy performance of a building shall be expressed by a numeric indicator of primary energy use in kWh/(m^2.y) for the purpose of both energy performance certification and compliance with minimum energy performance requirements. (…) The energy needs (…) shall be calculated in order to optimise health, indoor air quality and comfort levels defined by Member States at national or regional level» [15].

So, the EPBD sets the standard for all buildings, taking into account indoor comfort requirements and cost-effectiveness: EU countries must set cost-optimal minimum energy performance requirements for new buildings, existing buildings undergoing major renovation and components' replacement or retrofit, and also issue an energy performance certificate when a building is sold or rented.

1.2. Objectives

The objective of this dissertation is to successfully project a Net Zero Energy Home (NZEH) in the Mediterranean climate, by applying gathered knowledge on passive strategies and high performance construction, so that it:

- attains thermal comfort in a hybrid Heating, Ventilation and Air Conditioning (HVAC) mode of intermittent operation;
- ensures a satisfactory comfort index in full free-running mode, by exhibiting thermal discomfort on a maximum of 10% of the occupied hours;
- achieves the *Passivhaus Institut*'s new Low Energy Building standard, or even the Passive House Classic's energy requirements.

1.3. Overall Framework

Chapter 1 provides the background, including of the sector. Chapter 2 provides the theoretical basis of the Mediterranean climate and the low energy building. Chapter 3 gives an idea of how far the building industry is from where it should be, and the technical challenges of designing buildings in the Mediterranean climate. Chapter 4 shows an analysis of climatic data and the finding of the construction site. Chapter 5 explains and displays the footprint, windows, doors and overhang, all designed on SketchUp. Chapter 6 refers which construction were used and of which materials, based on a premium reference. Chapter 7 provides all of the house controls, schedules and energy inputs. Chapter 8 is the Results Analysis thus shows the results of the energy simulation. Chapter 9 draws some conclusions and potential futute work.

Chapter 2 – Theoretical Background

2.1. The Mediterranean Climate

The Mediterranean climate is the less extensive of the meso-thermal climates, according to the 20th century geographical classification system developed by the German climatologist Wladimir Köppen, which continues to be the authoritative map of the world climates in use today [16]. Currently, the upgraded version of the Köppen classification [17] uses six letters to divide the world into six major climate regions, based on average annual precipitation, average monthly precipitation and average monthly temperature. According to this classification system, the Mediterranean climate is defined as a warm temperate climate – type 'C' –, of dry summer – subtype 's' – typical but not exclusive to the Mediterranean Basin; this classification subdivides further in hot long summer, 'Csa', or warm summer, 'Csb' [17]. Köppen defined this climate as the area where:

- the mean temperature of the coldest month is between -3℃ and 18℃;
- the summer season is generally dry and the rainfall amount of the wettest month is at least three times greater than that of the driest month;
- the mean temperature of the warmest month is above 22℃;
- the mean annual rainfall amount (in mm) is over 20 times higher than the mean annual temperature (in ℃) [17].

The first three conditions also refer to semiarid and arid regions adjacent to the Mediterranean climate zones; thus, the crucial difference between the Mediterranean and adjacent arid climate zones is the mean annual rainfall [16]. The Mediterranean climate arises indeed as a combination of climates, approaching the oceanic ('Cfb' an 'Cfc') for the rainy winters, and the desertic arid ('BW') and semiarid ('BS') for the dry summers [17].

This climate – subtypes 'Csa' and 'Csb' – occurs mainly on the western coastlines around the 40° of latitude, both North and South, as roughly shown on Figure 2.1.

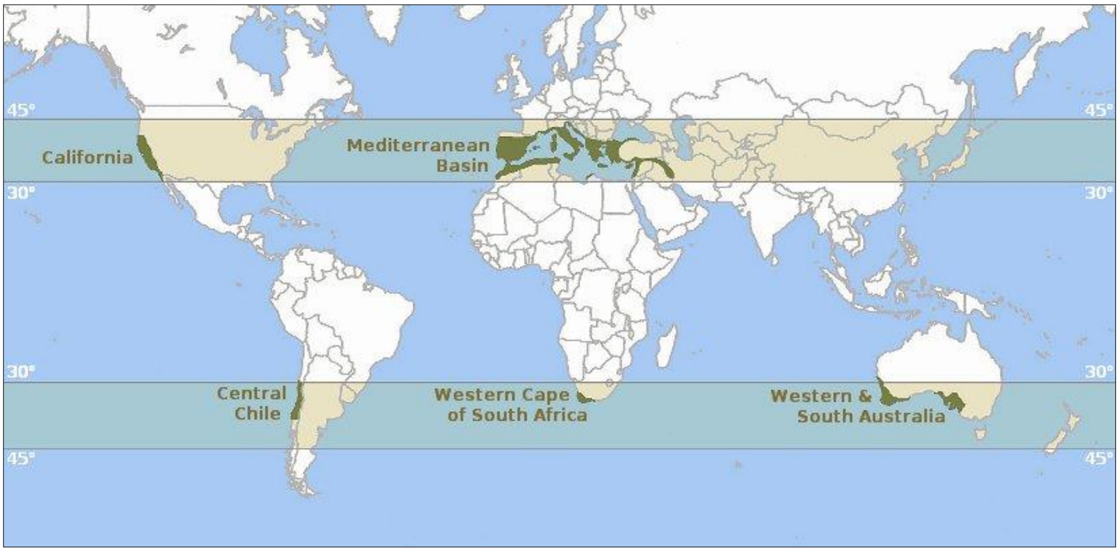

Figure 2.1 - World map of the Mediterranean climate zones [18]

2.2. The Low Energy Building

Many definitions of low and zero energy building exist [17]. In [19], the authors presented four well-documented and validated definitions of Zero Energy Buildings (ZEB)s:

1) Net-zero site energy: a site ZEB produces at least as much energy as it uses in a year, when accounted for at the site (secondary production=secondary consumption). This encourages energy-efficient designs, and the performance is verifiable through on-site measurements;
2) Net-zero source energy: a source ZEB produces at least as much energy as it uses in a year, when accounted for at (from the point of view of) the source; source energy refers to the primary energy used to generate and deliver the energy to the site; to calculate a building's total source energy, imported and exported energy are multiplied by the appropriate site-to-source conversion multipliers (primary export=primary import, supply to the grid=demand to the grid). This is a better model to assess the impact on the national energy system;
3) Net-zero energy costs: in a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount of money the owner pays the utility for the energy services and energy used over the year. The performance is verifiable from utility bills and requires net-metering (two-way) agreements, which are not well established, often have capacity limits and purchase rates (feed-in tariffs) much lower than the retail rates;
4) Net-zero energy emissions: a net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources ('Zero Carbon Building'). This is a better model for green power, but implies appropriate emission factors [19].

This dissertation's ZEB is thus a net-zero site energy, with energy assessment only at the site, also called a Net Zero Energy Building (NZEB), where 'Net Zero' refers to the null annual balance between the building's production and consumption. As the projected building is a residential detached house, it will be a Net Zero Energy Home (NZEH).

2.2.1. The Passive House Standard

Among high performance buildings and building energy certification schemes and standards, one stands out in Europe: the german Passive House, from the *Passivhaus Institut* (PHI). Passive House buildings are characterised by especially high levels of indoor comfort with minimum energy consumption. The Passive House Standard offers excellent economic efficiency especially for new builds, and is achieved through intelligent design and implementation of five basic construction principles (for central European and cool climates) [20]:

- quality thermal insulation: the opaque external envelope must be very well-insulated. For most cool temperate climates, a maximum heat transfer coefficient (U-value) of 0.15 W/m².K is implied;
- superior windows: the window frames must be well insulated and fitted with low-e glazings filled with argon or krypton. For most cool-temperate climates, this means a U-value of 0.80 W/m².K or less, with a total solar transmittance (g-value) around 50%;

- absence of thermal bridges: all edges, corners, connections and penetrations must be planned and executed with great care. Thermal bridges that cannot be avoided must be minimised as much as possible;
- airtight construction: uncontrolled leakage through gaps must be smaller than 0.6 air changes per hour (ach) of the total house volume during a pressure test at 50 Pa (ACH50) (in both pressurised and depressurised states);
- ventilation with heat recovery (HRV): efficient HRV provides good indoor air quality and energy savings. Through the heat exchanger, at least 75% of the heat in the exhaust air is transferred to the incoming fresh air.

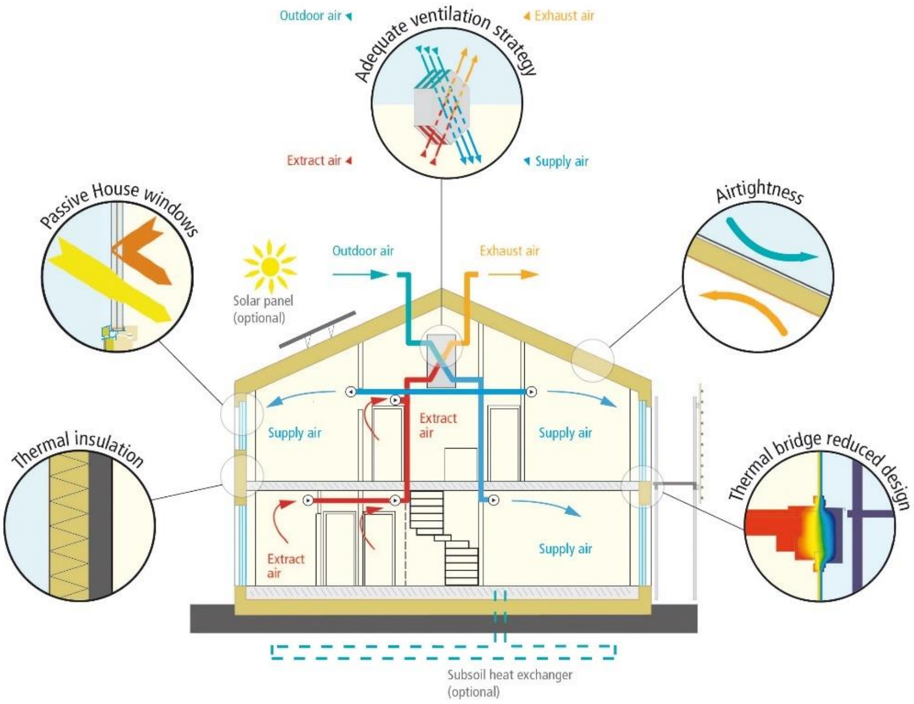

Figure 2.2 - Basic principles in Passive House construction [20]

Currently, for a building to be certified as a Passive House, it must satisfy the following requirements:

1) space heating (useful) energy demand cannot exceed 15 kWh/m².y of treated floor area (TFA) – which is the sum of the floor area of all habitable rooms. In climates where active cooling is needed, the space (sensible) cooling demand requirement agrees with the space heating threshold, and an additional fraction for dehumidification (latent cooling) is allowed;
2) the Renewable Primary Energy demand (PER), the total energy consumption of all domestic applications must not exceed 60 kWh/m².y of TFA, for the Passive House Classic class;
3) the air infiltration that cannot exceed 0.6 ach, which is verified through the onsite pressure test;
4) thermal comfort must be met for all living areas during winter as well as in summer, with a maximum frequency of overheating (operative temperatures above 25℃) without active cooling (so in free-floating mode) of 10% of the yearly occupied hours;
5) Passive House buildings are planned, optimised and verified with the PHI’s Passive House Planning Package (PHPP) tool [20].

The PHPP establishes a constant thermostat for the Heating, Ventilation and Air Conditioning (HVAC) system of 20℃ of operative design temperature for heating (in residential buildings) and 25℃ for cooling [21]; this tool classifies overheating rates as: between 0% and 2% excellent, 2-5% good, 5-10% acceptable, 10-15% poor and above 15% catastrophic [22].

Both the thermal energy demand and the overheating rate thresholds will be attempted to meet in this dissertation, and the thermostat and maximum air infiltration rate will be respected.

Chapter 3 – State-of-the-Art

3.1. Energy challenges of buildings in the Mediterranean climate

Southern Europe's homes represent over one third of EU's residential stock [23], and the widespread use of ACs within them has led to a particularly alarming electricity consumption trend over the last few decades, that is increasing much quicker than TPED, GDP and population growth [24].

The climate in southern Europe is predominantly Mediterranean: temperate with long, dry and warm or hot summers. Thus, southern european cities present high temperatures, intense solar radiation, recurrent heat waves, and an aggravation of the Urban Heat Island (UHI), a local warming effect, due to climate change [23]. The UHI is a result of the anthropogenic heat sources and heavy density canyon of highly populated cities, as the closed-up geometry (narrow streets, tall buildings, few open spaces) constrains the wind flow and radiative fluxes[e]; its intensity varies between 2°C and 10°C in the Mediterranean area, causing an average rise of 11% in total energy demand and 23% in cooling load [24].

With climate change, southern Europe will be exposed to longer and more intense heat waves [23]. The predicted climate scenarios for the next 100 years foresee an increase of tropical nights (minimum temperatures above 20°C) and hot days (maximum temperatures above 35°C) for the Mediterranean basin. In fact, temperate and mid-latitude climates are projected to face the largest rise in energy consumption, due to the progressive widening of summer and elimination of the intermediate seasons, asserting that cooling will also be needed in spring and autumn [24]. To ensure population's comfort and avert a disastrous escalating of the cooling needs it is pivotal to move towards efficiently designed buildings, as the EPBD imposes. However, there are significant differences in the progress of nZEB's implementation across the EU [23].

In cold climates, there is only one season to attend to while designing a building – winter – because the summers are mild, and basic passive strategies are generally sufficient, discarding the need for an active cooling system. Projecting towards winter comfort is easier than summer's, as it implies one main task: to thermally disconnect the building from the environment so it can maintain its internal and solar gains, which is simply attained through the addition of insulation and strict air tightness. This knowledge has proven successful and is well established among cold countries. Consequently, EU's northern Member States were able to develop construction technologies or adapt from existing efficiency standards, like the Passive House Standard, draft and execute their nZEB national plans efficaciously. But in southern countries the nZEB market is still in the predevelopment phase, and it is not always possible to keep the cooling demand below Passive House's threshold of 15 kWh/m^2.year [23].

In southern Europe's Mediterranean climate, there is a balance between heating and cooling loads, a plausible need to install a dual active system, so a necessity to address both winter, summer, and their potential conflicts of design. For instance, if a winter-focused design is adopted following the techniques of the heating dominated climates: the risk of summer overheating will intensify, as the capacity of the passive strategy in place (usually night ventilation) may not be enough to remove the additional heat

[e] The wind is practically absent at street level, as its flow regime is greatly restrained. The urban canyon enhances radiative trapping by creating multiple reflections between neighboring surfaces, during both daytime for the solar shortwave and nighttime for the longwave radiation, hindering its exchange with the night sky (radiative cooling) [24].

trapped and accumulated over the days due to the exaggerated insulation level, ultimately imposing an unnecessary mechanical consumption. This thermal behavior is known as ‘over’ or ‘superinsulation’ and implies that there is a thickness above which insulation is undesired, since cooling needs rise (point of inflexion) [23].

The quasi symmetric heating and cooling needs of this temperate climate demands for a tailored set of bioclimatic passive solutions to prevent, modulate and remove heat. Vernacular architecture strategies – like solar shading, evapotranspiration, evaporative cooling, thermal inertia, earth sheltering, natural ventilation and cool colors – are ancient Mediterranean techniques, still appropriate, efficient and adaptable today. Nevertheless, these too present challenges and limitations: natural ventilation at homes must consider other outdoor and human aspects like pollution, insects, noise, privacy, tresspass and safety; although the daily thermal amplitude of Mediterranean summer is set to be wide (due to clear sky conditions), at metropolises and coastal cities most nights’ temperatures are not low enough for natural ventilation to be effective, contributing to an overheating risk; this is caused by the UHI effect and the proximity to sea’s enormous inertia tank, respectively, while the latter may also introduce dehumidification concerns. In conclusion, highly efficient buildings in the Mediterranean climate require a careful and thorough design, and so specific expertise and skills [23].

3.2. Current knowledge on efficient construction in the Mediterranean climate

Energy efficient and bioclimatic buildings require a careful and thorough design, specific expertise and skills [23]. However, in most Mediterranean countries the buildings professionals’ know-how is (very) limited, as can be verified for six European and Mediterranean countries in Table 3.1. (shortened from 2017’s [23]).

Table 3.1 - Summary of nZEBs status in Southern Europe in 2017 (adapted from [23])

	Cyprus	France	Greece	Italy	Portugal	Spain
Legislation						
Definition nZEB available	Yes National Plan is in place	Yes, with Positive Energy Buildings and Low Carbon label	Not a concrete one (leg. 4122/2013)	yes	yes, National Plan is in place[e]	no, under development foreseen 2018
Min threshold set	Yes	Yes	no	Yes; Not explicitly in term of kWh/m^2; primary energy should be lower than in the baseline building; hence it depends on S/V, window/wall ratio	no	no
CO_2	no	yes, building + operation[g]	no	no	no	no
Thermal Comfort Limits						
Overheating risk	Yes	Feedback in progress for hotter climatic zones	There is high overheating risk in case of not proper design of ventilation and building insulation.	yes (20,000 deaths)[k]	yes, high risk (also high winter mortality)	
Construction Quality						
available materials	low	yes	low	low	medium	medium
available knowledge	low	medium	low	low	low	low

[e]However, numerical indicators are not exactly stated and they depends on several variables including technical viability, climate, type of construction, traditions, etc.
[g]Level "Carbon 1" overall impact of the building (building + operation) and Level "Carbon 2" impact of the construction only (non-operating).
[k]The health consequences of the combination of high temperature and low quality building envelopes were quite heavy with 20,000 deaths in summer 2003.

The table indicates which countries had implemented nZEB policy strategies at that time – in 2017, Greece and Spain did not yet have national plans in place to achieve 2020's EPBD nZEB targets. France goes beyond by additionally setting carbon emissions targets. The overheating risk and consequent mortality are indeed a reality in Southern Europe, and the construction quality, both in available materials and knowledge is consistently low, except for France.

In most southern Europe's countries, architects and building engineers generally do not have a comprehensive understanding of bioclimatic design integration, of correct adaptations and improvements of passive techniques, of suitable innovative technologies and standards, which leads in many cases to inefficient constructions and higher initial costs, due to the need of compensation with additional non-maximised energy efficiency solutions and oversized renewable energy systems. In fact, the potential and limits of passive strategies are often either overlooked or overestimated, with a general lack of optimised design (e.g. of horizontal overhangs) and impact quantification [23].

Bioclimatic design concepts and lessons from Mediterranean vernacular architecture have been partially forgotten and absent from last decades' standard practices. In that time, poor design, construction and documentation were prevalent practices (and are not uncommon still today) [23]. Consequently, Southern Europe's current stock is not prepared for global and urban warming, and the overheating risk's increase.

In [22] through extensive simulations of a real portuguese building case, the authors found that "with common building envelope solutions and construction materials, typically used in Portugal, simulations showed long periods of thermal discomfort for the heating season, as well as long periods of overheating during the summer". The same was found during heat waves in Athens, Greece [25].

The health penalties of combining high temperatures with low-quality building envelopes are quite severe [25], thus the renovation of existing building stock is crucial and presents a large potential.

More than 25% of 2050's building stock is still to be built (and "the energy consumption and related GHG emissions of those new buildings need to be close to zero in order to reach the EU's highly ambitious targets" [23]). The southern european countries' strive towards energy efficiency is just beginning, since presently they are not ready, and did not carry out a smooth and effective transition into the EPBD's 2020 nZEB target [23].

A limited number of nZEBs are properly constructed and a very small share of the existing building stock is renovated each year, in southern Europe [23]. Practical experience and know-how are still missing. Reaching a nearly zero consumption standard requires a change in construction practices and assumptions, a revival and contemporaneous adaptation of Mediterranean bioclimatic architecture's principles and techniques, a prioritization of passive cooling strategies in a mixed-mode (with both passive and active thermal conditioning) imposing temperate climate, that has progressively more and more similarities with cooling dominated climates.

Chapter 4 – Analysis of Mediterranean Climatic Data

Given the broad worldwide distribution of the mediterranean climate and weather files availability, the data sample space was restricted to southern Europe. Comparing EnergyPlus' online weather database map [26] with Google Earth's Köppen-Geiger classified globe [27], the Excel stats files for 81 locations of apparent Csa or Csb climate were collected; all geographic coordinates, monthly averages of dry bulb temperature (T [°C]) and global horizontal solar radiation (G [Wh/m^2]) were compiled into a single spreadsheet; a generic text file (notepad) was created with the data and imported to Google Earth, pinning the localities on Köppen-Geiger's globe; all locations' climates were verified, 13 were excluded, resulting in a sample of 68 localities across 7 countries, of which 11 – situated on the north or centre of Portugal, Spain and Italy – present Csb's warm summer subtype and, accordingly, lower average temperatures throughout the year. These 11 are highlighted in Table A.1 of Appendix A (pg. 63), which contains the 68 localities' names, climate subtypes, annual averages of temperature and global radiation, and is ordered by nation from West to East: Portugal, Spain, France, Italy, Montenegro, Greece, Turkey.

4.1. Representative locality

The location that best represents the mediterranean climate's norm was chosen as the construction site for this dissertation's NZEH. To find it, the sample's temperature and global radiation means were drawn, and the localities whose values stayed close to those throughout the year were identified. For a constant monthly variation of 10% tops, a single compatibility between the two parameters arised: the city of Nice in southern France (43°39'N 7°11'E), with an annual variation relative to sample's mean of 3.1% and 3.3% for temperature and radiation, respectively. This proximity can be verified in Figure 4.1.

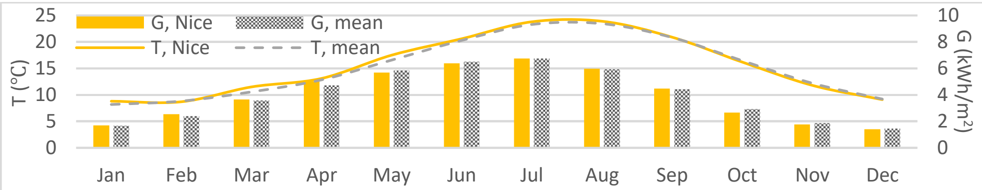

Figure 4.1 - Proximity of Nice to the sample's temperature and global radiation means

Figure 4.2 - Photographs of Nice, France [28]

Nice, shown in Figure 4.2, is a populous metropolis situated in *Côte d'Azur* or the French Riviera, the Mediterranean Sea's coastline in the southeast corner of France, next to Monaco, the Alps and the italian border. In order to analyse its Csa hot summer climate, additional data was collected from the weather stats file. Figure 4.3 presents a summary of the main climatic properties. The top left graph shows that: from late spring to late summer, Nice's mean temperature exceeds 20°C; the hottest months are July and August and the coldest January and February, hitting an absolute maximum of 30.6°C on 3rd July, a minimum of 2.0°C on 22nd February, and an annual average of 15.5°C. On the top right: Nice's mean global horizontal radiation is maximum in July and minimum in December, amounting to a yearly average of 4.0 kWh/m^2, while direct normal radiation reaches an absolute maximum of 8.5 kWh/m² on 21st June; air Relative Humidity (RH [%]) oscillates around its average of 71%.

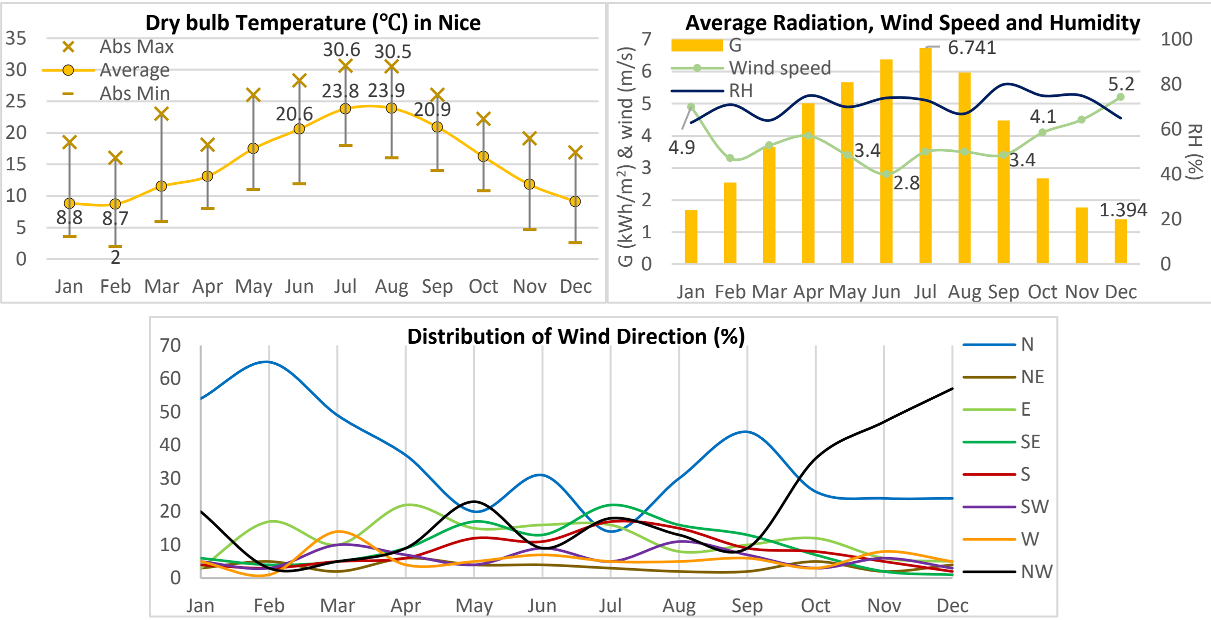

Figure 4.3 - Climate of Nice: monthly profiles of temperature, global radiation, relative humidity, wind's speed and direction

Still about the top right graph, Nice's wind speed pattern can be divided in three periods: strong currents with a mean speed above 4 m/s from October to January, with December as the windiest month, unstable average speeds from February to April, and a mildness around 3.3 m/s from May to September, with the weakest mean breeze in June; wind blows at an absolute maximum of 13.9 m/s on 7th October, 21st November and other instances, and at an annual average of 3.9 m/s. The bottom graph shows that wind's main direction is relatively consistent. In winter, North is clearly the prevailing direction; in spring and summer, the distribution is more balanced with NorthWest, SouthEast, South and East – the sea breeze is stronger during summertime; while in autumn, NorthWest takes the lead share. Still, as the northern wind blows at considerable levels year-round, it is by far the most predominant in Nice, while currents from SouthWest, West and NorthEast are considered negligible. In sum, the wind profile, thus, Nice's natural ventilation is characterized by the alternation between strong currents coming mainly from NorthWest in autumn and North in early winter (Oct-Jan), variable northern currents from mid-winter to early spring (Feb-Apr), and weaker breezes from North, NorthWest and SouthEast from mid-spring to late summer (May-Sep); the behaviour becomes evident upon observing Table A.2 (pg. 64), summarising Nice's data. This analysis was taken into consideration in the design and operation of the bioclimatic house.

4.2. Extreme temperature localities

To test the projected NZEH's climate sensitivity, the hottest and coldest localities of the mediterranean sample were assessed. The cities with the highest and lowest annual average temperature – 18.4°C and 9.9°C – hence, hottest and coldest throughout the whole year, are Seville and Burgos in the southwest and north of Spain, respectively. Seville is the capital and largest city of *Andalucía*, while Burgos is situated in the *Castilla y León* region and exhibits the Csb subtype, as expected.

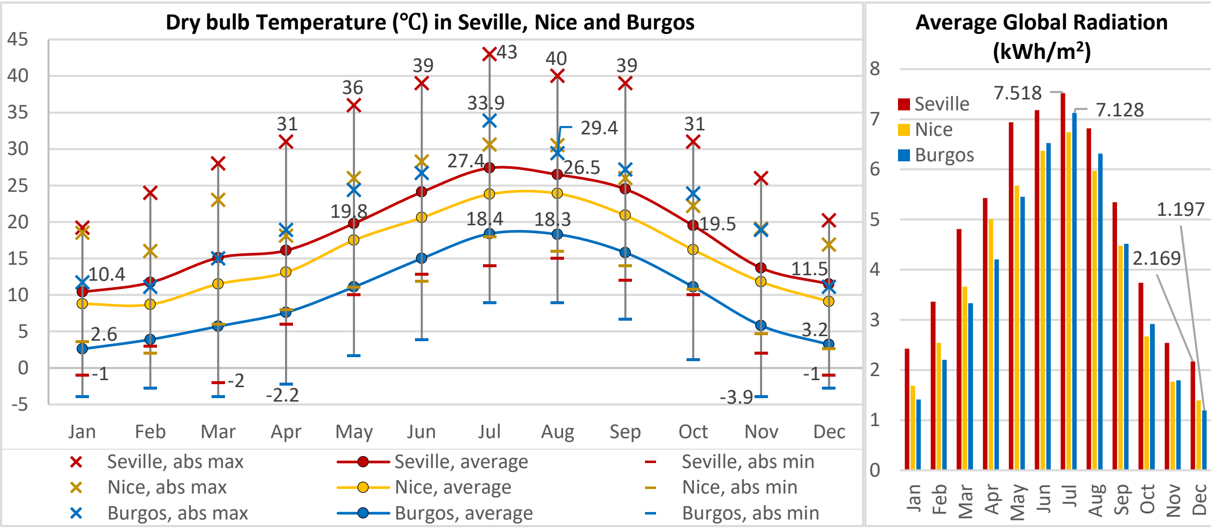

Figure 4.4 - Monthly profiles of temperature and average global radiation in Seville, Nice and Burgos

Additional data was collected from Seville's and Burgos' weather stats files as well. Figure 4.4 exhibits the temperature and global radiation profiles of the representative and the extreme-cities. Nice's mean temperature curve is closer to Seville's than Burgos' as they share a Csa subtype, and Seville's surpasses Burgos' by around 8.5°C consistently. Seville's mean curve exceeds 20°C from mid-spring to early autumn, presenting a wider and hotter summer, while Burgos never reaches that threshold with its mild Csb warm season. July is clearly Seville's hottest month, while the difference between July and August is minimal in Burgos, as in Nice; September is slightly hotter than June in all the cities. Seville hits unbearable absolute maximums starting in mid-spring with 36°C in May to 39°C in September, reaching an excruciating 43°C on 11th July. Unlike Nice, which exhibits both extremes really close to the mean, thus, a low thermal variability and amplitude, Seville isn't a coastal city affected by the thermoregulatory effect of the sea; moreover, Seville receives the highest levels of radiation all year long among the three cities. Burgos is also an inland city, and its average global radiation exceeds Nice's in summer and autumn (Jun-Nov), translating to slightly higher temperature maximums and 33.9°C on 30th July.

The coldest month in Seville and Burgos is January, followed by December. Seville's absolute minimums are really low, lower than Nice's throughout nearly the entire year, hitting -2°C on 2nd March. Burgos' mean curve falls below 10°C for half the year, mid-autumn to early spring (Nov-Apr), which corresponds to its absolute minimums dropping below zero, reaching -3.9°C on 25th November, 12th January and 20th March. The mean global horizontal radiation of all the cities is maximum in July and minimum in December, its annual average is 4.9 kWh/m^2 and 3.9 kWh/m^2, the direct normal's absolute maximum is 8.1 kWh/m² on 6th May and 10.9 kWh/m² on 22nd June for Seville and Burgos, respectively.

The weather stats files comprise the Heating degree-days (HDD) and Cooling degree-days (CDD) but only for baseline temperatures of 10°C and 18°C (or 18.3°C), which are about 5°C lower than the usual, so, must be based on a cold climates' standard. Nonetheless, Nice and Seville's files include the degree--days from AHSRAE's 2009 handbook: for a baseline of 10°C and 18.3°C respectively, Nice presents 117 HDD and 526 CDD, while Seville has 48 HDD and 1140 CDD – which is coherent with the graph above. Table A.2 (pg. 64) is comprised by three tables, one for each city, containing their geographic coordinates, the degree-days referent to the files own data, all the monthly values of temperature, average global radiation, relative humidity, wind speed and wind main direction. These show that Nice is windier than Seville, and that North is the prevailing direction across all cities (even though Burgos' wind data seem rather unreliable).

Figure 4.5 is a Google Earth picture of the Köppen-Geiger classified globe depicting the 68 localities of the data sample, with the cities of Nice, Seville and Burgos marked as the sun, fire and ice, respectively.

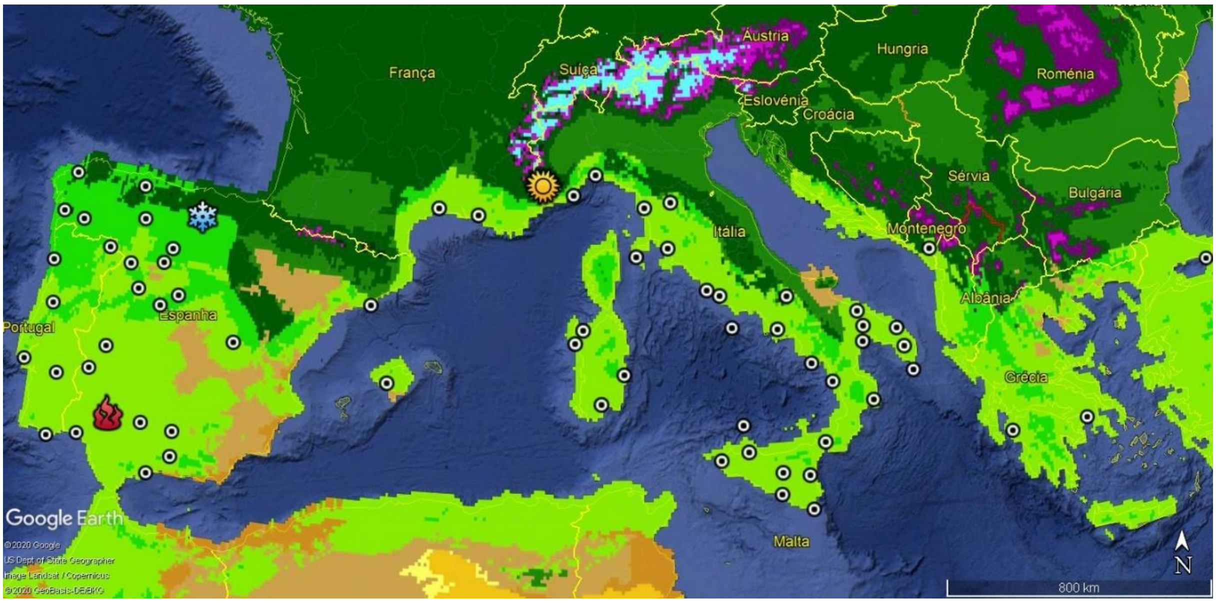

Figure 4.5 - Map of the climatic data analysis

Chapter 5 – Floor Plan and Design

For the building's 3D technical drawing, the software SketchUp [29] was used, with the OpenStudio [30] plug-in for the definition of thermal zones (now called 'spaces'), shading structures, and the file export feature; the energy simulation was then carried out on EnergyPlus [31] [32][f].

The building's typology is a single-family single-storey detached house, and it is occupied by two adults and two children. A sole floor was chosen since Nice's ground temperatures are mild, and a close contact with the soil's natural tank of thermal inertia is recommended for the Mediterranean climate.

5.1. Layout and Footprint

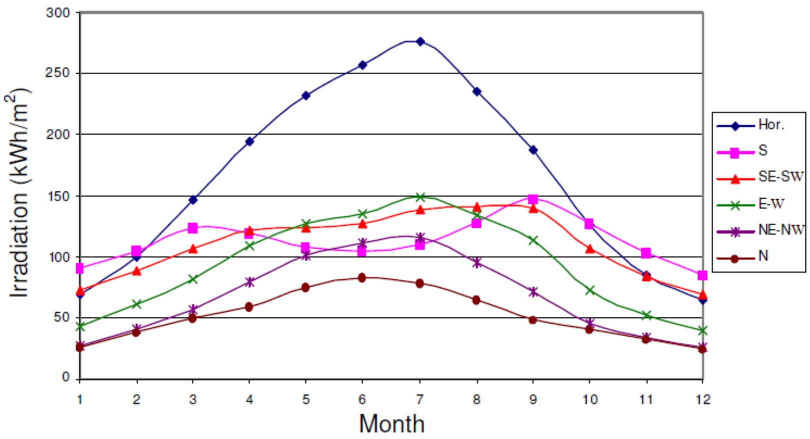

Figure 5.1 - Monthly Solar Insolation (sum) by orientation, for the North Hemisphere (adapted from [33])

The primary aspect to address when designing a building is orientation. Figure 5.1 shows the intensity of solar radiation throughout the year according to its direction, for a location in the North Hemisphere. Even though it does not refer to Nice (as such data wasn't included in Nice's weather stats file), the tendencies of the curves are valid anywhere in the hemisphere [33]. As seen above, South radiation trumps all others in autumn and winter, and decreases in spring and summer, making it the most desirable orientation for solar exposure. North, although good in summer, is the less advantageous annually, and East and West, while of intermediate levels before spring, pose the highest threat on summer.

In order to spare the bedrooms from the North's harshness on wintertime and the West exposure's aggravated risk of overheating on summer afternoons, a clear division in two sections was traced: the 'living area' to the West and the 'sleeping area' to the East, with a maximisation of the use of the South façade for habitable and conditioned (mechanically heated and cooled) zones. As shown on Figure 5.2, on the eastern section: the kids' individual bedrooms (BR1 and BR2) were placed facing South to provide the best natural lighting conditions, their bathroom (WC12) was placed on the border with the 'living area' to be easily accessed by guests as well, the corridor (CORR) provides access and

[f] The last free-of-charge version of SketchUp was Make 2017, so the last compatible versions of OpenStudio and EnergyPlus, 2.9.1 and 9.2 respectively, were used with it [32].

daylighting to the section, and the parents' suite (SUIT) was moved slightly North to assure privacy; to separate the latter from the cold enclosure, the suite's bathroom (WCSU) was placed along the North façade and NorthEast corner as a buffer zone, while still enjoying an operable East-facing window and the morning sun – previously, the walking closet was here and this WC was in the middle of the East façade to avoid overcooling, but that configuration implied an extension of the East-West walls, a decrease of compactness with exaggerated central corridor area, and an undesired square external shape with a reduction of the needed South wall.

The suite's walking closet (CLOS) was turned into the only internal room of the house, serving as the entry to the suite, this way replacing even more corridor area. Adjoining to the closet lies the main hall (HALL), placing the house entrance on the North side and connecting it solely to the 'living area'. The pantry (PANT), that once ran along the kitchen's whole North façade as a buffer zone, was changed into a small room between the hall and the kitchen, since it could severely hinder the Northern winds' night flushing of the living room (and amounted to an unnecessarily large area).

The West section is composed by a sunroom/laundry (SUNR) to the South, and an open concept of kitchen (KIT), dining and living room (DLIV) only apparently separated: to exclude the kitchen's area from the living room's air conditioning operation, the open concept was drawn on SketchUp as two thermal zones divided by a full-width full-height door that is permanently open. The sun gallery presents a narrow central wall with two wide collapsible glazed doors on the sides that open and close to the living room; although this partial internal wall may affect visual comfort and cross ventilation efficiency, used wisely, these buffer zones can have a significant thermal benefit, even in southern Europe [33].

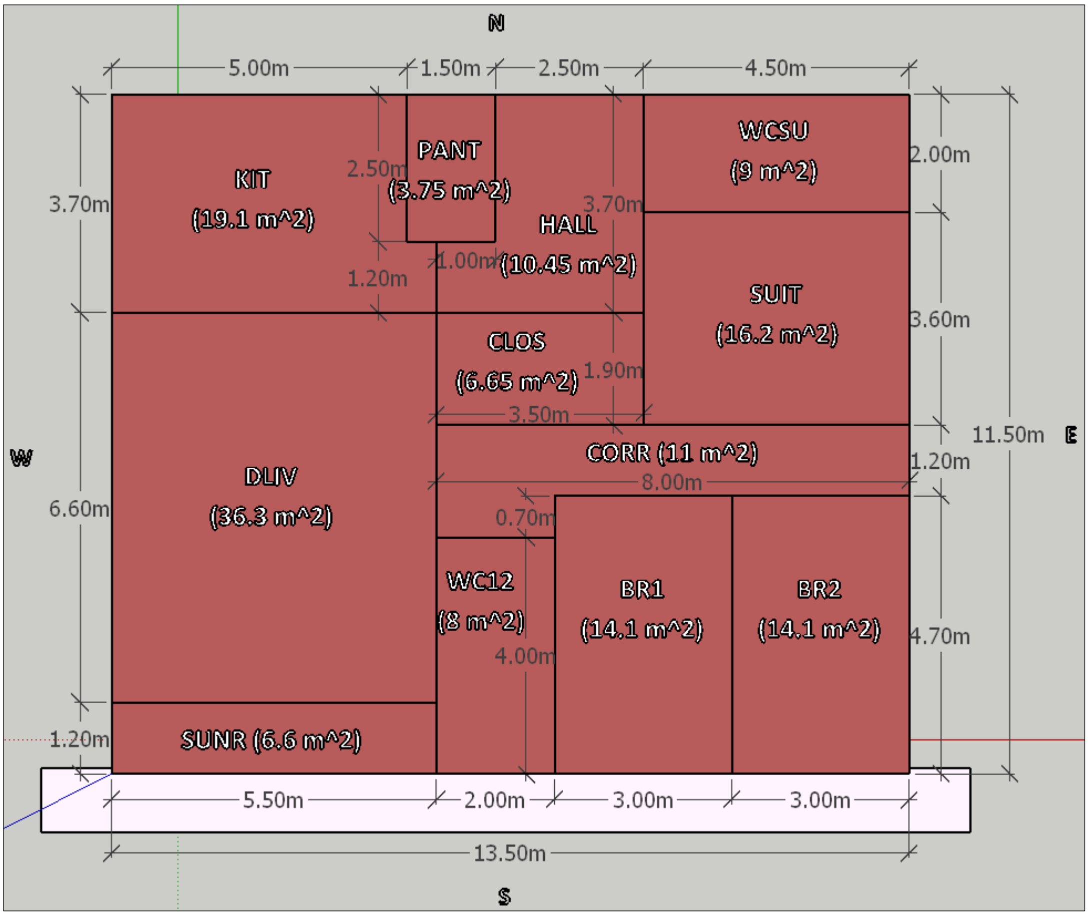

Figure 5.2 - Footprint with useful floor areas

In total, the house sums 12 thermal zones. The dimensions of each zone were carefully thought out in order to accommodate all the essential furniture (in a simple, appealing disposition) and provide practical, aesthetically comfortable, moderately big useful floor areas, suitable of a detached house. When referring to the rooms (furniture's denominations may differ), 'width' is measured along the same direction of the North and South façades, and 'length' along that of the East and West façades:

- the kids' bedrooms were designed to have a floor area of at least 14 m^2 and a big width, sufficient to fit a wide window to the South and a 1.9 m standard bed length plus free walking space; a minimum comfortable width of 3 m was chosen, dictating a length of 4.7 m to ensure 14.10 m^2 of floor area;
- the kids' bathroom was designed to have a medium-big area without being too narrow; a minimum comfortable width of 2 m and a length of 4 m were drawn, to deliver 8 m^2;
- these three rooms add up to a 'sleeping area' width of 8 m. The corridor runs along this width, with a length of 1.2 m to allow walking and the daylighting of the section through an East-facing window;
- the parent's suite was planned to have a width-centred Queen Size bed, 1.6x2 m, with on each side: a 0.5 m wide bedside table, a 0.7 m bathroom door space (which together sum up to sufficient walking space along the bed's sides), plus a few spare centimetres; thus, 1.45 m on each side of the 1.6 m bed was selected, totalling a suite's width of 4.5 m. The 3.6 m length considered the bed's 2 m, walking space and 0.4-0.6 m deep furniture (like a chest of drawers, desk or TV table), resulting in 16.20 m^2;
- the suite's bathroom agrees with the other WC's minimal side of 2 m and the suite's 4.5 m width, conveying 9 m^2 of area, and completing the East façade and the total length of the house at 11.5 m;
- the walking closet's width goes from the suite to the 'living area' border, so equals 3.5 m; its 1.9 m length considers a large wardrobe with 0.7 m of total external depth and a comfortable standing and walking space of 1.2 m that more than fits the 0.7 m doors; the closet's floor area is then 6.65 m^2;
- the entrance hall was planned as a close to a square, big, welcoming area; to that intent, the pantry wasn't fully included within this zone, leaving a not too narrow 2.5 m hall width; with the remaining 3.7 m of length and the 1.2 m decently-sized entry to the West section, the hall totals 10.45 m^2;
- the pantry was designed as a small area, with a small 1.5 m width to affect the kitchen's shape and glazing as little as possible, while still fitting in a corridor with shelving on one or both sides, the washing machine and other storage below the North window; at 2.5 m long, it accrues to 3.75 m^2.

A different approach was taken to define the West section's dimensions. If the house was square shaped, the 'living area' would have a width of 3.5 m, which is too little for the desired South glazing and imposes a very insufficient floor area. To find the appropriate width, a sunroom's length of 1.2 m, which assures a comfortable sitting and clothes drying space, and a moderately generous minimum area of 55 m^2 for the entire open concept were assumed; considering the latter, plus the portion of the pantry located inside the kitchen, and subtracting the sunroom's length from the house's total, the obtained rectangle's width is approximately 5.46 m. 5.5 m implies an open concept's floor area of 55.40 m^2, and a high level of heat loss surface oriented to the South, allowing for a large glazing, so a bigger width was deemed unnecessary. 5.5 m on the West and 8 m on the East section add up to a house width of 13.5 m, thus a bigger South and North than East and West (11.5 m) exposure. Regarding the individual thermal zones:

- the sunroom, at 1.2 m long and 5.5 m wide, presents a floor area of 6.60 m^2; its partial central wall is 1.3 m wide, enough to support a medium-high size TV (50", 1.12 m wide) facing the living room;
- the dining and living room were assigned two thirds of the open concept's 55.40 m^2, resulting (for the 5.5 m width) in a required length of 6.72 m, that placed the kitchen-dining room border at the middle of the kitchen entry; as such, the living room's length was defined as 6.6 m, which is sufficient to fit a properly distanced sofa, dining table set and walking space, totalling 36.30 m^2 of DLIV area;

- lastly, the kitchen has a 5 m wide wall suitable for catching Northern winds, and covers the 1.2 m long entry for a total length of 3.7 m, amounting to 19.10 m^2 of usable floor area.

Table 5.1 - Geometric properties of the building's frame

Geometric Characteristics of the Building	
Height (m)	3.00
Length-to-Width Ratio (%)	85.19
Gross Floor Area (m^2)	155.25
Gross Volume (m^3)	465.75
Treated Floor Area (m^2)	80.70
Treated Volume (m^3)	242.10
External Surface Area (m^2)	460.50
Form Factor (m^{-1})	1.90

As can be seen in Table 5.1, the house has a reasonably high ceiling of 3 m, a length-to-width ratio that attests the bigger South exposure, and a total footprint (gross floor area) of 155.25 m^2. Since only 4 of the 12 thermal zones are conditioned – the two kids' bedrooms, the suite, and the dining-living room –, the Treated Floor Area (TFA) constitutes only 52% of the total, 80.70 m^2. The Shape or Form Factor is the ratio between the external envelope's Surface area – external walls, roof and floor – and the Treated Volume (the TFA's volume), thus provides a measure of the building's geometrical exposure to external conditions, the inverse of its compactness, and is generally desired to be as low as possible, preferably below 1 (m^{-1}). As the typology is a detached house, a high Form Factor was expected, but the enormous 1.9 clearly indicates a low compactness, an apparent inefficient use of the dwelling's geometry, that results from the 48% of non-treated floor area. These unconditioned rooms greatly expand the heat loss surface area, however, they also represent a practical and realistic house, which was a design objective.

5.2. Windows and Doors

Interior doors (and windows) are usually excluded from 3D models as it is assumed that they do not significantly impact the results of the energy simulation. Often, the temperature difference between interior spaces is so negligible that there is little to no heat transfer between them; also, the heat transfer rate of an interior door/window is not much different from that of a regular interior wall. So, the added benefit of these internal subsurfaces – which increase the complexity of the building, thus the computing time necessary to run the model – is presumed to be small [34]. However, in an effort to accurately portray a realistic house, interior doors – which are operable, open and close on specific schedules – were included in this dissertation's model, and their placement was thought out in relation to the respective zone's window and the surrounding furniture.

Among these internal doors, there are three intended as 'open passages' with no physical door/wall: the one between the hall and the kitchen, its identical counterpart between the corridor and the dining room, and the huge one dividing the 'living area's open concept. These 'wall openings' modelled as open doors, could also be modelled as partition walls of air wall construction: a thin wall of air that lets almost all exchanges occur between zones. This could be done by using the new "Construction:AirBoundary" object on EnergyPlus, but it entails specific inaccuracies, problems, even bugs, and requires additional inputs specification (regarding inter-zone mixing airflow, daylight transfer and radiant heat exchange between the two zones) [35]. As such, simple always open doors were preferred. But these doors, along with sunroom's glass side doors and full-width glazing, also involve a small practical issue: when trying to draw a subsurface (window or door) on SketchUp with one or both side edges coinciding with a side wall, a partition in the main wall is created instead of the desired subsurface. Thus, a slight approximation was made: these subsurfaces were shortened by 1 cm on the problematic sides to avoid the issue, leaving 1 cm of wall; CORR's door was shortened on both sides to match HALL's door.

About dimensions and placement: all doors are 2 m high, the interior doors (excluding the exceptions listed above) are 0.7 m wide and were pushed to the corners of the rooms to facilitate furniture arrangement, distancing 0.15 m from such corners (to accommodate coats, e.g.).

In the kids' bedrooms, an East-facing window was not considered on the corner bedroom (BR2), in order to maintain similarity in natural ventilation patterns (and lighting) between the two rooms. The windows were placed on the opposite sides of the opposite walls to the doors to maximise airflow effects: doors were placed next to each other for identical access to the WC and 'living area', as such, the big 1.5 m windows of standard 1.2 m height [36] are on opposite corners of the South façade, as can be seen on Figure 5.3; study desks are considered to be facing the windows, rejecting the right or left-handed lighting issue (otherwise the bedrooms' layout wouldn't be symmetrical; assuming right-handedness, the windows would be by the West and doors by the distant East corners). With the windows placed on the farthest sides, the window next to the SouthEast corner of the building imposes the South façade's horizontal overhang to extend beyond the façade; nonetheless, the same occurs on the SouthWest due to the sunroom's glazing. Both bedrooms' windows distance 0.3 m from the opposite walls (for drapes or slim furniture) and 0.8 m from the floor to match the height of a fully sunlit desk without being too high for visual comfort.

In the kids' bathroom, the door was placed next to the West corner to possibly convey some South winds to the parents' closet (internal room) across the corridor, while the window was simply centred; the latter is decently sized, 0.7 m wide by 0.4 m high and was placed at 1.9 m high to assure privacy – both heights were moderated considering that an overhang sized for the lower-placed windows is installed here. The sunroom also on the South façade presents a pair of 2.09 m wide glazed doors (which nearly equals two sets of three 0.7 m doors) of 2 m height, on the sides of the 1.3 m wide central wall; the external glazing fills the whole width, so 5.48 m, with the standard 1.2 m height at 0.8 m floor distance.

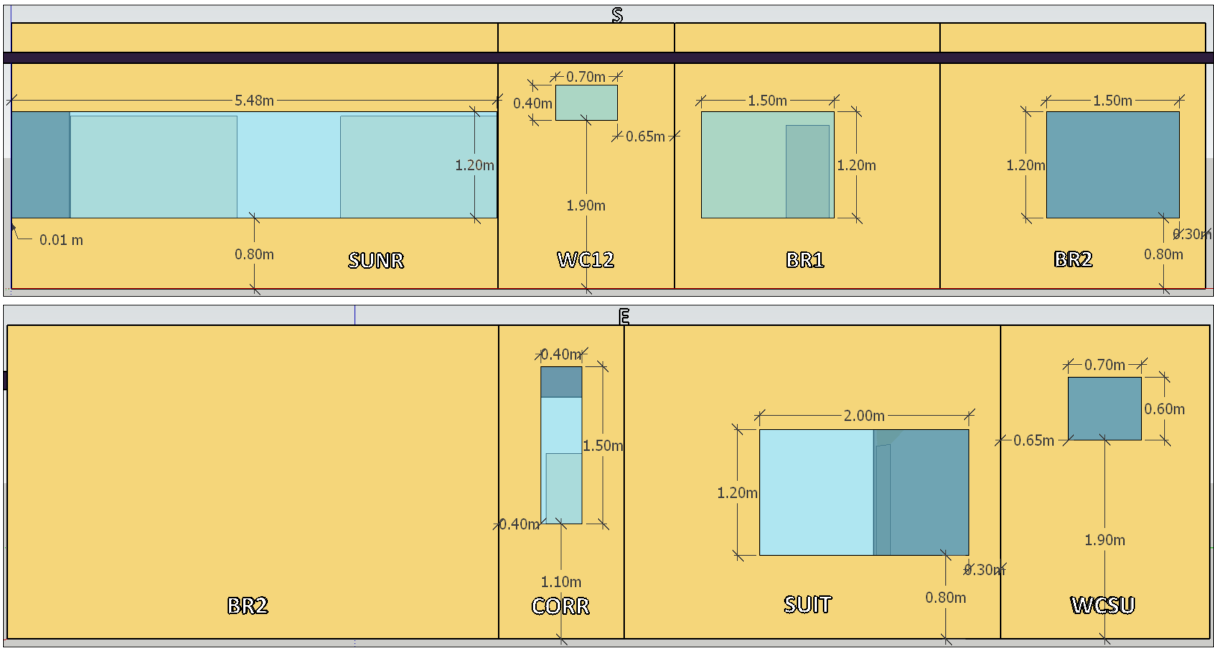

Figure 5.3 - Exterior windows of the South (top) and East (bottom) façades

As displayed, the corridor has an East-facing, long and slim, centred window for appeal and daylighting: 0.4 m wide, 1.5 m high, at a 1.1 m floor distance to provide a pleasant outdoor view; the corridor offers passage to the 'living area' through a 'wall opening', i.e., an always open door of 1.18 m width and only 2 m height (to fit a proper door if needed). The parents' walking closet – the internal room – has two doors, one on the West facing the corridor and one on the East giving access to the suite; for daylighting, the closet has a tiny 0.2 m wide by 0.25 m high internal window oriented to the dining room, at a 2.5 m height (centred within the space in front of the wardrobe). The suite's bathroom is accessed from the West corner, and has an East-facing centred window, which is bigger than the kids bathroom's by one half: 0.7 m wide, 0.6 m high, at a 1.9 m height. In the parents' suite, a window one third larger than the kids', 2 m wide by 1.2 m high, was placed alongside the bed to convey sunlight and a nice outdoor view; it was placed next to the NorthEast corner, yet it is so wide that surely insolates and ventilates the whole room and the closet in the SouthWest corner. This window also distances 0.3 m from the side wall and 0.8 m from the floor.

Unlike interior doors, the exterior door on the welcoming hall is centred and 0.85 m wide, as shown on Figure 5.4; no window is needed, since the hall receives daylight from the West section through a 'wall opening' equal to the one in the corridor. The pantry's door is located next to its SouthWest corner to affect the kitchen's furniture arrangement as little as possible, and the window is centred, facing North; the latter is similar to the closet's internal window: 0.25 m wide by 0.25 m high, at a 1.9 m height (to ventilate a 0.9 m high laundry machine). As previously stated, the 'living area' is an open concept only apparently separated by a full-width full height – thus 5.48 m wide by 2.99 m high – always open door, located at the KIT-DLIV border. As such, a window was placed on the kitchen to catch the predominant North winds and passively cool the living room: a high, width-centred, medium-size window of the same dimensions as the corridor's: 1.5 m wide by 0.4 m high, at a 2.5 m height (to allow for 2 m high cabinets below).

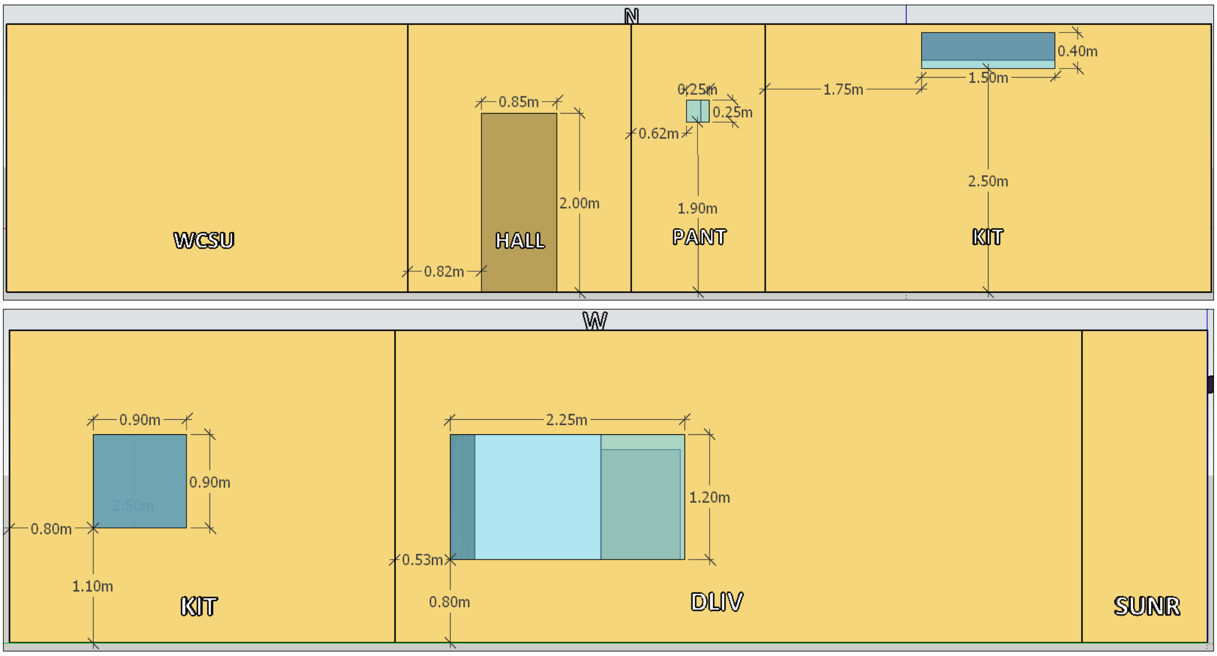

Figure 5.4 - Exterior windows and door of the North (top) and West (bottom) façades

The kitchen also has a West-facing window for visual comfort above the 0.9 m high counter: at a 1.1 m height, only 0.9 m high (to align with the usual upper edge) by 0.9 m wide; this is centred with the pantry's length, so at a North wall distance of 0.8 m, sufficient to fit the 0.6 m deep North-facing counter (and the above 0.3 m deep cabinets). Since DLIV is already graced with South sunlight and an outdoor view by the sunroom's glazing, also has North (and even East) indirect exposure, and West (like East) oriented glazing is harder to shade properly and should be moderate, a West-facing window was placed only on the dining room – the northern half of DLIV. A big 2.25 m wide by 1.2 m high window, at a 0.8 m height was centred with the dining room's length, so, with its dining table.

Table 5.2 - Summary of areas and window orientation by thermal zone

Areas and Window Orientation of the 12 Thermal Zones												
	BR1	BR2	WC12	CORR	CLOS	SUIT	WCSU	HALL	PANT	KIT		DLIV	SUNR
Floor Area (m²)	14.1	14.1	8	11	6.65	16.2	9	10.45	3.75	19.1		36.3	6.6
Glazed Area (m²)	1.8	1.8	0.28	0.6	0.05	2.4	0.42	-	0.0625	0.6	0.81	2.7	6.576
Orientation	South	South	South	East	(int)	East	East	(North)	North	North	West	West	South

Table 5.3 - Geometric properties of the exterior windows

Geometric Characteristics of the Windows					
	Total	North	East	South	West
External Walls Area (m^2)	150.00	40.50	34.50	40.50	34.50
External Glazed Area (m^2)	18.05	0.66	3.42	10.46	3.51
Window-to-Wall Ratio (%)	12.03	1.64	9.91	25.82	10.17
Window-to-Total Window Ratio (%)	100.00	3.67	18.95	57.93	19.45

Table 5.2 presents all the zones' floor area, window area and orientation, while Table 5.3 (which does not include the closet's glazing) shows that windows constitute 12% of the house's total external walls, specifically 26% of the South, 10% of the East and West each, and less than 2% of the North façade. Consequently, South-facing represents 58% of the total external glazing, East and West 19% each, and North less than a minimal 4%, ratios which perfectly comply with design recommendations.

Figure 5.5 showcases all the house geometries, both external and internal, in SketchUp's X-ray view. These are rendered by boundary condition: external structures are presented as blue, internal surfaces (walls) as dark green, and internal subsurfaces (doors and window) as light green (the green color evidences that the pairs of adjoining strucutures are correctly intersected and matched). The closet's tiny internal window, all the internal doors, the sunroom's glass doors, the three 'open passages' – including the open concept's massive divisory border – can be verified below.

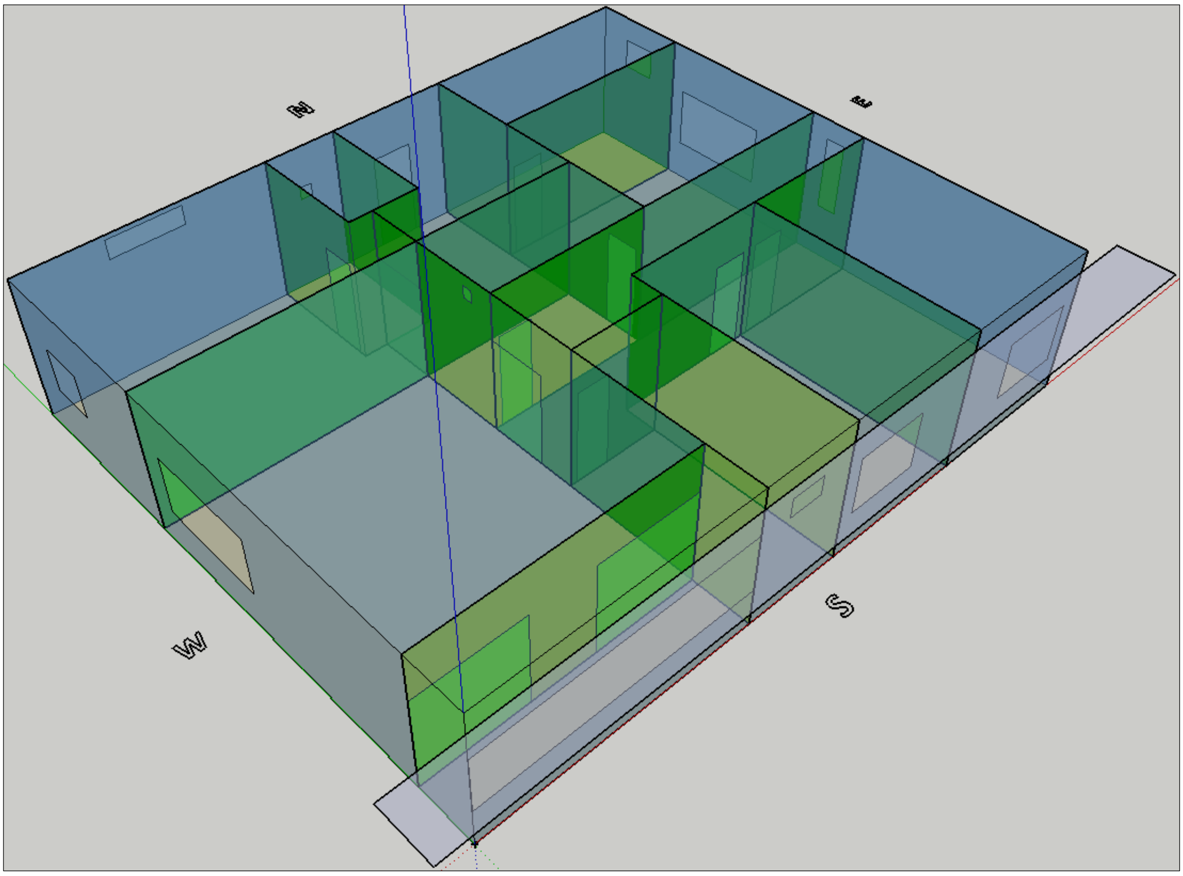

Figure 5.5 - External and internal geometry, X-ray view from the SouthWest corner

5.3. Analytical Sizing of the Overhang

All the glazing in the South façade is covered by a fixed horizontal overhang. Software and charts (solar stereographic projections, or sun path charts) were not resorted to, the structure was sized following the analytical method: the solar angles, profile angles and dimensions were obtained mathematically, for specific dates and times. Typically, this process is simplified by considering the summer cut-off period – dates within which the radiation incidence on the window is completely blocked – but ignoring solar exposure on winter by enforcing a desired overhang height, as suggested in [37]. To attain a properly sized overhang that guarantees obstruction on summer and insolation on winter, two constraining periods were considered: the 'rad-off' (cut-off) and the 'rad-on', as in [36].

But selecting these dates intervals is not straightforward, since sun position over the year – parameter at the base of shading setting calculations – and ambient temperatures do not go hand-in-hand. Solstices, the extremes of solar declination, define the start, not the height, of the seasons: for Nice, there is nearly a two months delay between solstices and the hottest and coldest month, as roughly seen on Figure 4.3 (pg. 17); temperature-wise, Nice's seasons could be interpreted as summer from June to September and winter from December to February, with mean monthly temperatures above 20℃ and below 10℃, respectively. However, when establishing the condition-periods, the solar symmetry around the solstices and its thermal consequences must be kept in mind. For example: the maximum blocking strategy (that traces the longest/deepest overhang) sets radiation to be 100% obstructed between the spring and autumn equinoxes (from 6 a.m. to 6 p.m. solar times), and partially obstructed in the other half of the year, except for the winter solstice in which it is 0% obstructed [36]; so, in April (which is still a rather cold month in Nice) there are no direct solar gains through the window in question, and in winter these gains are only a fraction of what they could be – a 'rad-on' period larger than the winter solstice's day was needed. This overhang may appear oversized, yet in hot climates it can produce more summer savings than winter increases in HVAC consumption, as occurred in [36] for Seville. In [37] (which is simply a calculations explanation sheet), the 'rad-off' period used was 15th April to 29th August (from 9 a.m. to 3 p.m. solar times), which seems a good compromise for thermal comfort.

Assuming the solstices as 21st June and 21st December (although the latter alternates with the 22nd), in a first trial: the 'rad-off' period was defined as 21st April (day 111 in the Julian calendar of a 365 days year) to 21st August (so, 61 days before to 61 days after the summer solstice), with solar times of 9 a.m. to 3 p.m., and the 'rad-on' period as 20th November (day 324) to 21st January (31 days before and after the winter solstice), for solar noon (sun's highest position during the day, thus assuring whole day exposure). For the intervals' start dates and solar times, and for Nice's latitude of 43°39' N, i.e., 43.65° in decimal degrees, the following equations were applied.

δ is the solar declination on the defined day n of the Julian calendar [37]:

$$\delta = 23.45 \times \sin\left(360 \times \frac{284 + n}{365}\right) \tag{5.1}$$

HA is the solar hour angle for the defined solar hour SH [37]:

$$\mathrm{HA} = 15 \times (SH - 12) \tag{5.2}$$

β is the solar altitude on the defined day and time, at the latitude LAT [37]:

$$\beta = \sin^{-1}(\cos LAT \cos\delta \cos HA + \sin LAT \sin\delta) \tag{5.3}$$

Φ is the solar azimuth on the defined day, time and location, and is null at solar noon [37]:

$$\Phi = \cos^{-1}\left(\frac{\sin\beta \sin LAT - \sin\delta}{\cos\beta \cos LAT}\right) \times \frac{HA}{|HA|} \tag{5.4}$$

γ_w is the solar azimuth of a surface of azimuth Ψ_w, which here is a South-oriented (0°) window [37]:

$$\gamma_w = \Phi - \Psi_w \tag{5.5}$$

Ω_o is the profile angle for the horizontal overhang of a vertical surface (window) [37]:

$$\Omega_o = \tan^{-1}\left(\frac{\tan\beta}{\cos\gamma_w}\right) \tag{5.6}$$

Considering Ω_o^{ON} and Ω_o^{OFF} as the profile angles for the ‘rad-on’ and ‘rad-off’ periods, respectively: by tracing a line that performs an angle of Ω_o^{ON} with the window’s normal at the upper edge of the window – assuring complete insolation – and another of Ω_o^{OFF} at the lower edge – assuring complete shading –, the lines’ intersection point reveals the overhang’s optimal dimensions [36]. These relations, which are illustrated at the end of the chapter, are expressed as

$$\tan\Omega_o^{ON} = \frac{h_o}{l_o + d_{w,w}} \leftrightarrow l_o + d_{w,w} = \frac{h_o}{\tan\Omega_o^{ON}} \tag{5.7}$$

$$\tan\Omega_o^{OFF} = \frac{h_o + h_w}{l_o + d_{w,w}} \leftrightarrow l_o + d_{w,w} = \frac{h_o + h_w}{\tan\Omega_o^{OFF}} \tag{5.8}$$

where l_o is the length (projection depth) of the overhang of height h_o above a window, which has a height h_w and is set back from the wall’s outer surface by a distance $d_{w,w}$. The latter was not defined in this dissertation (for any window), but as the insulation is external and it is recommended for windows to be inserted on the insulation layer to reduce thermal bridges, it would be very small and can be nulled.

Equalling the latter parts of the above equations, the overhang’s height comes as:

$$\frac{h_o}{\tan\Omega_o^{ON}} = \frac{h_o + h_w}{\tan\Omega_o^{OFF}} \leftrightarrow \frac{\tan\Omega_o^{OFF}}{\tan\Omega_o^{ON}} = \frac{h_o + h_w}{h_o} \leftrightarrow \frac{h_w}{h_o} + 1 = \frac{\tan\Omega_o^{OFF}}{\tan\Omega_o^{ON}} \leftrightarrow$$
$$\leftrightarrow \frac{h_w}{h_o} = \frac{\tan\Omega_o^{OFF}}{\tan\Omega_o^{ON}} - \frac{\tan\Omega_o^{ON}}{\tan\Omega_o^{ON}} \leftrightarrow h_o = h_w \times \frac{\tan\Omega_o^{ON}}{\tan\Omega_o^{OFF} - \tan\Omega_o^{ON}} \tag{5.9}$$

Upon finding the height through (5.9)'s final expression, the length is attained from either (5.7) or (5.8):

$$l_o = \frac{h_o}{\tan \Omega_o^{ON}} - d_{w,w} = \frac{h_o + h_w}{\tan \Omega_o^{OFF}} - d_{w,w} \tag{5.10}$$

Finally, the overhang's width w_o can be obtained through the calculation of pw_o, the partial width on each side (lateral extension) of the window of width w_w [37] (relation which is also illustrated below):

$$|\tan \gamma_w| = \frac{pw_o}{l_o} \leftrightarrow pw_o = l_o \times |\tan \gamma_w| \tag{5.11}$$

$$w_o = w_w + 2 \times pw_o \tag{5.12}$$

From (5.11) it can be inferred that pw_o differs for the 'rad-off' and 'rad-on' periods, and that it is null for a South-oriented surface at solar noon, so, it is null for the considered 'rad-on' solar time.

The horizontal overhang was optimally designed for the South-facing sunroom's and kids bedrooms' windows, which, intentionally, are both 1.2 m high and at a floor distance of 0.8 m. Varying the 'rad-on' dates, and the 'rad-off' dates and times, the following table was obtained.

Table 5.4 - Study of the overhang's optimal dimensions by date and time

SH^{on} (h)	**12**								
Rad-on	**20th November to 21st January**						**10th November to 31st January**		
Rad-off	**21st April to 21st August**			**11th April to 31st August**					
SH^{off} (h)	h_o (m)	l_o (m)	p_{wo}^{off} (m)	h_o (m)	l_o (m)	p_{wo}^{off} (m)	h_o (m)	l_o (m)	p_{wo}^{off} (m)
6	< 0	< 0	< 0	< 0	< 0	< 0	< 0	< 0	< 0
7	0.06	0.12	3.69	0.19	0.38	4.73	0.21	0.39	4.81
8	0.28	0.58	2.56	0.43	0.87	3.08	0.49	0.90	3.19
9	0.41	0.84	1.74	0.55	1.11	2.03	0.63	1.17	2.13
10	0.48	0.98	1.10	0.61	1.25	1.25	0.71	1.32	1.32
11	0.52	1.06	0.53	0.64	1.31	0.60	0.75	1.39	0.64

Table 5.4 shows that for the assumed criteria, it is not possible to satisfy the desired winter condition and the summer 100% obstruction condition for twelve hours of summer daylight (6 a.m. to 6 p.m. solar times), regardless of the dates configuration chosen. The overhang height rises as the daily obstruction schedule decreases (SH^{off} increases) to allow radiation during more time, and so does the length in order to still block radiation on the reduced schedule from the higher position; inversely, pw_o diminishes, to allow more sunlight laterally. When maintaining the 'rad-on' period and extending the 'rad-off' till the end of August – thus, by a total of 20 days from the initial interval, still remaining three weeks shorter on each side than the maximum equinox-to-equinox scenario – all the optimal dimensions increase, and curiously, these increase even further when widening the 100% exposure (thus shortening the partial obstruction) period by also 20 days, but only very minimally. So, larger daily periods of solar obstruction (lower SH^{off}) actually require lower and shorter but wider overhangs, larger annual periods of absolute blocking demand higher, longer and wider overhangs, and larger annual periods of complete insolation

have, in fact, nearly zero impact on the optimal sizing. Still, specifying a winter condition allows to find the overhang's height, rather than assuming a number or imposing the total height of the building/floor.

The initial dates configuration simply considered one month before to one month after the winter solstice as the 'rad-on', and twice that time before and after the summer solstice as the 'rad-off' period; widening the solar exposure to before the 20th November does not seem reasonable attending to Nice's temperature distribution (Figure 4.3), neither does shortening it, thus 20th November (day 324) to 21st January (day 21 [or 386]) was kept as the 'rad-on' interval. But, extending the 'rad-off' to fully include August, although further jeopardizing April, seems pivotal: it assures partial obstruction during September and, in fact, total blocking in the precise months of higher global horizontal irradiance – monthly averages above 5 kWh/m^2 from April to August, as seen on Figure 4.3. Therefore, 11th April (day 101) to 31st August (day 243) was chosen as the 'rad-off' period. The 'rad-off' lasts for 143 days and the 'rad-on' for less than half, 63 days, so the horizontal overhang enforces absolute obstruction and absolute insolation of the South-façade during 39.2% and 17.3% of the year, respectively.

As for the 'rad-off' daily schedule, 8 a.m. or 9 a.m. are the rational options. Since the sun position rises between the 'rad-off' limit-dates, the daily blocking schedule widens beyond the selected hours, thus the shorter option – that also assures a bigger height, which is useful because of the high-placed kids' bathroom window – seems appropriate, even though it implies a longer and wider overhang. 9 a.m. (to 3 p.m.) solar time was selected as the cut-off hour, and so the profile angles for the 'rad-on' and 'rad-off' were defined: 26.1° and 57.5° respectively, sizing the overhang as 0.55 m high above the window (thus, 2.55 m high above the floor) and 1.11 m long (deep).

The correct width lays between the blocking and insolation's pw_o of 2.03 m and 0 m, respectively. At this point in [36], the stereographic solar chart for Seville was consulted, and width was fixed to guarantee shade during the least favourable summertime hours. As sun path charts won't be resorted to, a simple weighted average was traced using each pw_o's respective period duration in days as the factor. The overhang's partial width is then 1.41 m. For the 'window width' (beyond which the overhang extends bilaterally by 1.41 m), both glazing-corner distances of 0.01 m and 0.3 m were subtracted to the South façade's width, conveying an asymmetric look to the house, but assuring an identical lateral shading of the sunroom's and the kids corner bedroom's windows. Overhang's total width is 16.01 m.

Lastly, the 0.4 m high South-facing window on the kids' bathroom narrowly sits below the 2.55 m high overhang, at a floor distance of 1.9 m. If the overhang was optimised for this window instead, its dimensions would be 0.18 m high above the window, so 2.48 m high, and 0.37 m long. This means that even though the installed overhang is somewhat appropriate for the bathroom window in terms of optimal height, the latter is completely overshadowed by the depth three times greater than necessary (1.11 m), which indicates that the bathroom is shaded for a large portion of the year.

The top image of Figure 5.6 illustrates the trigonometric relations (5.7) and (5.8) between the overhang's length, height, 'rad-on' and 'rad-off' profile angles, and window's height. The angular dimensions were obtained using a SketchUp's extension, they do not accurately agree with the utilised angles (26.1° and 57.5°) but aren't far off. The bottom figure demonstrates equation (5.11) between the window's solar azimuth (γ_w) and the overhang's length and partial width; the angle shown reads 51.8°, but it does not correspond to any meaningful γ_w, since the partial width used was manipulated and fixed – the 'rad-on' and 'rad-off' γ_w are in fact 0° and -61.3°, respectively. The bottom figure also displays the considered 'window width' (13.19 m) and the overhang's total width of 16.01 m.

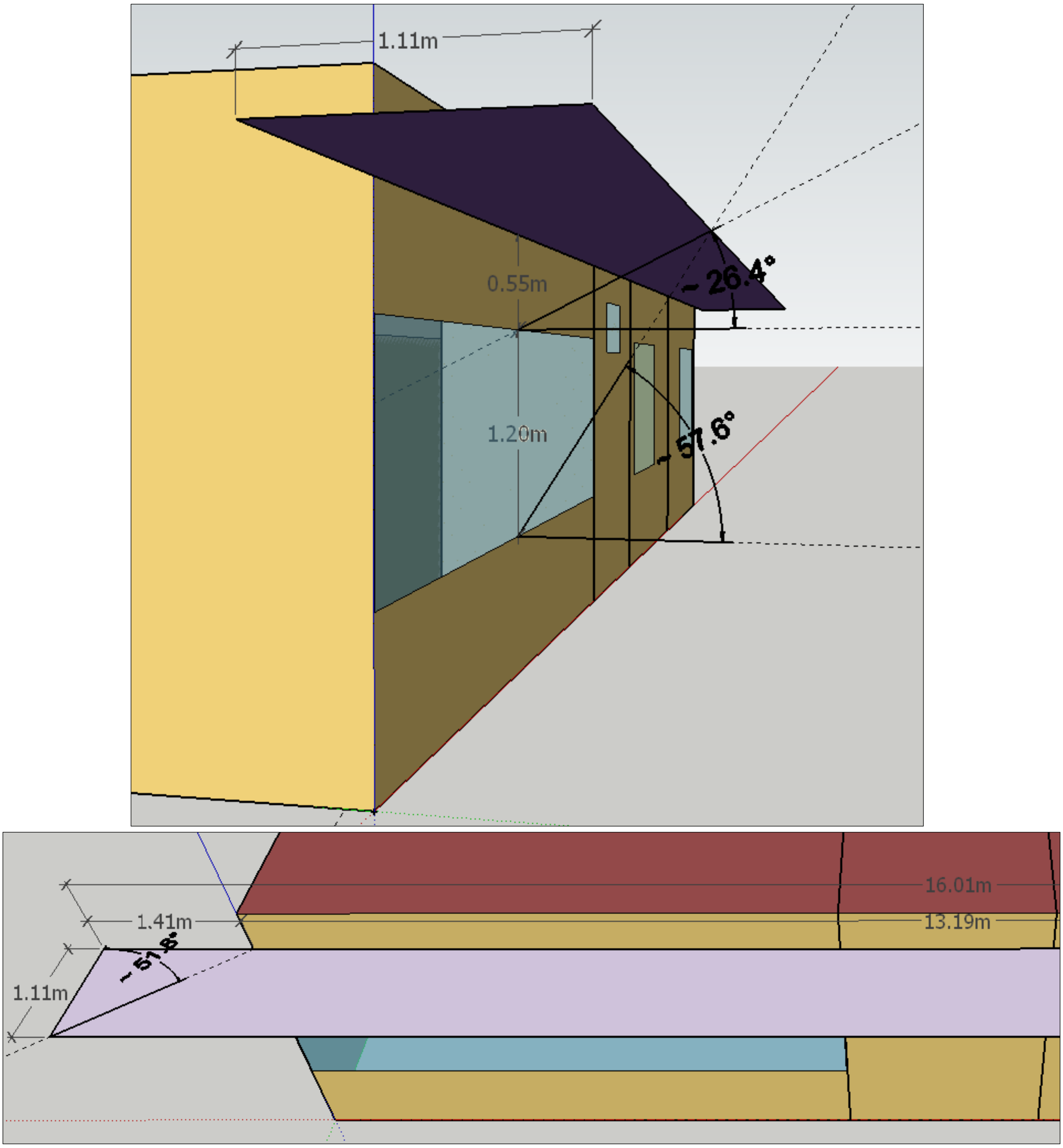

Figure 5.6 - Sizing of the overhang: height, length, width, and approximate angles

Chapter 6 – Thermal Envelope

6.1. Opaque Constructions

The basilar passive strategies relate to the composition of the thermal envelope: insulation to avoid/reduce heat losses/gains, and inertia (mass) to store and modulate desired loads to release at a later, more appropriate time. Roofs are more exposed to solar radiation than walls especially during summertime, due to their (nearly) horizontal tilt and reduced shading from surrounding buildings, thus for the Mediterranean climate of warm/hot summers and very intense radiation, the insulation level of roofs must be very high [33]; it should be medium high/high on exterior walls but slim on ground floors, to use the soil's inertia tank and underground temperature which approximates the pleasant annual average ambient temperature. Besides thicknesses, the position of these layers across a wall has great impact, with external insulation being the best for any climate since it acts as a themal barrier, promoting a detachment from the outdoor conditions, reducing the condensation risk and the technical difficulty in thermal bridges' avoidance, and internally exposed thermal inertia being suitable to maintain indoor conditions, attenuating temperature oscillations [33]. Figure 6.1 shows the peak operative temperatures for different wall configurations in a case-study house in Lecce, Italy (Csa climatic subtype) [38]; tuff was used for inertia and expanded cork panels for insulation; in free-running mode during summer, by increasing the thickness of the inertia layer the temperature decreases, while by shifting insulation from external to intermediate and then internal placement, the temperature drastically rises [38].

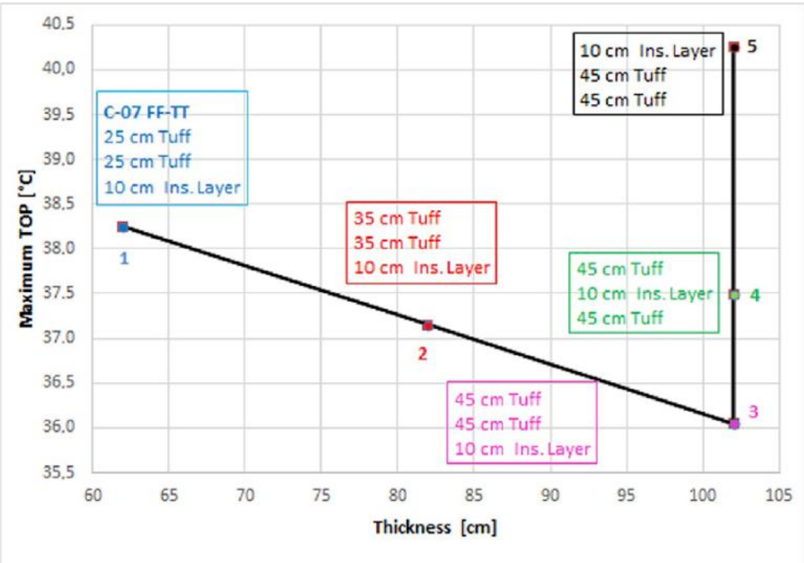

Figure 6.1 - Peak operative temperature, under free-floating regime, for different wall configurations of tuff and expanded cork, for a case-study house in Lecce, Italy (materials ordered from inside to ouside) [38]

In order to select adequate materials and thicknesses, an existing detached single-family house of very high-performance was taken as reference: a certified Passive House Premium (the first one in France) constructed in 2016-2017 in *Solliès-Pont*, just 115 km SouthWest of Nice, also in the *Provence-Alpes-Côte-d´Azur* region, by the Mediterranean Sea and with a Csa climate. Its PHI's database entry [39] is displayed in Appendix B (pg. 65), with the construction materials ordered from inside to outside and their names followed by the respective thermal conductivity and layer thickness (in mm). Materials of the same application and similar conductivities were chosen from the available on [40] to approximately match the reference constructions, while offering a façade's heat transfer coefficient (U-value) at least 3% higher, as can be seen on Table 6.1, in which materials are ordered from outside to inside.

Table 6.1 - Façades constructions (materials ordered from outside to inside): Solliès-Pont Premium Passive House [39] and proposed house (with conductivities from [40])

	Reference: Passive House Premium in Solliès-Pont					Proposed house for Nice					
	Material	Thickness (m)		Conductivity	U-value	Material	Thickness (m)		Conductivity	U-value ($W/m^2.K$)	
		total	layer	(W/m.K)	($W/m^2.K$)		total	layer	(W/m.K)	calc	$\Delta U/U_{ref}$ (%)
Exterior Wall	**Coating**	0.420	0.005	0.7	0.15	**External Rendering**	0.430	0.02	0.5	0.193	28.5
	Graphite Polystyrene		0.2	0.032		**Cork Board**		0.2	0.04		
	Concrete block		0.2	1.1		**Concrete (HW)**		0.2	1.63		
	Plaster		0.015	0.4		**Gypsum Plastering**		0.01	0.42		
Exterior Floor	**Misapor 10/50**	0.633	0.3	0.12	0.34	**Gravel**	0.633	0.22	0.36	0.365	7.4
	Concrete slab 2.3		0.25	2.3		**Cork Board**		0.07	0.04		
	Acoustic Insulation		0.003	0.04		**Concrete (HW)**		0.32	1.63		
	Screed		0.06	1.6		**Cork Tiles**		0.003	0.08		
	Tiles		0.02	2.6		**Timber Flooring**		0.02	0.14		
Exterior Roof	**-**	-				**External Rendering**	0.536	0.02	0.5	0.147	3.3
	Cellulose Wool	0.535	0.173	0.039	0.142	**Felt/Bitumen Layers**		0.003	0.5		
	Cellulose Wool (+ Wood struct)		0.097	0.039		**Cork Board**		0.25	0.04		
	Concrete slab 2		0.13	2		**Felt/Bitumen Layers**		0.003	0.5		
	Concrete slab 1.1		0.12	1.1		**Concrete (MW)**		0.25	0.51		
	Plaster		0.015	0.4		**Gypsum Plastering**		0.01	0.42		

In all the reference exterior surfaces – wall, floor and roof –, insulation is placed on the outside, with inertia – masonry (concretes) – on the inside, and the insulation thicknesses are very high, as expected of a certified Passive House. All the insulators were replaced by a single material: cork, which is sustainable and mostly produced in southern Europe. The used cork board from [40] has a conductivity, density and specific heat of 0.04 W/m.K, 160 kg/m^3 and 1888 J/kg.K, respectively, thus is very similar to the expanded cork panel of [38] – 0.038 W/m.K, 120 kg/m^3 and 1900 J/kg.K.

In the exterior wall: the thin coating layer was substituted by the available external rendering 2 cm thick, since «Traditional renders should be applied in 2 coats. The first coat should not exceed 15 mm thickness and the second coat should be 5-7 mm.» [41]; the cork maintained the 20 cm (high) level of insulation; heavyweight concrete was used for inertia and structure, also 20 cm thick, and is separated from the indoor air by 1 cm of plasterboard (gypsum plastering). As shown on the final data column of Table 6.1, the exterior walls' heat transfer coefficient is worse than (exceeds) the reference by a significant 28.5%, due to the cork's higher conductivity than the extremely thermally resistant graphite polysterene; still, increasing the cork's insulation further than the 20 cm seemed excessive. The wall is 43 cm thick total.

The floor's reference insulation level was already low, but its composition was simplified: the misapor 10/50 used for perimeter insulation was replaced by 22 cm of common gravel; the concrete layer was pushed further inside, and a 7 cm thick board of cork was added next to the gravel; the tiles flooring was exchanged for wooden and the screed deemed unnecessary, thus their thicknesses were added to the concrete layer as a way of maintaining inertia levels, totalling 32 cm of heavyweight concrete; since cork is also a very good acoustic insulator, cork tiles, still 3 mm thick, were used beneath the 2 cm thick timber flooring. The floor total thickness was kept at 63 cm, and the U-value increased by 7.4%. On

EnergyPlus, a 1.4 m layer of soil material was included on the floor slab construction (on the outer side of the gravel), for a total depth of 2.03 m, in order to allow the use of the ground temperatures at 2 m depth as the house's floor boundary condition, as described ahead on Chapter 7.

The reference roof was ignored, except for the U-value; based on [38] and the correct composition a roof should have – discriminated in Figure 6.2 – a new, more complex roof was traced, though structural beams were neglected since EnergyPlus does not possibilitate the assessment and insert of parallel configurations. 2 cm thick external rendering was used as the outer layer, not tiles nor gravel, since a flat cool-coloured roof was intended for both easy instalation of PV panels and to reflect incident radiation; the 3 mm felt/bituminous waterproofing membrane was followed by a 25 cm thick board of insulating cork; the previous waterproofing layer was also used as the vapor barrier material, with the same thickness; the reference 25 cm total of masonry was used with medium-weight concrete, followed by the 1 cm thick plasterboard. The U-value exceeds the reference by 3.3%, and the roof is 54 cm thick.

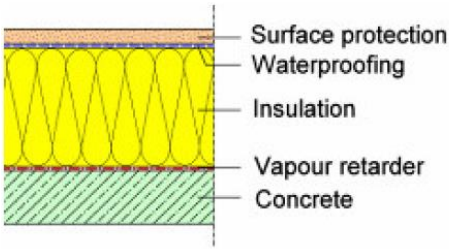

Figure 6.2 - Constructive detail of an example of a highly insulated concrete roof [33]

As recommended, the exterior wall, floor and roof have 20 cm, 7 cm and 25 cm of cork insulation, for heat transfer coefficients of 0.193 W/m^2.K, 0.365 W/m^2.K and 0.147 W/m^2.K respectively (Table 6.1), thus, even though no specific national building code was followed, it is very likely that the U-values obey the maximums imposed across the Mediterranean climate.

The interior wall is 20 cm thick to block sound and modulate heat: 18 cm of heavyweight concrete inbetween 1 cm of plaster on each side – 6.327 W/m^2.K of calculated U-value. Lacking references for doors, the EnergyPlus default constructions were consulted, in which interior doors are made of 2.5 cm thick wood. Comparing thermal properties of the unnamed timber to the listing in [40], an equivalence was found for heavyweight plywood, thus this was chosen as the material for both exterior and interior doors. The exterior door is 5 cm thick and has more than three times the U-value of the Passive House Premium's, 3 W/m^2.K; the interior opaque doors are 4 cm thick, as can be seen on Table 6.2.

Table 6.2 - Interior wall and doors (materials ordered from outside to inside, ref. U-value [39] and conductivities from [40])

	Material	Thickness (m)		Conductivity	U-value (W/m^2.K)		
		total	layer	(W/m.K)	calc	ref	ΔU/U$_{ref}$ (%)
Interior Wall	**Gypsum Plastering**	0.2	0.01	0.42	6.327	-	-
	Concrete (HW)		0.18	1.63			
	Gypsum Plastering		0.01	0.42			
Exterior door	**Plywood (HW)**	0.05	0.05	0.15	3.000	0.95	215.79
Interior door	**Plywood (HW)**	0.04	0.04	0.15	3.750	-	-

The materials' thermal absortance was fixed as 0.9 as usual, while the roughness, solar and visible absortances were obtained from similar materials of EnergyPlus' default constructions. The thicknesses and properties of the utilised opaque materials are also presented in Appendix B.

6.2. Glazed Constructions

The exterior windows of *Solliès-Pont*'s Passive House have triple panes, a glazing U-value of 0.53 W/m^2.K and a total solar transmittance (g-value) of 52%. 6 mm thick simple and low thermal emittance (LoE) glass panes of EnergyPlus' default window constructions were used; these have the same thermal conductivity. For (rough) calculations, the conductivities of air, argon, krypton and xenon were retrieved from the portuguese ITE 50 listing [42], and the gas filling was fixed at 12 mm thickness. Varying the gas and the number of layers between double and triple glazing, the following table was obtained:

Table 6.3 - Study of glazings' U-value based on gas filling and number of layers (ref. Ug [39], gas conductivities from [42])

Gas			Clear/LoE clear Glass		Double Glazing		Triple Glazing	
Name	Thickness (m)	Conductivity (W/m.K)	Thickness (m)	Conductivity (W/m.K)	U_g (W/m^2.K)		U_g (W/m^2.K)	
					calc	$\Delta U/U_{ref}$ (%)	calc	$\Delta U/U_{ref}$ (%)
Air	0.012	0.025	0.006	0.9	2.027	282.5	1.020	92.5
Argon		0.017			1.390	162.3	0.698	31.8
Krypton		0.009			0.743	40.1	0.372	-29.8
Xenon		0.0054			0.447	-15.6	0.224	-57.7

Table 6.3 shows that only the triple argon-filled, and the krypton and xenon-filled glazings come close to or surpass the reference triple glasses' heat transfer coefficient. The double LoE air-filled glazing – usually deemed sufficient for the warm temperate climate in question, even for high-performance buildings (except in inland, extreme weather locations) [33] – at 2 W/m^2.K is almost four times larger than the reference U-value, thus far too unsatisfactory. To avoid the much more expensive noble gases and a 4.2 cm thick triple window for the coastal, low thermal variability city of Nice, the double LoE argon-filled glazing of 1.4 W/m^2.K, much more efficient than the air-filled, was considered adequate for the house's exterior windows. A double air-filled construction was chosen for the sunroom's glazed doors – Table 6.4 – while a single glass was used for the closet's tiny interior window (and the always open doors [hall and corridor's open passages, and KIT-DLIV border]).

Table 6.4 - Glazed constructions (materials ordered from outside to inside, ref U-value [39] and gas conductivities from [42])

	Material	Thickness (m)		Conductivity	U_g
		total	layer	(W/m.K)	(W/m^2.K)
Exterior Window	**Clear 6mm**	0.024	0.006	0.9	1.390
	Argon 12mm		0.012	0.017	
	LoE clear 6mm		0.006	0.9	
Interior Window Open Passages	**Clear 6mm**	0.006	0.006	0.9	150.000
Interior Glazed Doors	**Clear 6mm**	0.024	0.006	0.9	2.027
	Air 12mm		0.012	0.025	
	Clear 6mm		0.006	0.9	

Chapter 7 – Energy Inputs and Operation Controls

For inputs other than the ones refered in this chapter, the default values of EnergyPlus version 9.2 were used. The building was stipulated as located on a city terrain – which is valid for towns and city outskirts too, according to the software's documentation [43] – and having a full exterior and interior solar distribution (radiation that reaches the internal surfaces by projection of direct solar radiation is assessed). The monthly averages of "undisturbed" ground temperature at 2 m depth were collected from Nice's weather stats file to characterise the 2 m deep floor slab's outside boundary condition – a simple approach validated in [44]. Specific sizing periods were not defined, the software operated only on the weather file's run period, which was set to have the duration of a year and start on a Tuesday, in order to allow for comparisons with the last common (365 days) year's dates and weeks later on (2019).

7.1. Internal Gains: Occupants, Lighting and Appliances

People-related inputs are the first to specify, as their schedule influences all others. The family consists of two adults working 8 h/weekday from 9 a.m. to 6 p.m. (9-to-5 plus a 1 h lunchtime) and sleeping for 8 h, and two small children that sleep 9.5 h; they always depart and arrive home all together, which during the week occurs at 8:30 and 18:30 respectively. On weekends the schedule differs, inclusively between the two days: on Saturday morning, the family leaves at 10:00 for two hours (for kids activities and grocery shopping e.g.) and again at 14:30 for 4 h, returning at the usual time, while on Sunday they only go out in the afternoon timeframe. Thus, on weekends the family leaves the house for the same time as one weekday (10 h) and on both afternoons, as the kids are considered to be small and the climate warm temperate. An annual seasonality, and special days like holidays were discarded.

Table 7.1 - Occupancy profile

<table>
<tr><th colspan="7">Occupancy Profile</th></tr>
<tr><th rowspan="2">Zone</th><th colspan="2">Persons</th><th colspan="3">Schedule</th><th rowspan="2">Activity Level (W/pers)</th></tr>
<tr><th>Max</th><th>Fraction</th><th>Weekdays</th><th>Saturday</th><th>Sunday</th></tr>
<tr><td>BR1</td><td>1</td><td>1</td><td>21:30 - 8:00</td><td colspan="2">21:30 - 9:30</td><td rowspan="3">99</td></tr>
<tr><td>BR2</td><td>1</td><td>1</td><td>21:30 - 8:00</td><td colspan="2">21:30 - 9:30</td></tr>
<tr><td>SUIT</td><td>2</td><td>1</td><td>23:00 - 8:00</td><td colspan="2">23:00 - 9:30</td></tr>
<tr><td rowspan="2">KIT</td><td rowspan="2">1</td><td rowspan="2">1</td><td>-</td><td colspan="2">12:00 - 13:00</td><td rowspan="2">135</td></tr>
<tr><td colspan="3">18:30 - 19:30</td></tr>
<tr><td rowspan="6">DLIV</td><td rowspan="6">4</td><td>1</td><td>8:00 - 8:30</td><td>9:30 - 10:00</td><td>9:30 - 12:00</td><td rowspan="6">126</td></tr>
<tr><td>0.75</td><td>-</td><td colspan="2">12:00 - 13:00</td></tr>
<tr><td>1</td><td>-</td><td colspan="2">13:00 - 14:30</td></tr>
<tr><td>0.75</td><td colspan="3">18:30 - 19:30</td></tr>
<tr><td>1</td><td colspan="3">19:30 - 21:30</td></tr>
<tr><td>0.5</td><td colspan="3">21:30 - 23:00</td></tr>
<tr><td rowspan="2">HOUSE</td><td rowspan="2">4</td><td rowspan="2">1</td><td rowspan="2">18:30 - 8:30</td><td>18:30 - 10:00</td><td rowspan="2">18:30 - 14:30</td><td rowspan="2">-</td></tr>
<tr><td>12:00 - 14:30</td></tr>
</table>

The house occupancy global profile and its breakdown by zone are shown on Table 7.1. On weekdays: kids and parents leave their rooms at 8:00 and spend half hour on DLIV – breakfasts, like all other meals, are had at the dining room table, and its preparation time in the kitchen was neglected since it's minimal; after all arriving home at 18:30, one parent cooks dinner for 1 h while the other takes care of the kids in DLIV, then everyone stays in the dining-living room until 21:30, time at which the kids go to their rooms, leaving the parents there for an additional hour and a half. On Saturdays: occupants only leave the bedrooms at 9:30, have breakfast and leave; after arriving at 12:00, one parent cooks lunch for 1 h, all stay in DLIV until 14:30, and after returning at late afternoon, the usual routines are resumed. On Sundays everyone also leaves their rooms at 9:30, but only go out at 14:30. Usage of the bathrooms, sunroom and crossing rooms were ignored, as their occupancy time is minor.

The radiant fraction of the sensible heat released by the residents was considered as default, 0.3, the clothing insulation calculation method was the embedded dynamic predictive model of ASHRAE Standard 55 – which varies the clothing as a function of the outdoor air temperature measured at 6 a.m. [43] –, and a verification by occupied zone of the compliance with EN 15251's [45] Adaptive Model of thermal comfort was requested for both passive and hybrid operation modes. This model «only applies to spaces where the occupants are engaged in near sedentary physical activities with metabolic rates ranging from 1.0 to 1.3 met» [45], thus excludes sleeping which typically has a level of 0.7 met [43]. But as an evaluation for the whole day and year, including nights, was desired, and the metabolic rate is traditionally fixed at 1.1 or 1.2 met regardless of the activity, the sleeping value was approximated to 1 met; similarly, cooking, which has a level of 1.6 met (to 2 met) [43] was rounded down to 1.3 met. The usual 1.2 met of sedentary activities (house, office, etc) was kept for DLIV occupancy. These were all inserted in correspondence with EnergyPlus' input units and tabulated values [43]: 99 W/pers (seated, reading) for sleeping, 135 W/pers (average between 1.2 and 1.4 met [standing, office filing]) for cooking, and 126 W/pers (seated, sedentary or standing, relaxed) for DLIV, as shown on Table 7.1.

Table 7.2 - Lighting profile

Lighting Profile		
Zone	Schedule	Design Level
	All Days	(W/m^2)
BR1, BR2	21:30 - 22:00	10
SUIT	23:00 - 23:30	
KIT	19:00 - 19:30	
DLIV	19:00 - 23:00	

Lights were sized to illuminate 10 W/m^2 of floor area with a radiant (thermal) fraction of 0.5, to turn on at 7 p.m. throughout the year in the occupied zones, and at night in the bedrooms for half hour before bedtime, which is 22:00 for kids and 23:30 for adults. This is presented in Table 7.2.

The house is equipped with the main basic appliances, all electric and with a radiant fraction of 0.4: fridge, freezer, a dishwasher set to operate for half hour everyday after the parents leave the living room at night (when the electricity is cheapest), cooking equipment, a washing machine placed below the pantry's window that turns on automatically as the weekend begins, laptops and audiovisuals in the living room. The washing machine does two nearly consecutive loads of laundry for 1.5 h each on Saturday mornings: it is left loaded with the first batch on Friday night, turns on at 8 a.m., finishes as soon as everyone leaves the bedrooms, 1 h later the second load starts, finishing as soon as the family gets home at noon. Two weekly batches were deemed necessary for a family of four with two small children, and the clothes are hanged to dry outside or in the sunroom – still, occupancy of the sunroom and pantry, even with internal heat gains, was neglected as it is very slim.

The equipments' design level (power) was determined in an inverted manner, by using the typical yearly electricity demands of portuguese families with only class A appliances (scenario 'BEST') listed in [46], and the annual operation hours according to the defined schedules for a year like 2019 (261 weekdays, 52 Saturdays and 52 Sundays). These calculations, schedules and inputs are displayed in Table 7.3.

Table 7.3 - Appliances profile (with reference electricity demand from [46])

Appliances Profile							
Zone	Appliance	Schedule			Operating Time (h/y)	Ref. Electric Demand (kWh/y)	Design Level (W)
		Weekdays	Saturday	Sunday			
KIT	Fridge	Always On			8760	140	15.98
	Freezer					225	25.68
	Dishwasher	23:00 - 23:30			182.5	53	290.41
	Cooking	KIT Occupancy			469	250	533.05
PANT	Washing machine	-	8:00 - 9:30 10:30 - 12:00	-	156	36	230.77
DLIV	PCs	DLIV Occupancy			2189	95	43.40
	Audiovisual					220	100.50

7.2. Infiltration (with AFN)

Since a North-facing window was placed on the kichen to ventilate the living room with cold winds, and the sunroom was placed on the other end to grace it with accumulated heat on cold nights, an assessment of multizone airflows was performed with Airflow Network (AFN). AFN ignores conventional fixed flow rate Infiltration and mechanical Ventilation objects, so infiltration was created within the Network as a Crack (and ventilation rates were considered in the HVAC Ideal Loads system).

«Infiltration is the unintended flow of air from the outdoor environment directly into a thermal zone. Infiltration is generally caused by the opening and closing of exterior doors, cracks around windows, and even in very small amounts through building elements» [43]. *Passivhaus Institut*'s (PHI) design rules impose for this unintentional flow a maximum rate of 0.6 ach of the total house volume during a pressure test at 50 Pa of pressure difference [21], and the *Solliès-Pont* Premium Passive House [39], that was used as the thermal envelope's reference, registers 0.26 ach (Appendix B), so 0.3 ach was chosen to attain an airtight house. To convey this to AFN's Crack object, a mathematical conversion through the power law of flow through an orifice (crack) – which is used on blower-door tests (on-site pressurisation tests that assess a building's leakage) – is needed, along with some assumptions. Simplifying the power law on EnergyPlus documentation [43] by discarding the temperature correction factor [47], the air mass flow coefficient at reference conditions C_Q^{NTP} (for a crack [opening] factor of 1) is given by:

$$\dot{m}_{infil} = C_Q^{NTP} \times \Delta P_{infil}{}^{n} \leftrightarrow C_Q^{NTP} = \frac{\rho_{air}^{NTP} \times \dot{V}_{infil}}{\Delta P_{infil}{}^{n}} = \frac{\rho_{air}^{NTP} \times ACH_{infil} \times V_{build}}{\Delta P_{infil}{}^{n} \times 3600} \qquad (7.1)$$

where ACH_{infil}, $\dot{m}_{infil}$ and $\dot{V}_{infil}$ are the infiltration's flow rate, mass and volumetric flow, ΔP_{infil} is the corresponding pressure difference, V_{build} is the building's gross volume, and ρ_{air}^{NTP} the air density at reference conditions – Normal Temperature and Pressure conditions (20°C and 101325 Pa [1 atm]) were considered, so 1.2401 kg/m^3 of air density. The airflow pressure exponent n represents the characteristic shape of the orifice and is unknown unless a blower-door test is performed; it ranges from 0.5 (perfect orifice) to 1.0 (very long and thin crack): for a fairly airtight envelope it is around 0.6 or 0.7, and for very good airtightness around 0.8 or even more [48], so it was assumed as 0.8. A house total C_Q^{NTP} of approximately 0.002044 kg/s.Pa^n was obtained, as shown on the bottom line of Table 7.4.

Infiltration occurs through all surfaces exposed to outdoor air, which in this case are 15 walls and the roofs of the 12 thermal zones. To assess the specific surface amounts: the above value was multiplied by the ratio between each zone's external walls and roof total area and these areas' house sum (4th column); the values were then simply divided by the number of outdoor air-exposed surfaces in the zone – mostly 2, 3 for the corner rooms and 1 for the internal closet (roof). This last simplification isn't accurate by surface but assures the correct infiltration by zone, and enables the definition of only one surface Crack object per zone (5th column); the latter were assigned to all the repective zone's surfaces.

Table 7.4 - Infiltration (crack) input

Infiltration (Crack) input				
Zone	Ext. Walls & Roofs		C_Q (kg/s.Pa^n)	
	Quantity	Area (m^2)	Zone	Surface
BR1	2	23.10	0.000155	0.000077
BR2	3	37.20	0.000249	0.000083
WC12	2	14.00	0.000094	0.000047
CORR	2	14.60	0.000098	0.000049
CLOS	1	6.65	0.000045	0.000045
SUIT	2	27.00	0.000181	0.000090
WCSU	3	28.50	0.000191	0.000064
HALL	2	17.95	0.000120	0.000060
PANT	2	8.25	0.000055	0.000028
KIT	3	45.20	0.000303	0.000101
DLIV	2	56.10	0.000376	0.000188
SUNR	3	26.70	0.000179	0.000060
Total	27	305.25	0.002044	-

7.3. Mechanical Ventilation and Air Conditioning

To select a fresh air flow rate that assures a 'healthy' house, the residential buildings' values and method of EN 15251 [45] were used: the rates (m^3/s) resulting from considering 0.42 l/s.m^2 for the gross floor area, 7 l/s.pers for the number of occupants and 1 l/s.m^2 for the living room and bedrooms area (TFA) were calculated, and the higher value among the three was fixed as the total ventilation rate – 0.0807 m^3/s obtained from the last condition, which translates to 1.2 ach for the treated volume. This value even surpasses the PHI's average household rate, 0.3-0.5 ach for the same volume (considering 20-30 m^3/h.pers [21], so 5.6-8.3 l/s.pers, very similar to EN 15251's people-value), thus is more than adequate.

EN 15251 and most regulations recommend or stipulate mechanical airflow rates on a continuous operation during occupied hours, but since AFN was included in the input file, the intake fan was assumed as integrated in the HVAC Ideal Loads system, providing fresh air to treated zones – bedrooms and living room – only when the HVAC is on. The 1.2 ach was multiplied by these zones' volumes to assess their outdoor air rates. An exhaust fan in the wet rooms (kitchen and bathrooms) was neglected.

Table 7.5 - HVAC profile

<table>
<tr><th colspan="5">HVAC Profile</th></tr>
<tr><th rowspan="2">Zone</th><th colspan="3">Schedule</th><th rowspan="2">Outdoor Airflow Rate (m^3/s)</th></tr>
<tr><th>Weekdays</th><th>Saturday</th><th>Sunday</th></tr>
<tr><td rowspan="2">BR1, BR2</td><td>7:00 - 8:00</td><td colspan="2">8:30 - 9:30</td><td rowspan="2">0.0141</td></tr>
<tr><td colspan="3">21:00 - 22:30</td></tr>
<tr><td rowspan="2">SUIT</td><td>7:00 - 8:00</td><td colspan="2">8:30 - 9:30</td><td rowspan="2">0.0162</td></tr>
<tr><td colspan="3">22:30 - 24:00</td></tr>
<tr><td rowspan="3">DLIV</td><td>7:30 - 8:30</td><td>9:00 - 10:00</td><td>9:00 - 14:30</td><td rowspan="3">0.0363</td></tr>
<tr><td>-</td><td>11:30 - 14:30</td><td>-</td></tr>
<tr><td colspan="3">18:00 - 23:00</td></tr>
</table>

An ideal HVAC system was defined with infinite heating and cooling capacity, and the respective fresh air flow rate for each treated zone. The system shuts off at nighttime and while the house is unoccupied, however it still tries to optimise occupant comfort by turning on earlier; it operates intermittently: on bedrooms from half hour before everyone wakes up till they leave the rooms, and again from half hour before they return till half hour after bedtime, and similary on DLIV – from half hour before they come in till they leave. Table 7.5 includes the HVAC's operation schedule and outdoor airflow rates. The system operates with a dual setpoint with deadband; the setpoints are presented at the end of the chapter.

7.4. Multizone Airflows (AFN)

To be able to use the simple Ideal Loads HVAC system, AFN was set to only simulate muiltizone airflows driven by wind, i.e., it performs complex natural ventilation but simple (default) forced ventilation calculations ('Multizone without Distribution'). The geometry inputs – building's azimuth angle (90°) and length-to-width ratio (85.19%) – were inserted in the Simulation Control to enable the calculation of the wind pressure coefficient, and all the controls were designed for each individual surface (external walls and roofs for Crack) or subsurface (openings), not at a zone level. The crack flow through closed openings was neglected and assumed as already included in the zones' infiltration; still, a non-null value for closed openings' airflow coefficient is mandatory in Detailed Opening, so a minimal 1E-9 kg/s.m was used, along with the 0.8 n exponent from Crack; the discharge coefficient, i.e., the airflow effectiveness through an opening was set as 0.6 when open (opening factor of 1), as in [44]. This opening control was assigned to all the doors and windows; the adjacent subsurface of the interior doors and window was not inserted, as recommended in [43].

7.4.1. Doors and Interior Window

Opaque doors operate solely based on schedule. The bedrooms' doors open when the occupants leave the rooms in the morning and close at night when the HVAC schedule begins, half hour before the occupants enter, to maximise comfort through either HVAC operation or natural ventilation. Both the closet's and suite bathroom's doors operate according to the suite's doors schedule, while the kids bathroom door is assumed as always open. Closet's internal window is always closed ('No Vent'), so is the pantry's door and the house exterior door. As stated on Chapter 5, the entrances to the West section from the hall and the bedrooms' corridor are fully open passages, thus always open doors, just like the massive kitchen-dining room border, as shown on Table 7.6.

Table 7.6 - Doors and interior window opening schedule

Doors and Interior Window Opening Schedule				
Door	Weekdays	Weekends	Window	All Days
BR1, BR2	8:00 - 21:00	9:30 - 21:00	CLOS interior	Always Off
SUIT, WCSU, CLOS	8:00 - 22:30	9:30 - 22:30		
WC12, CORR-DLIV, HALL-KIT, KIT-DLIV	Always On			
PANT, HALL exterior	Always Off			

7.4.2. Natural Ventilation and Buffer Zone Control (with EMS)

All of the house's exterior windows and the sunroom's two interior glazed doors are operable, and controlled without a modulation of the opening fraction based on the indoor-outdoor temperature (or enthalpy) difference, so simply with an opening factor of 0 or 1. Windows open for a minimum indoor temperature defined by the natural ventilation temperature setpoint schedule (setpoint schedules are presented at the end of the chapter) and, as an AFN embedded rule [43], only if the outdoor's is equal or lower than the indoor temperature – thus, venting is only considered for cooling (and not as a passive heating strategy in spring when the weather is warming up), and windows opening in winter has to be prevented. As shown on Figure 4.3, winter in Nice can be considered to be between December and February with monthly average temperatures below 10°C, but cold minimums are also registered in the final days of November and early days of March, so between one week before to one week after, from 25th November to 10th March exterior windows cannot open; solar gains are allowed to be collected without venting-induced dispersion, and ventilation is exclusively mechanical. Additionally, venting is never allowed in the bedrooms whenever the occupants are sleeping, while the sunroom doors are operable all year long, as can be seen on Table 7.7 (which excludes the hall and closet zones since they don't have temperature-dependent openings).

Table 7.7 - Exterior windows' and sunroom doors' opening schedule

Venting Schedule			
Zone	Date	Weekdays	Weekends
BR1, BR2	10/03	7:30 - 22:00	9:00 - 22:00
SUIT	-	7:30 - 23:30	9:00 - 23:30
All Other (except HALL and CLOS)	25/11	Always On	
SUNR doors	Always On		

The sunroom's doors were controlled according to the zone's temperature as well but for a different setpoint: they open sooner, for a temperature above the heating setpoint schedule, in order to pass on heat accumulated through solar gains in winter and minimise unfavourable overheating effects in summer. However, these simplistic AFN controls only apply for the bedrooms and the West section when in free-floating mode, and in both passive and hybrid modes for the exterior windows of the unimportant unconditioned zones: bathrooms, bedroom's corridor and pantry (Other Rooms).

AFN controls can define the opening of windows for indoor temperatures (or enthalpy, of the zone or the adjacent zone) above a given setpoint schedule (or an Adaptive Model's comfort [central] level), but cannot stipulate a maximum indoor temperature for closing, only an availability schedule. To, instead of narrowing the venting availability schedule, allow the model to assess the viability of using natural ventilation or the HVAC system when both options are available, the Energy Management System (EMS) was resorted to. This high-level control method was used to establish that necessary maximum indoor temperature (HVAC cooling setpoint) for the closing of all exterior windows and the sunroom's doors, this way assuring a proper hybrid mode without simultaneity of passive and active cooling. The 'AvailabilityManager:HybridVentilation' was not an option since it only works with an Airloop HVAC system, a complex user-defined system, and not zone equipment such as the simple Ideal Loads [43].

EMS emulates, inside EnergyPlus, the functionalities of the digital energy management systems used in real life buildings: it enables access to a wide variety of data, as if read by sensors, and uses it to create customised control actions of multiple possible types, overriding standard EnergyPlus control objects. It allows the user to define its functions through a programming language called *EnergyPlus Runtime Language* (*Erl*), so by coding [43]. *Erl* is a small programming language with underlying *C++* and *Fortran* language features to handle numeric variables and mathematical built-in functions, as stated in the EMS specific documentation [49]. It doesn't differ much from the simple *C* language, and coding *Erl* (which is done still within the EnergyPlus software) can solve many problems faced by energy modelers.

In practice, Sensor variables define the model's information the user wishes to retrieve (any of the data available through Output:Variable) to use on his program's conditions, and the Actuator variables define the model's information the user wishes to override/calculate based on his program's conditions; these Actuators can then be recognised as outputs by insert in EMS:OutputVariable, becoming available for export on Output:Variable. It is important to note that EMS controls override the whole actuated EnergyPlus object: the control conditions and the availability schedule, thus if schedules other than the assumed Always On are used, they need to be imported as Sensor objects and verified through *Erl* programs' conditions [50].

To produce the optimised hybrid venting model, Sensor objects were defined to consult the time-based data of: outdoor air (drybulb) temperature, the zones' mean air temperature, the temperature setpoint schedules created for natural ventilation, active heating and cooling, the availability schedules for venting (Table 7.7) and treated zones' HVAC operation (Table 7.5). The Actuator object is the opening factor (fraction), which was defined as only 0 or 1, of the exterior windows of the bedrooms, kitchen, DLIV and sunroom, as well as the sunroom's doors; this control type is called 'Venting Opening Factor' of the actuated component 'AirFlow Network Window/Door Opening' [49]. The codes were written for each separate zone, but aggregated (for compactness) in 2 Program objects: Bedrooms and Living Area. A minimum indoor-outdoor temperature difference of 1°C was imposed, i.e., outside needs to be at least 1°C colder than the zone for venting to be allowed.

Table 7.8 - AFN and EMS controls for the opening of exterior windows and sunroom's interior doors, in hybrid mode

<table>
<tr><th colspan="4">Venting Control Profile (AFN and EMS)</th></tr>
<tr><th>Zone</th><th>Rule</th><th>Condition 1</th><th>Condition 2</th></tr>
<tr><td>WC12, WCSU,
CORR, PANT</td><td>(AFN) ZoneT - OutdT ≥ 0</td><td>(AFN) ZoneT ≥ NatVentSP</td><td>-</td></tr>
<tr><td>BR1, BR2</td><td rowspan="3">Zone Venting Sched On
&&
ZoneT - OutdT ≥ 1</td><td rowspan="3">NatVentSP ≤ ZoneT ≤ CoolingSP</td><td rowspan="3">ZoneT > CoolingSP
&&
Zone HVAC Sched Off</td></tr>
<tr><td>SUIT</td></tr>
<tr><td>DLIV</td></tr>
<tr><td>KIT</td><td>Zone Venting Sched On &&
(DLIV HVAC Sched Off ||
HeatingSP ≤ DLIVT ≤ CoolingSP)</td><td rowspan="2">ZoneT - OutdT ≥ 1
&&
ZoneT ≥ NatVentSP</td><td rowspan="2">DLIVT - OutdT ≥ 1
&&
DLIVT ≥ NatVentSP</td></tr>
<tr><td>SUNR window</td><td>Zone Venting Sched On</td></tr>
<tr><td>SUNR doors</td><td>DLIV HVAC Sched Off
||
HeatingSP ≤ DLIVT ≤ CoolingSP</td><td>OutdT < HeatingSP - 8 &&
DLIVT < NatVentSP &&
DLIVT < ZoneT</td><td>DLIVT - OutdT ≥ 1 &&
DLIVT ≥ NatVentSP &&
DLIVT > ZoneT</td></tr>
</table>

Table 7.8 presents all zones' opening conditions in hybrid mode. The Bedrooms' programs were defined first: if the zone's availability schedule does not allow venting or the indoor-outdoor difference is below the minimum, the window is closed; if none of those conditions is true – so, if venting is possible – and the zone's temperature is between the venting and the HVAC cooling setpoints, the window opens; and if the indoor temperature is above the cooling setpoint but the HVAC system isn't available (since it has an intermittent operation), the window remains open; otherwise, i.e., under any other circumstance, the window closes (e.g. when the HVAC is running). The controls are the same for the three bedrooms.

In the Living Area, DLIV's match the bedrooms' controls. The kitchen is untreated, has two windows and controls that also depend on living room conditions, since they are connected as an open concept through the full-size open "wall": if venting isn't available or DLIV's HVAC is running – DLIV's temperature is above (or below) HVAC setpoints and within operation schedule – both windows are closed; if not, if venting is possible, and kitchen's indoor-outdoor difference and temperature are both above the required, or that is the case for DLIV instead, both windows open (it's unlikely that DLIV will ever be hotter than the kitchen, even with its huge West-oriented glazing, but just in case); otherwise, they're closed. Western winds may be negligible in Nice (Figure 4.3) but northwestern are not, and the living room stands in that direction from the kitchen's West window, so both windows were allowed to operate to flush the living room. As these zones are coupled, this ventilation condition may cause overcooling of one or the other zone at times.

The sunroom window controls are simple: if venting isn't allowed, the window is closed; if not, and either the sunroom's or DLIV's temperature is above the venting threshold (both with the needed indoor-outdoor difference), the window opens, otherwise it is closed. About this buffer zone's doors controls: whenever DLIV's HVAC is on (for heating or cooling), the glass doors are closed; if it's really cold, if the outdoor temperature is more than 8°C below the heating setpoint (for a setpoint of 20°C e.g., that means 12°C), and DLIV is below the venting setpoint and is colder than the sunroom, the doors open to release the accumulated heat into the living room (winter late afternoons, after a day of collecting South solar gains); on the other hand, if the temperature conditions for venting of DLIV apply, and DLIV is hotter than the sunroom (when sunroom's heat has already dispersed through its window), the doors open. Otherwise – when the sunroom is overheating or overcooling – the doors are closed, protecting the living room from unbeneficial exterior conditions.

EMS's Program Calling Manager specifies when individual *Erl* programs are run, both relative to the rest of the model and to each other. As in EnergyPlus example file "EMS Airflow Network Opening Control By Humidity", the calling point was defined as 'Begin Timestep Before Predictor', which happens near the beginning of each timestep, before the thermal loads are calculated, thus is indicated for controlling components that affect these loads that the system will attempt to meet [49]. The 2 *Erl* programs were ordered relative to each other in: Living Area, Bedrooms.

7.5. Movable Shading (with EMS)

Having defined the South-oriented fixed horizontal overhang as a shading group on SketchUp, EnergyPlus automatically recognizes the rectangular geometry and calculates its shadows, discarding any stipulation. Movable shading devices were installed on exterior windows, and an attempt was made to install internal shutters on the sunroom's glazed doors as well. All the exterior windows are equipped with both external shutters and internal blinds: the latter are horizontal on South and North, and vertical on East and West-oriented glazings, as recommended. Installing the blinds between the two glass panes was not possible, since the slats width surpasses the air gap's thickness.

The rolling shutter material is the high reflectivity and low transmission shade model of EnergyPlus' reference data sets: solar and visible reflectances are 0.8, transmittances 0.1, it has a low thermal conductivity of 0.1 W/m.K and, unlike common shutters, is considered as completely airtight (no holes); the only alteration was the thickness which was increased to the typical commercial value of 1.3 cm. An horizontal white painted (so, cool-coloured) metal blind from [43] was chosen: high solar and visible reflectances of 0.8 and 0.7 respectively, thermal conductivity 44.9 W/m.K, slats are 1 mm thick, 2.5 cm wide and distance 1.9 cm from each other; for the vertical blinds, only the slat orientation was changed.

Conventional EnergyPlus' Window Shading Control only allows one movable shading device per opening, with only one control type (condition and schedule), and solely on exterior windows/glass doors. Adding some complexity to the control is possible with EMS' control type 'Control Status' of the actuated component 'Window Shading Control' [49], however this only overrides the control of the window's associated device, it does not provide the option to assign more devices. Since on the standard Window Shading Control, devices can be associated to control objects in two ways, as the solo material or as a window construction that contains the device material to be controlled as one of its layers, and since EMS has a control type called ‘Construction State’ of the actuated component ‘Surface’ that allows to change any construction of the building’s thermal envelope, a theory was born: it should be possible to assign a second device to exterior windows, and one to interior windows, by changing the whole window construction with Construction Actuator, since this method would simply emulate the window construction option of the Window Shading Control through EMS. This way, the correct placement of the device layer would still be assured, since the material layers are defined by order in Construction, only it wouldn’t be operable, but that isn’t a problem since the construction change can be imposed on the *Erl* code only when the desired conditions for this secondary device deployment are met. And if this was a blind, it would simply be fixed at the slat angle defined on the blind material.

By pure chance (and not during the search for solutions which turned out empty), a post was found on Unmet Hours – the Building Energy Modeling forum (provided by Big Ladder Software LLC) that includes EnergyPlus developers as staff and has many experts answering and helping modelers; this post was related to a shading device on an interior window, and had a senior engineer and EnergyPlus trainer suggesting that same method [51]. Confirmed as valid, the author’s theory was applied.

The primary device of exterior windows, assigned on Window Shading Control, was the internal blind, in order to set the slat angle to follow and block beam radiation, providing near-optimal indirect radiation for daylighting [43]. An object per window was created with the respective blind material: horizontal slat orientation for BR1, BR2 WC12, PANT, KIT (North) and SUNR, and vertical for SUIT, WCSU, CORR, KIT (West) and DLIV. The secondary device, imposed through EMS construction changes, is the shutter: external for windows, internal for the sunroom’s doors (so, placed on the sunroom’s side). The exterior window and glazed doors constructions with these layers installed were added on Construction.

Unlike with venting, the EMS designed shading control actuates on all zones (except hall and closet), and on all modes. New EMS Sensors were added: the bedrooms ‘awake’ schedules – which match the hours but not the dates (fixed year-round) discriminated in the venting availability schedules of Table 7.7 –, the global house occupancy schedule (Table 7.1), the opening factors of the exterior windows operated only by AFN (bathrooms’, corridor’s and pantry’s), and an object of the solar radiation rate (per area) incident on the outside surface for each of the exterior windows. A ‘Window Shading Control - Control Status’ Actuator object was added per exterior window, as well as a ‘Surface - Construction State’ Actuator for these and the sunroom’s doors. The two new constructions were called to EMS and assigned names on EMS:ConstructionIndexVariable.

As in the example file “EMS Window Shade Control”, the EnergyPlus’ 9 specific numeric constants that define each shading control status were initialised, i.e., declared in a separate program and assigned names before being used. A new Calling Manager object was used solely for this with the calling point ‘Begin New Environment’, which occurs near the beginning of each environment period, and stipulates that the program is not called during individual timesteps, so is useful for initialising variables and calculations that are needed only once for each period [49]. The 3 user-defined shading programs run after the opening factor programs, and were ordered relative to each other in the same way as before, plus the new ‘Other Rooms’ at the end.

In general, the strategy behind the shading devices is: to use the shutters as "movable insulation" and the blinds to block radiation while still providing some daylighting when the occupants are home; hence the shutters were used at night, both while sleeping (to block external light and noise) and a bit before, and also to prevent overheating while the house is unoccupied, and the blinds mainly to block excessive sun when the house is occupied. A shutters' cold days strategy was not implemented, to allow the collection of solar gains through the house's immense glazing, as intended.

The two components actuated on – the shading status for the blinds and the construction for the shutters – were both set to null at the beginning of each Shading Control *Erl* program (saving many code lines, but potentially increasing the model's running time due to unnecessary changes and reversals). Although «It is assumed that the air flow through a window opening is unaffected by the presence of a shading device such as a shade or blind on the window» [43], to provide a realistic portrayal, the windows/doors open factor calculated by EMS and by AFN for Other Rooms were used, and it was imposed that the shading devices only deploy when the openings are closed (OpenFactor = 0); thus, they are never deployed while natural ventilation takes place. The devices' Availability Schedule is Always On, and an *Erl* built-in variable was used to assess if the sun is down [49].

Table 7.9 - EMS controls for the movable shading of exterior windows, in all modes

<table>
<tr><th colspan="5">Shading Control Profile (EMS)</th></tr>
<tr><th rowspan="2">Zone</th><th rowspan="2">General Rule</th><th colspan="2">External Shutters</th><th>Internal Blinds</th></tr>
<tr><th>Condition 1</th><th>Condition 2</th><th>Condition</th></tr>
<tr><td>BR1, BR2, SUIT</td><td rowspan="2">Window is closed</td><td>Sun is down ||
Zone Awake Sched Off</td><td rowspan="2">House Occupancy Sched Off
&&
ZoneT ≥ NatVentSP
&&
ZoneT < OutdT</td><td rowspan="2">ZoneT ≥ NatVentSP
&&
ZoneT < OutdT
&&
WindowRadInc > 150</td></tr>
<tr><td>All Other (except HALL and CLOS)</td><td>Sun is down</td></tr>
</table>

Table 7.9 shows all zones' shading conditions in all modes. In the bedrooms: if the sun is down or the occupant(s) is/are asleep, the external shutters are on; if the house in unoccupied, the indoor temperature is above the venting setpoint and below the outdoor temperature (hot days), shutters are on; if the house is occupied, the interior blinds deploy if the indoor temperature agrees with the previous conditions and the solar radiation incident on the window exceeds 150 W/m^2; in the latter, the hotter outdoor than indoor condition was kept, so that blinds won't deploy on cold late afternoons with surprisingly intense radiation (spring), in order to warm the house. The controls are the same for all three bedrooms.

For the Other Rooms (WC12, WCSU, CORR and PANT) and the Living Area (KIT, DLIV and SUNR's window), the controls are the same as for the bedrooms, minus the initial sleeping verification. Unlike with airflows, a dependency on DLIV's conditions is not needed.

About the internal shutters on the sunroom's doors: these were intended to accentuate the buffer zone effect, to better protect the living room by increasing its envelope's thermal resistance. To, just like with the other shading devices, allow natural lighting when the family is home, these only deployed if the house was unoccupied or the sun was down (and the doors were closed), as can be seen on Figure 7.1. Unfortunately, the inclusion of these code lines incurred in a severe Convergence error (for the adjacent surface of one of the two glazed doors manipulated with the EMS Construction State) that stopped EnergyPlus simulation still during Warmup. «Usually, a severe error related to "NANC" means that the user didn't set an input correctly or there is a bug in the EnergyPlus source code where a calculation variable or parameter is incorrectly set» [52]. This is a comment provided in the posting of this problem on Unmet Hours. Related posts were consulted, the mentioned tips were tried, nothing worked, and no user mistakes were found by the author on the input file. Ultimately, the shutters had to be removed.

```
EnergyManagementSystem:Program,
    Sunroom_doShadingControl,!- Name
    IF SUNRdoEOpenFactor == 0 && (HOUSEOccupancy == 0 || SunIsUp == 0),
    SET SUNRdoEConstruct = IntGlaDoorwIntShutter,
    SET SUNRdoWConstruct = IntGlaDoorwIntShutter,
    ELSE,
    SET SUNRdoEConstruct = Null,
    SET SUNRdoWConstruct = Null,
    ENDIF;
```

```
** Severe  ** Convergence error in SolveForWindowTemperatures for window SUNR_
DOE_ DLIV
**   ~~~   **  During Warmup, Environment=RUN PERIOD, at Simulation time=01/01
00:20 - 00:22
**   ~~~   ** Glazing face index = 1 ; new temperature =NANC  ; previous tempe
rature = 22.9865C
**   ~~~   ** Glazing face index = 2 ; new temperature =NANC  ; previous tempe
rature = 22.9870C
**   ~~~   ** Glazing face index = 3 ; new temperature =NANC  ; previous tempe
rature = 22.9983C
**   ~~~   ** Glazing face index = 4 ; new temperature =NANC  ; previous tempe
rature = 22.9988C
**  Fatal  ** Program halted because of convergence error in SolveForWindowTem
peratures for window SUNR_ DOE_ DLIV
   ...Summary of Errors that led to program termination:
   ..... Reference severe error count=1
```

Figure 7.1 - EMS controls for the sunroom glazed doors' shutters and consequent software error

In sum, the house promotes passive strategies with enhanced controls: natural ventilation in the warm seasons, shutters as movable insulation during most of the day, blinds for visual and thermal comfort, and an optimised use of the sunroom (even without the doors shutters). The full script from the *Erl* programs is presented in Appendix C (pg. 68).

7.6. Setpoints

The HVAC thermostat and venting setpoint was based on Passive House's constant range of 20℃ to 25℃, with the middle value, 22.5℃, as the natural ventilation setpoint. To improve the natural cooling of the thermal mass, a night setback for the venting setpoint was defined for the hotter months, which in Nice (as seen on Figure 4.3) go from June to September with average temperatures above 20℃, but already register maximums above 25℃ in the final days of May. Hence, from 20th May to 30th September, between 11 p.m. and 7 a.m. – from when the 'living area' is left unoccupied till half hour before the HVAC starts in the morning (so, 1 h before the occupants enter) – the venting setpoint was lowered to match the heating setpoint.

Table 7.10 - Temperature setpoints profile

Temperature Setpoints Profile				
Setpoint (℃)		Venting		
Heating	Cooling	Date	All Days	Setpoint (℃)
< 20	> 25	30/09 - 20/05	0:00 - 24:00	≥ 22.5
		20/05 - 30/09	23:00 - 7:00	≥ 20
			7:00 - 23:00	≥ 22.5

However, the temperatures in PHI's thermostat are operative, but EnergyPlus does not have an option to recognise inserted temperatures as operative, it only works with air temperatures for all inputs; even 'Zone Control: Thermostat: Operative Temperature' assumes the setpoint schedules provided as air and converts to operative before communicating them to the HVAC as operative temperatures [43]. Regardless, none of the setpoints were altered, they were inserted into EnergyPlus as air temperatures, also because they coincide with perfectly legitimate values for air temperature setpoints.

Chapter 8 – Processing and Discussion of Results

Timestep was kept at 6 per hour, so at 10 min, for all simulations. Additional schedules were created and simulated to assist in calculations when needed: occupancy regardless of the number of occupants, schedules' inverse (off), etc.

By including outdoor air in Ideal Loads, the HVAC system provides minimum treated fresh air ventilation while also satisfying the thermal loads of the zone. The 'Supply Air' output considers both portions, while 'Zone' only considers the latter; in consequence, 'Supply Air' revealed larger annual sums than 'Zone' for heating (because pre-heating for ventilation is included), and smaller for cooling because the outdoor air provides some (free) cooling, i.e. when outdoor air is cooler than indoor air, the outdoor air in the mix results in less energy required (to be taken) to cool the mix to supply conditions than it does without the outdoor air included ('Zone'). 'Supply Air' is the closest output to the actual thermal energy the HVAC system uses, as such it was the utilised output, and was considered for 'total', so sensible and latent (humidification/dehumidification) loads.

8.1. Heat Pump, Heating and Cooling Demand

The principal scenario is the hybrid mode filled with optimised strategies and controls. For this, 291.7 kWh/y and 234.1 kWh/y were obtained for the annual heating and cooling thermal loads respectively, thus the house has non-null cooling and quasi-identical conditioning needs, as expected for a warm temperate Mediterranean climate. These equal 3.62 kWh/m^2.y and 2.90 kWh/m^2.y per Treated Floor Area (80.7 m^2) for (useful) heating and cooling demand respectively: the house reveals extremely high performance, with energy needs well below the PHI's 15 kWh/m^2.y threshold for (thermal) heating and 15 kWh/m^2.y for sensible cooling, complying with the energy requirements even without a heat recovery system, and attaining nearly zero HVAC needs, as intended.

Since an HVAC equipment was not defined within EnergyPlus and Ideal Loads was used, it is necessary to define it. A theoretical reversible heat pump that provides both heating and cooling was assumed.

$$COP = \frac{Q}{E} \leftrightarrow E = \frac{Q}{COP} \tag{8.1}$$

The electrical consumption E, for heating or cooling, is obtained from the thermal load Q and the equipment's Coefficient of Performance (COP). COP is obtained from the ideal COP_{Carnot}, which was assumed as time-variant, dependent on the site's outdoor air temperature $T_{outdoor}$, and the system's efficiency η, that in this case was assumed as equal to 20% for both heating and cooling modes. The heating's condensator and cooling's evaporator, T_{cond}^{h} and T_{evap}^{c}, consider a feeding fluid's temperature, T_{fluid}, of 50°C and 0°C, respectively. These relations are expressed below.

$$COP_h = \eta \times COP^h_{Carnot} = \eta \times \frac{T^h_{cond}}{T^h_{cond} - T^h_{evap}} = \eta \times \frac{T^h_{flu} + 5}{(T^h_{flu} + 5) - (T_{outdoor} - 5)} \quad (8.2)$$
$$\leftrightarrow \; COP_h = \eta \times \frac{T^h_{flu} + 5}{T^h_{flu} - T_{outdoor} + 10}$$

$$COP_c = \eta \times COP^c_{Carnot} = \eta \times \frac{T^c_{evap}}{T^c_{cond} - T^c_{evap}} = \eta \times \frac{T^c_{flu} - 5}{(T_{outdoor} + 5) - (T^c_{flu} - 5)} \quad (8.3)$$
$$\leftrightarrow \; COP_c = \eta \times \frac{T^c_{flu} - 5}{T_{outdoor} - T^c_{flu} + 10)}$$

The COPs and electric needs for heating and cooling were calculated on an Excel spreadsheet. A yearly average of 1.51 and 2.24 were obtained for the heating and cooling COPs, respectively.

Table 8.1 - Annual HVAC electric needs for treated zones and the entire house

	HVAC yearly electric consumption (kWh/y)					
	BR1	BR2	SUIT	DLIV	House	
Heating	28.3	29.4	53.0	115.4	**226.1**	per TFA
per Floor Area	2.0	2.1	3.3	3.2	1.5	**2.8**
Cooling	3.5	5.1	12.3	134.9	**155.8**	-
per Floor Area	0.2	0.4	0.8	3.7	1.0	**1.9**
Total HVAC	31.8	34.5	65.3	250.3	**381.9**	-
per Floor Area	2.3	2.4	4.0	6.9	**2.5**	**4.7**

As Table 8.1 shows, even though the kids bedrooms, BR1 and BR2, have equal floor and South-facing glazing areas, the corner bedroom (BR2) presents bigger heating and cooling needs due to its additional East-exposed wall; both have nearly zero cooling demand, thanks to the South's pleasant exposure and overhang. The parents' suite has larger needs, even per zone floor area, due to a worse exposition – East only with a large glazing. Since the dining-living room can enjoy the afternoon sun through its immense West glazing and is connected to the sunroom, that collects solar gains and provides winter comfort, it has lower heating needs per floor area than the suite, even though its HVAC is available for far more hours – from 6 p.m. to 11 p.m. everyday, 1 h on weekdays' mornings and more on weekends, while the bedrooms HVAC is only available for 1.5 h every night and 1 h every morning (Table 7.5). DLIV has much bigger cooling loads, in fact it is the only zone where cooling surpasses heating, probably because of that same huge West-facing glazing, possibly detrimental in summer and harder to shade properly (even with vertical shading devices), the fact that it is permanently connected to a big untreated zone, the open-concept kitchen, and that it operates mostly at late afternoons and early nights, when the overheating risk is at its peak. Also, both of the latter zones have internal gains from appliances which the bedrooms do not. Despite DLIV's cooling load (which translates to 6.9 kWh/m^2.y of HVAC needs per area), the house has 382 kWh/m^2 of total HVAC needs, 2.5 kWh/m^2.y per gross floor area, and less than 5 kWh/m^2.y of heating, cooling and HVAC electric consumption per TFA, thus a high efficiency.

Figure 8.1 exhibits the monthly sums of heating and cooling consumptions throughout the year. There are heating needs during a larger portion of the year, October to April; in July and August the cooling spikes, while it is neglible in June and September, probably due to a low thermal amplitude and potential for natural ventilation in the former months.

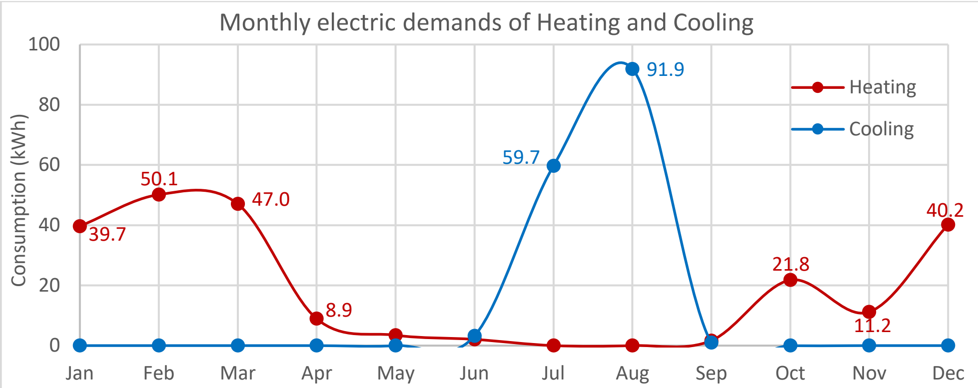

Figure 8.1 - Monthly electric demands of heating and cooling

8.2. Lighting, Appliances, Total Electricity Consumption and Production

Table 8.2 - Annual electricity consumption

	Annual Electricity Consumption (kWh/y)								
	Fridge & Freezer	Dishwasher	Cooking	Washing Machine	PCs & Audiovisual	Total Appliances	Lighting	HVAC	TOTAL
Consumption	364.9	53.0	250.0	36.0	258.7	**962.7**	**645.9**	381.9	**1990.4**
per Gross Floor Area	-	-	-	-	-	6.2	4.2	2.5	**12.8**

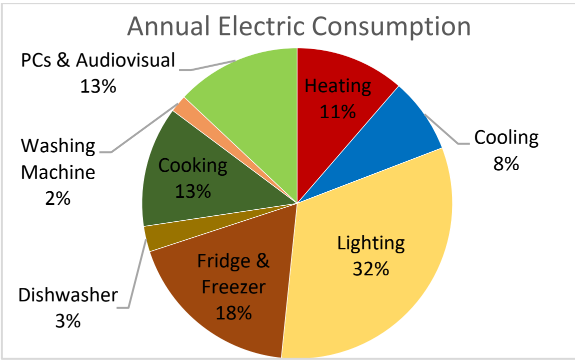

Figure 8.2 - Breakdown of annual eletricity consumption by end-use

Table 8.2 presents the yearly electric consumption of all end-uses, and the house total demand of 1.99 MWh/y. The breakdown of Figure 8.2 further emphasises how small the HVAC demands are: appliances consume 49% of the electricity, with big equipments as the bigger slice, lighting consumes 32%, while HVAC is responsible for only 19% of the electric demand.

8.2.1. PV Generator for the NZEH

A photovoltaic generator was installed to supply the house needs on a yearly basis. The model LX-200M of Luxor's series of monocrystalline modules was used [53]; it has 200 Wp of peak power, an efficiency (in standard conditions) of 15.79%, is 158 cm long and 80.8 cm wide. For the inverter – that converts the panels' Alternate Current in Direct Current to supply the house – the Struder's model C 4000-48 was used [54], which has a maximum efficiency of 95%, and is also a Load Regulator (would be useful if there was batteries storage). The data sheets of both equipments are presented in Appendix D (pg. 72).

The modules were installed facing South, with the length (bigger side) up – since it was unlikely that more than one string would be needed (no need to worry about shadowing effects) – and at a 50 cm minimum distance from the edges. By diving the house's South façade length (13.5 m) by the module width, and discarding any distance between modules, a maximum number of 15 panels can be installed, for a total string width of 12.12 m. At first, the whole 15 modules were considered, for a total PV area of 19.15 m^2 (frames included). According to the documentation [53], each module is composed by 72 square PV cells of 156.25 cm^2, so the collecting fraction is 88.12%, and the collecting area 1.125 m^2 and 16.875 m^2 for each module and the entire string, respectively. With 15 modules, the only string, hence the generator has an output power of 3 kWp.

To define the panels inclination, the online tool PVGIS was resorted to [55]; for the city of Nice, a fixed azimuth of 0° (South) and, additionally, the system's peak power: an optimal slope of 38° and a yearly PV production of 4530.28 kWh were obtained. The predicted production for 15 panels more than doubles the needed output to achieve an annual zero balance between consumption and production, thus the string was reduced. PVGIS indicates a yearly production of 2114.13 kWh and 1812.11 kWh for 7 (1.4 kWp) and 6 modules (1.2 kWp) respectively, so 7 were installed. A string of 7 modules is 5.656 m wide, sits at a roof edges' distance of 3.922 m, has a total area of 8.94 m^2, a solar collecting area of 7.875 m^2, and the installed peak PV power of 1.4 kWp.

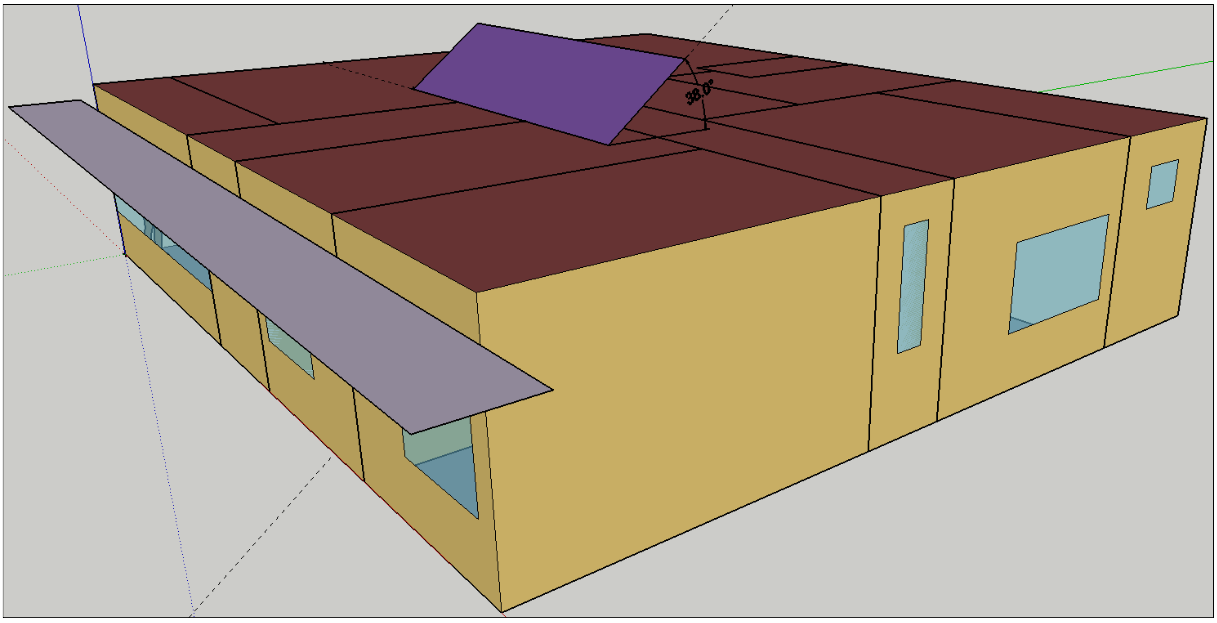

Figure 8.3 - SketchUp representation of the PV generator

As Figure 8.3 shows, the PV string was designed on SketchUp with a tilt of 38° and the collector (darker) face up. The collecting area ratio, the technical data of the module and the inverter were inserted on EnergyPlus. Upon simulation, a yearly PV production of 2031.12 kWh, so 2.03 MWh/y, was obtained – slightly under the PVGIS projection, but still 2% over the house electric consumption, assuring an annual balance very close to zero, as intended for the NZEH.

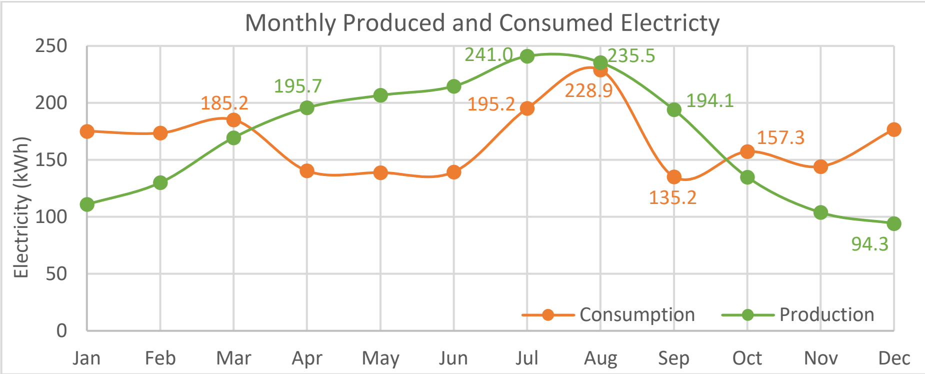

Figure 8.4 - Monthly produced and consumed electricity

Figure 8.4 shows that PV production and electric consumption in monthly amounts are consistenly close throughout the year, with production surpassing consumption for half of the year, April to September, and being sufficient to supply the cooling peaks. The house is grid-connected, but this graph evidences that it could be fully autonomous with battery storage.

8.3. Hours with Operating HVAC, Natural Ventilation and Shading

Outputs were requested with an hourly frequency: when there are HVAC loads, the considered value is that of the HVAC availability schedule at that time – 1 h or 0.5 h – not less; this may produce an excess rounding of the actual operating times, which could only be unveiled with a Detailed frequency analysis (smaller than the 10 min timestep, about 3 min but inconstant). On another note: typically, for constant Always On HVAC operations, the system's operating hours are assessed for when the house is occupied, since this need of operation shows that there is discomfort. However, the present HVAC does not operate on all occupancy hours, it excludes sleeping time, thus an assessment based on the full occupancy schedule would be erroneous; it was made for the actual HVAC availability schedules, since these cover the entire DLIV occupancy, some unoccupied half hours (exclude the sleeping time in bedrooms), and also provide an indication of the intermittent operation efficacy, if the HVAC is used whenever available in this reduced, non-constant, schedule or not.

Table 8.3 presents the annual sums of the zones' HVAC operating hours, and the ratios (%) between these and the yearly total available hours for that zone's system. For the operating hours of the whole house, each hour was only counted once even if the HVAC was operating on several zones, by registering only the maximum of the four treated zones' operating times; for the latter's ratio, a global house HVAC schedule was created and summed.

Table 8.3 - Annual HVAC operating hours in treated zones and the entire house

	HVAC Operating Hours (h)					
	BR1	BR2	SUIT	DLIV	**House**	
Heating	400.5	405.5	426.0	591.0	**1002.0**	per 8760 h
per HVAC Sched (%)	43.9	44.4	46.7	22.9	**32.0**	**11.4**
Cooling	81.0	85.5	113.0	308.0	**416.0**	-
per HVAC Sched (%)	8.9	9.4	12.4	11.9	**13.3**	**4.7**
Total HVAC	**481.5**	**491.0**	**539.0**	**899.0**	**1418.0**	-
per HVAC Sched (%)	**52.8**	**53.8**	**59.1**	**34.8**	**45.3**	**16.2**

Even with an intermittent HVAC – that turns on half hour before the occupants enter the space, shutts off when they leave, turns off at night on bedrooms half hour after the occupants go to sleep and then on half hour before they wake up (Table 7.5) – the effective operating hours never surpassed 60% of the available time. The bedrooms' very limited schedule excludes most sleeping time but includes 1.5 h of operation at night and 1 h in the morning, so still covers crucial hours, potentially very cold, or hot from daytime heat accumulation, and yet the HVAC was not needed in 40% of the yearly time. The dining-living room has a much more extensive HVAC schedule, covering all of DLIV's occupancy plus 0.5 h before breakfast and 0.5 h before the family arrives in the afternoon, still the system was disregarded in 65% of the time, indicating that there was thermal comfort without the HVAC during 65% of that schedule; the latter is on for 900 h, approximately two thirds for heating and one third for cooling, even though it consumed slightly more electricity for cooling than heating – Table 8.1 above. The house had at least one of the treated zones' HVAC systems operating for 1002 h in heating mode, 416 h in cooling, hence for a total of 1418 h, only 45% of the available time, resulting in 16% of the total year (8760 h). Thus, choosing an intermittent instead of a constant operation was apparently sufficient and successful.

Table 8.4 - Annual natural ventilation effective hours

	Natural Ventilation Hours						
	BR1	BR2	SUIT	DLIV	KIT (N, W)	SUNR	SUNR doors
(h)	319.2	372.2	466.0	994.3	1167.0	1595.5	1441.7
per Venting Sched (%)	8.7	10.2	11.5	15.9	18.7	25.6	-
per 8760 h (%)	3.6	4.2	5.3	11.4	13.3	18.2	16.5

Table 8.4 displays the yearly hours that the exterior windows (except of bathrooms, pantry and corridor) and the sunroom's interior glazed doors operate according to the EMS optimised controls, and the ratios between these and the yearly hours of the respective zone's venting schedule (which for the sunroom's doors is Always On, 8760 h). The corner kids bedroom (BR2) window opens more often than the BR1 window, since it has East wall exposure and more cooling needs, as already seen. Suite's window opens even more often, so does DLIV's, the kitchen's North and West window operate always at the same time. The kitchen and sunroom's windows are the ones that open the most since they're in untreated zones and their operation depends on DLIV's conditions as well: the sunroom's large South-facing window opens the most frequently, in 26% of the available time and 18% of the whole year, since DLIV's heat removal and the buffer zone operation depend on it. The buffer zone operates successfully since the glazed doors (which are closed when DLIV's HVAC is on) open, not as often as its window to allow cooling of the buffer zone first, but still for a significative 16.5% of the year's hours.

Table 8.5 Annual natural ventilation during hybrid HVAC schedule, and night ventilation hours

	Natural Ventilation during HVAC Availability Hours				Night Ventilation Hours			
	BR1	BR2	SUIT	DLIV	DLIV	KIT (N, W)	SUNR	
(h)	72.2	83.2	143.2	285.2	609.5	1167.0	1595.5	(h)
per HVAC Sched (%)	7.9	9.1	15.7	11.1	18.7	35.8	49.0	per DLIV HVAC OFF Night Sched (%)
per 8760 h (%)	0.8	0.9	1.6	3.3	7.0	13.3	18.2	per 8760 h (%)

Table 8.5 presents the yearly sum of hours that the exterior windows open while the HVAC is available, so when passive ventilation occurs during hybrid mode, as determined by the EMS controls. The kitchen and sunroom's windows resulted in 0 h, which is curious since it was not imposed for them to close on the availability hours, only for the kitchen's windows (and the sunroom's doors) when DLIV's HVAC is indeed on. The ratios here presented aren't entirely valid, since they don't correspond to the windows' opening availability on those terms (an intersection with venting schedule was needed). Suite's and DLIV's window open for 143 h and 285 h, respectively, during the HVAC schedule. Night ventilation isn't possible in the bedrooms but it is in the 'living area'. All the windows in the West section open frequently at night, from 600 h to 1600 h, 7% to 18% of the year for DLIV's and sunroom's window.

Table 8.6 - Annual operation hours for the movable shading devices of exterior windows

		Movable Shading Devices Operation Hours						
		BR1	BR2	SUIT	DLIV	KIT N	KIT W	SUNR
Shutters	(h)	5422.0	5383.3	5248.5	4287.3	0.0	4196.0	3904.7
	per 8760 h (%)	61.9	61.5	59.9	48.9	0.0	47.9	44.6
Blinds	(h)	16.5	16.2	54.7	62.5	30.7	62.3	6.5
	per 8760 h (%)	0.188	0.185	0.624	0.713	0.350	0.712	0.074

Table 8.6 exhibits the successful implementation of the movable shading devices on exterior windows, except for the shutters on the kitchen's North window. This window construction is properly defined and is assigned as an actuator object, its EMS code equals the one from the kitchen's West window, still it doesn't work, nor gives any running errors or warnings. Despite that specific case, the external shutters assigned with window construction changes work efficaciously. These provide external movable insulation to prevent overcooling and overheating on both nights ands days when unoccupied, and this particular family spends many hours outside of the house, hence the operation on over 40% of the year's hours. The shutters operate more often in the bedrooms since these close every night while sleeping. The blinds on the other hand operate rarely, as expected from the house's occupancy profile; these are only on when the house is occupied, close to overheating and with high radiation incidence, and the family only arrives at late afternoon on weekdays, when the radiation isn't that high anymore. These are more useful in the weekends at lunch time, since the family also leaves the house at afternoon. Still, none has null operation, especially in the East and West-facing windows of the suite, DLIV and kitchen; the blinds operate most often on DLIV which partially justifies the high cooling load (Table 8.1), it is a result of the large West window, as predicted. The blinds operate even for the kitchen's Nort window, and negligibly on the South-facing windows of the kids bedrooms and sunroom, since there's already an external horizontal overhang in place at this façade.

8.4. Thermal Comfort

For the outside-of-thermostat comfort assessment, the outputs 'Setpoint Not Met While Occupied Time' gave wrong values and a lot of zeros: there was no overcooling anywhere and no overheating on the living room which has a high cooling load. Thus, the overcooling, overheating and discomfort hours and rates when occupied were calculated for the treated zones, and for the house by again registering the maximum time-value when discomfort in several zones occurred at the same time. The thermostat is the constant 20°C to 25°C, and the occupancy schedules' total hours were used to obtain the rates.

Table 8.7 - Extreme indoor air temperatures in the treated zones, discomfort hours and rates when occupied

	Extreme Temperatures and Discomfort Hours when occupied				
	BR1	BR2	SUIT	DLIV	**House**
Max T_{air} (°C)	25.97	26.22	27.39	25.63	27.39
Min T_{air} (°C)	19.45	19.41	18.64	18.00	18.00
Overcooling (h)	23.00	24.00	103.50	117.50	239.00
Rate (%)	**0.58**	**0.60**	**3.01**	**5.37**	**4.25**
Overheating (h)	361.00	421.50	474.50	132.00	677.00
Rate (%)	**9.05**	**10.57**	**13.79**	**6.03**	**12.02**
Discomfort (h)	384.00	445.50	578.00	249.50	916.00
Rate (%)	**9.63**	**11.17**	**16.80**	**11.40**	**16.27**

Table 8.7 shows the zones' extreme temperatures, the discomfort hours and rates when occupied. The treated zones temperatures don't distance too much from the thermostat setpoints, even with the the reduced intermittent HVAC operation used. Overcooling rates are minimal, below 5.5%, while overheating is considerable; the house's overheating rate surpasses the desired maximum of 10%, so does the suite's, which probably suffers due to its East-facing large glazing. Global discomfort is thus 16.8% in the suite and 16.3% for the house as a whole, due to slightly excessive overheating derived from the HVAC's intermittent operation.

8.5. Free-Floating Mode

The two devices EMS-controlled shading strategy is kept through free-floating mode. In this, mechanical air conditioning and ventilation are discarded by removing the Ideal Loads system, and Airflow Network's venting controls are used and not overridden by EMS (these *Erl* programs aren't called on Program Calling Manager), since there aren't maximum temperature thresholds to oblige to, as the cooling is exclusively passive. Additionally, for the shading *Erl* programs to run without errors, since they check if the window is closed, sensors with the AFN's determined open factors and the respective name change on the code are necessary.

The EN 15251's Adaptive Model of thermal comfort (Category II) outputs were requested from EnegyPlus. This retrieves the hourly results for its status assessment with values between -1 and 1: -1 represents that the zone is unoccupied and/or out-of-model's validity range (running average outdoor air temperature for the last 7 days below 10℃ or above 30℃), 0 for hourly occupied discomfort, 1 for hourly occupied comfort, and values between 0 and 1 for partial hourly comfort based on both the timestep evaluation and the zone's occupancy schedule (schedules include half hours for beginning or end of occupation periods). However, it also retrieved values between -1 and 0, indicating out-of-schedule in some timesteps and discomfort/comfort in others of the same hour. As a consequence, a simple '1 - value' manipulation for values other than -1, in order to convert comfort into discomfort times, would not be accurate. So, a separate simulation was run to request Adaptive Model's results and the occupancy schedules in Timestep frequency. With the data columns of only -1, 0 and 1, the comfort was converted to discomfot times. The house discomfort was assigned when at least one of the zones showed discomfort. Since each timestep has 10 min, the yearly sums of discomfort times were divided by 6 to obtain the discomfort hours.

Table 8.8 shows the Adaptive Model's results for the house in free-floating mode, and they're quite good. The house has a discomfort rate when occupied below 10%, at 8.3%.

Table 8.8 - Discomfort when occupied according to EN 15251's Adaptive Model, in free-floating mode

	Adaptive Model's Discomfort Hours when occupied				
	BR1	BR2	SUIT	DLIV	**House**
Discomfort (h)	99.67	75.67	294.00	110.33	467.33
Rate (%)	**2.50**	**1.90**	**8.54**	**5.04**	**8.30**

Chapter 9 – Conclusions and Future Work

A nearly zero energy building with thermal loads below the PHI's requirements was achieved, even if not with the intended thermal discomfort below 10%. The simplifications of the reference premium thermal envelope may have been too extensive, but more likely it was the intermittent HVAC of reduced schedule that hindered the occupants comfort. Nonetheless, for a large house with an open concept and apparent poor geometry ratios, by developing strong thermal resistance (insulation and shutters), shading (overhang, high reflectance and low transmittance shutters and blinds) and ventilation passive strategies (a complex airflow model with EMS controls), a very low consumption was achieved, which required only 7 PV modules to supply its annual amount of electricity.

Comparison scenarios and further optimisation could have improved this model. One interesting point to manipulate futurely would be the thermostat and setpoints, both availability and values schedules; arrange and test different combinations to check which works best in a specific local climate.

Other future work ideas that would benefit the model are:

- Daylighting assessment instead of fixing the lighting schedule;
- Modulation of the windows according to wind's speed (by using an EMS Sensor) or the indoor-outdoor temperature difference: minimum difference of 5℃ (to start varying the open factor) till a max of 15℃, at which the window stays at a 0.1 Open Factor, for example;
- Battery system for off-grid self-sustainable nZEB. A residential building like the one designed mainly uses energy at night, thus there's a displacement from the peak PV production, and a storage system would be useful;
- Study of other shading structures, mainly for East-West windows: vertical overhang (side fin) or louver on the West façade;
- Operable and shaded skylight for stack-effect ventilation (by thermal buoyancy) and daylighting (with assessment);
- Ground cooling, like a horizontal earth-to-air heat exchanger;
- For a completely different building: an internal courtyard (like Andalusians) with a deciduous vegetation cover (vines or wisteria), and study of a deciduous pergola instead of an overhang.

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Appendix A – Mediterranean Climatic Data

Table A.1 - Data sample's 68 localities, climatic subtypes and annual averages of temperature and global radiation

Locality	Climate	Annual Average	
		T (°C)	G (Wh/m²)
Bragança, PRT	Csa	12.4	4317
Coimbra, PRT	Csa	15.3	4294
Évora, PRT	Csa	15.8	4660
Faro, PRT	Csa	17.7	5098
Lisboa, PRT	Csa	16.3	4506
Porto, PRT	Csb	14.3	4284
Ávila, SPA	Csb	10.4	4361
Badajoz, SPA	Csa	16.4	4719
Barcelona, SPA	Csa	15.7	3995
Burgos, SPA	Csb	9.9	3916
Cáceres, SPA	Csa	16.2	4552
Córdoba, SPA	Csa	17.5	4733
Cuenca, SPA	Csa	12.2	4274
Granada, SPA	Csa	14.8	4860
Huelva, SPA	Csa	18.3	4788
Jaén, SPA	Csa	16.9	4812
La Coruña, SPA	Csb	14.1	3590
León, SPA	Csb	10.8	4142
Málaga, SPA	Csa	18.0	4828
Orense, SPA	Csb	14.3	3617
Oviedo, SPA	Csb	12.6	3149
Palencia, SPA	Csb	11.7	4311
Pontevedra, SPA	Csb	15.0	4137
Salamanca, SPA	Csa	11.6	4436
Segovia, SPA	Csb	11.8	4055
Seville, SPA	Csa	18.4	4857
Valladolid, SPA	Csa	12.2	4238
Zamora, SPA	Csa	12.5	4362
Palma (Mallorca), SPA	Csa	16.7	4504
Marseille, FRA	Csa	14.8	4224
Montpellier, FRA	Csa	14.8	4005
Nice, FRA	Csa	15.5	3998

Locality	Climate	Annual Average	
		T (°C)	G (Wh/m²)
Bari (Palese-Macchie), ITA	Csa	15.9	3604
Bonifati, ITA	Csa	14.3	3583
Brindisi, ITA	Csa	16.6	3626
Campobasso, ITA	Csb	11.2	3627
Capo Palinuro, ITA	Csa	16.3	3565
Crotone, ITA	Csa	16.2	3702
Florence (Peretola), ITA	Csa	14.2	3118
Genova, ITA	Csa	16.0	3538
Gioia del Colle, ITA	Csa	13.6	3621
Grosseto, ITA	Csa	14.8	3158
Lecce, ITA	Csa	16.1	3644
Naples, ITA	Csa	16.3	4019
Pisa, ITA	Csa	14.6	3976
Pratica di Mare, ITA	Csa	14.7	3500
Roma (Fiumicino), ITA	Csa	15.2	3494
Santa Maria di Leuca, ITA	Csa	16.8	3665
San Remo, ITA	Csa	15.2	3205
Taranto, ITA	Csa	16.6	3635
Pianosa, ITA	Csa	16.6	3525
Ponza, ITA	Csa	15.9	3546
Alghero, ITA	Csa	16.2	3631
Cagliari (Elmas), ITA	Csa	16.4	3677
Capo Bellavista, ITA	Csa	16.8	3587
Olbia (Costa Smeralda), ITA	Csa	16.0	3547
Catania (Fontanarossa), ITA	Csa	17.1	3812
Cozzo Spadaro, ITA	Csa	18.1	3866
Enna, ITA	Csa	12.3	3700
Gela, ITA	Csa	17.0	4073
Messina, ITA	Csa	17.9	3782
Palermo (Boccadifalco), ITA	Csa	18.0	3987
Trapani (Birgi), ITA	Csa	17.5	3999
Ustica, ITA	Csa	16.5	3863
Podgorica, MTN	Csa	15.1	4464
Andravida, GRC	Csa	16.7	4151
Athens, GRC	Csa	17.9	4565
Istanbul, TUR	Csa	14.5	3810

Table A.2 - Climates of Nice, Seville and Burgos: HDD and CDD calculated from the weather files, monthly profiles of temperature, average global radiation, relative humidity, wind speed and wind main direction

HDD (base 10°C)	132	CDD (base 18°C)		551			
Nice (43°39'N 7°11'E)							
	T (°C)			G	RH	Wind	
	Avg	Min	Max	(Wh/m²)	(%)	(m/s)	Direction
Jan	8.8	3.6	18.5	1684	63	4.9	N
Feb	8.7	2.0	16.0	2540	71	3.3	N
Mar	11.5	6.0	23.0	3660	64	3.7	N
Apr	13.1	8.0	18.1	5010	75	4.0	N
May	17.5	11.0	26.0	5677	70	3.4	NW
Jun	20.6	11.9	28.3	6375	74	2.8	N
Jul	23.8	18.0	30.6	6741	73	3.5	SE
Aug	23.9	16.0	30.5	5972	67	3.5	N
Sep	20.9	14.0	26.0	4480	80	3.4	N
Oct	16.2	10.8	22.2	2671	75	4.1	NW
Nov	11.8	4.7	19.1	1768	75	4.5	NW
Dec	9.1	2.6	16.9	1394	65	5.2	NW

HDD (base 10°C)	60	CDD (base 18°C)		1063			
Seville (37°25'N 5°54'W)							
	T (°C)			G	RH	Wind	
	Avg	Min	Max	(Wh/m²)	(%)	(m/s)	Direction
Jan	10.4	-1.0	19.2	2423	75	2.2	N
Feb	11.7	3.0	24.0	3365	77	2.2	N
Mar	15.1	-2.0	28.0	4811	59	2.6	N
Apr	16.1	6.0	31.0	5430	57	2.9	N & W
May	19.8	10.0	36.0	6938	55	3.4	W
Jun	24.1	12.8	39.0	7180	50	2.9	W
Jul	27.4	14.0	43.0	7518	53	2.9	N
Aug	26.5	15.0	40.0	6819	54	2.6	N
Sep	24.5	12.0	39.0	5349	51	2.1	N
Oct	19.5	10.0	31.0	3738	70	2.4	N
Nov	13.7	2.0	26.0	2541	73	3.3	NE
Dec	11.5	-1.0	20.2	2169	78	2.6	NE

HDD (base 10°C)	978	CDD (base 18°C)		46			
Burgos (42°21'N 3°37'W)							
	T (°C)			G	RH	Wind	
	Avg	Min	Max	(Wh/m²)	(%)	(m/s)	Direction
Jan	2.6	-3.9	11.7	1410	82	6.7	N
Feb	3.9	-2.8	11.1	2205	74	6.7	N
Mar	5.7	-3.9	15.0	3331	75	6.7	N
Apr	7.6	-2.2	18.9	4205	72	6.7	N
May	11.1	1.7	24.4	5453	69	6.7	N
Jun	15.0	3.9	26.7	6524	64	6.7	N
Jul	18.4	8.9	33.9	7128	60	6.7	N
Aug	18.3	8.9	29.4	6316	63	6.7	N
Sep	15.8	6.7	27.2	4515	64	6.7	N
Oct	11.1	1.1	23.9	2919	73	6.7	N
Nov	5.8	-3.9	18.9	1792	83	6.7	N
Dec	3.2	-2.8	11.1	1197	84	6.7	N

Appendix B – Reference Passive House Premium in *Solliès-Pont*, and opaque materials utilised

Passive House Database Search 4969 buildings Advanced Search Information Contact Lang

General Information

ID: 5266

Certified building - Passive House Premium new build

Description
1st Passive House Premium in France

Building type
detached single family house

Location
F - 83210 Sollies-Pont (Provence-Alpes-Côte-d´Azur)

Number of appartments / units :	Treated Floor Area according to PHPP	Construction type	Year of construction
1	122 m^2	masonry construction	2016

Other parties involved

Architecture
Ideatectum

Building services
HELIASOL

Craftsperson / parties involved
Propassif (formerly La Maison Passive Services)

Thermal envelope

Exterior wall
Plaster 0,400 15
Concrete block 1,100 200
Graphite Polystyrene 0,032 200
Coating 0,700 5

U-value = 0.15 W/(m^2K)

Basement floor / floor slab
Tiles 2,600 20
Screed 1,600 60
Acoustic insulation 0,040 3
Concrete slab 2,300 250

Misapor 10/50 0,120 300
U-value = 0.34 W/(m^2K)

Roof
Plaster 0,400 15
Concrete slab 1,100 120
Concrete slab 2,000 130
Cellulose wool 0,039 Wood structure 0,130 97
Cellulose wool 0,039 173

U-value = 0.142 W/(m^2K)

Frame
MENUISERIES ANDRE, SMARTWIN
Smartwin 1 vantail (SuperSpacer Tri-Seal)
Smartwin OF 2 vantaux partie gauche et droite (SuperSpacer Tri-Seal)

Glazing
Triple glazing 0,52 0,53
Triple glazing with high g-factor (TRIIIE) 0,63 0,64
U_g-value = 0.53 W/(m^2K)
g -value = 52 %

Entrance door
U_d-value = 0.95 W/(m^2K)

Figure B.1 - Passive House Premium in *Solliès-Pont*: presentation and thermal envelope [39]

Mechanical systems

Ventilation
PAUL, NOVUS 300
eff. spec. HRS 87% Low electric consumption 0,24 Wh/m3

Heating installation
Electric heating

Domestic hot water
DHW provided by an electric tank

Additional information

Ecological aspects
42m² photovoltaic panel
4m² thermal solar panel

PHPP values

Air tightness
n_{50} = 0.26/h

Annual heating demand
1 kWh /(m²a) calculated according to PHPP

Heating load
4 W/m²

Primary energy requirement
31 kWh /(m²a) on heating installation, domestic hot water, household electricity and auxiliary electricity calculated according to PHPP

Figure B.2 - Passive House Premium in *Solliès-Pont*: air tightness, mechanical systems, energy consumption and production [39]

Table B.1 - Thicknesses and properties of the used opaque materials (thermal properties from [40])

Opaque Material	External Rendering	Gypsum Plastering	Felt/Bitumen Layers	Concrete (HW)
Roughness	MediumRough	MediumSmooth	VeryRough	MediumRough
Thickness (m)	0.02	0.01	0.003	0.18 | 0.2 | 0.32
Conductivity (W/m.K)	0.5	0.42	0.5	1.63
Density (kg/m³)	1300	1200	1700	2300
Specific Heat (J/kg.K)	1000	837	1000	1000
Thermal Absortance	0.9	0.9	0.9	0.9
Solar Absortance	0.65	0.4	0.7	0.65
Visible Absortance	0.65	0.4	0.7	0.65

Opaque Material	Concrete (MW)	Cork Board	Cork Tiles	Timber Flooring
Roughness	MediumRough	MediumSmooth	MediumSmooth	MediumSmooth
Thickness (m)	0.25	0.07 | 0.2 | 0.25	0.003	0.02
Conductivity (W/m.K)	0.51	0.04	0.08	0.14
Density (kg/m³)	1400	160	530	650
Specific Heat (J/kg.K)	1000	1888	1800	1200
Thermal Absortance	0.9	0.9	0.9	0.9
Solar Absortance	0.65	0.5	0.5	0.5
Visible Absortance	0.65	0.5	0.5	0.5

Opaque Material	Gravel	Soil	Plywood (HW)
Roughness	Rough	Rough	MediumSmooth
Thickness (m)	0.22	1.4	0.04 | 0.05
Conductivity (W/m.K)	0.36	1.729	0.15
Density (kg/m³)	1840	1842	700
Specific Heat (J/kg.K)	840	837	1420
Thermal Absortance	0.9	0.9	0.9
Solar Absortance	0.7	0.7	0.5
Visible Absortance	0.7	0.7	0.5

Appendix C – Script of the EMS Programs for Hybrid Mode

```
!-   ===========  ALL OBJECTS IN CLASS:
ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER ===========

EnergyManagementSystem:ProgramCallingManager,
    EMSManager,              !- Name
    BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point
    LivingArea_wiOpenControl,!- Program Name 1
    Bedrooms_wiOpenControl,  !- Program Name 2
    LivingArea_wiShadingControl,  !- Program Name 3
    Bedrooms_wiShadingControl,  !- Program Name 4
    OtherRooms_wiShadingControl;  !- Program Name 5

EnergyManagementSystem:ProgramCallingManager,
    EMSInitShadingConstants, !- Name
    BeginNewEnvironment,     !- EnergyPlus Model Calling Point
    InitialiseShadeControlFlags;  !- Program Name 1



!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ===========

EnergyManagementSystem:Program,
    Bedrooms_wiOpenControl,  !- Name
    IF (BR1a2Venting == 0) || (BR1AirTemp - OutdAirTemp < 1),  !- Program Line 1
    SET BR1wiOpenFactor = 0, !- Program Line 2
    ELSEIF BR1AirTemp >= NatVentSetpoint && BR1AirTemp <= CoolingSetpoint,  !- A4
    SET BR1wiOpenFactor = 1, !- A5
    ELSEIF BR1AirTemp > CoolingSetpoint && BR1a2HVAC == 0,  !- A6
    SET BR1wiOpenFactor = 1, !- A7
    ELSE,                    !- A8
    SET BR1wiOpenFactor = 0, !- A9
    ENDIF,                   !- A10
    IF (BR1a2Venting == 0) || (BR2AirTemp - OutdAirTemp < 1),  !- A11
    SET BR2wiOpenFactor = 0, !- A12
    ELSEIF BR2AirTemp >= NatVentSetpoint && BR2AirTemp <= CoolingSetpoint,  !- A13
    SET BR2wiOpenFactor = 1, !- A14
    ELSEIF BR2AirTemp > CoolingSetpoint && BR1a2HVAC == 0,  !- A15
    SET BR2wiOpenFactor = 1, !- A16
    ELSE,                    !- A17
    SET BR2wiOpenFactor = 0, !- A18
    ENDIF,                   !- A19
    IF (SUITVenting == 0) || (SUITAirTemp - OutdAirTemp < 1),  !- A20
    SET SUITwiOpenFactor = 0,!- A21
    ELSEIF SUITAirTemp >= NatVentSetpoint && SUITAirTemp <= CoolingSetpoint,  !-
A22
    SET SUITwiOpenFactor = 1,!- A23
    ELSEIF SUITAirTemp > CoolingSetpoint && SUITHVAC == 0,  !- A24
    SET SUITwiOpenFactor = 1,!- A25
    ELSE,                    !- A26
    SET SUITwiOpenFactor = 0,!- A27
    ENDIF;                   !- A28

EnergyManagementSystem:Program,
    LivingArea_wiOpenControl,!- Name
    IF (Venting == 0) || (DLIVAirTemp - OutdAirTemp < 1),  !- Program Line 1
    SET DLIVwiOpenFactor = 0,!- Program Line 2
    ELSEIF DLIVAirTemp >= NatVentSetpoint && DLIVAirTemp <= CoolingSetpoint,  !- A4
    SET DLIVwiOpenFactor = 1,!- A5
    ELSEIF DLIVAirTemp > CoolingSetpoint && DLIVHVAC == 0,  !- A6
    SET DLIVwiOpenFactor = 1,!- A7
    ELSE,                    !- A8
    SET DLIVwiOpenFactor = 0,!- A9
    ENDIF,                   !- A10
    IF Venting == 0,         !- A11
```

```
    SET KITwiNOpenFactor = 0,!- A12
    SET KITwiWOpenFactor = 0,!- A13
    ELSEIF DLIVHVAC == 1 && (DLIVAirTemp < HeatingSetpoint || DLIVAirTemp >
CoolingSetpoint),  !- A14
    SET KITwiNOpenFactor = 0,!- A15
    SET KITwiWOpenFactor = 0,!- A16
    ELSEIF (KITAirTemp - OutdAirTemp >= 1 && KITAirTemp >= NatVentSetpoint) ||
(DLIVAirTemp - OutdAirTemp >= 1 && DLIVAirTemp >= NatVentSetpoint),  !- A17
    SET KITwiNOpenFactor = 1,!- A18
    SET KITwiWOpenFactor = 1,!- A19
    ELSE,                    !- A20
    SET KITwiNOpenFactor = 0,!- A21
    SET KITwiWOpenFactor = 0,!- A22
    ENDIF,                   !- A23
    IF Venting == 0,         !- A24
    SET SUNRwiOpenFactor = 0,!- A25
    ELSEIF (SUNRAirTemp - OutdAirTemp >= 1 && SUNRAirTemp >= NatVentSetpoint) ||
(DLIVAirTemp - OutdAirTemp >= 1 && DLIVAirTemp >= NatVentSetpoint),  !- A26
    SET SUNRwiOpenFactor = 1,!- A27
    ELSE,                    !- A28
    SET SUNRwiOpenFactor = 0,!- A29
    ENDIF,                   !- A30
    IF DLIVHVAC == 1 && (DLIVAirTemp < HeatingSetpoint || DLIVAirTemp >
CoolingSetpoint),  !- A31
    SET SUNRdoEOpenFactor = 0,  !- A32
    SET SUNRdoWOpenFactor = 0,  !- A33
    ELSEIF OutdAirTemp < HeatingSetpoint - 8 && DLIVAirTemp < NatVentSetpoint &&
DLIVAirTemp < SUNRAirTemp,  !- A34
    SET SUNRdoEOpenFactor = 1,  !- A35
    SET SUNRdoWOpenFactor = 1,  !- A36
    ELSEIF DLIVAirTemp - OutdAirTemp >= 1 && DLIVAirTemp >= NatVentSetpoint &&
DLIVAirTemp > SUNRAirTemp,  !- A37
    SET SUNRdoEOpenFactor = 1,  !- A38
    SET SUNRdoWOpenFactor = 1,  !- A39
    ELSE,                    !- A40
    SET SUNRdoEOpenFactor = 0,  !- A41
    SET SUNRdoWOpenFactor = 0,  !- A42
    ENDIF;                   !- A43

EnergyManagementSystem:Program,
    InitialiseShadeControlFlags,  !- Name
    SET NoShading = 0.0 - 1.0,  !- Program Line 1
    SET ShadingOff = 0.0,     !- Program Line 2
    SET InteriorShadeOn = 1.0,  !- A4
    SET SwitchableDark = 2.0,!- A5
    SET ExteriorShadeOn = 3.0,  !- A6
    SET InteriorBlindOn = 6.0,  !- A7
    SET ExteriorBlindOn = 7.0,  !- A8
    SET BetweenGlassShadeOn = 8.0,  !- A9
    SET BetweenGlassBlindOn = 9.0;  !- A10

EnergyManagementSystem:Program,
    Bedrooms_wiShadingControl,  !- Name
    SET BR1wiConstruct = Null,  !- Program Line 1
    SET BR1wiShadiStatus = ShadingOff,  !- Program Line 2
    IF BR1wiOpenFactor > 0,  !- A4
    SET BR1wiConstruct = Null,  !- A5
    ELSEIF SunIsUp == 0 || BR1a2Awake == 0,  !- A6
    SET BR1wiConstruct = ExtWindowwExtShutter,  !- A7
    ELSEIF HOUSEOccupancy == 0 && BR1AirTemp >= NatVentSetpoint && BR1AirTemp <
OutdAirTemp,  !- A8
    SET BR1wiConstruct = ExtWindowwExtShutter,  !- A9
    ELSEIF BR1AirTemp >= NatVentSetpoint && BR1wiSolRadIncid > 150 && BR1AirTemp <
OutdAirTemp,  !- A10
    SET BR1wiShadiStatus = InteriorBlindOn,  !- A11
    ENDIF,                   !- A12
    SET BR2wiConstruct = Null,  !- A13
    SET BR2wiShadiStatus = ShadingOff,  !- A14
```

```
    IF BR2wiOpenFactor > 0,  !- A15
    SET BR2wiConstruct = Null,  !- A16
    ELSEIF SunIsUp == 0 || BR1a2Awake == 0,  !- A17
    SET BR2wiConstruct = ExtWindowwExtShutter,  !- A18
    ELSEIF HOUSEOccupancy == 0 && BR2AirTemp >= NatVentSetpoint && BR2AirTemp <
OutdAirTemp,  !- A19
    SET BR2wiConstruct = ExtWindowwExtShutter,  !- A20
    ELSEIF BR2AirTemp >= NatVentSetpoint && BR2wiSolRadIncid > 150 && BR2AirTemp <
OutdAirTemp,  !- A21
    SET BR2wiShadiStatus = InteriorBlindOn,  !- A22
    ENDIF,                    !- A23
    SET SUITwiConstruct = Null,  !- A24
    SET SUITwiShadiStatus = ShadingOff,  !- A25
    IF SUITwiOpenFactor > 0, !- A26
    SET SUITwiConstruct = Null,  !- A27
    ELSEIF SunIsUp == 0 || SUITAwake == 0,  !- A28
    SET SUITwiConstruct = ExtWindowwExtShutter,  !- A29
    ELSEIF HOUSEOccupancy == 0 && SUITAirTemp >= NatVentSetpoint && SUITAirTemp <
OutdAirTemp,  !- A30
    SET SUITwiConstruct = ExtWindowwExtShutter,  !- A31
    ELSEIF SUITAirTemp >= NatVentSetpoint && SUITwiSolRadIncid > 150 && SUITAirTemp
< OutdAirTemp,  !- A32
    SET SUITwiShadiStatus = InteriorBlindOn,  !- A33
    ENDIF;                    !- A34

EnergyManagementSystem:Program,
    OtherRooms_wiShadingControl,  !- Name
    SET WC12wiConstruct = Null,  !- Program Line 1
    SET WC12wiShadiStatus = ShadingOff,  !- Program Line 2
    IF WC12wiAFNOpenFactor > 0,  !- A4
    SET WC12wiConstruct = Null,  !- A5
    ELSEIF SunIsUp == 0,      !- A6
    SET WC12wiConstruct = ExtWindowwExtShutter,  !- A7
    ELSEIF HOUSEOccupancy == 0 && WC12AirTemp >= NatVentSetpoint && WC12AirTemp <
OutdAirTemp,  !- A8
    SET WC12wiConstruct = ExtWindowwExtShutter,  !- A9
    ELSEIF WC12AirTemp >= NatVentSetpoint && WC12wiSolRadIncid > 150 && WC12AirTemp
< OutdAirTemp,  !- A10
    SET WC12wiShadiStatus = InteriorBlindOn,  !- A11
    ENDIF,                    !- A12
    SET CORRwiConstruct = Null,  !- A13
    SET CORRwiShadiStatus = ShadingOff,  !- A14
    IF CORRwiAFNOpenFactor > 0,  !- A15
    SET CORRwiConstruct = Null,  !- A16
    ELSEIF SunIsUp == 0,      !- A17
    SET CORRwiConstruct = ExtWindowwExtShutter,  !- A18
    ELSEIF HOUSEOccupancy == 0 && CORRAirTemp >= NatVentSetpoint && CORRAirTemp <
OutdAirTemp,  !- A19
    SET CORRwiConstruct = ExtWindowwExtShutter,  !- A20
    ELSEIF CORRAirTemp >= NatVentSetpoint && CORRwiSolRadIncid > 150 && CORRAirTemp
< OutdAirTemp,  !- A21
    SET CORRwiShadiStatus = InteriorBlindOn,  !- A22
    ENDIF,                    !- A23
    SET WCSUwiConstruct = Null,  !- A24
    SET WCSUwiShadiStatus = ShadingOff,  !- A25
    IF WCSUwiAFNOpenFactor > 0,  !- A26
    SET WCSUwiConstruct = Null,  !- A27
    ELSEIF SunIsUp == 0,      !- A28
    SET WCSUwiConstruct = ExtWindowwExtShutter,  !- A29
    ELSEIF HOUSEOccupancy == 0 && WCSUAirTemp >= NatVentSetpoint && WCSUAirTemp <
OutdAirTemp,  !- A30
    SET WCSUwiConstruct = ExtWindowwExtShutter,  !- A31
    ELSEIF WCSUAirTemp >= NatVentSetpoint && WCSUwiSolRadIncid > 150 && WCSUAirTemp
< OutdAirTemp,  !- A32
    SET WCSUwiShadiStatus = InteriorBlindOn,  !- A33
    ENDIF,                    !- A34
    SET PANTwiConstruct = Null,  !- A35
    SET PANTwiShadiStatus = ShadingOff,  !- A36
```

```
    IF PANTwiAFNOpenFactor > 0,   !- A37
    SET PANTwiConstruct = Null,   !- A38
    ELSEIF SunIsUp == 0,      !- A39
    SET PANTwiConstruct = ExtWindowwExtShutter,   !- A40
    ELSEIF HOUSEOccupancy == 0 && PANTAirTemp >= NatVentSetpoint && PANTAirTemp <
OutdAirTemp,   !- A41
    SET PANTwiConstruct = ExtWindowwExtShutter,   !- A42
    ELSEIF PANTAirTemp >= NatVentSetpoint && PANTwiSolRadIncid > 150 && PANTAirTemp
< OutdAirTemp,   !- A43
    SET PANTwiShadiStatus = InteriorBlindOn,   !- A44
    ENDIF;                    !- A45

EnergyManagementSystem:Program,
    LivingArea_wiShadingControl,   !- Name
    SET DLIVwiConstruct = Null,   !- Program Line 1
    SET DLIVwiShadiStatus = ShadingOff,   !- Program Line 2
    IF DLIVwiOpenFactor > 0, !- A4
    SET DLIVwiConstruct = Null,   !- A5
    ELSEIF SunIsUp == 0,      !- A6
    SET DLIVwiConstruct = ExtWindowwExtShutter,   !- A7
    ELSEIF HOUSEOccupancy == 0 && DLIVAirTemp >= NatVentSetpoint && DLIVAirTemp <
OutdAirTemp,   !- A8
    SET DLIVwiConstruct = ExtWindowwExtShutter,   !- A9
    ELSEIF DLIVAirTemp >= NatVentSetpoint && DLIVwiSolRadIncid > 150 && DLIVAirTemp
< OutdAirTemp,   !- A10
    SET DLIVwiShadiStatus = InteriorBlindOn,   !- A11
    ENDIF,                    !- A12
    SET KITwiNConstruct = Null,   !- A13
    SET KITwiNShadiStatus = ShadingOff,   !- A14
    IF KITwiNOpenFactor > 0, !- A15
    SET KITwiNConstruct = Null,   !- A16
    ELSEIF SunIsUp == 0,      !- A17
    SET KITwiNwiConstruct = ExtWindowwExtShutter,   !- A18
    ELSEIF HOUSEOccupancy == 0 && KITAirTemp >= NatVentSetpoint && KITAirTemp <
OutdAirTemp,   !- A19
    SET KITwiNwiConstruct = ExtWindowwExtShutter,   !- A20
    ELSEIF KITAirTemp >= NatVentSetpoint && KITwiNSolRadIncid > 150 && KITAirTemp <
OutdAirTemp,   !- A21
    SET KITwiNShadiStatus = InteriorBlindOn,   !- A22
    ENDIF,                    !- A23
    SET KITwiWConstruct = Null,   !- A24
    SET KITwiWShadiStatus = ShadingOff,   !- A25
    IF KITwiWOpenFactor > 0, !- A26
    SET KITwiWConstruct = Null,   !- A27
    ELSEIF SunIsUp == 0,      !- A28
    SET KITwiWConstruct = ExtWindowwExtShutter,   !- A29
    ELSEIF HOUSEOccupancy == 0 && KITAirTemp >= NatVentSetpoint && KITAirTemp <
OutdAirTemp,   !- A30
    SET KITwiWConstruct = ExtWindowwExtShutter,   !- A31
    ELSEIF KITAirTemp >= NatVentSetpoint && KITwiWSolRadIncid > 150 && KITAirTemp <
OutdAirTemp,   !- A32
    SET KITwiWShadiStatus = InteriorBlindOn,   !- A33
    ENDIF,                    !- A34
    SET SUNRwiConstruct = Null,   !- A35
    SET SUNRwiShadiStatus = ShadingOff,   !- A36
    IF SUNRwiOpenFactor > 0, !- A37
    SET SUNRwiConstruct = Null,   !- A38
    ELSEIF SunIsUp == 0,      !- A39
    SET SUNRwiConstruct = ExtWindowwExtShutter,   !- A40
    ELSEIF HOUSEOccupancy == 0 && SUNRAirTemp >= NatVentSetpoint && SUNRAirTemp <
OutdAirTemp,   !- A41
    SET SUNRwiConstruct = ExtWindowwExtShutter,   !- A42
    ELSEIF SUNRAirTemp >= NatVentSetpoint && SUNRwiSolRadIncid > 150 && SUNRAirTemp
< OutdAirTemp,   !- A43
    SET SUNRwiShadiStatus = InteriorBlindOn,   !- A44
    ENDIF;                    !- A45
```

Appendix D – Photovoltaic Modules [53] and Inverter [54] Data Sheets

LUXOR
the sunshine people

10-year product guarantee

12-year guarantee for 90 % rated power

25-year guarantee for 80 % rated power

ECO LINE
72/185 – 200 W

Monocrystalline module family

Longlife tested
- Selection of components
- Cross-linking degree test

Power proofed
- Performance surplus of 1.5 to 6.49 Wp
- Impp sorting

Safety provided
- Special packing to avoid micro cracks in the cells
- German warrantor

Wherever flexibility is especially sought after, this module is in top form. With its dimension in a 1:2 ratio, it can always be optimally arranged in every roof covering and open-field installation. Our 72-cell module portrays a positive image with plus tolerances of 1.5 to 6.49 Wp, through exemplary energy output. This is achieved through high-quality solar cell with an efficiency up to 18.5 % at the best possible low light behaviour. A durable plug-in connection guarantees reliable power contact for every weather. Compatible with current assembly systems through the torsionally stiff and corrosion-free hollow-section frame made of anodised aluminium. Manufactured according to German standards and under the strict eyes of our engineers, each Luxor photovoltaic module is marked by a special level of durability and reliability.

Luxor Solar GmbH | Königstraße 26 | 70173 Stuttgart | Germany | T +49.711.88 888-999 | info@luxor-solar.com | www.luxor-solar.com

ECO LINE ECO LINE 72/185 – 200 W

Monocrystalline module family

Electrical data	LX-185M	LX-190M	LX-195M	LX-200M
Rated power Pmpp [Wp]	185.00	190.00	195.00	200.00
Pmpp range	186.50 - 191.49	191.50 - 196.49	196.50 - 201.49	201.50 - 206.49
Rated current Impp [A]	5.16	5.28	5.33	5.39
Rated voltage Vmpp [V]	36.15	36.27	36.87	37.39
Short-circuit current Isc [A]	5.62	5.71	5.79	5.87
Open-circuit voltage [V]	43.58	43.81	44.04	44.27
Efficiency at STC	14.61%	15.00%	15.39 %	15.79%
Efficiency at 200 W/m²	14.21 %	14.61%	15.00 %	15.39%
NOCT [°C]	47 ± 2°C	47 ± 2°C	47 ± 2°C	47 ± 2°C

Specification as per STC: 1000 W/m², 25°C, AM 1.5 / STC Irradiance: 1000 W/m²,
Module temperature: 25°C, AM=1.5 | NOCT: 47°C

Limiting values	LX-185M / LX-190M / LX-195M / LX-200M
Max. system voltage [V]	1000 V
Max. return current [I]	12A
Temperature range	-40 to 85°C
Snow-load zone[1]	approval up to SLZ 3 (according to DIN 1055)
Max. pressure load (static)	5400 Pa

Temperature coefficient	LX-185M / LX-190M / LX-195M / LX-200M
Temperature coefficient [V] | [I] | [P]	-0.35% / °C | 0.04% / °C | -0.45% / °C

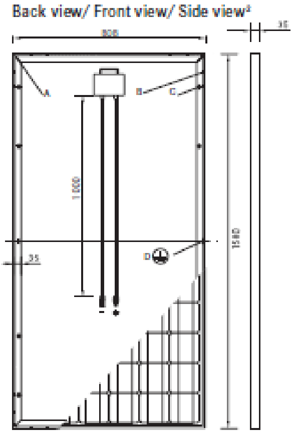
Specifications	LX-185M / LX-190M / LX-195M / LX-200M
Number of cells (matrix)	6 x 12, three strings in a row
Cell size	125 mm x 125 mm (diagonal: 165 mm)
Module dimensions (L x W x H)[2] | Weight	1,580 mm x 808 mm x 35 mm | 15.0 kg
Front-side glass	3.2 mm hardened solar glass with low iron content
Frame	stable, anodised aluminium frame in a hollow-section design
Socket	plastic (PPO), IP65, ventilated and strain-relieved
Cable	4 mm² solar cable, cable length 1.0 m
Plug-in connection	high-quality plug-in system, (IP65) MC4 or equivalent
Hail test (max. hailstorm)	ø 45 mm | impact velocity 23 m/s
General technical approval	classified according to DIN EN 13501-5 as B_{ROOF}(t1)

Packing	LX-185M / LX-190M / LX-195M / LX-200M
Packing unit	28 modules, 2 Impp classes | 28 PU/ 40' container
Dimensions (L x W x H) | Weight	168 cm x 110 cm x 105 cm | 496 kg gross

The specifications and average values can vary slightly. Decisive is the corresponding data of the individual measurement. Specifications are subject to change without notice. Measurement tolerance: rated power +/- 3%, other values +/- 10%, all information in this data sheet corresponds to DIN 50380, other information to be found in the installation guidelines.

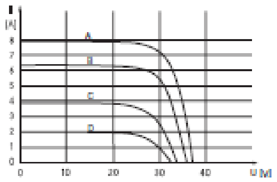
1 For standing installation
2 Tolerance L/W = +/- 3 mm, H = the dimensions given in the order confirmation will be decisive
3 Location on request

Back view/ Front view/ Side view[2]

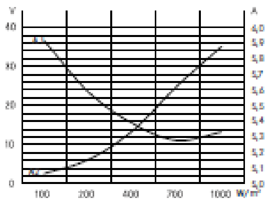


A: 4 x drainage 10*10 mm
B: 16 x ventilation aperture 3*7 mm
C: 8 x mounting hole[3] d = 7 mm
D: 2 x earthing d = 2 mm

Characteristics



A: 1000 W/m² | B: 800 W/m² | C: 600 W/m²



A1: Impp | A2: Vmpp

Luxor, your specialised company

Guidelines:
2006/95/EG - 2006/95/EC, 89/336/EWG - 89/336/EEC, 93/68/EWG - 93/68/EEC

IEC 61215
IEC 61730

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Eco Line 72/185- 200 W_102012

COMPACT series

Model	XPC 1400-12	XPC 2200-24	XPC 2200-48	C 1600-12	C 2600-24	C 4000-48	HPC 2800-12	HPC 4400-24	HPC 6000-48	HPC 8000-48
Inverter										
Nominal battery voltage	12V	24V	48V	12V	24V	48V	12V	24V	48V	
Input voltage range	9.5 – 16V	19 - 32V	38 - 64V	9.5 - 16V	19 - 32V	38 - 64V	9.5 - 17V	19 - 34V	38 - 68V	
Continuous power @ 25°C	1100VA	1600VA	1600VA	1300VA	2300VA	3500VA	2500VA	4000VA	5000VA	7000VA
Power 30 min. @ 25°C	1400VA	2200VA	2200VA	1600VA	2600VA	4000VA	2800VA	4400VA	6000VA	8000VA
Power 5 sec. @ 25°C	3 x Pnom									
Maximum power	Up to short-circuit									
Maximum asymmetric load	Up to Pcont.									
Stand-by adjustment	1 to 25W									
Cos φ	0.1 - 1									
Maximum efficiency	94%	95%		94%	95%		93%	94%	96%	
Consumption OFF/Stand-by/ON	0.5/0.6/4W	0.8/0.9/7W	1.2/1.3/7W	0.5/0.6/6W	0.8/0.9/9W	1.2/1.4/12W	1.4/1.8/10W	1.7/2/16W	2/2.5/18W	2/3/30W
Output voltage	Sine wave 230Vac (+0/- 10%) (XPC also available in 120Vac)									
Output frequency	50Hz +/- 0.05% (crystal controlled)									
Total harmonic distortion	< 4%	< 2%								
Dynamic behaviour	0.5 ms (on load change 0 to 100%)									
Overload and short-circuit protection	Automatic disconnection with 3 time restart attempt									
Overheat protection	Acoustic warning before shut-off - with automatic restart									
Battery charger (4 STEP) I-U-Uo-Equalize (every 25 cycles)										
Charging current adjustable	0 - 45A	0 - 37A	0 - 20A	0 - 55A		0 - 50A	0 - 110A	0 - 100A	0 - 70A	0 - 90A
Input current balance adjustment	Not available			1 - 16A			1 - 30A			1 - 50A
Maximum input voltage	265Vac									
Input AC voltage range	Adjustable threshold from 150 to 230Vac (XPC also available in 120Vac)									
Input frequency	45 - 65Hz									
Power Factor Correction (PFC)	EN 61000-3-2									
Optional solar charger (4 stages) I-U-Uo-Equalize (every 25 cycles)										
Maximum PV open circuit voltage (V)	25V	45V	90V	25V	45V	90V	Not available			
Maximum charge current (A)	30A	30A	20A	30A	30A	20A	Not available			
Charging curve	I-U-Uo-Equalize (every 25 cycles) / Not available						Not available			
Battery control (thresholds and times adjustable by the user)										
Absorption time	0-4 h									
End charge cycle voltage*	14.4V	28.8V	57.6V	14.4V	28.8V	57.6V	14.4V	28.8V	57.6V	
Floating voltage	13.6V	27.2V	54.4V	13.6V	27.2V	54.4V	13.6V	27.2V	54.4V	
Equalization time	0-4 h									
Equalization voltage	15.6V	31.2V	62.4V	15.6V	31.2V	62.4V	15.6V	31.2V	62.4V	
Deep-discharge protection	10.8V	21.6V	43.2V	10.8V	21.6V	43.2V	10.8V	21.6V	43.2V	
Temparature compensation (optional CT-35)	-3mV / ° C / Cell									
General data										
Multifunction contact programmable	16A - 250Vac (potential free 3 points)									
Max. current on transfer relay	16A						30A			50A
Transfer time	< 40 ms									
Weight	11.7 kg	12.6 kg		16 kg	17.1 kg	29.4 kg	33 kg	39 kg	41 kg	45 kg
Dimension hxwxl [mm]	124x215x410			124x215x480		124x215x670	242x288x480			242x288x500
Protection index	IP20 (IP22 with top cover C-IP22)						IP 20			
Certification ECE-R 10 (E24)	•	•	Not available	•	•	Not available				
EC conformity	EN 61000-6-1, EN 61000-6-3, EN 55014, EN 55022, EN 61000-3-2, Dir. 89/336/EEC, LVD 73/23/EEC									
Operating temperature range	-20°C up to +55°C									
Relative humidity in operation	95% without condensation									
Ventilation	From 45°C									
Accoustic level	<40dB / <45dB (without/with ventilation)									
Warranty	2 years									
Options										
Solar charge controller	30A	30A	20A	30A	30A	20A				

* Factory settings

Data may change without any notice.