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ALGORITHMIC DESIGN FOR BUILDING PHYSICS

IMPACT OF COMPUTATIONAL ALGORITHMS IN PRELIMINARY DESIGN ON RENEWABLE RESOURCE SELF-CONSUMPTION & LOAD MATCHING POTENTIAL

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ABSTRACT

It is estimated today that almost 40% of all green house gas emissions derive from the building and construction industry, of which almost 30% attributable to operating costs [38]. As resources become scarcer and scarcer indeed - both tangible building materials, and intangible energetic ones - the need to optimise and reduce the various layers of consumption - throughout all stages of a building's design, construction and use - has become a necessary priority for all building cultures around the world.

On the specific issue of a building's (thermal) operating energetic consumption, existing research has focused on the improvement and optimisation of *thermal energy systems generation, distribution and control* efficiency; as well as on the development, simulation and control of *energy storage systems* to alleviate renewable resource and thermal demand mismatch - the goal being to reduce grid interaction and dependancy; as well as to maximise load-matching (self-consumption potential). Parallel to such work, a series of *computational-based simulation, calculation, performance predicition tools* were developed, allowing for the introduction of mathematics and algorithmic design in architectural composition.

Lying at the crossroads between such considerations, the present work aims at the 1) development and definition of an algorithmic preliminary design process for the selection of core design variables (ex: glazing ratios, envelope and glazing component characteristics, orientation, positionon site etc..); followed by 2) the analysis and evaluation of the influence and effects of such a process on A) thermal demand and consumption; B) heat-pump and photovoltaic performance; C) water-based thermal energy storage dimensioning, performance and control; and D) consequent renewable resource self-consumption and load-matching potential.

The performances of two (identically constrained) buildings - one following such algorithmic design process, the other one following traditional consensual design processes - are compared, discussed and analysed.

Looking now at the results, the potential and superior performance of the proposed algorithmic preliminary design process was demonstrated with respect to all considered objectives: the algorithm-based project outperformed the generic-based project by over 20 [kWh/m²] (23% decrease) with respect to their yearly thermal demands; and by 7% with respect to UDI.

The viability and potential of such processes was then demonstrated on the building's consequent consumption profiles; energy system generation needs; as well as in the design and dimensioning of water thermal energy storages. Indeed, thermal demand was decreased by 9% with respect to the generic project, allowing for an identical 9% reduction of PV panel peak power size. The lower electrical demand resulted in a lower instantaneous consumption profile, allowing for a 4% higher proportion of storable energy for the optimised project - and thus of tank capacity. These trends were then verified when looking at localised behaviours of both consumption and system configurations in reference seasonal weeks.

Overall, research has demonstrated the viability, potential and superior performance of algorithmic design in preliminary architectural composition, with respect to consequent (thermal) demand and consumption; load-matching capabilities; grid interaction probability; renewable energy proportional use; and manufacturing of processed and carbon-hungry materials.

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CHAPTER 1

INTRODUCTION

OBJECTIVES

GENERAL

The use of software to simulate, study and optimise a building's heating and cooling performance, with the ambition of maximum energetic independency through renewable resource self-consumption.

Such consumption performance will be optimised through the manipulation of a building's architecture, materials, construction, and energy system components. Parameters such as visual comfort, daylighting potential, carbon price, economics and designability will also be considered.

A computational and algorithmic design process will thereafter be presented, discussed, and applied on the development of an architectural project; and then compared to a control building not following such process.

The end goal being to understand how much influence algorithmic, computationally-aided preliminary design can have on a project's renewable resource self-consumption and load-matching potential.

PRELIMINARY

MOTIVATION

As resources become scarcer indeed, the need to optimise and reduce the various layers of need and consumption on one hand; as well as properly manage the available resources on the other, has become a growing concern and a necessary priority in all industrial strata of the world.

Although punctual phenomenon like the Covid-19 pandemic may reduce (though negligibly) the need of energy and raw materials in industries such as real estate construction, the demand is still increasing exponentially – and will continue to do so, even as the world population stabilises in the coming 2 decades. In France in 2019 alone, over 450 000 houses were built – equivalent to almost 1250 houses each day [35]. These constructions were most of the time built with profit in mind, rather than with energetic, material, constructive, or social sustainability as constraining factors.

T oday, it is estimated that almost 40% of all green house gas emissions derive from the building and construction industry [38]. From lighting, heating, cooling, through the creation and distribution of raw and processed materials, to the carbon fuel-based machines needed to construct and erect buildings; the need to modify the approach and methods that this industry has with the construction and maintenance of the building sector represents one of contemporary architecture's core responsibilities.

Responding to the material and energetic issues of our time, the revised Energy Performance of Buildings Directive (EPBD 2018/844/EU) [39] underlines the core necessity and potential of energy efficiency at all stages of consumption and demand; the widespread use and production of renewable energy sources - most often sourced from photovoltaic panels - all coupled to a culture of total electrification. In this scenario indeed, the culture of energetic sovereignty and independancy might grow massively - incurring very beneficial effects in all stratas of the environment .. but unfortunately not to the existing public grid. In such framework indeed, grids would probably be overloaded and stressed due to this massive new influx of locally sourced renewable energy. This is why today's buildings need a proper and optimised design process, allowing for a drastic reduction in energy demand through the sole manipulation of design variables (WWR, envelope components constructions, etc); as well as energy consumption systems (Heat Pump + PV + TES) that allow maximum renewable resource self-consumption and (multi-format) energetic storability - thus minimising grid interaction and its related stresses.

This "High Design, High Tech" approach to building undeniably holds a lot of promise; especially if coupled with the advances of computational power, algorithmic software, and properly chosen simulation tools and technologies.

In this framework, the goal of this applied research would be to develop, then study the effects and influence of algorithmic preliminary design on 1) (thermal) demand and consumption; 2) heat-pump and photovoltaic system design, performance and use; 3) thermal energy storage dimensioning, performance and control; and 4) consequent renewable resource self-consumption and load-matching potential.

SCOPE

The following architectural project being studied is limited by a number of factors: its location and consequent weather file and sky matrix; the building's area, plan and volume – as well as the relevant functional distribution; the number of people living there as well as their occupancy schedule. Indeed, the studied building is a house for living – a dwelling – occupied by a couple of 2 adults. The house is located in Cintegabelle, southwestern France - 60km north of the Pyrenees – on a planar surface with 2 buildings in its direct vicinity.

However, while the study of the energetic consumption and consequent potential for energetic independency is limited to a house with such characteristics, the process may be used and applied on a wide range of architectural typologies: from the single-family home to office and/or mixed use buildings. The proposed process may very well be applied to different locations, different geometries and different schedules. The proposed procedure can be used as a tool in the preliminary design part of a construction project to firstly quantify and simulate; then to justify the choice of certain building, design, material, and energy system characteristics.

METHODOLOGY

RESEARCH PROTOCOL

As part of the research on the influence of computationally-aided, algorithmic preliminary design on renewable resource self-consumption and load-matching potential; the performance of two buildings - houses for living - will be presented, discussed and analysed. As specified, these two buildings will be constrained by the same plan, volumetric dimensions, climatic data, solar matrix and shading contexts. A set of design variables will be decided: on the one hand ones that influence the building's geometry - position on the site and orientation; on the other ones that influence the building's envelope and consequent thermal demands - from WWR through envelope and glazing component constructions, to outdoor shading devices.

The difference between the two buildings is as follows: one building will undergo a thorough preliminary design optimisation process consisting of algorithmic computation, to select the values for all variables; while the other building's variables will be assigned and selected by existing theory, common knowledge and architectural consensus. The former will be assigned the name of «optimised building»; whilst the latter will be assigned the name of «generic/control building».

Following the selection of both project's variable values, the thermal energetic demand (heating and cooling only) will be computed, analysed and compared. Ultimately, these values will represent the basis and foundations for the next step: the computation of energetic consumption.

Considering an air-water heat pump with hourly-varying COP/EER values, the consequent annual electrical demand for both buildings will be computed, discussed, and compared. The heat heat pump's electrical demands will be derived so as to cover the building's total yearly consumption - taking into account their respective peak heating and cooling loads.

From the computation of such heat pump electrical yearly demand, a photovoltaic system power size will be derived so as to cover and satisfy both building's total yearly thermal demand (heating and cooling only). From an hourly photovoltaic productivity profile specific to the solar context in question (computed using the relevant formulas and performance ratios); the hourly photovoltaic production for both building's systems will be calculated, discussed, analysed, and compared. The amount and usability of each configuration's photovoltaic production will thus be known, and will represent the basis for the next step - namely the computation and comparison of renewable resource self-consumption and load matching potential.

According to both energetic potential on one end; and economic prospective value on the other; a water-based thermal energy storage will be optimised and calculated considering both building's demand profiles and consequent systems configurations - the variable being tank volume/size. Following the methodology as developed and provided by [1], a mathematical model implemented in excel will be used to replicate and represent the hourly performance of both project's system configurations with respect to: heating/cooling thermal and electrical demand; the photovoltaic system's energetic production and consequent proportional distribution of consumed, stored and sold energy (during the whole year as well as during localised time-frames); and finally the building's yearly load matching potentials; capacity factors; proportional uses of renewable energies; and grid energy use and dependencies.

Such performances will then be thoroughly represented, discussed, and compared- specifically focusing on the consequent performance differences that the proposed, initial preliminary design process has had on the optimised project with respect to the generic - in terms of its renewable resource self-consumptive ability; energetic autonomy, sovereignty; and overall sustainability.

The performance comparison will also include both projects considering they do not make use of a thermal energy storage - thus making a complete case as to the preliminary design process's benefits and potential in residential energetic consumption performance.

COMPUTATIONAL & ALGORITHMIC DESIGN

INTRODUCTION

As described in the previous section, a computational and algorithmic preliminary design process was developed. Such process is based on the conjoined use of a series of tools and softwares - both tools for calculations/simulations, as well as representative tools. The softwares, tools, and relevant programming languages are detailed thereafter.

I/ RHINOCEROS

The main modelling software used to represent, project and form the basis for computational aided design (CAD) is Rhinoceros 3D, an application software developed by Robert McNeel & Associates. It is based on the NURBS mathematical model which focuses on producing mathematically induced representations of curves, freeforms, and surfaces in computer graphics (as opposed to traditional polygon mesh-based applications).

II/ GRASSHOPPER

Grasshopper is a visual programming language and environment that runs with the above-described Rhinoceros 3D CAD software. It was developed by David Rutten and Robert McNeel Associates. Programmes or «scripts» are created by dragging components - algorithms - onto a canvas. It is based on the Python programming language, and is read from left to right. It essentially parallels a computer code, but with an easier way of manipulating it. Advanced applications include dynamic and parametric modelling for structural and energetic design and analysis.

III/ LADYBUG

Ladybug is an array of free computer applications using the Grasshopper interface through Rhinoceros 3D that support environmental design and analysis. It connects 3D CAD interfaces to a large variety of validated simulation engines. It helps designers create environmentally-conscious designs - allowing the analysis and representation of all kinds of weather data; as well as allows the possibility of challenging our preliminary design ideas in terms of solar radiation and potential sunlight hours.

IV/ HONEYBEE

Honeybee is a plugin for Grasshopper/Rhino as part of the Ladybug family that creates, runs and visualises simulations connected to engines such as Radiance for daylighting simulation; OpenStudio for energetic models; and THERM for envelope heat flow calcultations. It indeed hosts and supports detailed - usually very difficult to use - simulations through the Grasshopper visual programming language, and is one of the most comprehensive plugins available for environmental design.

In the following works, it will most notably be used to model, study, compute and extract precisely the proposed building's thermal energy; and indoor lighting models. The results of such calculations will be used throughout the whole research - and form the basis for the desired objectives, handled by the following software plugin.

V/ OCTOPUS

Octopus is a plugin for Grasshopper/Rhino used to apply evolutionary mathematical principles to parametric design and problem solving. Contrary to other existing solutions on the (open source) market, it allows the search of many goals at once, producing and allowing for the representation of a range of optimised trade-off solutions between goal's extremes. It was developed by Robert Vierlinger and is based on SPEA-2 and HypE from ETH Zurich and Ravid Rutten's Galapagos user interface.

In the following works, it will be used on one side so as to manipulate all of the previously discussed design variables through Grasshopper-based dynamic sliders; while on the other used to search for the best possible solutions with respect's to the fed objectives. In our case, it will indeed search for the optimal position and orientation so as to benefit as much as possible from existing solar radiation; as well as aim to optimise (minimise) thermal energy demand; maximise indoor useful daylight illuminance - through the manipulation of the building's envelope components and characteristics.

CHAPTER 2

STATE OF THE ART

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WORLD GLOBAL WARMING

In any given year, "Earth Overshoot Day" marks the date when humanity's demand of both ecological resources and services exceeds what Earth can regenerate in that same year. In 2021, it fell on July 29 - more than 5 months prior to the year's end. Moreover, in 2016 already, the UK Met Office [35] predicted an already existing 1.14°C increase of temperatures with respect to pre-industrial times - just 3/4 of a degree shy of the 2°C increase limit we have imposed ourselves with at the Paris UN Summit.

So far, the consequences to Earth's integrity have been disastrous - with massive biodiversity loss, frequent and extreme weather events, as well as the destabilisation/destruction of a wide variety of naturally occuring and fundamental-to-life systems & mechanisms. Such transformations imply massive consequences for all living organisms, and most importantly for all men, women and children of this earth who will need to radically transform their various layers of lifestyle and cultures; in order to adequately respond to the wrath left by climate change and global warming.

ENERGY CONS. RESIDENTIAL SECTOR

While many causes can be attributable to the onset of climate change, global warming and its consequences on biodiversity and life as a whole - we shall here only focus on the energy consumption (and underlying carbon emission) directly caused by the global residential sector.

In France in 2019 alone, over 450 000 houses were built – equivalent to almost 1250 houses each day. These constructions were most of the time built with profit and operative dependency in mind, rather than with energetic, material, constructive, or social sustainability as constraining factors. Although the Covid-19 pandemic may have reduced this trend slightly, demand is still rising and will continue to do so in the next 2 decades until the world population stabilises.

In 2010, approximately 2070 million tonnes of oil-equivalent were consumed [37] globally as a result of the residential sector. This equates to around 23,7% of the total energy consumed in a year globally; and just shy of 30,000 Mt of CO2 emission. In 2013, over 2125 million tonnes of oil-equivalent were consumed [37] - increasing by 3% with respect to three years prior - but only represented 22,8% of the total energy consumed in a year globally. This means that while energy consumption in the residential sector is increasing, it is however decreasing in proportional terms with respect to other industries.

That said, the residential sector remains the biggest emittor (different to consumer) of greenhouse gases in the world - with as nearly as 40% of total energy-related CO2 emissions being a consequence of buildings, of which almost 30% due to operational emissions. Given these numbers, the realisation that the residential sector and building/construction industry needs to transform and optimise all layers of their logistical, material, cultural ... processes is evident. The revised Energy Performance of Buildings Directive (EPBD 2018/844/EU) [39] indeed underlining the necessity of energy efficiency; and use of renewable energy sources RES coupled with a culture of total electrification.

NEAR ZERO ENERGY HOUSES (nZEB)

Given the circumstances in which both building engineers and architects find themselves with respect to the current global energetic situation, a multitude of research has been realised - ultimately yielding new theories and practices in the overall pursuit of the drastic reduction and optimisation of residential energetic demand and operation-related consumption. These studies developed new building cultures; all implying the reduction in electrical consumption, proper (air-tight) insulation; as well as new construction concepts and methodologies.

For example, the "near-Zero Energy House nZEB", defined in the EU's EPBD as "a building with a very high energy performance. The near zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby" [39] - the specificities of which - regulations, thresholds and limits, etc - being decided individually by each country. In France for example, the Ministry of Ecological Transition has defined in their 2018 (RE2020)

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Decret [41] the nZEB threshold to be strictly below 50 [kWh/m²] of primary energy consumption per year. Also, France went even as far as implenting this maximum threshold to all new constructions - ultimately forcing for nZEB to become the construction culture standard.

ALGORITHMIC DESIGN

With the advent of programming and software development tools for architecture and building construction; a plethora of new design processes and methodologies have been developed - at all stages of the design, planning and construction process - to facilitate the designer's work; expose him to a larger panel of solutions responding to his particular constraints; as well as allow for bespoke solutions in unique situations and constrains. D. Hobbs and his team [13] were among the first in 2003 to demonstrate the benefits of using building simulation tools within architectural design processes. On the other hand, massive developments in the mathematical world have led to the arrival of (user-friendly) multi-objective, multi-variable optimisation solvers.

Parametricism; building simulation tools; and the existence of multi-objective, multi-variable solvers; allowed for the development of algoritmic design in the building and construction industry.

GEOMETRY

As we will see in the following parts, the last couple decades have been to the family of "architectural materials, components and systems" times of enormous innovation and fertility. In other words, all the components, materials and mechanisms related to building construction and ongoing operation have been developed, re-developed, re-imagined, and optimised. However, the "soft" factors related to building geometry (orientation, size, height, glazing proportion and frequency, roof pitch, ... to name only a few) can all have massive impacts on a given building's final thermal demand.

Studies and research developed by M. Sadeghipour [12] - where building geometry is optimised according to incident solar radiation with respect to orientation, roof-pitch and S/V using algorithmic tools and multi-objective evolutionary algorithms - have demonstrated the potential benefits of the proper preliminary study of a building's geometry when considering consequent thermal demand. Y. Fang and S.Cho [15] also demonstrated the potential reduction of a building's thermal demand through the careful (or computationally-aided) manipulation of a building's height, surface, perimeter, and glazing ratios (keeping all of what is related to material, system, machine , component performance constant: for example, glazing ratios were variable, but glazing thermal resistance was not).

ENVELOPE

Similar to the research and development on the influence of building geometry on final thermal demand and UDI; studies have demonstrated that proper envelope design can have tremendous (positive) consequences on a building's design, construction and operational costs. Contrary to research on building geometry alone, the components, systems and their respective performances are here also variable. As clearly shown in the work of R. Azari's [16] on the design optimisation of a building envelope for life cycle environmental performance, where the materials themselves and their characteristics are variable - such as resistance values and insulation types. Indeed, envelope design coupled with algorithmic tools is gaining traction worldwide.

This is also a field of research where localised systems/mechanisms are optimised one at a time (considering varying objectives). For example, a Politecnico di Milano team lead by N. Aste [27] studied specifically glazing components and their consequent techno-economic performance when manipulating its thermophysical characteristics, optical properties, shading systems and glazing ratios - in an office setting in varying climates.

ENERGY EFFICIENT MACHINES

Today, existing research have focused on the development and optimisation of energy systems' efficiency, both at the level of generation, emission, control and distribution; as well as at the level of renewable resource generation, control and storability

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- with photovoltaic systems coupled with air-water heat pumps remaining the most diffused, effective and viable solution to cover thermal and HVAC demand from renewable energy sources. The scientific literature on the subject is highly developed, with studies having focused on (but not limited to) the development of models to anticipate the hourly behaviours and coefficient of performances COP/EER of vapour compression heat pumps; or on the optimisation of the machines or underlying components themselves.

That said, while new technologies may increase the efficiency and longevity of machines, technology cannot be the only answer. However, it is not to say that new technologies like photovoltaic panels, and highly efficient heat pumps or insulation materials have no place in our design; but rather that we need to start to look at how the influence of the design itself of a building – its orientation, its placement and number of windows, its shape and size, among many other “soft” factors – may have on the overall consumption of the house at all stages of its construction, use and ongoing maintenance - allowing us to fully embrace the "low-tech high-design" approach.

LOAD MATCHING - DESCRIPTION

As discussed earlier, the coupling of highly efficient thermal power generators with a renewable energy resource generator remains the most diffused method to satisfy thermal demand. However efficient and "green" this system may be; due to the intermittent nature of renewable energy resource generation - especially photovoltaic panels and their ineffectiveness at night - these systems cannot satisfy thermal demand 100% of the time. While solutions have been developed (such as the passive house standard) to reduce as much as possible thermal demand; another solution is called "Load Matching" - where the idea of storability for later restitution; and the idea of maximising renewable energy use come into sense.

"Load Matching" refers to the use of various techniques, methods or systems to store excess energy during low demand periods for release as demand rises [33]. In residential and/or architectural settings, this most often takes the form of an energy storage system connected to a thermal power generator + photovoltaic panels couple. The goal being to reduce the mismatch between energy resource generation and thermal loads. The consequence being a reduction in grid dependancy, a fuller use of the generated renewable energy - which benefits economically and energetically both the owners of the dwelling, and the public electrical infrastructure.

ENERGY STORAGE TECHNOLOGIES

Energy storage is the capture of energy at one time for later restitution at another; to reduce imbalances between energy demand and production. As energy comes in multiple forms - from radiation, through gravitational potential, to electricity and thermal energy - storing it also comes in multiple forms. In the framework of architectural design or use specifically in buildings, energy storage technologies come into 3 families:

The first is the electro-chemical battery. It is the most conventional type of battery, and holds energy in the form of stored electricity - the most transformable energetic medium there is. Although efficient and easy to use, they often have short lifespans, are extremely destructive in terms of ecological impact in all processes involved to produce and maintain such components. The second is the mechanical battery, where energy is stored in the form of (relative) movement like flywheels. Finally, the third and most potential filled energy storage technology the thermal battery - where stored energy is in the form of a heated or cooled medium. It is cheaper to produce, install and maintain and can resist a comparatively high number of charge/discharge cycles throughout its lifespan.

On the specific subject of energy storage technologies and its consequent use, research has either developed and innovated on the design, use, control and dimensioning; or the mechanism and phase-changing medium itself. For example, a Politecnico di Milano team led by A. Miglioli focused on the techno-economic assessment and optimisation of a TES unit coupled with a vapour compression heat pump and PV panels [1]. The goal being to maximise renewable energy self-consumption; as well as minimise non-renewable primary energy demand in a residential setting. The me-

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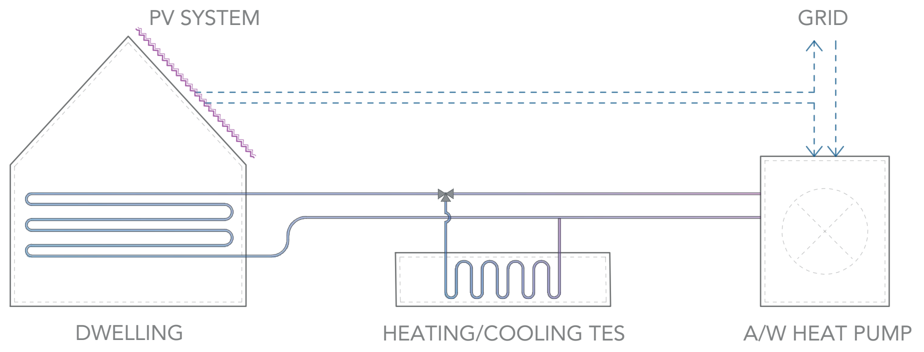
thodology, scientific precedence, tools and knowledge provided by the above paper represented one of the cornerstones of the present work.

Other work has also focused on the optimisation of storage sizes during the design process; on the study of the variation of medium temperature in different storage sizes; or on the mathematical relation between system COP, storage volume, and collector efficieny - ultimately identifying an optimal ratio of the storage size to the collector area.

SOLAR PV + HEAT PUMP + WATER TES



In the framework of the current research, both the optimisation of load matching and renewable resource self-consumption will be done through the scope of the above system, composed of 3 main systems/components:

The first is a high efficiency air-water heat pump which meets the building's thermal loads (heating and cooling). The considered machine has continuous power modulation itselft driven by component 2, the photovoltaic system array. In the case of surplus photovoltaic energy, the energy is stored in the form of thermal energy - heated or cooled water depending on the season and needs - using a water-based thermal energy storage TES able to restitute energy at night, or when needed. It also boasts a central control and management system, able to optimise the plant's whole operation - controlling the various interactions between the photovoltaic array; heat pump; thermal energy storage; and grid.

Based on this system configuration, a Politecnico di Milano team of Energy Engineers led by Alessandro Miglioli developed a model to predict and simulate the hourly performance of a water-based TES throughout a whole year. Based on hourly solar radiation values from which we derive photovoltaic power profiles [1 kW_p] on one end; and on hourly thermal demand for both heating, cooling and DHW on the other end; with in between a series of thermodynamic equations allowing to evaluate/simulate the thermal energy storage's water temperature variations incurred by the storage of photovoltaic energy. In addition, a series of equations allowing for the evaluation of economic potential - based on real buying/selling values of electricity; equations to compute tank sizes; and various consumption profiles or energy recuperation techniques - were developed.

Implemented in Excel, this simulation and performance prediction model represents one of the following research's cornerstones.

CHAPTER 3

PRELIMINARY ANALYSIS & DESIGN

CONTEXT & PROGRAM

AMBITION

As part of the research on the influence and potential of algorithmic preliminary design on energetic demand/consumption, energy system dimensioning and consequent load matching potential; a realistic case study comprised of a context on one hand, and an architectural program on the other was developed so as represent the foundations on which all experiments would rely.

In the last decade, architecture, design and the construction industry has been subject to a massive shift in building cultures - compounded even more by the arrival of Covid-19 and the growing necessity/popularity of working from home. As a result, people are moving back to the country side to settle down and build their homes. The following program and site respond directly to this premise.

PROGRAM & INHABITANTS

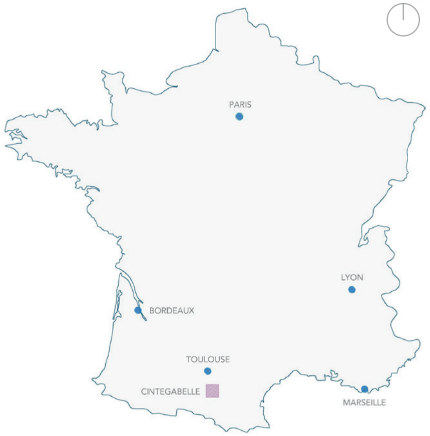
Single volume house/dwelling for two people under 130m², boasting all relevant functions (kitchen, sanitary and water rooms, living room, ..) as well as all necessary storage. Two adults are assumed to live there, and considered present during the weekends and holidays, and absent during work-weeks from 9am to 5pm.

SITE DESCRIPTION

The site is located a dozen kilometers south of the small village of Cintageballe, in the French Midi-Pyrenees region. The considered dwelling's future site is located on a larger piece of property, containing 2 houses, 1 stable, 1 old abandoned farm and a 10 acre plot of land. The Ariege river passes throughout the site from north to east. The direct context is defined by a multitude of tall and short trees, as well as 2 buildings - one smaller than the other - representing the only potential shadow source for the project. Nature is predominant, as attests the following pictures. Indeed, the site resembles a city where all buildings were replaced by trees (some being over 300 years old), where concrete was replaced by grass, and where people were replaced by wild animals, smells and colors.

LOCATION

Country	[-]	France
City	[-]	Cintegabelle
Altitude	[m]	205
Latitude	[DD]	43.269151
Longitude	[DD]	1.567034
Climate	[-]	Oceanic



3.1 SITE DESCRIPTION & SURVEY

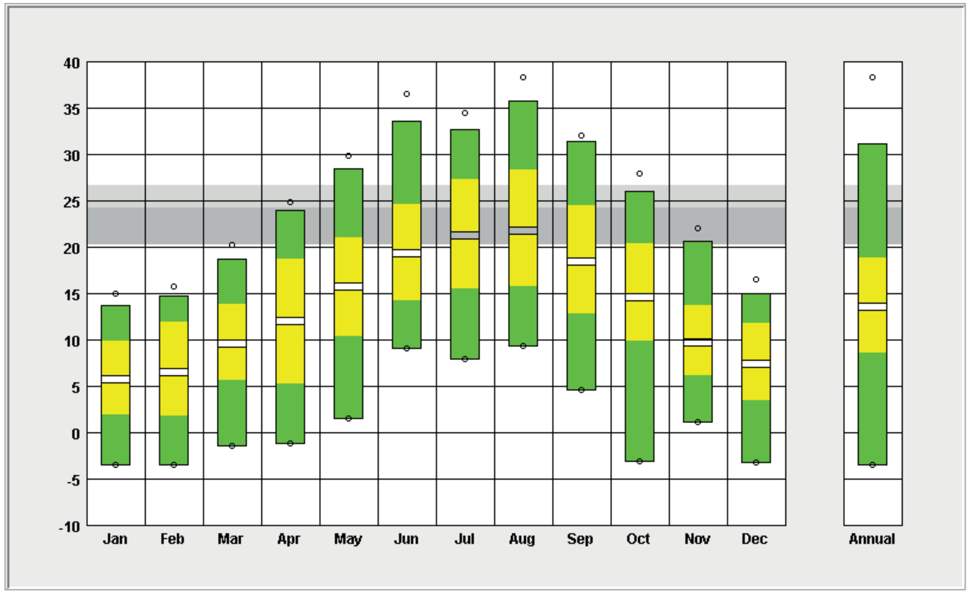
GENERAL RANGES

TEMPERATURE RANGE

The following graph depicts the range of temperatures that were recorded throughout the years 2003 to 2018; as well as showing us, within these ranges, where the comfort zones lie (represented by the grey horizontal bars). Temperatures range from -5C in December to 38C in August.

Indeed, a first look at the graph will tell us that most monthly average temperature ranges fall under the comfort bracket; thus meaning that this climate is heating dominant. If we look specifically at the average range (showed in yellow), it seems that even in the months of July and August - the two warmest months - only the exceptionally warm days would need cooling.

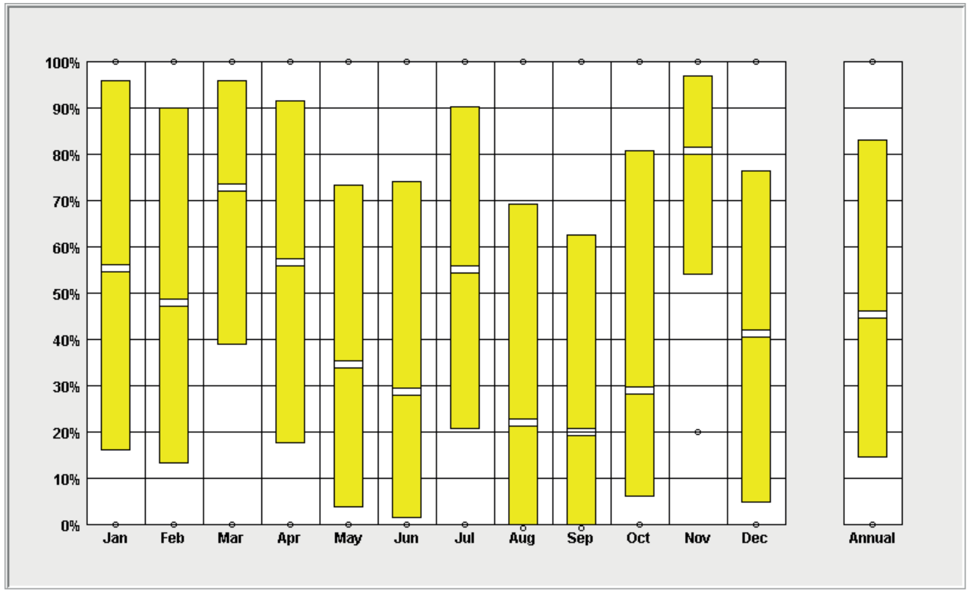
A closer look at the graph will also show us that high thermal mass is needed - even in summer - to be able to provide warmth in the morning hours, or at night, when the temperature drops significantly.



SKY COVER RANGE

The following chart depicts the average, and average ranges of cloud coverage over this specific climate in percentage points. High and low recorded peaks are also shown.

The average annual sky coverage seems to be around 45%, with peaks at 100% and lows at 0% (except for November which has a minimum sky coverage of 20%). A noticeable trend is that the winter months have the highest sky coverage ratios, and the summer months wih the lowest - with an exception in July. Given these relatively high average values of sky coverage - especially in the winter/heating months, a PV system might be put into question : this is why a thermal storage system needs to be dimensioned in order to satisfy most annual thermal needs.

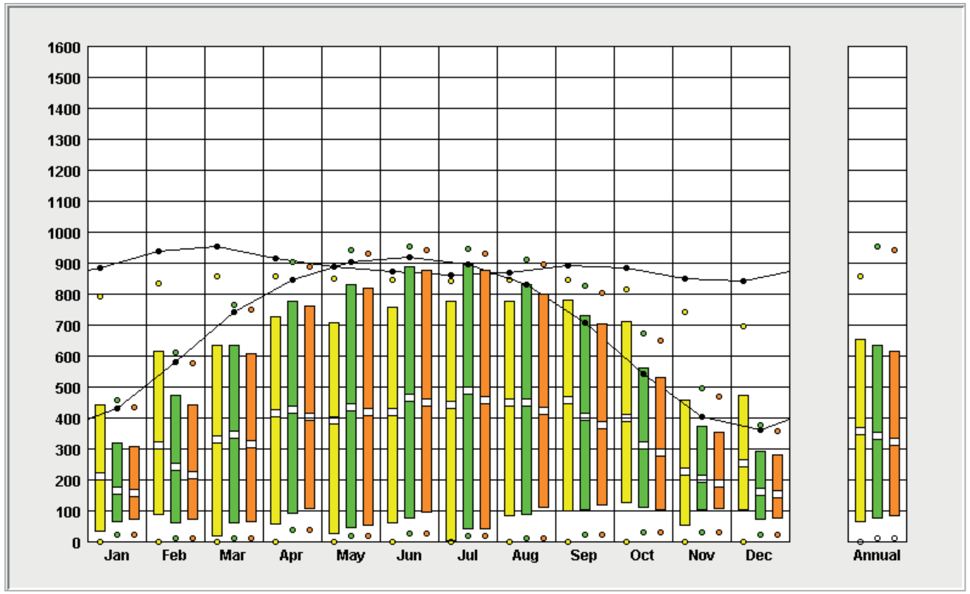


GENERAL RANGES

RADIATION RANGE

This chart plots the amount of average hourly radiation (daylit hours only) that this specific climate receives in [Wh/m^2] for Direct Normal and Global Horizontal. It is also possible to specify a surface, with a specific tilt and bearing angle, in order to anticipate the potential radiation that a planar portion of a project can receive. It also takes into account ground reflectance, in this case grass.

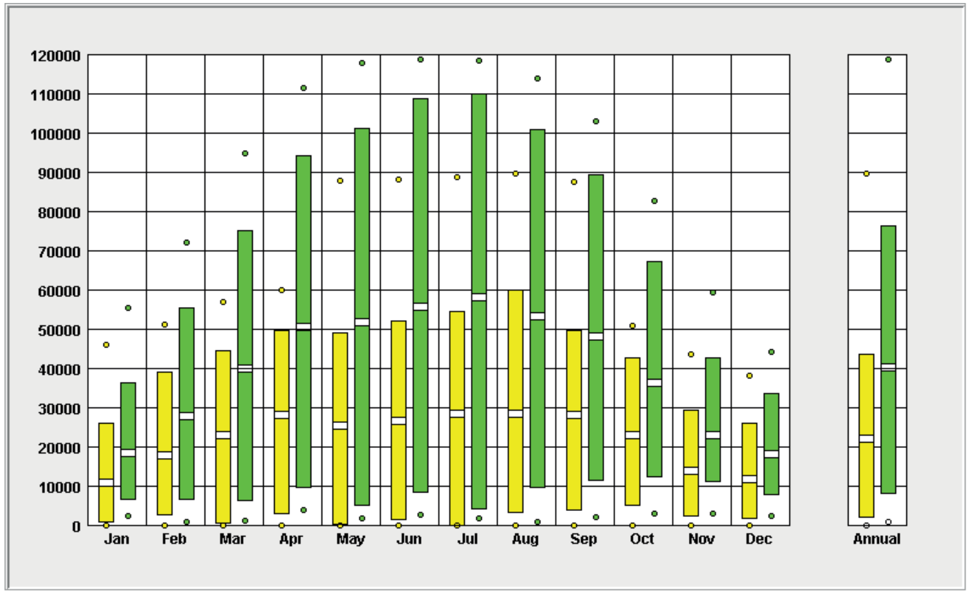
This plot allows us to see that a photovoltaic panel could be used in this climate, but also tends to show that there are days, in each month, where the solar radiation levels are negligeable. This means that this climate cannot allow for a PV system to fully fuel a residential project's electrical needs - no matter the amount and surface of the panels - as there are days where there is no radiation. On the other hand, it seems that there are moments where the radiation is so high, that excess radiation could theoretically be stored in order to be restituted, either at night; or when the sun is hidden behind the clouds.



ILLUMINATION RANGE

The following chart also plots the amount of monthly average hourly radiation (daylit hours only) that this climate receives, but this time in [lux], for Direct Normal and Global Horizontal cases. Knowing that various operations require varying levels of illumination (working vs living vs minute visual tasks, etc), this chart essentially allows us to know when to turn on the lights, or when a form of shading is needed so as to limit uncomfortable dazzlement.

An average of 5000 to 1000 [lux] is needed for daily residential life. These values seem to be provided on average every day of every month, with notable exceptions which need to be taken into account. Also, turning on the lights adds to the space's warmth, and thus needs to be limited in some cases (summer period for example).

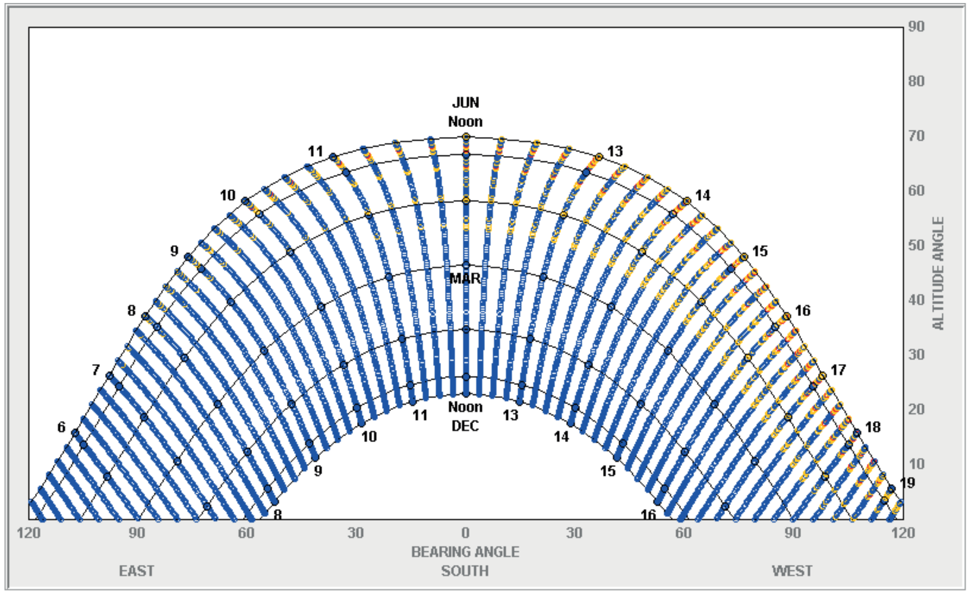


GENERAL RANGES

SUN SHADING CHART - WINTER

The following graph plots all of the hours of the winter months, which is from december 21 to june 21. These hours are color coded so as to indicate if they fall above the comfort zone, within the comfort zone,or beneath the comfort zone (characteristics that were derived from the Ashrae 55 comfort model). Whilst the following graph is somewhat generic, as it doesn't take into account a specific window orientation, environing obstructions, and potential horizontal and vertical shading devices, it does help us understand however how much our building's windows would need exposure and/or shading.

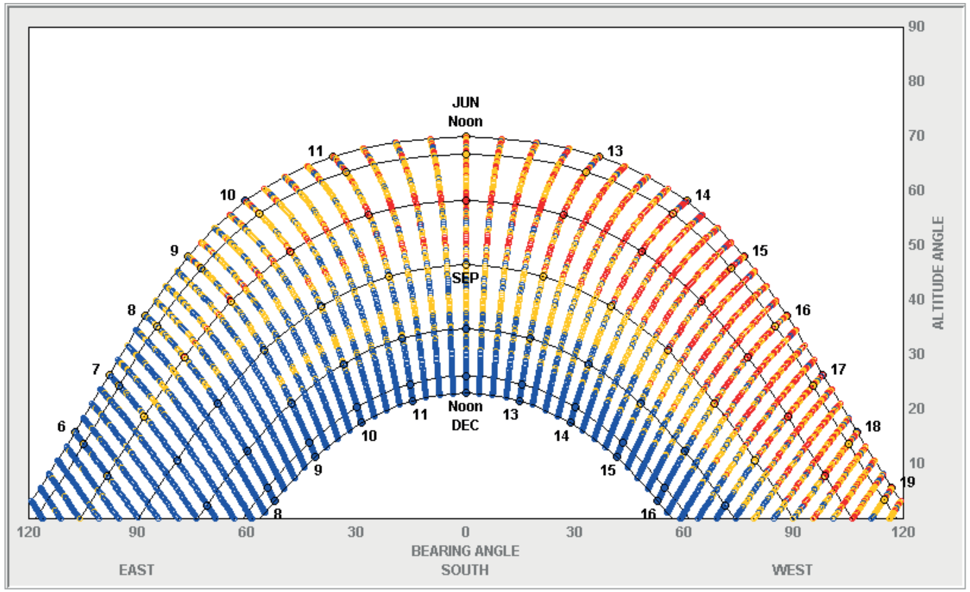
A first look indicates that within this period, 43 hours in total would necessitate shading, 257 hours would benefit from shading without it being necessary; and 1893 hours which would benefit from being fully exposed to the sun - the latter representing 85 % of the given period. It also seems as though a sun with an altitude angle lower than 40 degrees is fine to penetrate within a residential setting.



SUN SHADING CHART - SUMMER

A first look at the summer months sun shading charts indicates that within this period, 364 hours would absolutely need shading, 694 hours would benefit from it, and 1150 hours would necessitate exposure so as to benefit from direct solar radiation and its potential heat gain. A quick ratio indicates that within this time frame, 51% would need shading, and 49% would need exposure. Once again, it seems as though a sun position with an altitude angle of less than 40 degrees would not need any shading.

A closer look also indicates that most warm/hot hours needing shading are during the afternoon from 12AM to 6-7 PM. An interesting exception is in July, supposedly one of the warmest months, where shading be beneficial yet not compulsory. Western oriented windows need to be correctly shaded so as to limit unecessary heat gain.



CLIMATE CONSULTANT

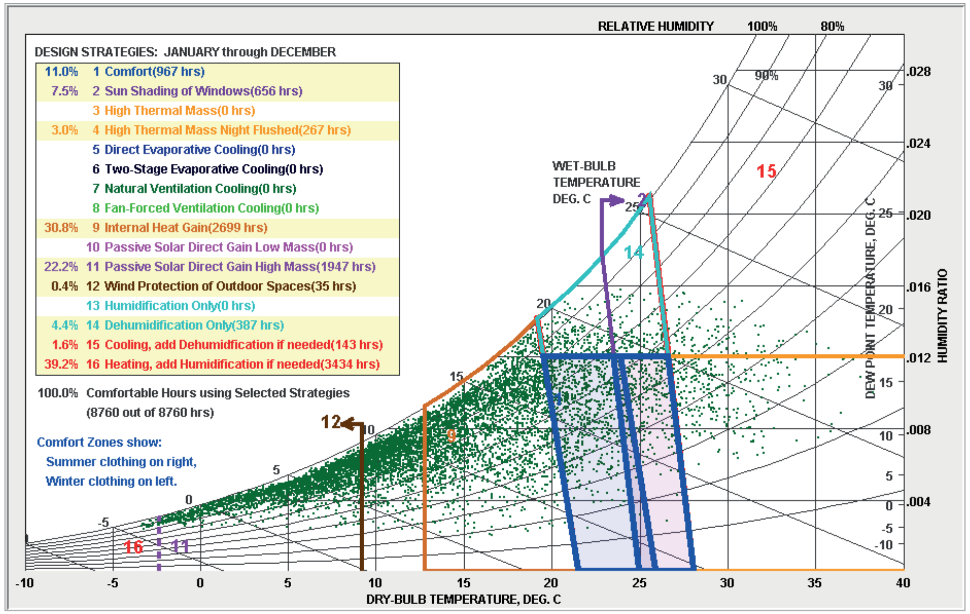
PSYCHROMETRIC CHART

The following interactive chart allows us to better understand the relationship between physical and thermal properties of moist air in a graphical form. These properties will in effect influence the comfort levels felt by the inhabitants. In addition to providing climate - time - specific information, it also indicates which (generic) design strategies may help in augmenting comfort hours to all the hours of the year.

Indeed, a first look at the graph shows us that 11 % of the year (967 hours) fall within a comfortable range, without the need to add/remove anything. In addition to this, the psychrometric chart seems to show that 39.2% of the year would greatly benefit from «Heating and punctual humidification», representing 3434 hours. On the other hand, only 1.6% - 143 hours - of the year would benefit from direct cooling.

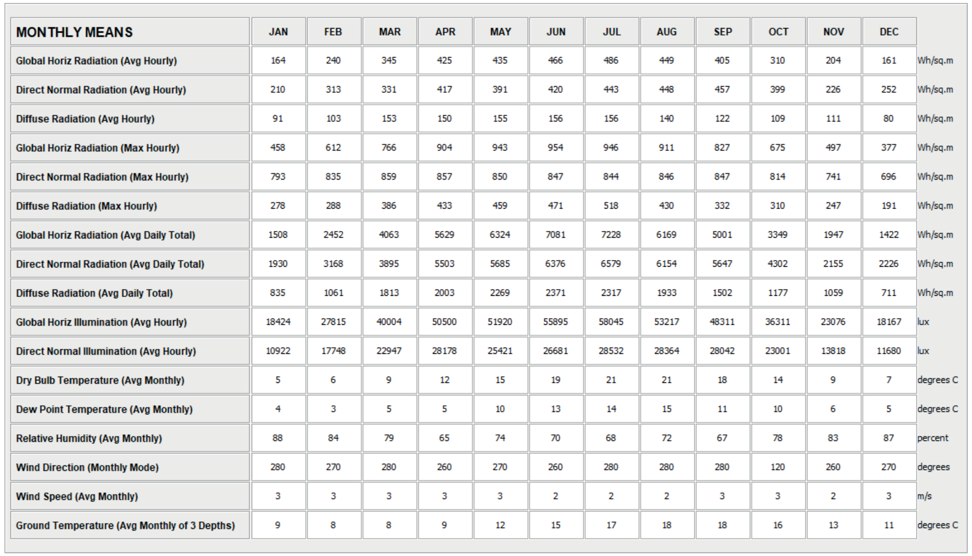
There are however other methods to increase or decrease the felt warmth or temperature of a space, without the need for direct heating/cooling. A substitute for heating are : «High Thermal Mass» which would restitute gained heat during the night; or «Internal Heat Gain», which would provide 30.8% - or 2699 hours - of heat. Also, 22% - or 1947 hours - would benefit from direct solar gain, once again eliminating the use for direct heating.

Other passive strategies resulting in cooling would be preferred, such as «Sun Shading» or the simple «Dehumidification». These passive methods in turn greatly reduce HVAC needs, which in turn reduce the need for photovoltaics and consequent thermal energy storages - all through the careful design of homes, thus preventing the unnecessary use of carbon fueled thermal equipment. Indeed, the ambition of this project is one of a «Low-Tech - High Design home».



WEATHER DATA SUMMARY

The following chart plots the monthly average values for each weather data, as given by the software Climate Consultant. It provides valuable monthly information which will be used in the following chapter regarding the optimisation of energy demand.



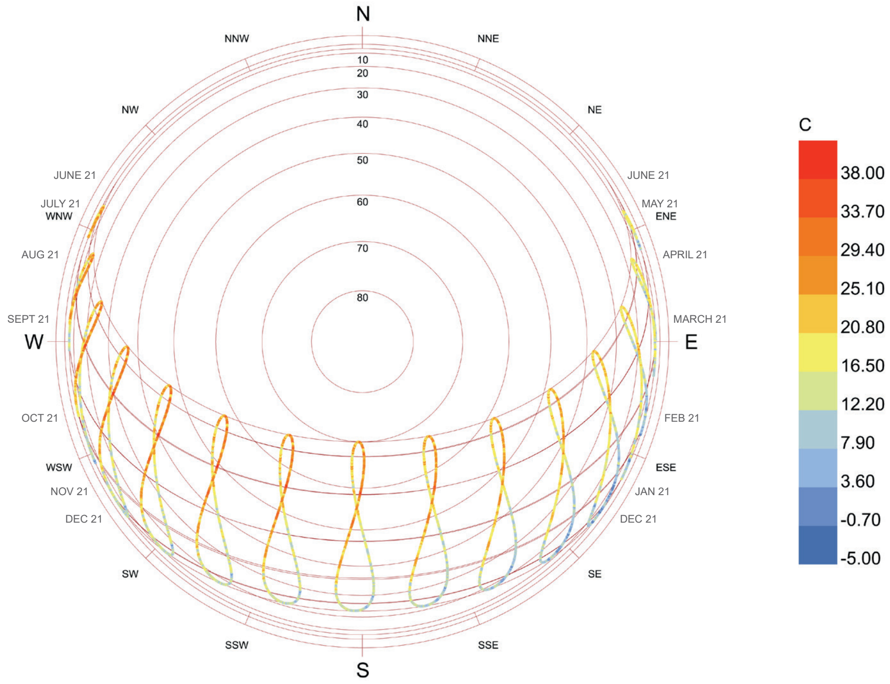
MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	164	240	345	425	435	466	486	449	405	310	204	161	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	210	313	331	417	391	420	443	448	457	399	226	252	Wh/sq.m
Diffuse Radiation (Avg Hourly)	91	103	153	150	155	156	156	140	122	109	111	80	Wh/sq.m
Global Horiz Radiation (Max Hourly)	458	612	766	904	943	954	946	911	827	675	497	377	Wh/sq.m
Direct Normal Radiation (Max Hourly)	793	835	859	857	850	847	844	846	847	814	741	696	Wh/sq.m
Diffuse Radiation (Max Hourly)	278	288	386	433	459	471	518	430	332	310	247	191	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	1508	2452	4063	5629	6324	7081	7228	6169	5001	3349	1947	1422	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	1930	3168	3895	5503	5685	6376	6579	6154	5647	4302	2155	2226	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	835	1061	1813	2003	2269	2371	2317	1933	1502	1177	1059	711	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	18424	27815	40004	50500	51920	55895	58045	53217	48311	36311	23076	18167	lux
Direct Normal Illumination (Avg Hourly)	10922	17748	22947	28178	25421	26681	28532	28364	28042	23001	13818	11680	lux
Dry Bulb Temperature (Avg Monthly)	5	6	9	12	15	19	21	21	18	14	9	7	degrees C
Dew Point Temperature (Avg Monthly)	4	3	5	5	10	13	14	15	11	10	6	5	degrees C
Relative Humidity (Avg Monthly)	88	84	79	65	74	70	68	72	67	78	83	87	percent
Wind Direction (Monthly Mode)	280	270	280	260	270	260	280	280	280	120	260	270	degrees
Wind Speed (Avg Monthly)	3	3	3	3	3	2	2	2	3	3	2	3	m/s
Ground Temperature (Avg Monthly of 3 Depths)	9	8	8	9	12	15	17	18	18	16	13	11	degrees C

DRY BULB TEMPERATURE ANALYSIS

SUN PATH - TEMPERATURES

The following chart puts the position of the sun in relation to felt temperature at the given altitude. As we may see, the lowest temperature recorded is -5°C, while the highest is 38°C. It also appears as though western oriented suns provide the greatest warmth, around the summer solstics days - and the lowest temperatures seem to be early morning in the east.

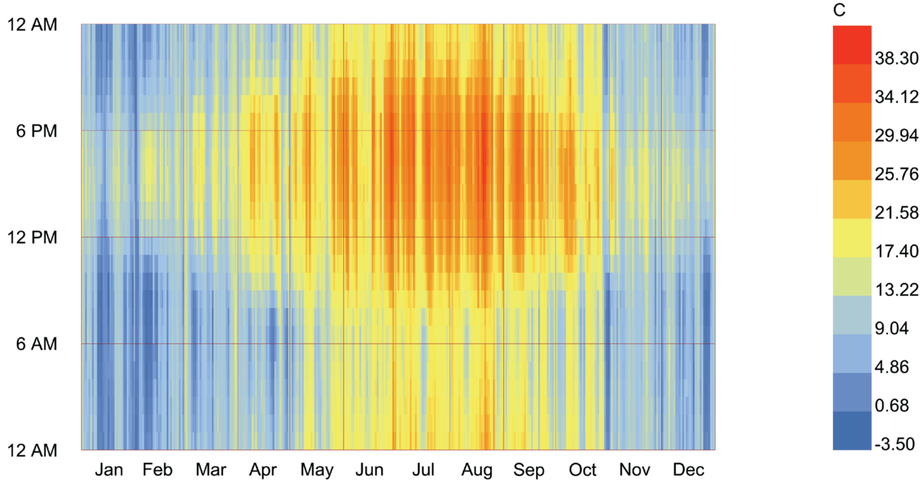
From this chart we also understand that this particular climate boasts 4 seasons, as the temperatures vary greatly from the winter to the summer solstice. Although the summer months seem to boast the highest temperatures, it is not uncommon to see temperatures well below the extremes, even in July and August - the two warmest periods of the year. Although the temperature range is almost 43°C, 95% of all recorded temperatures are below 30°C, and in the same manner, only 5% of all temperatures fall below freezing temperatures in winter. The averag dry bulb temperatures range from 5°C in january to 21°C in July and August.



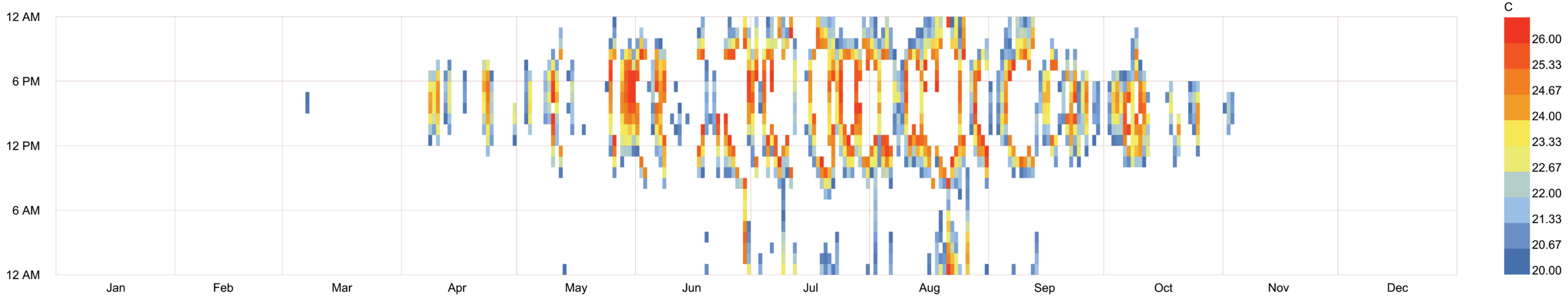
YEARLY PLOTS

The following 4 charts plot the dry bulb temperatures at each hour of the day, for the whole year. While the first one depicts the annual temperature range, the 3 charts on the right page show respectively comfort hours (20<t<26°C), heating hours (t<20°C), and cooling hours (t>26°C). As the chart suggests, the climate we are in is heating dominant, as almost 75% of the year, and each month - will have temperatures needing heating either the whole day - or part of the day (in a verty uncommon scenario where the inhabitants are totally exposed to outdoor temperature). Cooling hours do exist, and are present from march to early november - but represent a minimum. Comfort hours can be found punctually from april to october.

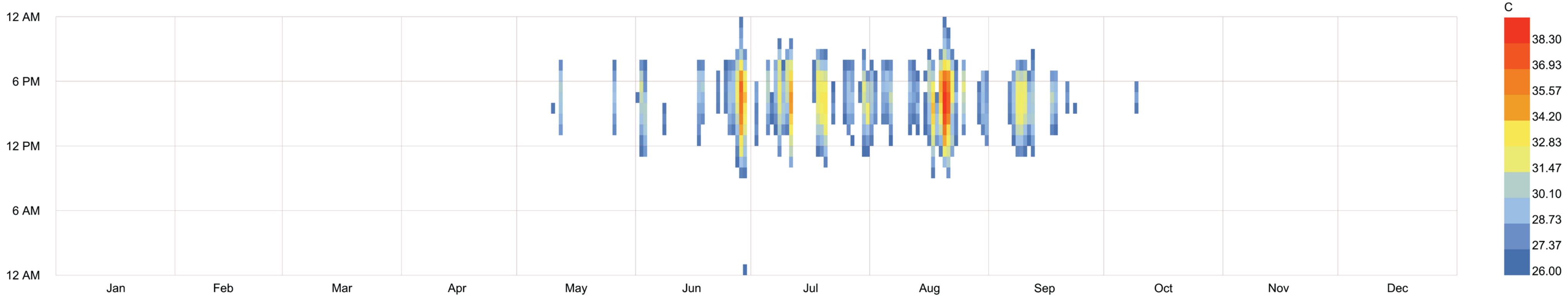
HEATING DEGREE DAYS	**[<20°C]**	**2620**
COOLING DEGREE DAYS	**[>26°C]**	**71**



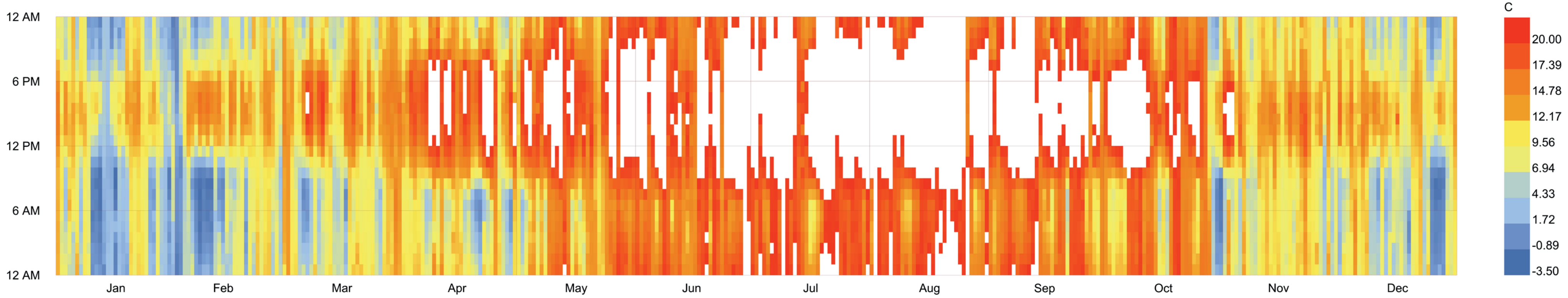
COMFORT HOURS



COOLING HOURS



HEATING HOURS



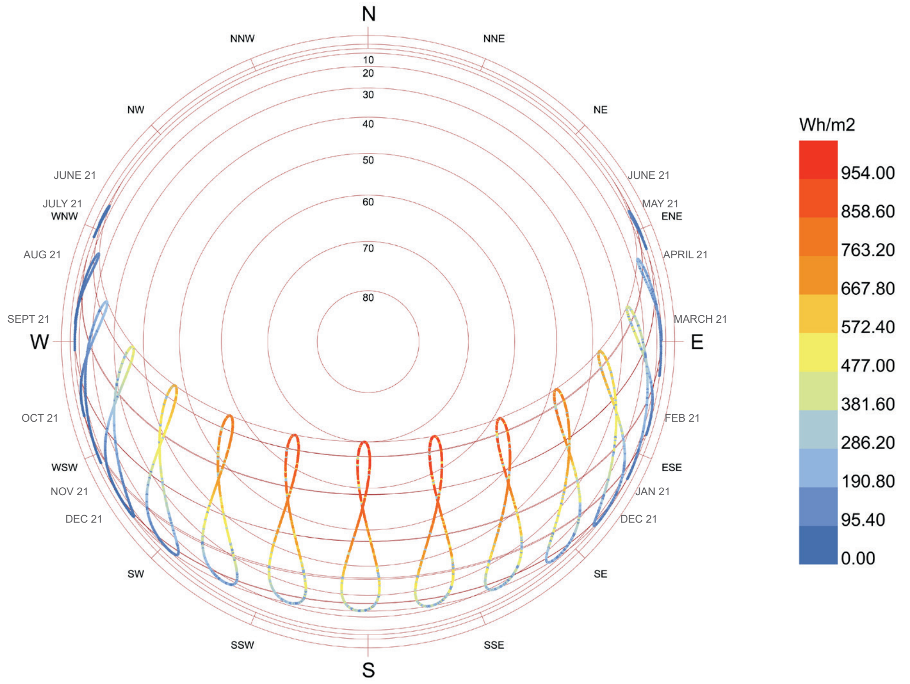
SOLAR RADIATION ANALYSIS

SKY MATRIX

The following chart puts the position of the sun in relation to incident global horizontal solar radiation. It allows us to better perceive the orientation of more potent suns, as well as to generally challenge the utility of using photovoltaic panels in this particular climate.

The 3 charts on the right page graph each hour of each day, during the whole duration of the year and its recorded diffuse, direct normal - and consequent global horizontal solar radiation. Indeed, while solar radiation may be immensely useful to understand the potential that photovoltaic panels may hold - it can also represent immense heating potential as a source of free energy. Unsurprisingly, it seems as though the more potent suns radiate during the afternoon from a southern and western solar orientation; while the lesser potent suns happen in the morning from an eastern solar orientation. The average total daily horizontal global radiation ranges from 1500 [Wh/m^2] in January, to 7300 [Wh/m^2] in July.

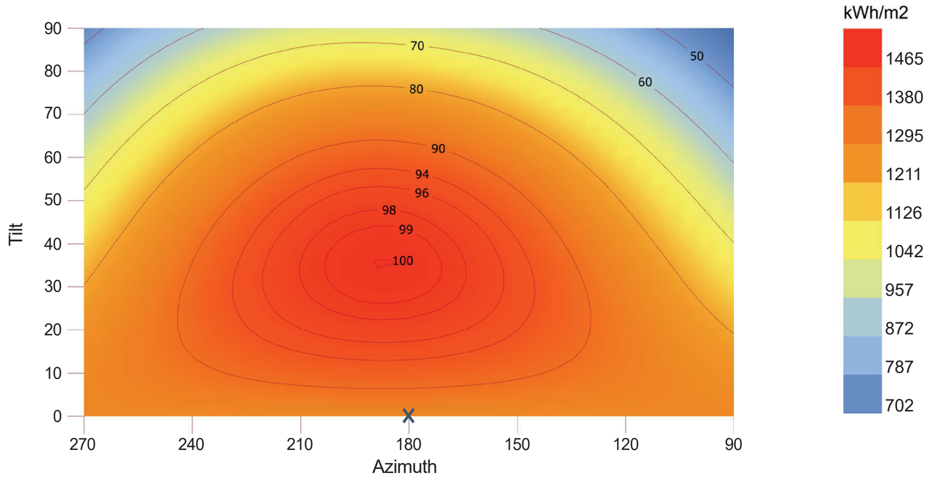
Also, while the maximum 954 [Wh/m^2] can allow - given an extremely efficient opaque and window construction - for a completely passive heating system, it would be more logical, and economical to use the sun as an aid, rather than as the only driving heating force of a building.



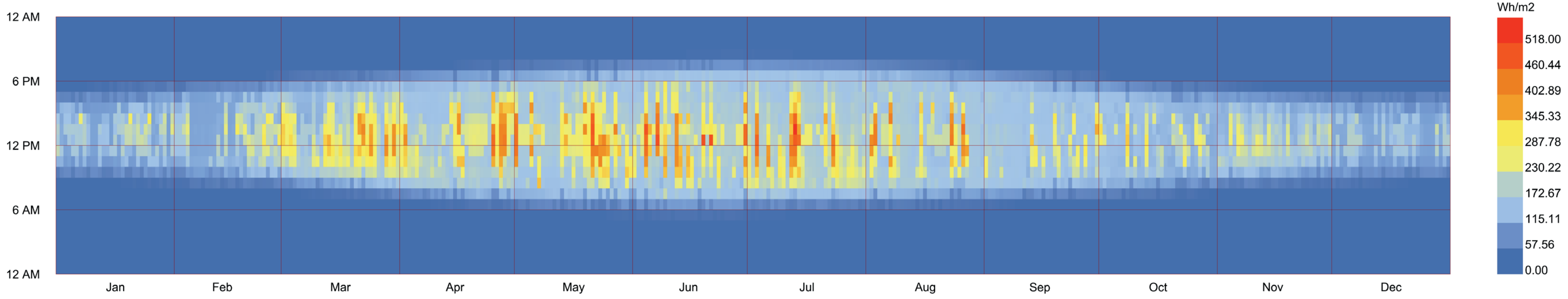
TILT ORIENTATION FACTOR

The following chart - aimed at the proper dimensioning of photovoltaic panels - depicts the relationship between azimuth angle and panel tilt, and its consequent influence on incident solar radiation. Indeed, when designing a solar panel, these variables may have dramatic consequences on its ability to optimise the reception of solar radiation. In this particular climate indeed, the maximum incident yearly solar radiation seems to be 1465 [kWh/m^2] given the following dimensioning criterias are followed :

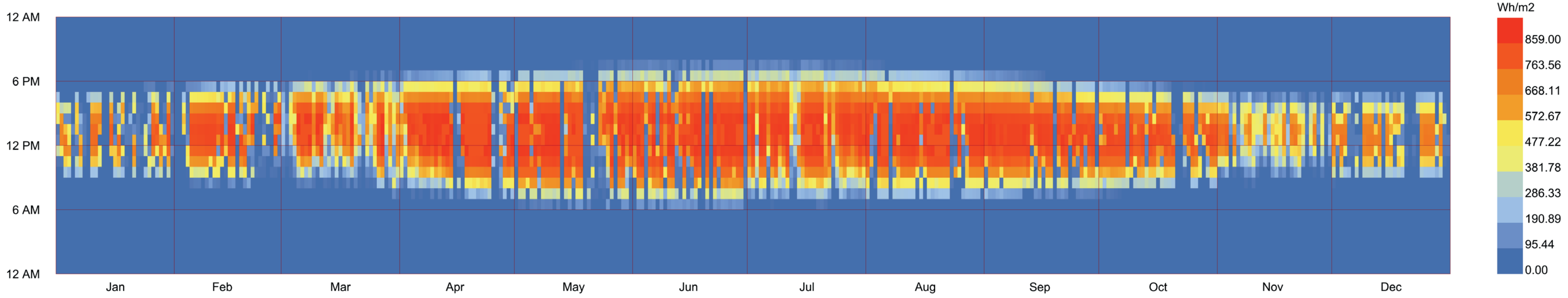
OPTIMAL PV PANEL TILT	**[°]**	**36**
OPTIMAL AZIMUTH ANGLE	**[°]**	**180**



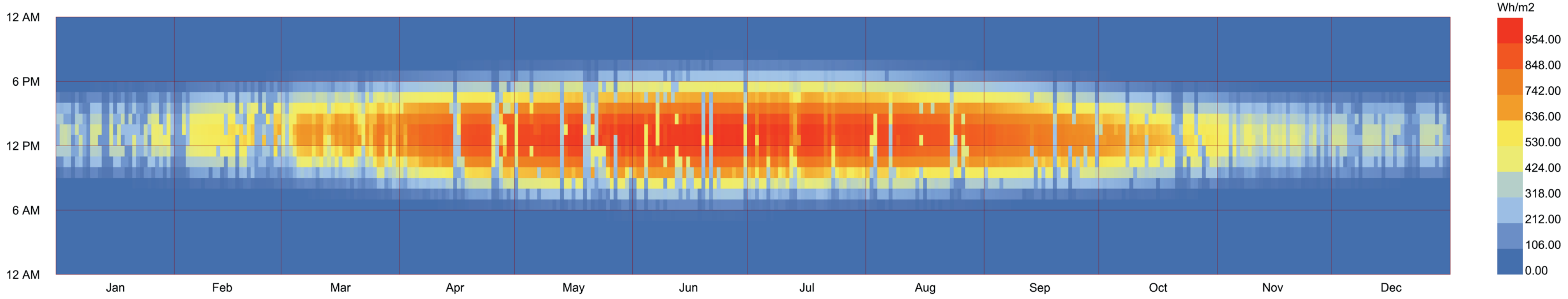
DIFFUSE HORIZONTAL



DIRECT NORMAL



GLOBAL HORIZONTAL



OBJECTIVES & SCOPE

AMBITION

The goal of this operation is to determine the base plan, dimensions, and general orientation of the dwelling project - the fixed values as well as the variables - which will in turn be used as the basis for energetic demand optimisation, and subsequent design and detailing.

In the framework of the research on the potential and application for renewable resource self optimisation, our main goal is to lower as much as possible the Heating and Cooling Demand. Indeed, the goal is to determine a geometry and envelope that will lower as much as possible the needed heating/cooling demand, so that it lowers in turn the Heat Pump use and consumption; which will consequently lower the photovoltaic panel energetic output needs; and consequently influence the optimisation of a Thermal Energy Storage.

PROGRAM & FIXED CONSTRAINTS

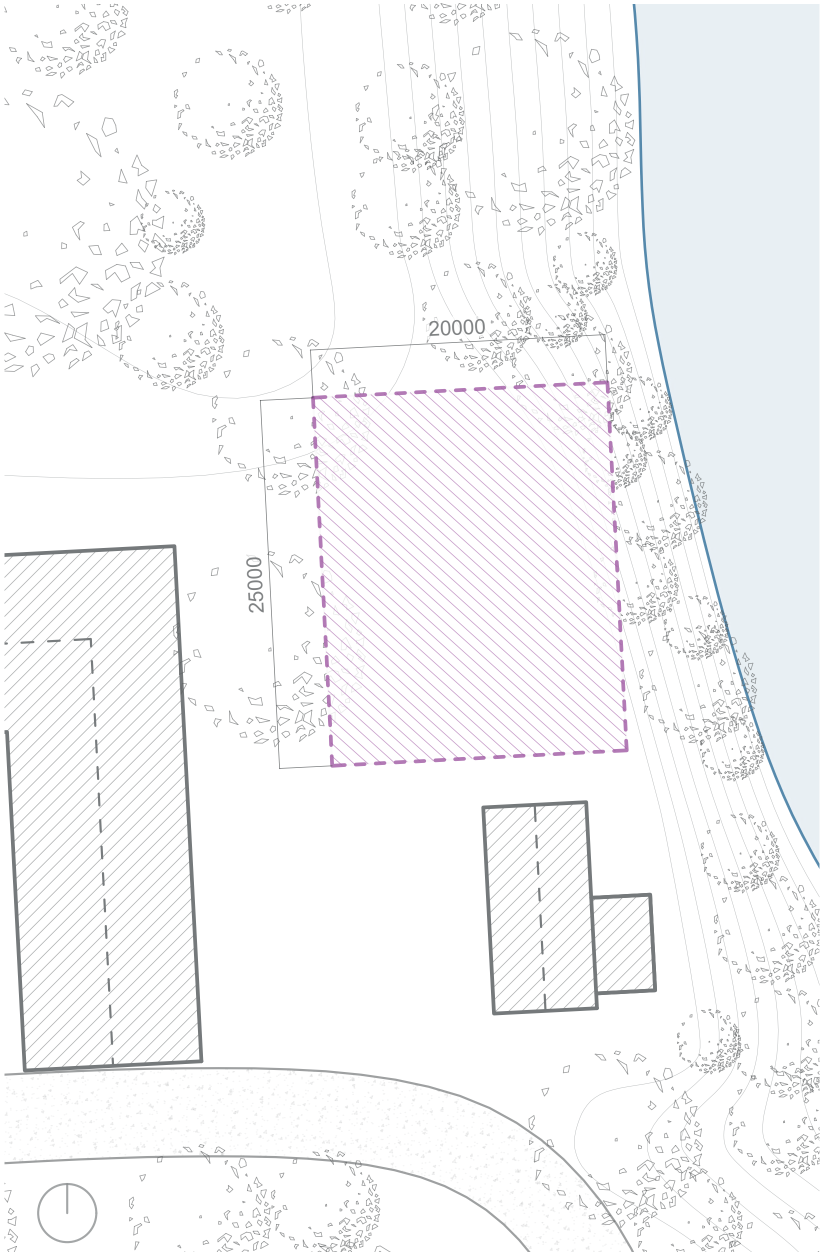
Single volume dwelling for 2 people under $130m^2$. All relevant functions need to be present (kitchen, sanitary and water rooms, living room, entrance, and bedroom) with the appropriate amount of services and storage. The plan will be mostly open, with only the bedroom, sanitary rooms and water rooms independantly closed off from the rest of the house by walls and doors.

The surface, and the general functional allocation (the plan) are fixed and will determine the starting point of our research. The plan will be rectangular based, with a general East-West orientation (following the river).

VARIABLES

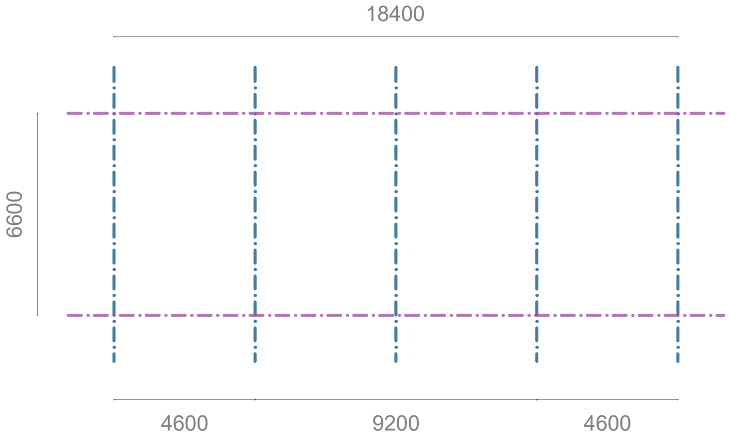
Although the planar surface is fixed, the Aspect Ratio S/V and its relevant dimensions (height, angles of pitched roof) are variable. The minimum height will be 3m, and the max pitched roof angle will be 15°. The East-West orientation may vary within a polar range of 30° on each side, from the river alignment which will be chosen as the base orientation.

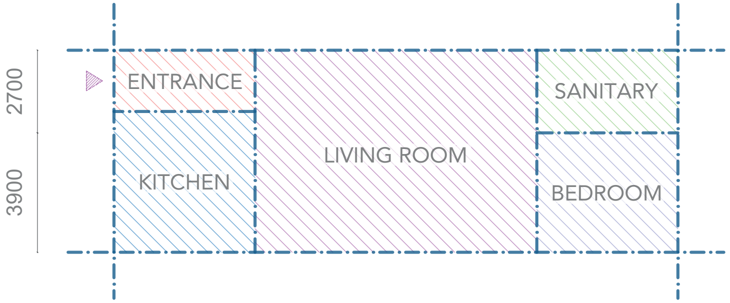
The WWR per facade, U values for the walls and windows, as well as the amount and placement of shaders, are completely variable. The constraints related to these will be detailed in the next chapter.



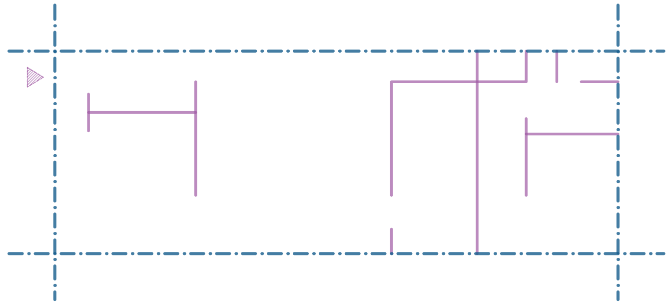
PLAN & ORGANISATION

COMPOSITION

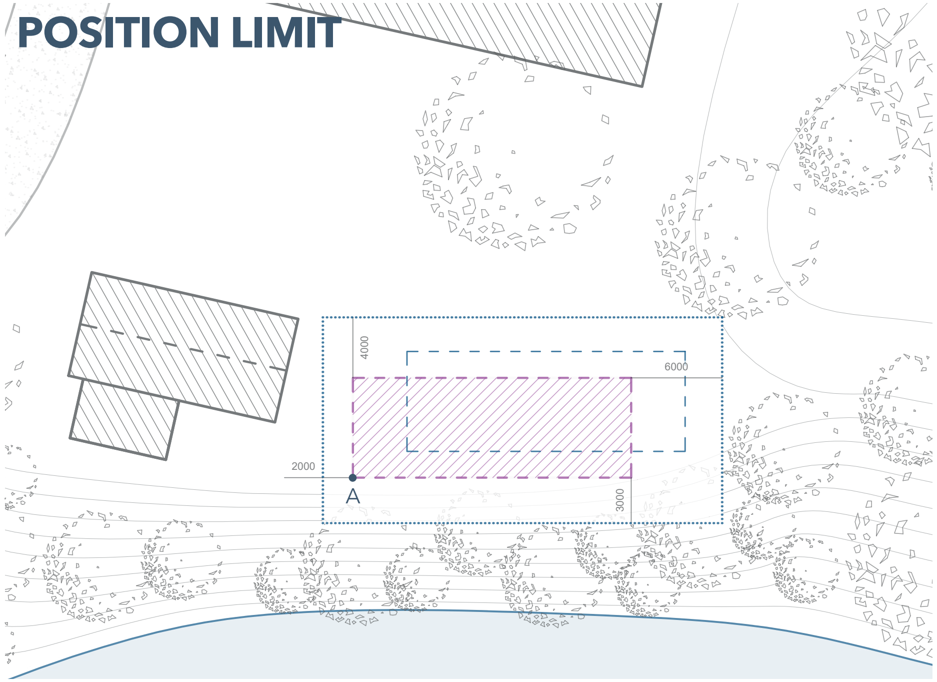




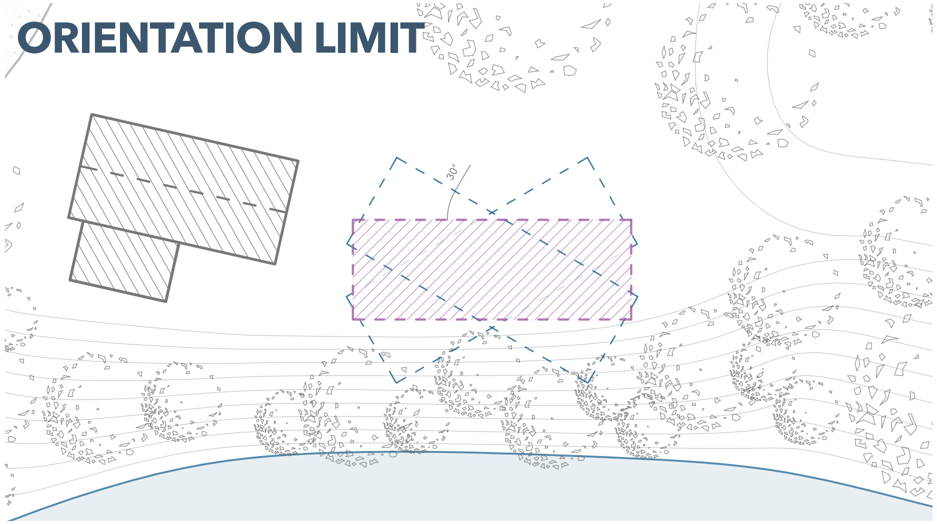
PLAN SCHEME



POSITION LIMIT



ORIENTATION LIMIT



CHAPTER 4

ENERGY DEMAND OPTIMISATION

RESEARCH PROTOCOL 1 - BUILDING GEOMETRY

AMBITION

The goal of this experimental protocol is to find the optimal geometrical characteristics of the studied volume in order to optimise the potential heat gain provided by solar radiation.

The location of this project - and its relevant weather data and sky matrix - are fixed. The plan and volume (660x1880cm) and the contextual buildings are also constant. The starting height of the building for analysis is considered at 300cm, whilst roof pitch is considered 0°. The few environing trees are considered negligeable in their influence on the building's incident solar radiation. However, floor reflectance is constant at 20% (default value for grass and greenery).

Heating Period is considered from October 15 to April 15; whilst the Cooling Period is from April 16 to October 14.

METHODOLOGY

The first step is to model our geometry parametrically (Rhino, Grasshopper) using the below-listed variables. The second step is the development and simulation of a radiation analysis (Ladybug) computed from said variables. The third step is an analysis and commentary of the influence of each variable individually, whilst the other variables stay at a fixed median value (listed below). 6 simulations will be performed for each variable in order to explore and analyse its full range.

The final step is a multi-objective optimisation simulation (objectives/performance indicators are detailed below) of all variables simultaneously using an evolutionary solver plug-in (Octopus).

VARIABLES

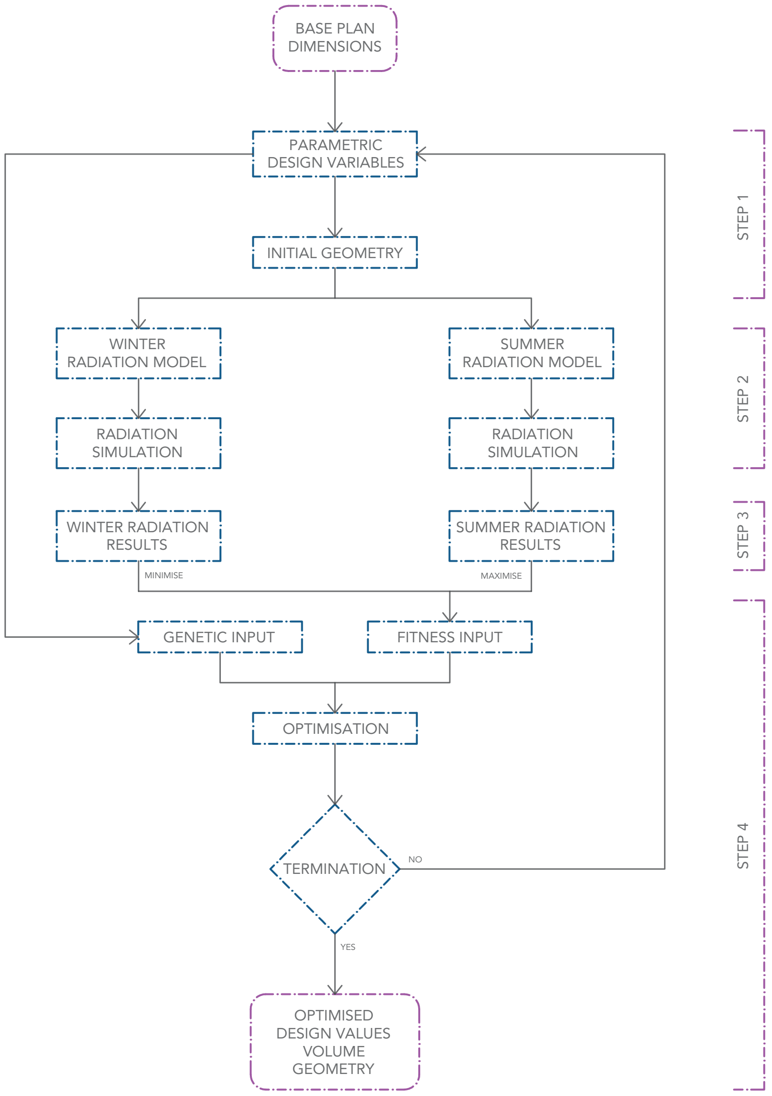
1. Position on site (point A)	[m]	Median Value = A (0 ; 0)	Min = A (-2 ; -3)	Max = A (6 ; 4)
2. Volume Orientation	[o]	Median Value = 0	Min = -30	Max = 30

OBJECTIVES

Maximise incident solar radiation during heating period.

Minimise incident solar radiation during cooling period.

OPTIMISATION PROCESS


BASE PLAN DIMENSIONS

PARAMETRIC DESIGN VARIABLES

INITIAL GEOMETRY

WINTER RADIATION MODEL

RADIATION SIMULATION

WINTER RADIATION RESULTS

MINIMISE

SUMMER RADIATION MODEL

RADIATION SIMULATION

SUMMER RADIATION RESULTS

MAXIMISE

GENETIC INPUT

FITNESS INPUT

OPTIMISATION

TERMINATION

NO

YES

OPTIMISED DESIGN VALUES VOLUME GEOMETRY

STEP 1

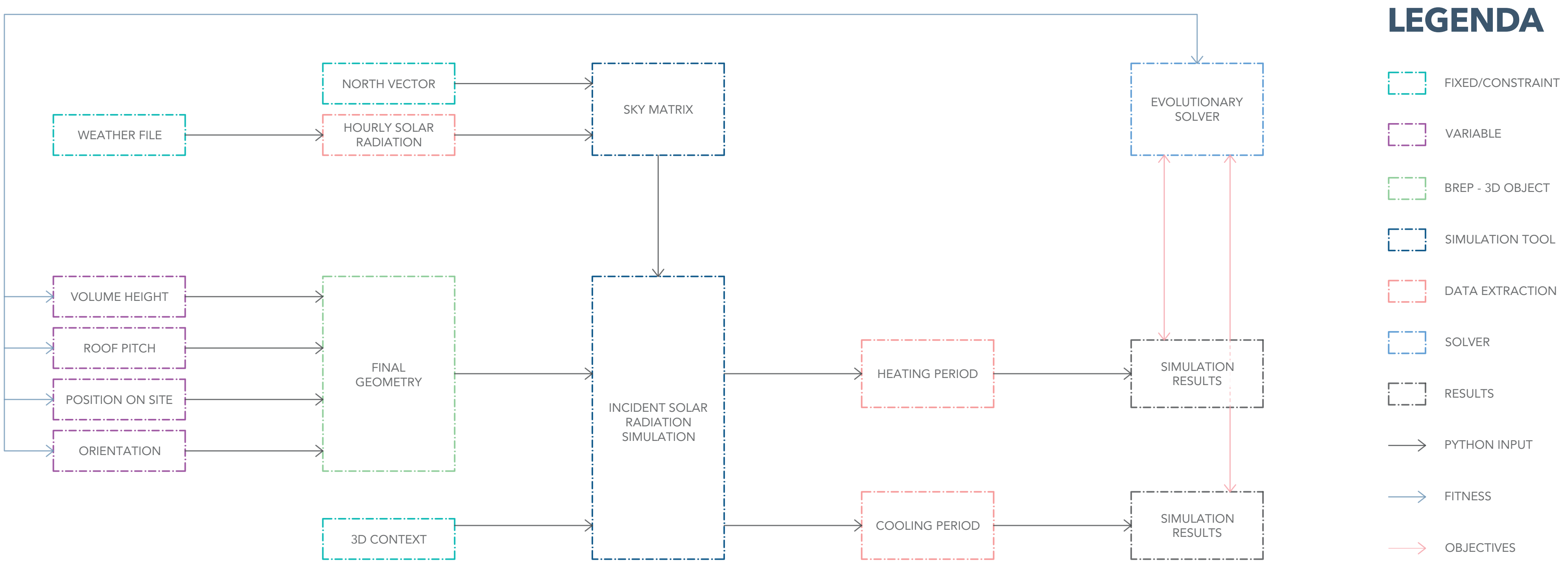
STEP 2

STEP 3

STEP 4

SCRIPT & SIMULATION DETAIL

GRASSHOPPER/PYTHON SCRIPT



WEATHER FILE

NORTH VECTOR

HOURLY SOLAR RADIATION

SKY MATRIX

EVOLUTIONARY SOLVER

VOLUME HEIGHT

ROOF PITCH

POSITION ON SITE

ORIENTATION

FINAL GEOMETRY

3D CONTEXT

INCIDENT SOLAR RADIATION SIMULATION

HEATING PERIOD

COOLING PERIOD

SIMULATION RESULTS

SIMULATION RESULTS

LEGENDA

- FIXED/CONSTRAINT
- VARIABLE
- BREP - 3D OBJECT
- SIMULATION TOOL
- DATA EXTRACTION
- SOLVER
- RESULTS
- PYTHON INPUT
- FITNESS
- OBJECTIVES

SIMULATION LIST

1. SITE POSITION

- All other variables constant.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

2. ORIENTATION

- All other variables constant.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

3. VOLUME HEIGHT

- Results too biased to be used.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

4. ROOF PITCH

- Results too biased to be used.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

5. MULTI VARIABLE

- All variables can be modified.
- **1 simulation**
- Output is fittest variable setting with respect to objectives.

RESEARCH PROTOCOL 2 - BUILDING ENVELOPE

AMBITION

The goal of this experimental protocol is to find the optimal characteristics of the studied envelope in order to optimise energetic demand relating to heating, cooling and lighting loads.

The location of this project - and its relevant weather data and sky matrix - are fixed. The previously set volumetric geometry is also constant. 2 people are assumed to live there; and are considered present during the weekends and holidays; and absent during work-weeks from 9AM to 5PM. The loads related to lighting, electrical equipment and occupancy are combined and considered at $4W/m^2$. Useful Daylight Illuminance is between 100lux and 3000lux, and is considered all year between 8AM and 10PM. Air volume renewal is considered at 0.3V/h (equivalent to 1/3 of the air volume renewed hourly). Cooling setpoint is 26°C; whilst Heating setpoint is 20°. Three opaque constructions are considered : Low - Medium - High Thermal Mass.

METHODOLOGY

The first step is to model our envelope parametrically (Rhino, Grasshopper) using the below-listed variables. The second step is the development and simulation of a daylight and energy model analysis (Honeybee, through Energy Plus and Radiance) computed from said variables. The third step is an analysis and commentary of the influence of each variable individually, whilst the other variables stay at a fixed median value (median value listed below). 6 simulations will be performed for each variable in order to explore and analyse its full range. The final step is a multi-objective optimisation simulation (objectives/performance indicators are detailed below) of all variables simultaneously using an evolutionary solver plug-in (Octopus). This step is solved twice, considering the 2 best performing opaque construction types.

VARIABLES

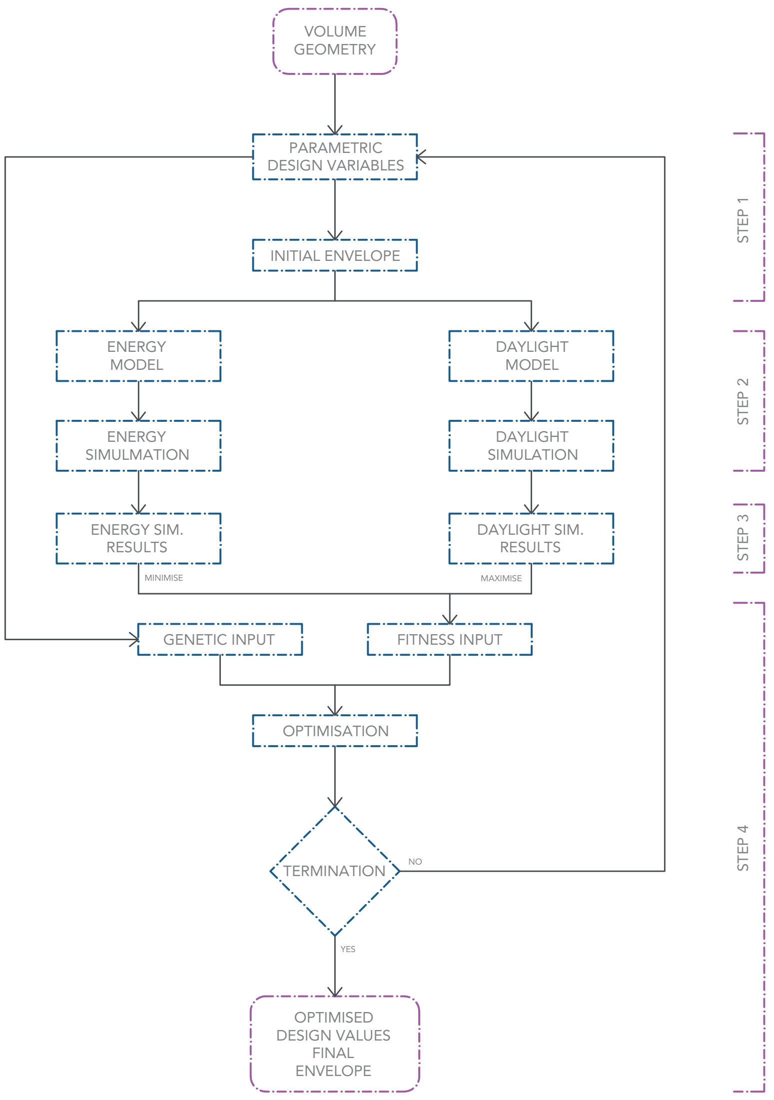
1. Glazing Ratio (per facade)	[%]	Median Value = 30	Min = 15	Max = 80
2. Shader Depth (per facade)	[cm]	Median Value = 30	Min = 5	Max = 100
3. U_{glaze} - SHGC	$[W/m^2K]$	Median Value = 1,1 - 60%	Min = 2,0 - 35%	Max = 0,6 - 80%
4. Insulation thickness (per const.)	[cm]	Median Value = 15	Min = 5	Max = 50

OBJECTIVES

Minimise Heating + Cooling Load.

Maximise Useful Daylight Illuminance.

OPTIMISATION PROCESS



VOLUME GEOMETRY

PARAMETRIC DESIGN VARIABLES

INITIAL ENVELOPE

ENERGY MODEL

DAYLIGHT MODEL

ENERGY SIMULMATION

DAYLIGHT SIMULATION

ENERGY SIM. RESULTS

DAYLIGHT SIM. RESULTS

MINIMISE

MAXIMISE

GENETIC INPUT

FITNESS INPUT

OPTIMISATION

TERMINATION

NO

YES

OPTIMISED DESIGN VALUES FINAL ENVELOPE

STEP 1

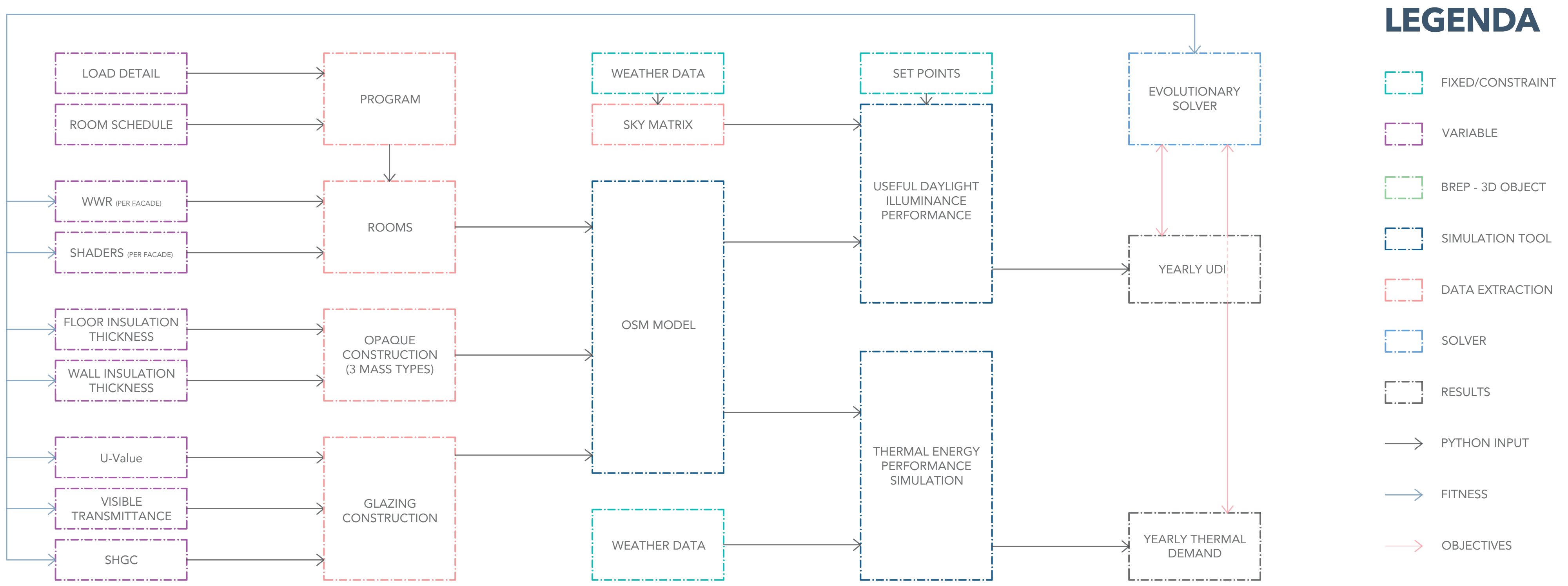
STEP 2

STEP 3

STEP 4

SCRIPT & SIMULATION DETAIL

GRASSHOPPER/PYTHON SCRIPT



LOAD DETAIL
ROOM SCHEDULE
WWR (PER FACADE)
SHADERS (PER FACADE)
FLOOR INSULATION THICKNESS
WALL INSULATION THICKNESS
U-Value
VISIBLE TRANSMITTANCE
SHGC

PROGRAM
ROOMS
OPAQUE CONSTRUCTION (3 MASS TYPES)
GLAZING CONSTRUCTION

WEATHER DATA
SKY MATRIX
OSM MODEL
WEATHER DATA

SET POINTS
USEFUL DAYLIGHT ILLUMINANCE PERFORMANCE
THERMAL ENERGY PERFORMANCE SIMULATION

EVOLUTIONARY SOLVER
YEARLY UDI
YEARLY THERMAL DEMAND

LEGENDA

- FIXED/CONSTRAINT
- VARIABLE
- BREP - 3D OBJECT
- SIMULATION TOOL
- DATA EXTRACTION
- SOLVER
- RESULTS
- PYTHON INPUT
- FITNESS
- OBJECTIVES

SIMULATION LIST

1. GLAZING RATIO

- All other variables constant.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

2. SHADER DEPTH

- All other variables constant.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

3. U-GLAZE

- All other variables constant.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

4. INSULATION

- All other variables constant.
- **6 simulations** with random variable values to explore range.
- **1 simulation** using the solver to find optimum value.

5. MULTI VARIABLE

- All variables can be modified.
- **1 simulation**
- Output is fittest variable setting with respect to objectives.

POSITION ON SITE

PRELIMINARY

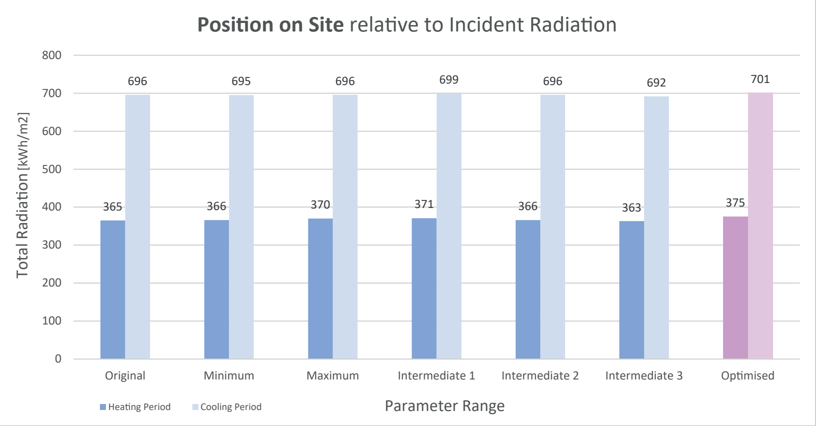
The first element to optimise is the position of the site. Indeed, where some sites lack contextual buildings that may affect the total incident solar radiation, the plot of land that was selected to carry out this case study holds 2 buildings. We note once agin that only the position of the site is here modified and analysed, whilst the other variables remain at their median value (see previous page).

COMMENTS

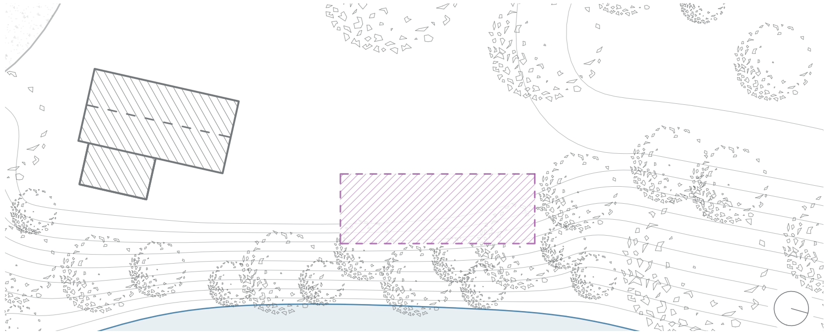
A total of 6 experiments were carried out so as to evaluate the influence of site position on total incident solar radiation. We notice straight away a general trend - without too much of a surprise - that the closer our volume gets to the building A on the left, the less solar radiation it receives - as this building is directly south from our project. However, having a contextual block may hold some benefit, especially in the heating period as shade can be provided. Also building B, oriented west from our project, can also represent potential sun block in the summer months.

The values range from 284000 to 292000 [kWh], and once again the farther away our building is from environing context, the more incident solar radiation it receives. Unsurprisingly indeed, when we launch the evolutionary pareto-front solver (Octopus), it selects the farthest possible position (within the given constraints) from both buildings - so as to limit as much as possible incident shadowing. Also, we note that almost twice the radiation occurs in the heating period.

PERFORMANCE COMPARISON



OPTIMISED POSITION



DATABASE

POSITION ON SITE								
Experiment		1	2	3	4	5	6	7
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised
Coordinates Point A	[m]	A (0 ; 0)	A (-2 ; -3)	A (6 ; 4)	A (2,8 ; -0,6)	A (-0,9 ; 1,8)	A (1,2 ; 3,1)	A (6 ; -3)

Period	[t]	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	All Year
Total Radiation	[kWh/m2]	365	696	366	695	370	696	371	699	366	696	363	692	375	701	1076
Total Radiation	[kWh]	99008	188851	99241	188843	100433	188826	100937	189662	99263	188945	98638	187984	101810	190265	292075

ORIENTATION

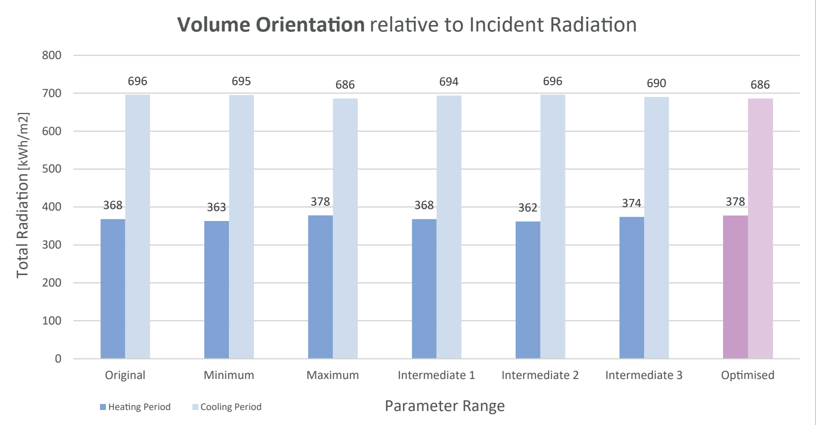
PRELIMINARY

The second element to optimise is the orientation of the building. Indeed, whilst orientation was here constrained by the site conditions to 30° on either side from the volume centroid, it plays a key role in the potential use of existing solar radiation to heat and power a home. The building being parallellepipedic also compounds this potential, as square based volumes would benefit less from changing their orientations. Once again, only the building rotation is here analysed and discussed, whilst the other variables remain at their median values.

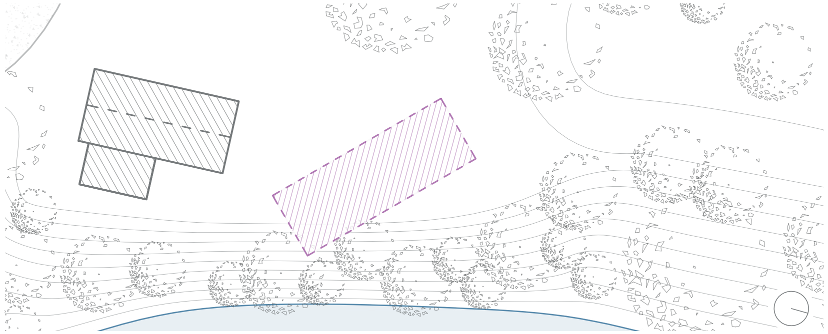
COMMENTS

For a given volume height, and in the position in which was tested the potential for orientation; it doesn't seem that influencing this parameter manifests as extreme changes as in the previous «Position of Site» experiment. Indeed, all values seem to be within a 2000 [kWh] range - with the minimum at 287000 and the maximum optimised at 289000 [kWh]. While orientation is defintely a key factor in the design of energy-smart, self-consumptive homes, we suspect that this parameter needs to be coupled with the previous position on site so as to reap its full potential benefits. In the climate hereby analysed, most incident solar radiation happens after 12AM when the sun is oriented in the west; this is why the optimised solution found by the solver defines a volume orientation which maximises its surface area towards the west. While a radical southern exposure would have been better, it was factually impossible given the site constraints.

PERFORMANCE COMPARISON



OPTIMISED ORIENTATION



DATABASE

VOLUME ORIENTATION								
Experiment		1	2	3	4	5	6	7
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised
Angle (relative to river)	[°]	0	-30	30	8	-12	21	30

Period	[t]	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	All Year
Total Radiation	[kWh/m2]	368	696	363	695	378	686	368	694	362	696	374	690	378	686	1064
Total Radiation	[kWh]	99008	188851	98643	188608	102522	186087	99889	188476	98328	188909	101393	187277	102522	186087	288609

FINAL OPTIMISATION

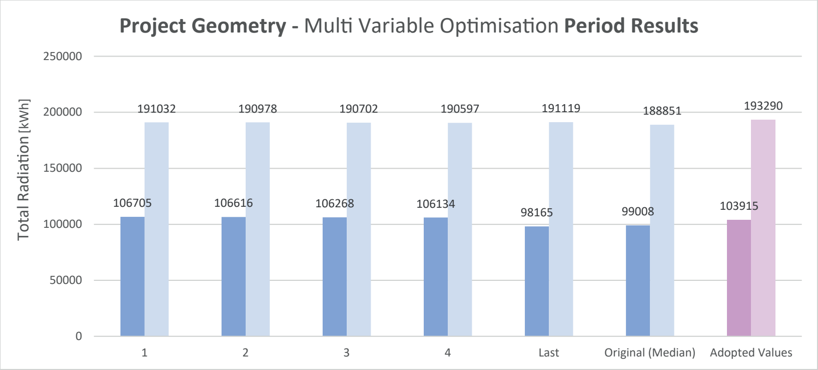
PRELIMINARY

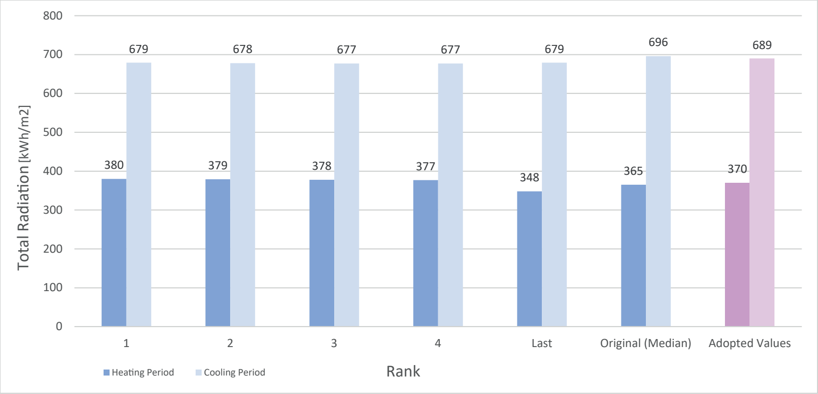
Where previous experiments discussed and analysed single variables - while the others remained at their constant median value - the following results were calculated so as to account for all variables at once. The evolutionary pareto-front solver Octopus allowed us to solve this multi-variable, multi-objective, equation in the framework of optimising building geometry for incident solar radiation - namely maximised in winter, and minimised in winter. The following graphs plot the 4 best solutions found by the solver, the worst possible one, the original and uneducated initial choice, as well as the final and chosen adopted building geometry.

COMMENTS

While the results span a significant 90000 [kWh] from the top ranking situation (297000 [kWh]to the worst one (288000 [kWh]) this difference is mostly compounded during the summer months; less in the winter months : 40000 versus 20000 [kWh] range difference for the summer and winter months respectively. The difference between the original, uneducated, choice and the top performer is also close to 5000 [kWh/m^2], thus underlining the benefits thats such parametric softwares and solvers may hold. Also, it is crucial to note that the ranges each variable were purposefully increased and decreased so as to analyse more closely the influence of each parameter on incident solar radiation, but however do not completely represent potential design applications.

PERFORMANCE COMPARISON





DATABASE

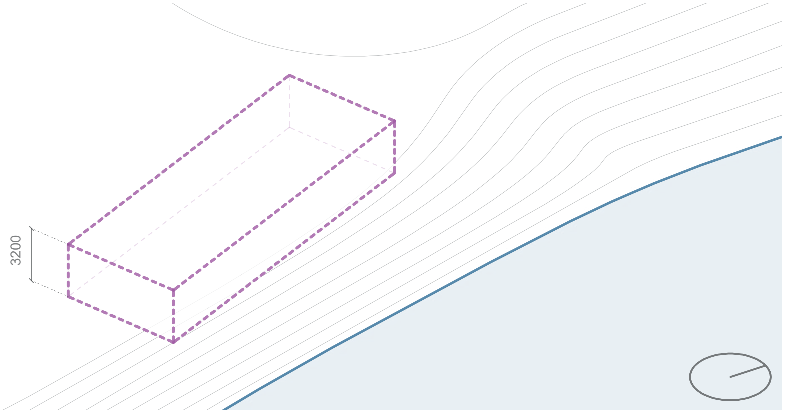
PROJECT GEOMETRY - MULTIVARIABLE OPTIMISATION PARAMETERS									RESULTS [kWh]		RESULTS [kWh/m2]	
Rank	Position on Site	[m]	Orientation	[°]	Volume Height	[m]	Roof Pitch Angle	[°]	H Period	C Period	H Period	C Period
1	A (3,0 ; -2,2)		30		3,2		0		106705	191032	380	679
2	A (5,1 ; 0,1)		30		3,2		0		106616	190978	379	678
3	A (1,3 ; -1,6)		30		3,2		0		106268	190702	378	677
4	A (0,7 ; -1,6)		30		3,2		0		106134	190597	377	677
Last	A (-1,1 ; 2,8)		-8		3,2		0		98165	191119	348	679
Original (Median)	A (0 ; 0)		0		3,0		0		99008	188851	365	696

CONCLUSION & ADOPTED VALUES

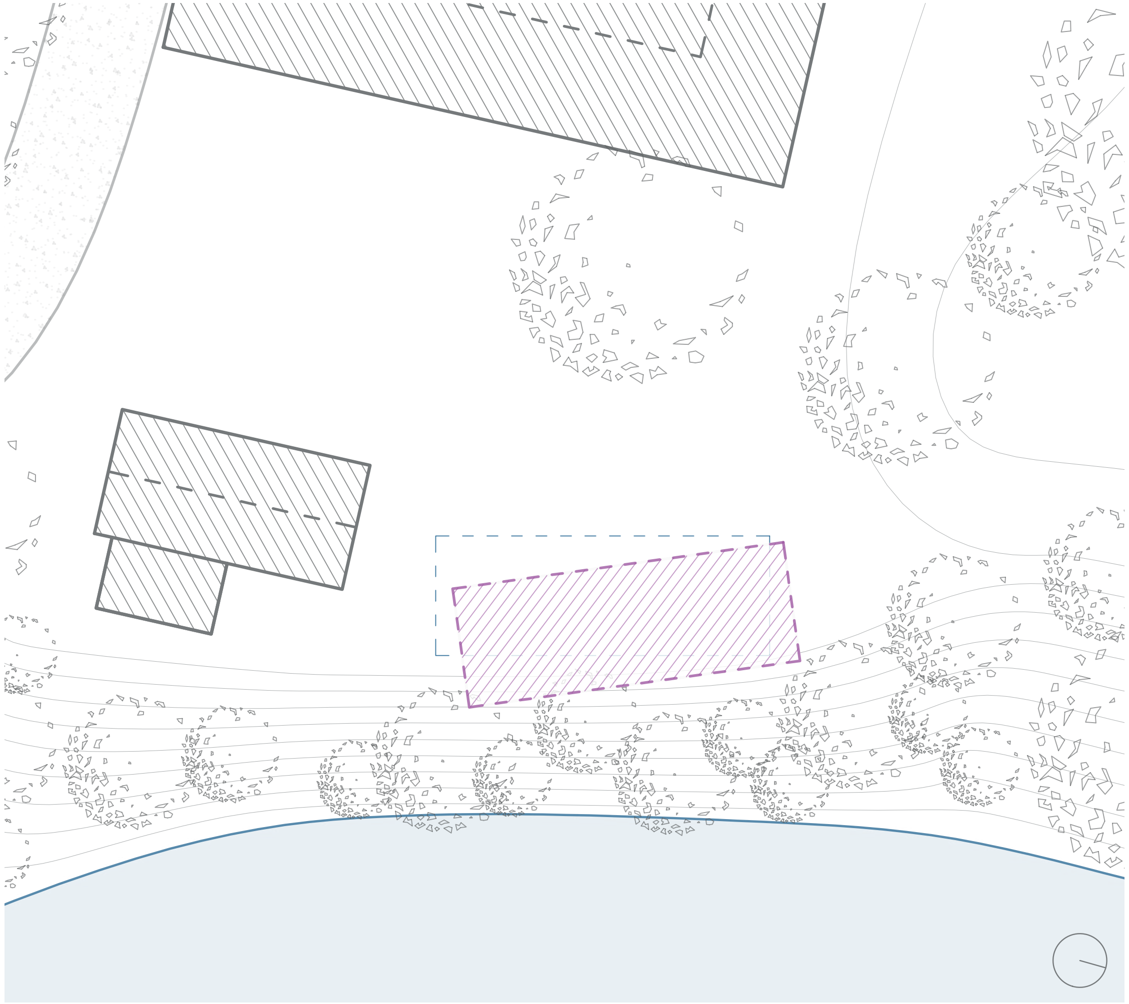
CONCLUSION

While computational tools may provide valuable insight into understanding the driving parameters of a given problematic framework, they remain a tool which may hold a non-negligeable amount of biases. The information provided needs to inform the project, rather than radically constrain it - as tools will never understand the full spectrum of an architectural problem and decision, and will remain unidirectional in their pursuit of a particular objective. The chosen values, although not optimal, still maintain an excellent level of satisfaction when it comes to optimising solar heat gain from incident solar radiation. They remain far greater than the worst possible outcome and the original uneducated median values; while remaining sufficiently close to the optimum.

ADOPTED VOLUME



ADOPTED POSITION & ORIENTATION



ADOPTED VALUES DETAIL

PROJECT GEOMETRY - ADOPTED VALUES									RESULTS [kWh/m2]			
Parameters	Position on Site	[m]	Orientation	[°]	Volume Height	[m]	Roof Pitch Angle	[°]	H Period	C Period	H Period	C Period
Adopted Values	A (1,3 ; -1,6)		8		3,2		0		103915	193290	370	689

WINDOW WALL RATIO

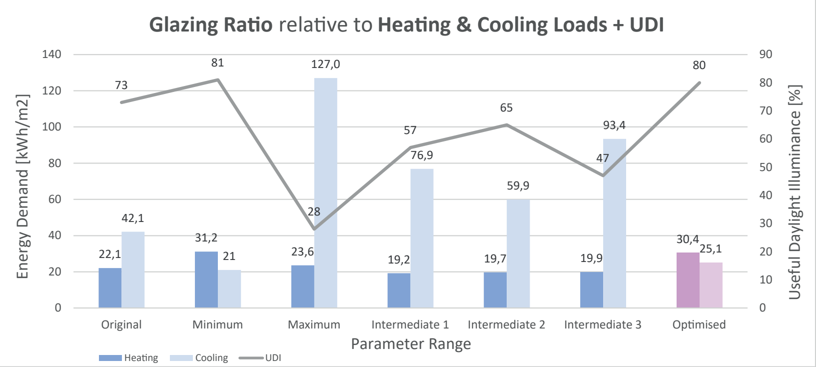
PRELIMINARY

The first element to optimise energy demand and useful daylight illuminance through is the glazing ratio. The ratios of each facades will be considered independently. Indeed, windows and openings represent one of architecture's core components, but remain an element which is most often poorly designed, with aesthetic and cosmetic considerations coming before their utility, and consequent energetic performance. How good is a full window facade if the price of heating, and the drastic increase in cooling demand outweighs its benefits ? Or if shades need to be permanently deployed so as to limit glare and visual discomfort, thus blocking outdoor views ? The present analysis aims at optimising energy performance and incident daylighting potential through the manipulation of glazing ratio only.

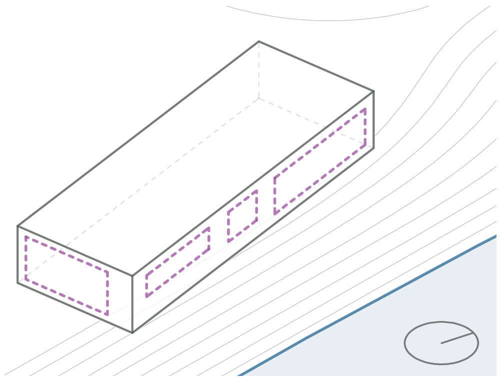
COMMENTS

It generally seems as though, as portrayed by the «minimum» experiment, that a lower WWR will drastically decrease the overall demand. However, the decrease is mostly felt for cooling needs, as smaller bay windows will necessarily incur less incident solar radiation, as well as represent a smaller thermal leak surface (compared to the higher performing opaque envelope). On the other hand, smaller glazing ratios also mean less potential for solar radiation, and thus less potential for free heating. This is shown in the «maximum» scenario, where a higher WWR actually decreases the heating demand, but consequently dramatically increases the cooling demand to 127 [kWh/m²]. The UDI is in this case also drastically decreased to only 28 % of the year, not because there is not enough light entering, but because the entering light tends to be vastly superior to the admissible 3000lux. It also seems as though larger openings towards more potent suns seem to benefit the overall energetic demand, while larger openings towards shadowy zones (north) increase the useful daylight illuminance.

PERFORMANCE COMPARISON



OPTIMISED WWR CHARACTERISTICS



North	[%]	25
East	[%]	15
South	[%]	20
West	[%]	20

DATABASE

GLAZING RATIO - WWR

Experiment		1	2	3	4	5	6	7			
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised			
Glazing Ratio (per façade)	N - E - S - W [%]	30	15	80	50	40	60	N 25	E 15	S 20	W 20

Total Yearly		H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	Heating	Cooling	UDI
Results	[kWh/m2] - [%]	22,1	42,1	73	31,2	21	81	23,6	127,0	28	19,2	76,9	57	19,7	59,9	65	19,9	93,4	47	30,4	25,1	80

OUTDOOR SHADERS

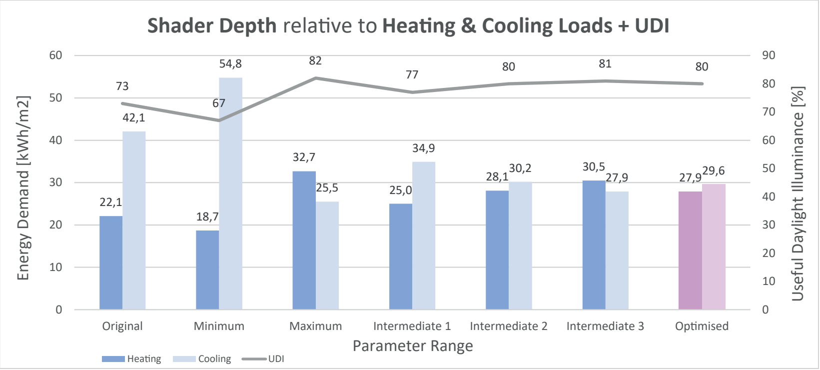
PRELIMINARY

The project has a composite shading system; namely an outdoor permanent one bordering the window panes - composed of wooden planks of 5cm thickness and 35% material reflectance; and an indoor automatic shading system composed of cotton blinds. Only the outdoor permanent shading system will hereafter be analysed and optimised, while the indoor shading system will be considered constant throughout. Although an indoor shading system would have sufficed, the goal is to maintain the views on nature, and maximise useful daylight illuminance which an only-indoor shading system would have poorly influenced - this is why it was decided to try to rely mostly on outdoor shaders that do not block the views, and only use the indoor blinds when necessary. The characteristics of the cotton automatic and actionable indoor shading system are as follows :It has a solar/light transmittance of 40%; a solar/light reflectance of 50%; a conductivity of 0.05 [W/m²K]; a permeability of 10%; an infrared hemispherical emissivity of 90%; and a 2mm thickness. They can only be deployed from 15 april to 15 october, if the incident radiation on the window surface exceeds 200 [W/m²].

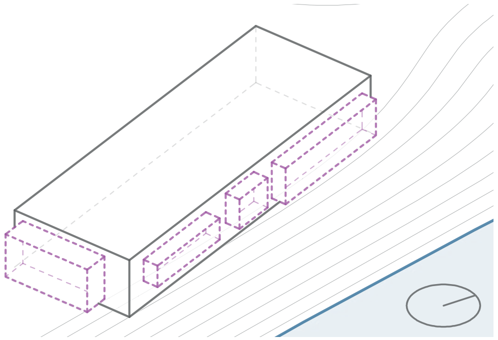
COMMENTS

It generally seems as though a deeper shade will decrease the energy demand and increase the useful daylight illuminance. Indeed, while a shallow shade means more incoming radiation on the window surfaces in winter, it also allows for unwanted solar rays in summer - thus increasing drastically the cooling demand. A deeper outdoor window shade (as portrayed here) has the advantage of blocking sunrays in the summer months, but may allow incident radiation in the winter months when the sun is lower. It also generally seems as though eastern radiation is preferable to western radiation.

PERFORMANCE COMPARISON



OPTIMISED SHADER CHARACTERISTICS



North	[cm]	100
East	[cm]	70
South	[cm]	100
West	[cm]	75

DATABASE

SHADER DEPTH											
Experiment		1	2	3	4	5	6	7			
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised			
Shader Depth (per façade)	N - E - S - W [cm]	30	5	100	50	70	85	N 100	E 65	S 90	W 65
Material Reflectance	[%]	35	35	35	35	35	35	35			

Total Yearly		H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	Heating	Cooling	UDI
Results	[kWh/m2] - [%]	22,1	42,1	73	18,7	54,8	67	32,7	25,5	82	25,0	34,9	77	28,1	30,2	80	30,5	27,9	81	27,9	29,6	80

GLAZING COMPONENT CHARACTERISTICS

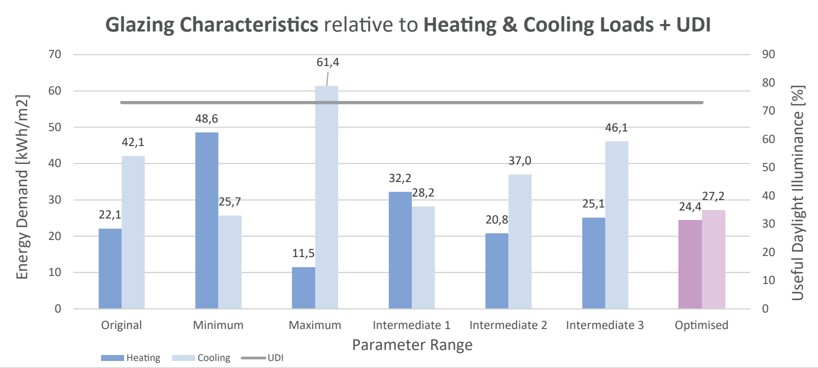
PRELIMINARY

The third element to optimise energy demand and useful daylight illuminance through is the glazing component. Indeed, the windows and transparent elements of a structure most often represent the primary thermal leakage surfaces, and represent the main «entry points» to unwanted warmth in the summer periods - so an adequate analysis and dimensioning is necessary in energy smart homes. For the sake of the analysis, the transmittance values will also consider the chassis, and thus represent the whole glazing construction - a single value which can be inputted directly in Honeybee and its underlying EnergyPlus computation. Also, only the solar heat gain factor, and the transmittance will here be considered variable, the visible transmittance remaining constant throughout at 70%.

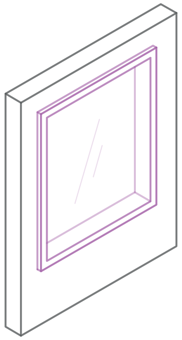
COMMENTS

The original median construction, with a 1,1 [W/m²K] and 60% SHGC - typical double pane high performing windows - induced a respectable 22,1 [kWh/m²] for heating, it also induced a 42,1 [kWh/m²] for cooling - underlining the fact that high performing windows will also proportionally increase the cooling demand, as heat is trapped inside. This effect is vastly compounded when the SHGC is increased to its maximum. This is the reason why a simple 20% difference in SGHC between the «maximum» and «optimised» scenarios produce a massive increase in cooling demand; and decrease in heating demand. The «minimum» values also tend to show this effect, as transmittance is poor, yet SHGC is low - inducing low cooling demand as trapped heat may evacuate in the summer months, but represents a vast increase in heating demand in the winter months.

PERFORMANCE COMPARISON



OPTIMISED GLAZING COMPONENT



Transmittance U	[W/m²K]	0,60
Solar Heat Gain Factor	[%]	60
Visible Transmittance	[%]	70

DATABASE

GLAZE THERMAL PROPERTIES								
Experiment		1	2	3	4	5	6	7
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised
U_{glaze}	[W/m2K]	1,1	2,0	0,6	1,2	0,8	1,5	0,6
Solar Heat Gain Factor	[%]	60	35	80	40	50	70	35

Total Yearly		H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	Heating	Cooling	UDI
Results	[kWh/m2] - [%]	22,1	42,1	73	48,6	25,7	73	11,5	61,4	73	32,2	28,2	73	20,8	37,0	73	25,1	46,1	73	24,4	27,2	73

OPAQUE CONSTRUCTION - A) LOW MASS

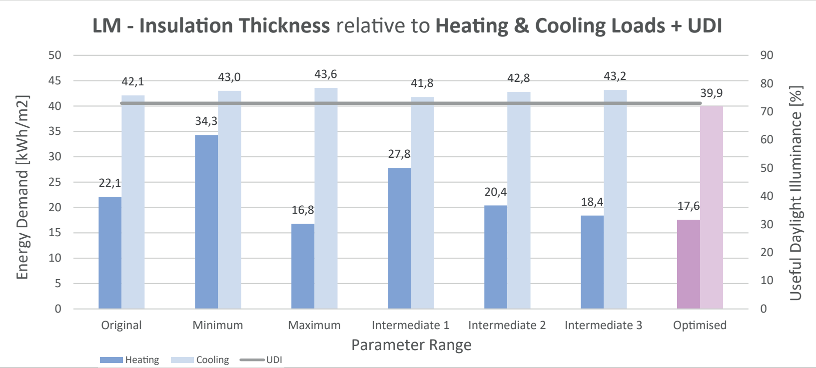
PRELIMINARY

The final element to optimise energy demand and UDI through is the construction/composition of the opaque envelope - both for 1) the wall/roof which we consider to have the same interior structure; and 2) the floor. For the sake of the analysis, 3 different construction masses will thereafter be analysed : A) Low Mass; B) Medium Mass; and High Mass constructions. Indeed, while the U-value for the envelope's opaque structure is one of the main drivers in reducing energy demand, the construction's mass and consequent thermal capabilities - expressed in its ability to retain heat, or coldness, and its capacity to restitute it later through time lag - are very much crucial in the design of energy-smart homes. The first construction to be analysed is a low mass wooden based structure, and the variable is insulation thickness.

COMMENTS

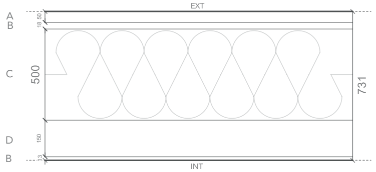
The first noticeable - yet unsurprising - trait of the opaque envelope is its inability to influence UDI - which therefore remains constant throughout all experiments. In the Low Mass Construction scenario, it generally seems that more insulation induces less heating demand for the building, but might have dramatic consequences as to the cooling demand - as heat is trapped inside with no way out. It also appears that the wall/roof insulation has more influence in driving down the energy demand than floor insulation. The final optimised U values for the wall/roof is a very small 0,054 [W/m²k], with a 21-28h time lag between peak outdoor temperature and peak indoor influence. Although a time-lag closer to 12h would be more interesting, it would also mean a poorer energy demand performance. This very high time-lag is a direct consequence of the wall's thermal characteristics - mainly given by the 50cm of high performing insulation.

PERFORMANCE COMPARISON

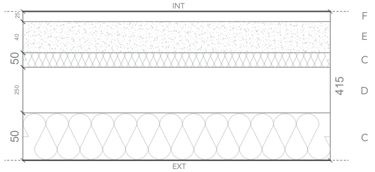

LM - Insulation Thickness relative to **Heating & Cooling Loads + UDI**

OPTIMISED LOW MASS CONSTRUCTION

WALL/ROOF



FLOOR



A = Outdoor Timber Battens ; B = Plasterboard ; C = Insulation ; D = Timber Stud Structure ; E = Concrete Screed ; F = Timber Flooring/Parquet

Transmittance U	[W/m²K]	0,054
Superficial Mass	[Kg/m²]	147,900
Decrement Factor	[-]	0,013
Time Lag	[h]	27,962

Transmittance U	[W/m²K]	0,175
Superficial Mass	[Kg/m²]	189,500
Decrement Factor	[-]	0,012
Time Lag	[h]	21,160

DATABASE

INSULATION THICKNESS - LOW THERMAL MASS CONSTRUCTION								
Experiment		1	2	3	4	5	6	7
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised
Wall/Roof Ins. Thickness	[cm]	20	5	50	10	25	35	50
Floor Insulation Thickness	[cm]	15	10	30	10	20	25	10
Material Properties	Exp. Polyurethan	0,30 [W/mK] - 40 [KG/m3] - 1670 [J/kgK]						

Total Yearly		H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	Heating	Cooling	UDI
Results	[kWh/m2] - [%]	22,1	42,1	73	34,3	43,0	73	16,8	43,6	73	27,8	41,8	73	20,4	42,8	73	18,4	43,2	73	17,6	39,9	73

OPAQUE CONSTRUCTION - B) MEDIUM MASS

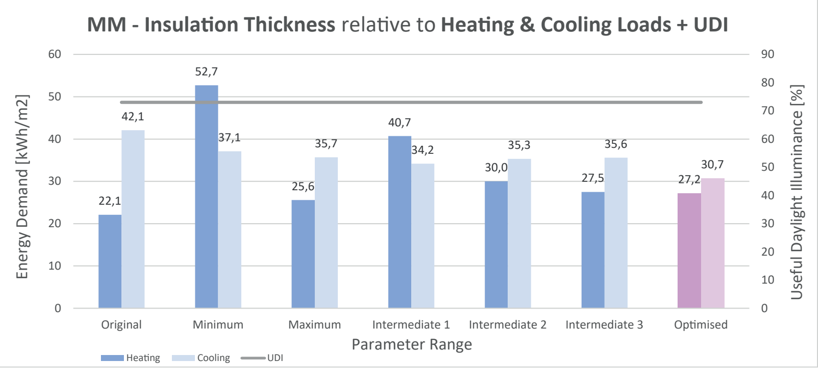
PRELIMINARY

The second and third opaque envelope compositions to be considered are the Medium and High Mass constructions. While the previous construction had a wooden structure and a wooden timber floor, here the two constructions have a cast concrete structure and a cement screed floor. The cast concrete for both medium and high mass constructions are respectively 5cm and 15cm thick for all walls, roofs and floor. The cement screed flooring is the same thickness as the previously analysed timber flooring, - namely 2,5cm. The goal is here to compare energy demand performance for all 3 mass construction types, considering their U-Value Transmittance differences to be negligeable (0.03 [W/m²K] delta between top and bottom performer).

COMMENTS

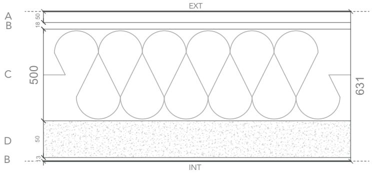
While for the wooden, low mass structure, the main issue was related to cooling demand; it seems that for medium mass, concrete based constructions, the problem lies in the heating demand. Indeed, the worst performing scenario for energy demand is when insulation is minimised, and the heating and cooling demand have a 15 [kWh/m²] delta. A possible explanation is fact that concrete will efficiently store heat in the winter months and restitute it later, but also means it will store unwanted heat in the cooling periods. This is compounded by the fact that the very high performing wall/roof with a 0,058 [W/m²K] will trap the heat inside and thus increase the sense of discomfort. This coalition of high thermal mass and high performing walls is underlined when the wall's performance is dramatically decreased in the «Intermediate 1» experiment, as both cooling and heating demand seem to reduce, even though its envelope is less performing.

PERFORMANCE COMPARISON

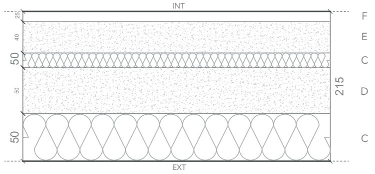


OPTIMISED MED. MASS CONSTRUCTION

WALL/ROOF



FLOOR



A = Outdoor Timber Battens ; B = Plasterboard ; C = Insulation ; D = Cast Concrete Structure ; E = Concrete Screed ; F = Concrete Floor Finishing

Transmittance U	[W/m²K]	0,058
Superficial Mass	[Kg/m²]	172,900
Decrement Factor	[-]	0,048
Time Lag	[h]	22,043

Transmittance U	[W/m²K]	0,275
Superficial Mass	[Kg/m²]	202,000
Decrement Factor	[-]	0,094
Time Lag	[h]	9,886

DATABASE

INSULATION THICKNESS - MEDIUM THERMAL MASS CONSTRUCTION								
Experiment		1	2	3	4	5	6	7
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised
Wall/Roof Ins. Thickness	[cm]	20	5	50	10	25	35	50
Floor Insulation Thickness	[cm]	15	10	30	10	20	25	10
Material Properties	Exp. Polyurethan	0,30 [W/mK] - 40 [KG/m3] - 1670 [J/kgK]						

Total Yearly		H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	Heating	Cooling	UDI
Results	[kWh/m2] - [%]	22,1	42,1	73	52,7	37,1	73	25,6	35,7	73	40,7	34,2	73	30,0	35,3	73	27,5	35,6	73	27,2	30,7	73

OPAQUE CONSTRUCTION - C) HIGH MASS

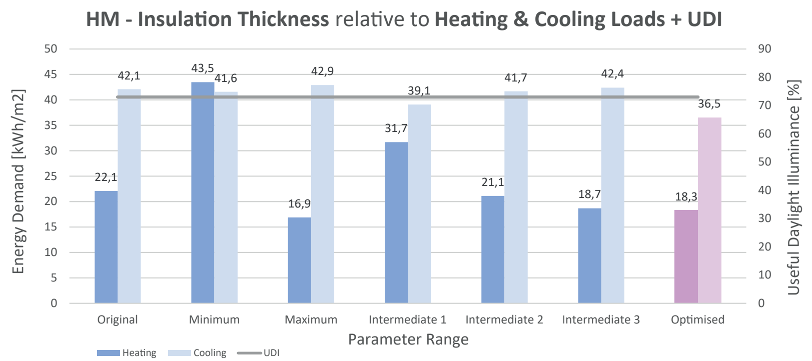
COMMENTS

The final opaque composition to be considered is the High Mass, concrete based construction. Contrary to the medium mass construction, the energetic demand seems to be mostly a cooling demand, as heat is trapped inside and unable to leave. This is compounded, as in the previous example, by the envelope's high thermal performance which traps even more the heat in, with a high time lag. While the example of maximum insulation produces the best performing heating demand out of all three construction types, at an extermely small 16,9 [kWh/m²] per year, it also represents the greatest cooling demand at 42,9 [kWh/m²]. This is why the optimised solution for both medium and high mass constructions seem to maximise insulation in the wall/roof to store the heat effectively, and minimise it in the floor to allow unwanted heat to dissipate, in the cooling period, thus limiting the increase in cooling demand as a result of trapped heat.

CONCLUSION & COMPARISON

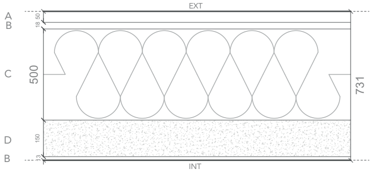
In an optimal insulation thickness scenario; the low, medium and high mass constructions respectively represent a 57,5 ; 57,9 ; and 54,8 [kWh/m²] yearly total energy demand. Out of all 3, it seems that the low mass and high mass constructions seem to be the better performing, when looking at energetic demand performance. However, high mass concrete construction - although being the best year-round performer - necessarily represents a vast increase in economic and carbon cost; when compared to the low mass wooden-based construction. It is also less performing when it comes to transmittance values at equal insulation, and less performing in its heat time lag ability. However, both low and high mass constructions will be considered in the final multi variable optimisations, as they might influence other factors, such as WWR, and shader depth.

PERFORMANCE COMPARISON

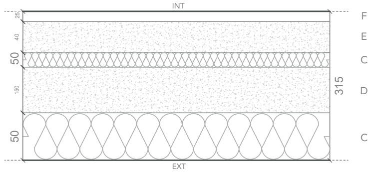

HM - Insulation Thickness relative to **Heating & Cooling Loads + UDI**

OPTIMISED HIGH MASS CONSTRUCTION

WALL/ROOF



FLOOR



A = Outdoor Timber Battens ; B = Plasterboard ; C = Insulation ; D = Cast Concrete Structure ; E = Concrete Screed ; F = Concrete Floor Finishing

Transmittance U	[W/m²K]	0,057
Superficial Mass	[Kg/m²]	372,900
Decrement Factor	[-]	0,017
Time Lag	[h]	24,848

Transmittance U	[W/m²K]	0,269
Superficial Mass	[Kg/m²]	402,000
Decrement Factor	[-]	0,031
Time Lag	[h]	11,642

DATABASE

INSULATION THICKNESS - HIGH THERMAL MASS CONSTRUCTION								
Experiment		1	2	3	4	5	6	7
Parameter Range		Original	Minimum	Maximum	Intermediate 1	Intermediate 2	Intermediate 3	Optimised
Wall/Roof Ins. Thickness	[cm]	20	5	50	10	25	35	50
Floor Insulation Thickness	[cm]	15	10	30	10	20	25	10
Material Properties	Exp. Polyurethan	0,30 [W/mK] - 40 [KG/m3] - 1670 [J/kgK]						

Total Yearly		H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	H	C	UDI	Heating	Cooling	UDI
Results	[kWh/m2] - [%]	22,1	42,1	73	43,5	41,6	73	16,9	42,9	73	31,7	39,1	73	21,1	41,7	73	18,7	42,4	73	18,3	36,5	73

FINAL OPTIMISATION

PRELIMINARY

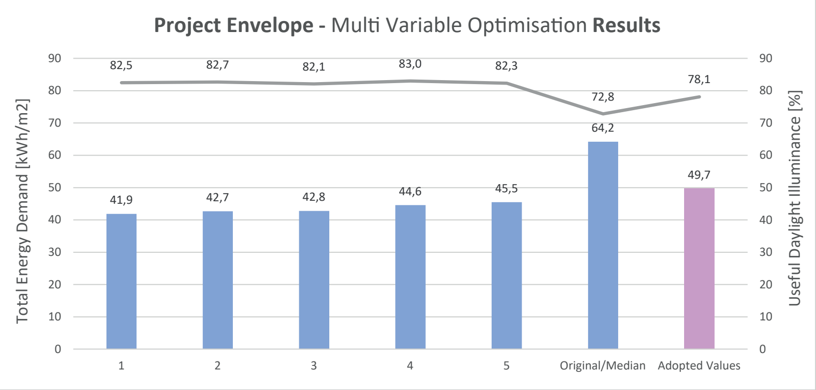
Where previous experiments discussed and analysed single variables - while the others remained at their constant median/generic value - the following results were calculated so as to account for all variables at once. The evolutionary pareto-front solver Octopus allowed us to solve this multi-variable, multi-objective, equation in the framework of optimising building envelope for energy demand and useful daylight illuminance - namely minimising both heating and cooling demand; and maximise useful daylighting.

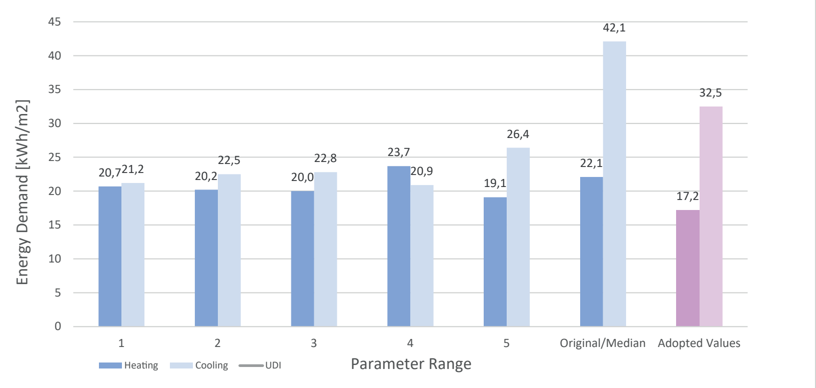
The following graphs plot the results relating to the 5 best solutions found by the solver (considering the 2 best construction types - the low and high mass); the original and uneducated generic initial choice; as well as the final adopted envelope characteristics.

COMMENTS

Within the constraints that were defined, and the constants applied (interior self-controlling shading system characteristics, window visible transmittance, and shading material reflectance), the solver Octopus determined that a low thermal mass construction was best suited, coupled with small window openings; deep outdoor shading devices; and relatively thick layers of (high performing insulation) - as described in the following table. This is probably due to the higher potential for heat dissipation that the wooden-based construction can attain as a result of its lower thermal inertia. Indeed, we previously noted that while adding relatively large layers of insulation was resulted in

PERFORMANCE COMPARISON





DATABASE

PROJECT ENVELOPE - MULTIVARIABLE OPTIMISATION PARAMETERS							RESULTS			
Construction	Rank	WWR (per façade) [%]	Shader Param. (per façade) [cm]	Glazing Param. [W/m2K]	[%]	Insulation Thickness [cm]	UDI [%]	Heating	Cooling	H+C Total [kWh/m2]
Low Thermal Mass	1	N 15 E 30 S 15 W 15	N 55 E 80 S 55 W 70	0,75	60	Wall/Roof 35 Floor 25	82,5	20,7	21,2	41,9
Low Thermal Mass	2	N 20 E 30 S 15 W 15	N 55 E 75 S 50 W 90	0,75	60	Wall/Roof 35 Floor 25	82,7	20,2	22,5	42,7
High Thermal Mass	3	N 25 E 40 S 20 W 15	N 70 E 80 S 85 W 85	0,9	60	Wall/Roof 35 Floor 10	82,1	20,0	22,8	42,8
Low Thermal Mass	4	N 20 E 30 S 15 W 15	N 55 E 80 S 55 W 70	0,85	60	Wall/Roof 35 Floor 25	83,0	23,7	20,9	44,6
High Thermal Mass	5	N 25 E 40 S 20 W 15	N 50 E 80 S 90 W 90	0,95	60	Wall/Roof 35 Floor 25	82,3	19,1	26,4	45,5
Low Thermal Mass	Original/Median	30	30	1,1	60	Wall/Roof 20 Floor 15	73	22,1	42,1	64,2

RESULTS & DISCUSSION

a significant decrease in heating demand - the opposite was true for cooling demand. The solver's choice for the lower thermal mass indeed accounts for this phenomena as it searches for ways to diminsih either cooling demand directly, or through lower time-lags - and consequent higher heat dissipation capabilities.

However, although low mass constructions were better performing globally, high mass constructions seemed to allow for greater WWR - especially on the eastern and southern fronts; significantly higher window transmittance values; and almost half as thick insulation values for the floor's construction. This can be an attractive criteria when considering either the advantages of site-specific viewpoints and of overall economic investment potential. In this case indeed, higher thermal mass, and consequent lower heat dissipation capability, is counter-effected by lower window transmittance values and lower insulation thicknesses - ultimately providing the lowest heating demand out of all possible configurations at 20,0 [kWh/m²]; as well as increasing the cooling demand by «only» 1,6 [kWh/m²] with respect to the best performing scenario over a whole year.

As the solver demonstrates, the best performing variable settings all gravitate around 42-44 [kWh/m2] final demands, which is almost 20 [kWh/m2] better than the original, uneducated, generic parameters. These numbers, considering that it is only demand and not consumption, represent a very high performing home. UDI is at maximum 83%, which means that on average, only 17% of the time corrections to the lighting environment need to be made (either by turning the lights on, or drawing the shades down). This very high UDI value thus prevents from unwanted heat, and useless electricity use. Also it needs to be noted that UDI - not daylight autonomy - was considered. This means that the illuminance values over 3000lux count in the 17%, but represent moments when activities needing light are absolutely feasible.

Finally, it appears the top perfomers have strongly balanced heating and cooling demands, with a slightly higher cooling demand - a necessary consequence of the very high performing envelope and windows; and consequent lower time-lags and heat dissipation overall capabilities.

CONCLUSION

The use of the multi-objective pareto front solver Octopus has allowed to 1) understand the driving parameters influencing the annual energy demand and useful daylight illuminance; as well as 2) provide us with multiple scenarios of variables which would best satisfy the objectives we had set.

From the single variable analysis, we came to understand the importance of low mass timber based opaque constructions, in its ability to drive the cooling energy demand very low, as it allowed for heat to dissipate in the summer months - while on the other hand, high mass concrete based opaque constructions incurred the lowest heating demand, but incurred heavy losses when it came to cooling demand. Also, at an equal annual energy demand, high mass constructions allowed for bigger windows, thus increasing visual comfort; as well as allowed for higher window transmittance values, which consequently drive the building's economics down.

A composite mass composition was thus chosen - as it takes the advantages of both construction mass types : A low heating demand, an impressive ability to store heat and restitute it, a higher window transmittance value and a larger possibility of WWR - from the high mass concrete base; and a lower cooling demand, an ability to dissipate heat more efficiently, and a general lower economic and carbon cost - from the low mass timber based constructions.

While computational tools may provide valuable insight, they remain oblivious to other important variables - for instance the appreciation of environing views or of adequate social exposure. This is why it was chosen to increase the WWR, to take into account such parameters. Although slightly less optimal, the final result maintains an excellent level of <50 [kWh/m2] annual demand and 78% UDI - but however provides larger comfort.

Regardless of its limitations, it is clearly apparent as to how much potential such computationally-aided; algorithmic process of preliminary design can have on the reduction and overall optimisation of thermal energetic demand.

ADOPTED VALUES - OPTIMISED PROJECT

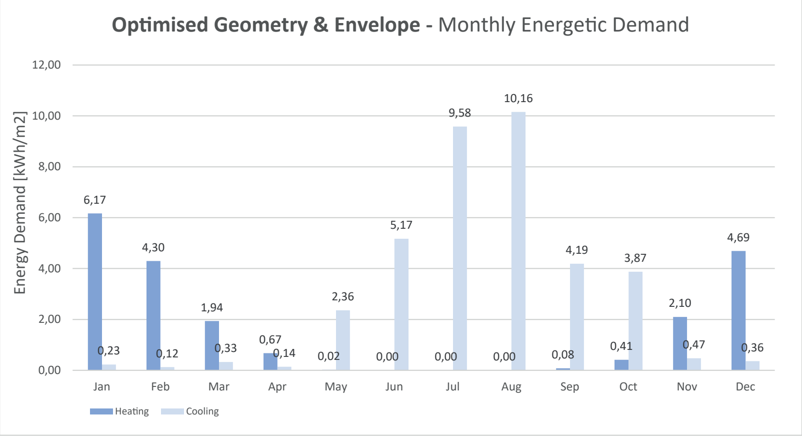
PERFORMANCE COMPARISON

As stated in the previous conclusion, it is evident that following such algorithmic computationally-aided process of preliminary design can have in terms of overall thermal demand reduction. Although existing, easily and broadly appliable, construction cultures (with respect to WWR; shader characteristics; glazing and wall component configurations) incur attractive values of thermal energetic demand; the use of algorithimic computation broadens significantly the spectrum of possible choices given to the designer - ultimately resulting in better performing buildings.

The following two pages recap the differences between the generic/control building; and the final optimised building; in terms of their variable and performance differences. Indeed, when comparing the two configurations (and consequent performances); several trends seem to appear :

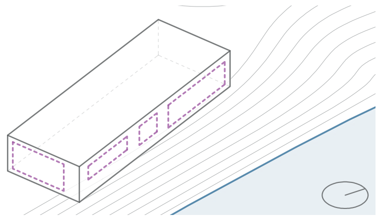
Firstly, it is evident that the optimised building outperforms the generic building in all of the previously set objectives : namely the minimisation of thermal demand; and the maximisation of useful daylight illuminance UDI. More specifically, the yearly total thermal demand difference is 14,5 [kWh/m²]; within which heat demand differing by 4,9 [kWh/m2]; and cooling demand differing by 9,6 [kWh/m²]. This trend is observable throughout all months of the year - overall representing a significant 23% decrease with respect to the generic project. At the scale of a single project, this can already incur huge differences in terms of decarbonisation. As

FINAL DEMAND - PEAK LOADS



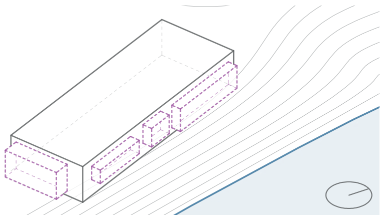
PEAK HEATING LOAD	**[W]**	**2374**
PEAK COOLING LOAD	**[W]**	**3170**

WWR



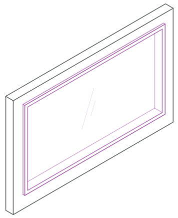
North	[%]	15
East	[%]	60
South	[%]	20
West	[%]	40

SHADER DEPTH



North	[cm]	55
East	[cm]	100
South	[cm]	85
West	[cm]	100

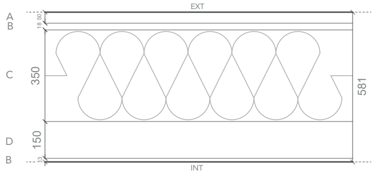
GLAZING



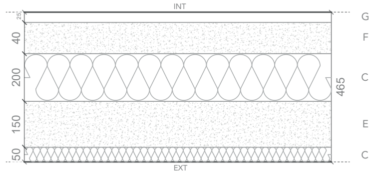
Transmittance U	[W/m²K]	0,85
SGHC	[%]	50
Visible Transmittance	[%]	70

OPAQUE CONSTRUCTION

WALL/ROOF - TIMBER



FLOOR - CONCRETE



A = Outdoor Timber Battens ; B = Plasterboard ; C = Insulation ; D = Timber Stud ; E = Cast Concrete ; F = Concrete Screed ; G = Concrete Floor Finishing

Transmittance U	[W/m²K]	0,074
Superficial Mass	[Kg/m²]	141,900
Decrement Factor	[-]	0,035
Time Lag	[h]	22,807

Transmittance U	[W/m²K]	0,115
Superficial Mass	[Kg/m²]	408,000
Decrement Factor	[-]	0,015
Time Lag	[h]	15,513

PROJECT ENVELOPE - ADOPTED VALUES									RESULTS					
Parameters	WWR (per façade)	[%]	Shader Param. (per façade)	[cm]	Glazing Param.	[W/m2K] [%]	Insulation Thickness	[cm]	UDI	[%]	Heating	Cooling	H+C Total	[kWh/m2]
Adopted Values	N 15 E 60 S 20	W 40	N 55 E 100 S 85	W 100	0,85	50	Wall/Roof 35 Floor 25		78,1		17,2	32,5	49,7	

ADOPTED VALUES - GENERIC PROJECT

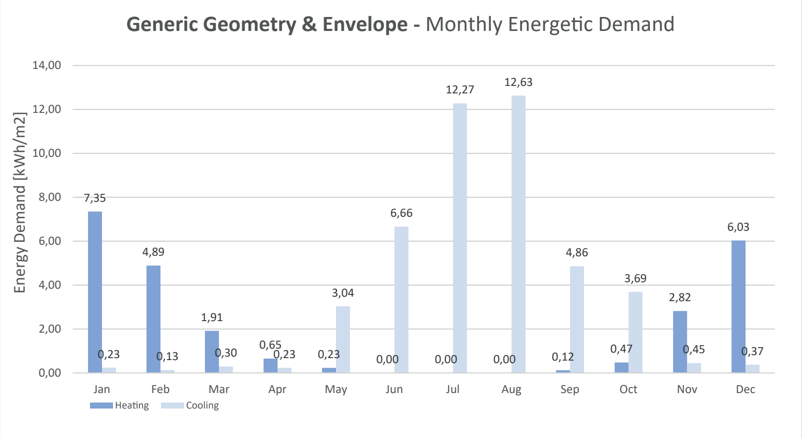
a direct consequence, the peak loads of both configurations also differ greatly (although both being relatively low with respect to the existing market) : a 200 [W] and 730 [W] difference for peak heating and cooling loads respectively. This means that the optimised project would need a significantly smaller heat pump (in terms of power output), inducing a chain of beneficial reactions - which we will study in the next part.

As far as UDI goes, the difference is of 6%, at the benefit of the optimised project. Calculated in terms of hours during a year, this represents over 306 more hours of avoided light correction. Put in the perspective of a whole neighborhood, city or country, and the avoided electrical and associated carbon consumptions are very significantly reduced.

That said, it must be noted that the initial economic investment (with respect to each building's configurations) underlines an advantage for the generic project. There would indeed be less uniquely sized elements (windows and shaders for example); and significant decreases in glazing price and insulation needs - ultimately driving the economics down. If we however factor in the subsequent energy-related expenses; the differential need for heat pump power and consequent photovoltaic panel size needs; then the optimised project remains the clear top economic performer.

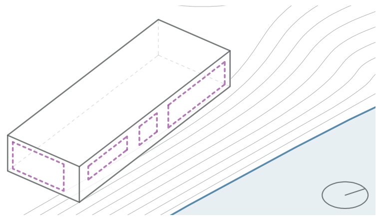
To conclude, regardless of its limitations, such research confirms vast benefits associated to the following of the proposed algorithmic preliminary design process - both in terms of thermal demand and UDI.

FINAL DEMAND - PEAK LOADS



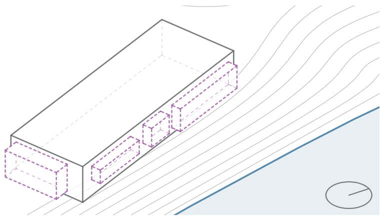
PEAK HEATING LOAD	**[W]**	**2570**
PEAK COOLING LOAD	**[W]**	**3908**

WWR



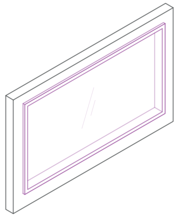
North	[%]	30
East	[%]	30
South	[%]	30
West	[%]	30

SHADER DEPTH



North	[cm]	30
East	[cm]	30
South	[cm]	30
West	[cm]	30

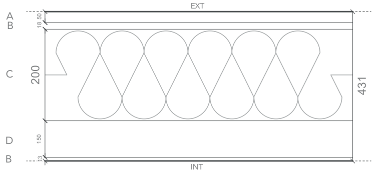
GLAZING



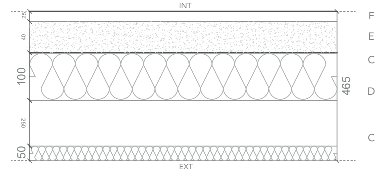
Transmittance U	[W/m²K]	1,1
SGHC	[%]	60
Visible Transmittance	[%]	70

OPAQUE CONSTRUCTION

WALL/ROOF - TIMBER



FLOOR - TIMBER



A = Outdoor Timber Battens ; B = Plasterboard ; C = Insulation ; D = Timber Stud Structure ; E = Concrete Screed ; F = Timber Flooring/Parquet

Transmittance U	[W/m²K]	0,118
Superficial Mass	[Kg/m²]	139,500
Decrement Factor	[-]	0,085
Time Lag	[h]	17,623

Transmittance U	[W/m²K]	0,136
Superficial Mass	[Kg/m²]	191,500
Decrement Factor	[-]	0,008
Time Lag	[h]	22,371

PROJECT ENVELOPE - ORIGINAL/GENERIC VALUES									RESULTS					
Parameters	WWR (per façade)	[%]	Shader Param. (per façade)	[cm]	Glazing Param.	[W/m2K] [%]	Insulation Thickness	[cm]	UDI	[%]	Heating	Cooling	H+C Total	[kWh/m2]
Adopted Values	30		30		1,1	60	Wall/Roof 20	Floor 15	72,8		22,1	42,1	64,2	

CHAPTER 5

ENERGY CONSUMPTION OPTIMISATION

RESEARCH PROTOCOL 3 - THERMAL ENERGY STORAGE

INTRODUCTION

As resources become scarcer and scarcer as times moves forward - both tangible building materials, and intangible energetic ones - the need to optimise and reduce the various layers of consumption as much as possible has become a growing concern and a necessary priority in all industrial stratas of the world.

Today, it is estimated that over 40% of all green house gas emissions derive from the building and construction industry - and as the erection of buildings and urbanisation keeps increasing, it seems at first glance as though this trend will only rise.

Although much emission comes from the preliminary process of construction - the impact of production and distribution of raw and processed materials, to the carbon and electrical footprint of the machines used to plan and erect constructions; it is generally agreed upon that 30% of those 40% are rather operational emissions - ones that happen once the building is set and working. It is indeed the method with which we light, cool and heat our homes - as well as the way we source, store and use the energy to power such systems - that are in great need of innovation and development.

According to the Revised Energy Performance of Building's Directive (2018/844EU) [2], the path to decarbonisation is one of 1) general electrification and use of renewable energy sources RES, and 2) widespread energetic efficiency in all stratas of construction/operation involved. While the preliminary portion of this research was aimed at the optimisation of energetic efficiency, namely through the reduction of heating and cooling needs through a proper, computationally aided, form finding process of designing building geometry and building envelope; the present research protocol is aimed at the optimisation of renewable energy use, namely through the optimisation of renewable resource self consumption.

While electrical energy sourced by efficient solar photovoltaic panels seems to be an increasingly popular system to source and use electrical energy for a household's various needs, it is also most often poorly dimensioned, as well as extremely agressive in terms of carbon footprint : the cells, inverters and implementation all require vast amounts of carbon based energy. More so, they most often lack storage systems and thus either still rely greatly on grid energy to power their homes, or are simply radically oversized. Finally, it is important to note that although complete electrical autonomy for all is attractive, it isn't necessarily the best option. This is because centralised system are often more efficient and less energy/carbon hungry than localised, small scale systems.

Where energetic efficiency and sustanability in the scheme of HVAC needs is greatly enhanced by the widespread utilisation of high COP/EER vapour compression heat pumps powered by properly dimensioned photovoltaic panels, the intermittent nature of the sourcing of photovoltaic energy poses a threat to a building's general autonomy. Indeed, in most places of the world (except those who have climates not even allowing for solar photovoltaic sourcing), solar potential is volatile between seasons, and during the 24hours of a single day as well. However, that is not to say that solar potential is unreliable, rather that it is reliable but not all the time.

As broached earlier, a potential solution to this would be the widespread use of energy storages through load matching technologies - where excess energy is stored for later restitution. While energy storages do exist, the most popular ones are electrochemical based, and thus improper in the scheme of carbon footprint reduction and general sustainability. Other solutions do exist -especially to cover a building's HVAC needs - is high efficiency heat pumps connected to thermal energy storages TES to store excess photovoltaic energy in the form of heated/cooled materials (as outlined by [3]). While phase change materials are plentiful, water remains one efficient and very sustainable way of storing energy. As outlined by [1], it is non-toxic, affordable and allows for a very high amount of charge/discharge cycles without losing performance.

AMBITION & METHODOLOGY

In the continuation of such analysis, the present research protocol aims at the proper dimensioning of a water-based thermal energy storage in the framework of its coupling with a vapor-compression heat pump driven by a PV array. This methodology replicates - bar the consideration of domestic hot water - the one discussed in [1].

The previously defined heating and cooling demand for both the optimised building, and generic/control building will be used as the basis for the dimensioning of both the PV array; and the subsequent thermal energy storage.

Following the methodology presented in [1], energy performance and economic potential

PRELIMINARY DATA

will be used as the basis for the proper sizing of a water based thermal energy storage. Such system will be sized to maximise the renewable energy self-consumption; and minimise the potential for grid energy use.

The first operation is to size the heat pump on the basis of the previously found yearly thermal loads (heating and cooling only) for both considered buildings - properly considering peak load. A recap of thermal loads for each building can be found in the figure hereafter.

It is important to note that contrary to the methodology presented in [1] (which set the basis of the protocol used thereafter), we shall not consider domestic hot water demand when sizing both the heat pump, and consequent PV array and thermal energy storage. Only heating and cooling loads will be considered. The reason is that this DHW demand is the same for both the optimised and the generic/control building. Because this protocol is aimed at the comparison of thermal energy storage performance and RES self consumption potential due to varying processes of geometry/envelope design; all of what is constant in terms of thermal loads is relatively useless and can be considered negligeable.

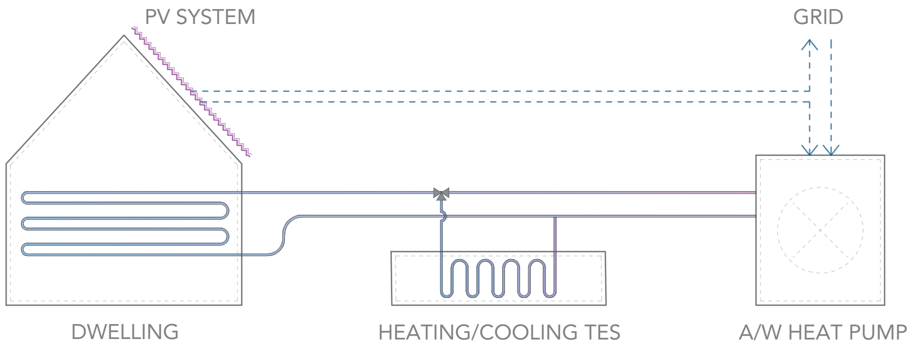
The hourly performance of such HP systems will be computed (based on hourly COP/EER values), thus allowing for the extraction of the yearly heat pump consumption. Once the yearly electrical consumption of such HP system is defined, the second operation is to size a photovolaic panel array (following a climatically accurate productivity profile) covering the total yearly HP electrical consumption.

The third operation will consist in the evaluation of several TES tank sizes and their respective performance along energetic and economic parameters. Various performance indicators will be presented and discussed allowing for the choice of an optimal TES size.

OBJECTIVES

In the framework of the overall research on the role and influence of proper preliminary design on renewable resource self consumption potential and consequent energetic autonomy; the goal of this research protocol is analyse and optimise of a water-based thermal energy storage unit working alongside a vapour-compression heat pump coupled to properly sized photovoltaic panels considering energetic; and prospective economic value potential. The proposed TES systems will be optimised to maximise renewable energy self-consumption; and minimise potential for grid energy use (comprised of non-renewable energy).

SYSTEM SCHEME & ORGANISATION



CLIMATIC CONTEXT RECAP

Heating Degree Days	[-]	2620
Cooling Degree Days	[-]	71
Maximum Temperature	[°C]	38,3
Minimum Temperature	[°C]	-3,5

MAIN FEATURES RECAP

Number of People	[-]	2
Floor Area	$[m^2]$	121,4
Volume	$[m^3]$	388,6
S/V	[-]	0,3125

ENERGY DEMAND RECAP

		GENERIC		OPTIMISED	
		HEATING	COOLING	HEATING	COOLING
Total	[kWh]	3228	7864	3701	6016
Per Surface	$[kWh/m^2]$	26,6	64,8	30,5	49,5
Per Volume	$[kWh/m^3]$	8,31	20,24	9,52	15,48

SYSTEM & COMPONENTS DESCRIPTION

GENERAL SCHEME & FUNCTIONING

As described in [1], and as shown in the diagram on the previous page, the proposed system is composed of 3 different components. The first is a high efficiency air-water heat pump which meets the respective thermal loads (heating and cooling load). The considered machine has continuous power modulation itselft driven by component 2, the photovoltaic system. In the case of surplus photovoltaic energy, the energy is stored in the form of thermal energy - heated or cooled water depending on the season and needs - using a water-based thermal energy storage TES able to restitute energy at night, or when needed. More specifically, and as detailed in [1]:

- A reversible vapour-compression air source heat-pump for heating and cooling.
- A solar photovoltaic system dimensioned to meet the heat pump's annual electrical demand, without considering TES influence.
- A water based thermal energy storage for heated or chilled water, depending on the season and or relevant needs.
- A central control and management system, able to optimise the plant's whole operation - controlling the various interactions between the photovoltaic; heat pump; thermal energy storage; and grid.

HEAT PUMP - CHARACTERISTICS

As described in [1], the heat pump considered in such research is of «inverter type», meaning it can regulate its compressor rotational speed and effectively follow instantaneous photovoltaic production. The machine's function is to provide both heat and cold, through a commonly used floor heating system. The performance and efficiency of the heat pump in operative conditions is simulated using hourly COP/EER values, described thereafter, allowing for a precise and accurate documentation of the system's performance - used subsequently by the control system to adapt interactions between various subsystems. The average COP/EER values is between 5,14 for floor heating/cooling; and 4,42 for connection to the thermal energy storage. Both values range between a minimum of approximately 3,0 and a maximum of approximately 8. This means that in the worst case scenario, the heat pump produces 3 times more energy than it needs to run - underlining once again the spectacular advances that recent innovation have allowed in heating and cooling systems.

COP/EER FORMULA

As described in [1], the COP/EER formula is simulated using a typical curve that well defines the heat pump's performance:

$$COP = 0{,}001 * \Delta T^2 - 0{,}17 * \Delta T + 9$$

COP = Coefficient of Performance and ΔT is the difference between evaporation or condensation temperature; representing the difference between hot and cold sources. It can either be outside temperature for COP_{User}; or the thermal energy storage temperature for $COP_{Storage}$.

The Energy Efficiency Ratio EER is derived from the COP as follows :

$$EER = COP - 1$$

Both efficiency/performance ratios are calculated hourly, so as to decrease the margin of error to a maximum.

COP/EER VALUES

		TO USER	TO STORAGE
Average/Mean	[-]	5,14	4,42
Maximum	[-]	8,0	8,19
Minimum	[-]	3,0	2,57

ELECTRICITY CONSUMPTION - NO TES

		GENERIC	OPTIMISED
Total	[kWh]	2321	2059
Per Surface	[kWh/m²]	19,11	16,95
Per Volume	[kWh/m³]	5,97	5,30

CONSUMPTION & PV COMPONENT DESCRIPTION

ENERGY CONSUMPTION PERFORMANCE

While knowing the previously computed energy demand (ranging around 91 and 80 [kWh/m²] for the generic and optimised project respectively) may be useful, it does not properly represent and approximate the final energetic efficiency of both households. However, considering the heat pump performance does allow us to approximate what the total electrical consumption might be - and thus a more potent idea of what final primary energy demand and consequent energetic efficiency might be. More so, the fact that the heat pump's performance is computed on an hourly basis allows a significant reduction of the margin of error to a minimum. Indeed, the COP/EER values given by the constructors are most often median/mean averages, and do not depict precisely the machine's performance over a single year. Once the performance ratios are known, it is possible to derive the heat pump's yearly electrical demand from the following formulas :

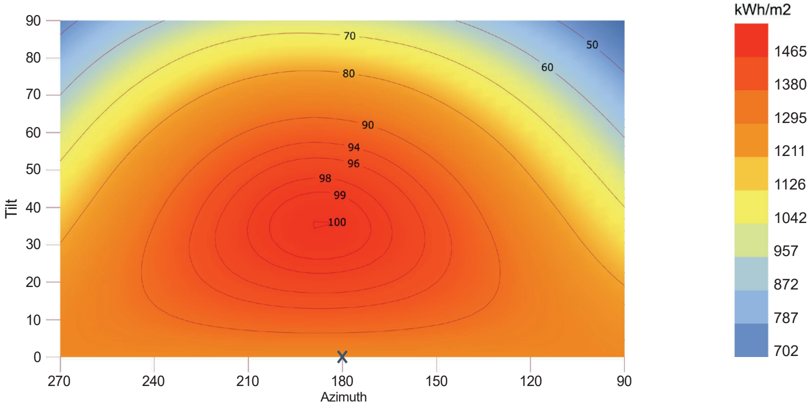
$$E_{total} = E_{heating} + E_{cooling} \quad \text{where} \quad E_{heating} = Q_{heating} / COP \;\; ; \;\; E_{cooling} = Q_{cooling} / EER$$

Falling at 19,11 and 16,95 [kWh/m²] for the generic and optimised project respectively, there is already a significant 2,16 [kWh/m²] difference between both project's annual energetic consumption profiles. The average energetic consumption for low energy houses being at 65 [kWh/m²], while the average for passive houses being at 13,4 [kWh/m²], we may say that both buildings have extremely good performance when compared to what exists on the market (especially considering the 112 [kWh/m²] average in Germany in 2013 [4]) - both falling in the passive range as under 30 [kWh/m²]. (That said, passive range consider DHW as well as total electrical demand - but nethertheless).

PV SYSTEM - CHARACTERISTICS

Following the protocol given by [1], the PV system was designed so as to cover the heat pump's total yearly electrical demand. Following an annual productivity profile for a 1kW$_p$ panel of 1193 [kWh] (derived from the climate specific hourly global solar radiation multiplied by a performance factor of 0,75), both PV array dimensions were able to be determined and are described in the following table. Optimal system configurations were considered for both. Already, there is a very significant 0,2 kW$_p$ difference - 9% - between both projects; with the optimised project being lowest. While at the scale of the single building this may seem insignificant, drawn to a whole neighborhood or country - this already makes a huge difference in terms of energetic efficiency and unecessary carbonisation.

TILT ORIENTATION FACTOR



OPTIMAL CONFIGURATION

PV Panel Tilt	[°]	36	Azimuth Angle	[°]	180

GLOBAL SOLAR RADIATION DETAIL

Annual	[kWh/m²]	1465
Hourly Average	[Wh/m²]	181,6
1 kW$_p$ Panel Production Profile	[kWh]	1193

PHOTOVOLTAIC SYSTEMS DESCRIPTION

		GENERIC	**OPTIMISED**
Brand & Model	[-]	SunPower XPR-MAX 3	
Technology	[-]	Monocrystalline Silicon	
Panel Peak Power	[W$_p$]	390	350
Panel Number	[-]	5	5
Photovoltaic Size	[kW$_p$]	1,95	1,75
Electricity Production	[kWh$_y$]	2326	2088

TES COMPONENT & SYSTEM CONTROL

WATER TES - CHARACTERISTICS

Following once again the protocol as given by [1], the considered thermal energy storage is a water based cylindrical tank, and positioned on the (relatively un-exposed) north facade. It is charged (either heated or cooled) by the heat pump when excess power from the photovoltaic panels is present, and is discharged when needed to provide either cooling or heating when there is no available photovoltaic energy. It uses fresh water - a widely available, non-toxic phase changing material - as inertial mass whose specific heat capacity is described in the following table. The tank's wall transmittance and thickness are set, with its dimensions being derived from the tank's max acceptable volume.

CONTROL MODEL & LOGIC

The control model - developed by the Politecnico di Milano team author of [1] - was modified so as not to account for DHW demand and consequent DHW TES tank dimensioning (the reasons why are detailed in the methodology above). Implemented in Excel, the model considers both hourly weather data and heating/cooling consumptions - as well as previously set photovoltaic panel and water TES characteristics. Two operative modes are considered, and detailed in the following table. Hourly electrical consumption (based on the formula described in the previous page) and PV production are compared. These 2 values represent the basis for the logic which is described as follows:

As a priority, heating and cooling demand is met by the heat pump when there is available photovoltaic energy. In case PV energy is either insufficient, or completely null (during specific seasons, at night; or punctually during very cloudy days), energetic demand is met by the thermal energy storage. In a last resort, if either stored or photovoltaic energy isn't enough, the heat pump is powered by grid electricity - of course at a price. In the case however that both the energy demand is met; as well as the thermal storage temperature being 100% charged (= at its seasonal set point temperature limit); then excess photovoltaic energy is sold to the grid.

The system, whose annual hourly performance is simulated through excel, is based on a series of reference temperatures consisting of set-points and limits - as described in the following table. Also, the excel model being filled with multiple data loops, some initial values need to be set. For example, it is considered that on the 1st of January at 01 AM; the initial thermal energy storage tank temperature is 30°C; and the initial COP/EER values for both storage and user are 3,0.

MODEL OPERATIVE MODES [1]

Heating: The heat pump evaporates on the air heat exchanger side and condenses on the user side, heating the TES or radiant floor water circuit till set point temperature.

Cooling: The heat pump condenses on the air heat exchanger side and evaportates on the user side, cooling the TES or radiant floor water circuit till set point temperature.

Contrary to the model and process followed by [1], DHW is not considered. Had we considered DHW, we could have also benefited from «heat recovery» given the conditions where DHW and cooling are simultaneously requested. Functioning as follows, the heat pump condenses on the DHW storage side and evaporates on the user side, cooling the water circuit or TES till set point temperature. Although small, the gains would have been non-negligeable.

H/C TES BASE CHARACTERISTICS

Specific Heat Capacity - Water	[kJ/kgK]	4,186
Transmittance U	[W/m²K]	0,30
Tank Wall Thickness	[mm]	10,0

TEMPERATURE SET-POINTS & LIMITS

Heating Supply Temp. (Radiant Floor)	[°C]	30
Cooling Supply Temp. (Radiant Floor)	[°C]	15
Maximum TES Temp. (Heating)	[°C]	50
Minimum TES Temp. (Heating)	[°C]	Supply T°
Maximum TES Temp. (Cooling)	[°C]	Supply T°
Minimum TES Temp. (Cooling)	[°C]	5

ENERGETIC PERFORMANCE

ENERGY - PRELIMINARY

In the framework of the broader research on the influence of preliminary design on renewable energy self-consumption potential; the ambition of this energetic analysis was to determine the impact of varying sizes of thermal energy storages on the eventual (instantaneous/hourly) mismatch between electrical based thermal demand and photovoltaic production. This is why the following data is relative to photovoltaic energy production in terms of its *proportion;* that was 1) stored; 2) consumed; 3) stored + consumed; and 4) sold to the grid. In the framework of this research, one obvious goal was to maximise consumed + stored energy - thus maximising renewable resource self consumption; while energy sold to the grid - in essence lost PV potential - is ideally minimised.

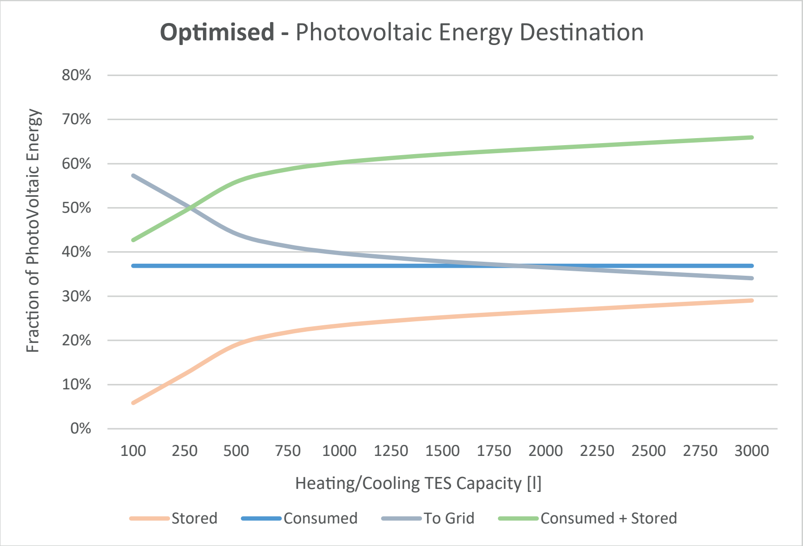
ENERGY - PERFORMANCE & COMPARISON

13 different TES tank capacities were analysed for both projects - ranging from 100l to 3000l. Among the common results between the various destinations of photovoltaic energy for both projects PV systems configurations, two trends seem to appear.

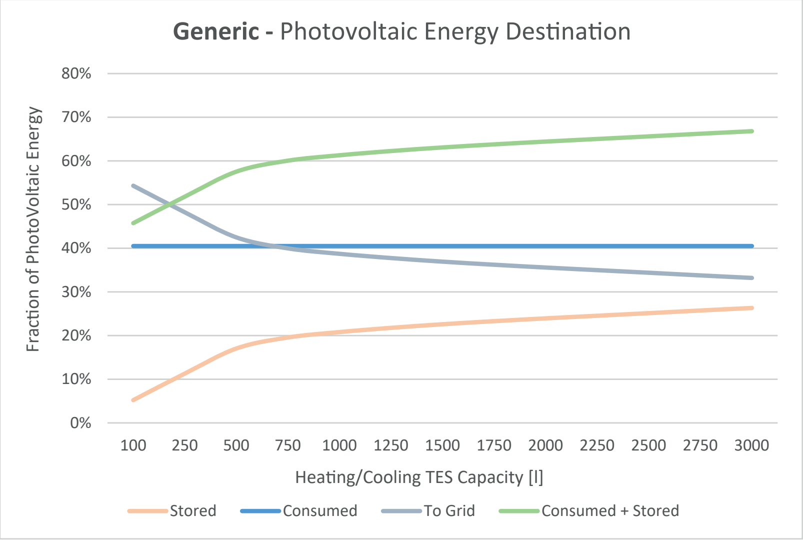
Firstly, it appears stored energy seem to increase linearly from the smallest tank size, to around 500l. Because both PV systems were sized considering a whole year's electrical demand, they were in essence oversized with respect to instant/hourly electrical needs. Consequently, consumption profiles are never 100% (gravitating here around 40% on average for both projects; 60% being essentially useless and sold to the grid). This is why introducing any kind of storage system to collect the necessarily existing PV excess is instantly beneficial and rises until a certain level - here 500l for both; with a steeper rise for the optimised project.

Secondly, it seems that once this «instantly beneficial storage capacity threshold» is passed, storage size still induces an increase in stored energy - and thus an increase in renewable resource self consumption; and decrease in sold energy. Contrary to the first trend however, this one shows a smaller growth with respect to increasing tank size - especially after 750l; as well as seems to tend following a curve towards 66-68% maximum of consumed + stored energy. Trying to increase the storage size to (absurdly) high levels - even beyond 3000l - will still provoke an increase in stored energy - but will tend towards 0 - or negligeable levels - very quickly. This means that whataver may be the size of the TES we select; around 30% of photovoltaic energy will still be lost and sold to the grid.

OPTIMISED PROJECT RESULTS



GENERIC PROJECT RESULTS



ECONOMIC PERFORMANCE

Among the results that differ between the various destinations of photovoltaic energy for both projects PV configurations, one trend seems to appear:

As stated earlier, the yearly electrical consumption profiles differed by 9% with the optimised project having the lowest at 16,95 [kWh/m²]; against 19,11 [kWh/m²] for the generic/control. If we now look at the instantly consumed proportions of PV energy, we notice that the optimised project is constant at 36,9%; while the generic is constant at 40,5%. Because the demand is lower, the instant consumption is necessarily so too. This is apparent, even though there was also an approximately 9% difference in peak power needs (1,75 vs 1,95 [kW$_p$]) which has necessarily counter-effected the difference in instant PV consumption profiles proportions. Even considering this counter effect, the difference is still 5%. (Had both systems been at 1,75 [kW$_p$], the difference would have been >7% with the generic project's proportion of instantly consumed energy being raised to 42,6%). This difference is however beneficial to the amount of energy that the optimised project can store - the opposite for the generic project. Indeed, it appears the optimised projects stores constantly 4% more energy than the generic project.

ECONOMICS - PRELIMINARY

While optimising according to proportional distribution of photovoltaic energy is necessary; it only tends to orient us towards the larger TES tank sizes. This is why - following once again the protocol in [1] - an economic analysis was performed. Although the investment cost is necessarily higher with a TES, it reduces the exchange of electricity with the grid - thus of yearly operational expenses. A Net Present Value formula was calculated in order to understand the influence of such tank sizes on potential profitability; and is based on differential cost between necessary expenses of both projects 1) with; and 2) without thermal energy storages. Details in the following table.

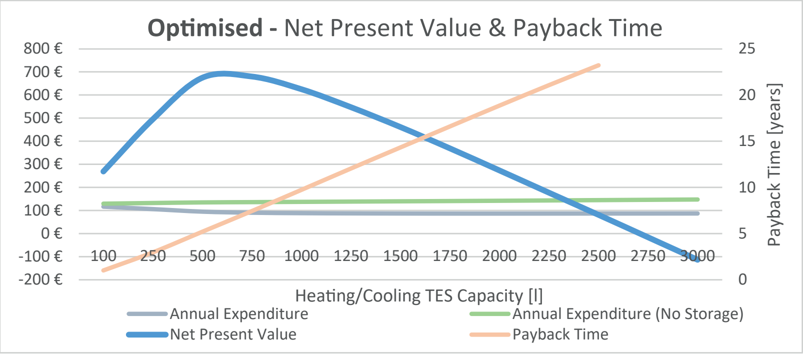
ECONOMICS - PERFORMANCE & COMPARISON

As shown by the following graphs, 2 trends seem to appear. Firstly, the highest possible NPV is for both projects around 690€ considering 600l and 650l for the optimised and generic project respectively. A peak is noticed between 400l and 900l for the optimised project; between 500l and 800l for the generic. NPV seems to decrease more rapidly for the optimised project - and consequently the payback time is generally lower by about 1 year for the generic project. However, annual expenditures are systematically lower (15%) for the optimised project - stabilising around 90€ (versus 104€).

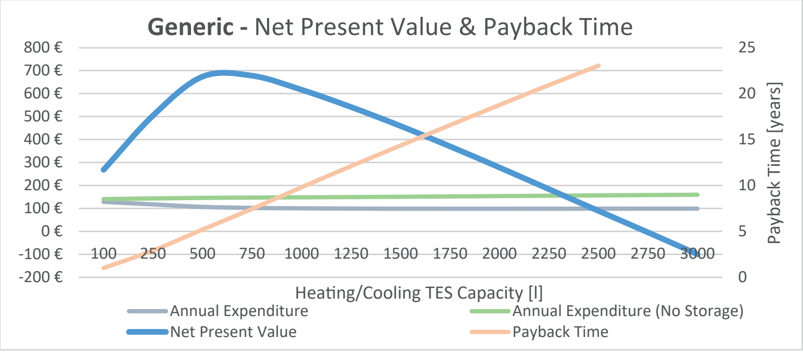
ECONOMIC PARAMETERS [1]

Grid Electricity Price	[€/kWh]	0,20
Remuneration for PV Electricity	[€/kWh]	0,10
H/C Storage Cost	[€]	300 + V/2
Lifetime	[y]	25
Discount Rate	[%]	2
Annual Increase of Electricity Price	[%]	1

OPTIMISED PROJECT RESULTS



GENERIC PROJECT RESULTS



OPTIMAL CONFIGURATION

OPTIMAL TES - PERFORMANCE & COMPARISON

Following on the analysis of both project's energetic and economic potentials; considering on the one hand renewable energy proportional distribution (aimed to maximise renewable energy self-consumption); and on the other the search for the highest possible prospective economic value through the computation of a Net Present Value; two optimal tank sizes were selected. While increasing tank size manifested a continual growth (although tending towards 0) as far as storable energy potential went - and thus of self-consumption; increasing tank sizes incurred on the other hand an important decrease in Net Present Values. These two opposing trends in effect allowed to select the optimal tank sizes for both - and are described below.

OPTIMAL TES SIZE - GENERIC	**[l]**	**600**
OPTIMAL TES SIZE - OPTIMISED	**[l]**	**800**

As previously stated, the optimal sizes when considering net present value ranged between 500l and 800l for both projects totaling NPV values in the 640-690€ range (noticing a slightly higher tank capacity at equal NPV for the generic project). However, the 9% higher electrical demand profile for the generic project incurred a heavier dependency on instantly consumed PV electricity; and consequently necessarily reduced the fraction of potentially storable energy. When compared to the optimised project; the latter had a 5-7% lower lower instant consumption profile - which allowed for a larger amount of storable energy - and ultimately larger proportion of consumed + stored PV energy - itself directly linked to a more attractive level of self-consumption. This is one of the reasons why a significantly larger tank was chosen for the optimised project; as a larger tank would benefit from a higher level of storable energy potential.

That said, a higher tank size for the optimised project induced a non-negligeable decrease in both NPV and payback time - 19€ and 1,8 years respectively. This is however not due to the annual expenditures which are here 15% lower for the optimised project; but rather due to the higher initial investment cost. That said, NPV is in this case siginficantly biased and criticisable due to the fact that it is based on differential costs which are relative to each project - 43€ and 46€ for the generic and optimised project respectively. A lower differential cost value for the generic project being explained by a larger proportional instantaneous consumption profile to start with - inducing a significant decrease

ENERGY INDICATORS

		GENERIC	OPTIMISED
PV Electricity Consumed	[%]	40,5	36,9
PV Electricity Stored	[%]	18,4	22,2
PV Consumed + Stored	[%]	58,8	59,1
PV Electricity to the Grid	[%]	41,2	40,9
Avoided Cons. due to PV Stored	[%]	18,0	22,0
NO TES - Demand Covered by PV	[%]	39,8	36,5
NO TES - Demand Covered by Grid	[%]	60,2	63,5

ENERGY DEMAND RESPONSE

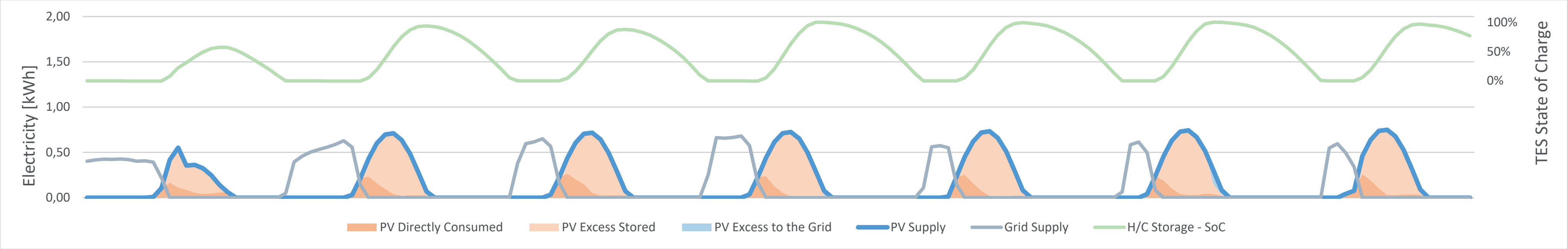
NO TES - Total Electricity Demand	[kWh]	2321	2059
Total Electricity Consumption	[kWh]	2367	2110
Demand Covered by PV Self Cons.	[kWh]	942	770
Demand Covered by Grid	[kWh]	999	876
PV Excess Stored	[kWh]	427	463
PV Excess to the Grid	[kWh]	957	854

ECONOMIC INDICATORS

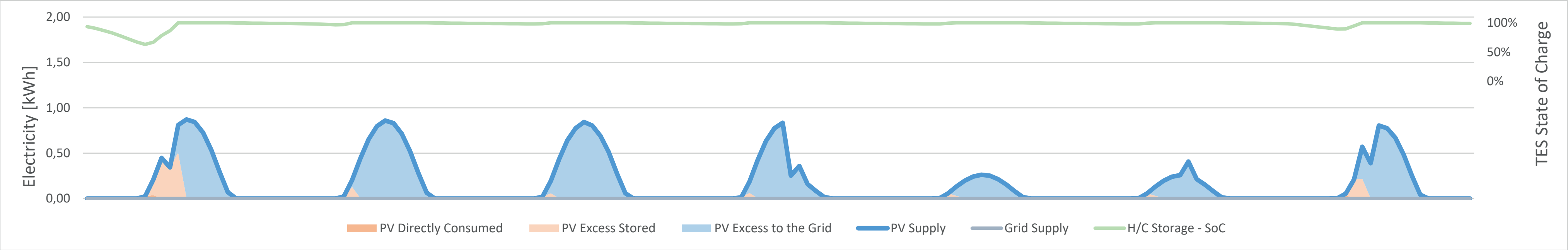
Investment Cost	[€]	500	600
Annual Elec. Expenditure	[€]	104	90
Annual Elec. Expenditure - NO TES	[€]	147	136
Net Present Value	[€]	691	672
Payback Time	[years]	6,1	7,9

GENERIC - SEASONAL TES/DEMAND PERFORMANCE

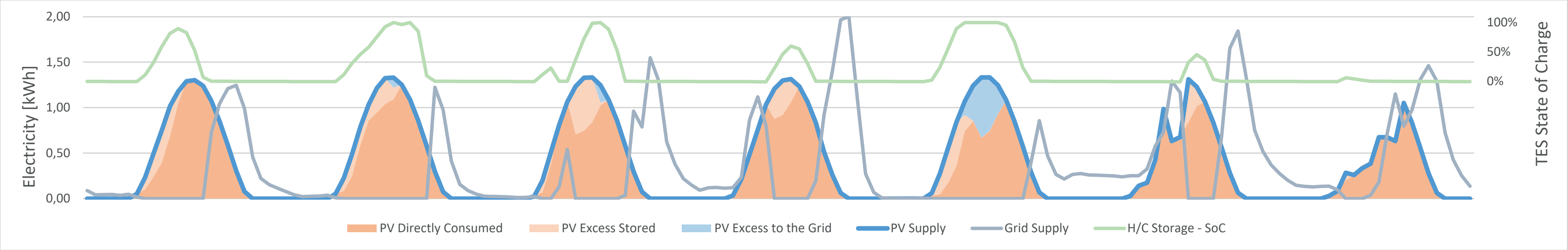
REFERENCE HEATING WEEK - 04/02 to 10/02



REFERENCE MID SEASON WEEK - 17/10 to 23/10

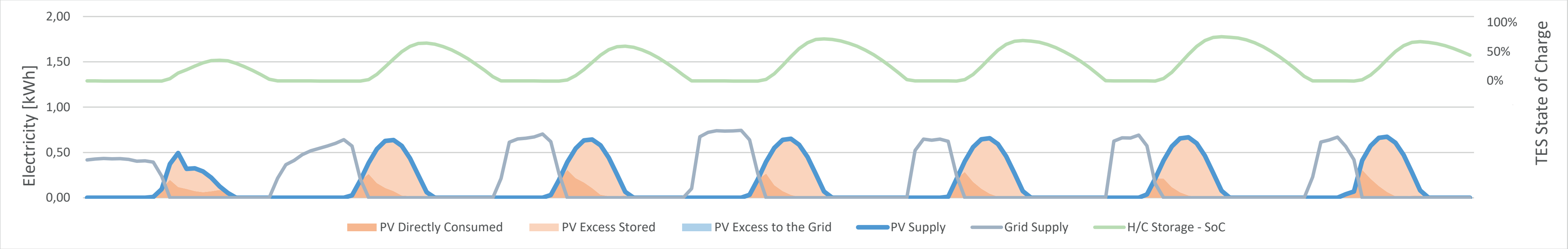


REFERENCE COOLING WEEK - 28/07 to 03/08

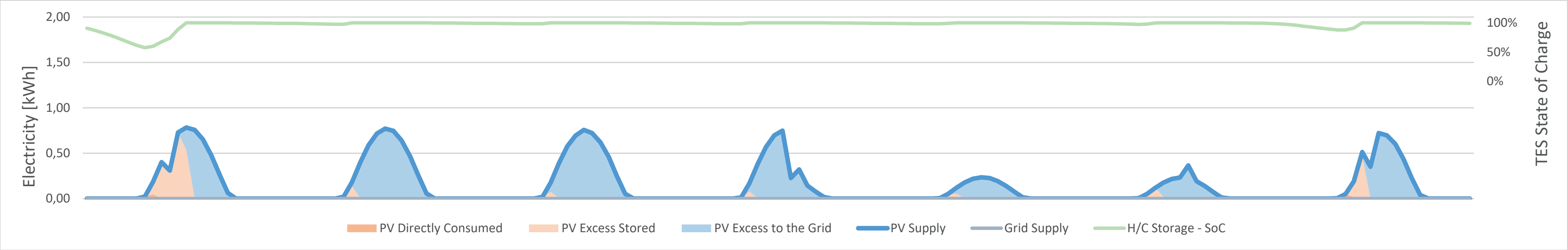


OPTIMISED - SEASONAL TES/DEMAND PERFORMANCE

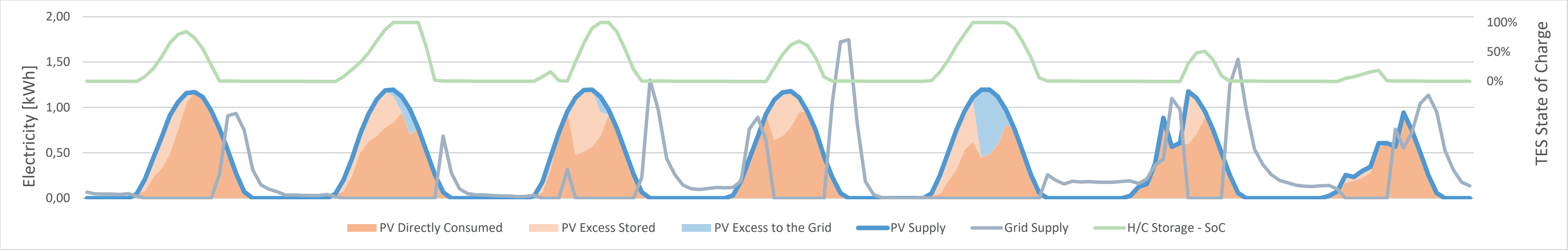
REFERENCE HEATING WEEK - 04/02 to 10/02



REFERENCE MID SEASON WEEK - 17/10 to 23/10



REFERENCE COOLING WEEK - 28/07 to 03/08



PERFORMANCE COMPARISON

in proportional energy sold to the grid. Moreover, having a substantially larger photovoltaic peak power configuration, the generic project necessarily yields more electricity every year - thus selling a larger amount of [kWh] to the grid; and making more money in the process - ultimately biasing the NPV comparison.

In any case, the higher proportion of renewable energy self-consumption potential; the 9% lower need of peak power (and thus of photovoltaic carbon-hungry cells); the 4% higher potential for storable energy; the 4% higher avoided consumption due to PV stored; are all worth 19€ - especially when put in the perspective of world sustainability and decarbonisation.

Indeed, if we look at the more specific - not proportional - energetic demand response as described in the table in the previous pages; total electric consumption is lower for the optimised project by >250 [kWh]; has a lower demand (but higher proportionally) covered by photovoltaic self consumption; has a 120 [kWh] lower grid coverage necessity; a 40 [kWh] larger amount of stored energy; and finally a significant >100 [kWh] lower amount of photovoltaic energy excess given to the grid.

Regardless however of the optimised project's higher TES performance; both projects appear to significantly benefit from a TES when compared to the same projects without storage capacities. Indeed, both project's instantly consumed photovoltaic energy are 2-3% higher than the proportion of demand covered by PV without TES. The very significant difference in performance is however more notably felt when comparing the necessary grid coverage interventions for both projects with; and without TES. Indeed, without storage systems, grid supply to cover demand represents an extremely high 62%; where for the projects with a water-based TES it is reduced to an average and more respectable 41% - resulting in an avoided consumption due to stored PV energy of 18% to 22% for the generic and optimised project respectively.

LOCALISED BEHAVIOUR - PRELIMINARY

While looking at the annual performance and relative proportional distribution of photovoltaic energy is intersting, it is also necessary to verify localised behaviours and performances. Following indeed the protocol as given by [1], three reference weeks were selected to properly represent a typical heating; mid-season; and cooling week's performance profiles.

On one hand, the various energetic fluxes are reported so as to underline self-consumptive potential : comparing photovoltaic production on one end, with its proportional energetic distribution to instantaneous consumption; stored energy for later restitution; and proportion sold to the grid. Parallel to this, grid supply is also plotted to underline both project's instantaneous grid dependency. On the other hand, the State of Charge SoC is plotted so as to give an idea of the charging level of the thermal energy storage - 100% meaning it has reached its (seasonally relative) temperature limit - while 0% means it is empty.

Among the significant phenomenas that are common to both project's PV and TES configurations - whatever the season may be - two trends seem to appear. The first obvious one is that the higher PV system peak power for the generic project necessarily induces a higher production of electrical energy. However, the production difference is mostly noticeable during mid-day, when PV production potential is maximum. Indeed, during the mornings and afternoons, it appears the difference in photovoltaic energy production is negligeable. Secondly, a noticeable (yet predictable) phenomena - especially in the summer period - is that the thermal energy storage takes longer to charge for the optimised project. This is however unsurprising for two reasons: the first being the previously discussed lower amount of PV energy produced due to lower peak power and thus of potential energy (although we will challenge this claim later); the second being the size of the tank which is 33% bigger than the generic's.

HEATING SEASON REFERENCE WEEK

Although photovoltaic production is almost twice reduced as during the summer and mid-season months, it appears that during the day (except for the first hour), PV production is instantly and totally self-consumed. This tends to show the potential that such storage systems may hold. Indeed, it seems for both projects as though electrical demand to heat and cool is met during the whole day; with a large chunk of PV energy

PERFORMANCE COMPARISON

being stored in the tank. On average, it seems as though almost 75% of the energy produced by the PV system is stored - and directly restituted during the night until around 4-5AM; point at which grid supply is necessary to cover thermal load demand. Had there been no storage capabilities, grid supply would have been essentially instantaneoulsy necessary at the exact moment at which the sun would have set. This trend is especially noticeable in the summer period - although still existant throughout the rest of the year. The state of charge clearly shows how the thermal energy storage slowly restitutes its thermal inertia during the night - up until the point where it is empty.

When comparing the two project's configurations, several trends appear. Firstly, and as discussed before, the tank in the optimised project takes longer to charge, and is also discharged earlier than for the generic's project - resulting in a dependency on grid energy earlier in the night. Moreover grid energy dependency is at a higher intensity than for the generic project. Both trends are explained by the fact that heating demand is actually higher for the optimised project. Another consequence of this is the apparent higher instantaneous consumption proportion for the optimised project - and thus lower potential to store energy. That said, this also results in moments when energy is sold to the grid - something that we ultimately would like to avoid; phenomena which does not happen for the optimised project.

Overall in the heating season however, it generally appears as though the generic project's PV and TES configuration outperform the optimised project in terms of energetic self-consumption potential.

MID-SEASON REFERENCE WEEK

Mid-season performance is characterised on one hand by a variable photovoltaic energy production - both throughout the week and during the day itself; and on the other hand of an extremely low electrical based thermal demand. Indeed, mid-season for both configurations is the moment when outdoor temperatures fall in the comfortable range. The consequence is that a very strong proportion of photovoltaic energy is usually sold to the grid. It appears PV consumption is almost negligeable, and happens exclusively during the first hours of daylight. Thermal energy storage is permanently charged at 100%, allowing for direct use during spontaneous moments of unwanted temperature volatility. In this climate indeed, temperature differences can reach almost 20°C in the span of 24 hours in this season. The presence of a large thermal energy storage is indeed very beneficial. This is one of the reasons why the larger tank's configuration - coupled with a lower overall demand - of the optimised project outperforms significantly the generic's project configuration. Indeed, more energy can be stored to account for those temperature differences, even though photovoltaic production is (slightly, yet significantly) lower.

Overall mid-season represents a moment when both project's energetic autonomy is at 100%, needing no grid supply whatsoever - with a significant advantage to the optimised project who needs less photovoltaic peak power, while still allowing for a larger proportion of storable energy.

COOLING SEASON REFERENCE WEEK

Among the responses that are common to both configurations, it generally appears that all of the photovoltaic energy is instantly self-consumed - with only punctual moments (very sunny and clear days) where PV excess is actually sold to the grid - with an average of 20% being stored, whilst the rest is instantly self consumed. The temperatures are high, and the high thermal inertias of both buildings provoke also significant cooling demands during the nights. However, contrary to the heating season, the optimised project has a significantly lower cooling demand when compared to the generic project - and is also (logically) higher in the evening. This incurs a chain of events :

Firstly, the instantaneous consumption is overall lower for the optimised project, and thus allows for a significantly larger energetic storability. The SoC of both configurations are identical, but the optimised project's tank being 33% larger, it in effects is able to store more thermal cooling energy - even though PV production is lower. It thus discharges more cooling energy, reducing significantly the need for grid supply. Indeed, if we look at the graphs, the grid supplies have lower intensities; are shorter lived; have lower peaks; are more stable and less prone to volatility. For these reasons, it overall appears the optimised project's configuration has a clear advantage.

PERFORMANCE COMPARISON

KEY PERFORMANCE INDICATORS

In addition to a proportional analysis of photovoltaic energy distribution both considering the whole year; and seasonally localised timle-frames; a series of key performance indicators were computed - once again following closely the protocol given by [1]. The aim was to evaluate the potential of both project's overall configurations in the framework of the broader research on the influence of (proper/computationally-aided) preliminary design on self-consumption and thermal energy storage performance.

The *Load Matching Index* «represents the degree of utilisation of energy generated locally - calculated by averaging the system's capacity to cover local load with local production» [1].

The *Capacity Factor* «measures the interaction between building and electric grid - itself calculated as the ratio of grid energy exchange with the total energy that would have been exchanged at nominal capacity» [1]

The *Primary Energy Covered by RES* is «the fraction of total primary energy covered by RES (considering self-consumed PV electricity) and the fraction of renewable energy absorbed from the grid» [1].

The *No Grid Interaction Probability* «represents the probability for the building to be autonomous from grid power; and is calculated as the fraction of time in which there is no electricity exchange with the grid» [1]. All 4 indicators are described below.

KPI COMPARISON

		GENERIC		OPTIMISED	
		NO TES	TES	NO TES	TES
Load Matching Index	[%]	34,3	44,2	33,6	44,7
Capacity Factor	[%]	15,4	10,9	16,5	11,0
Primary Energy Covered by RES	[%]	75,8	82,4	74,1	82,4
No Grid Interaction Probability	[%]	9,8	51,2	9,3	52,6

The first noticeable to trend that we may analyse is how effective the presence of a thermal energy storage can have on the potential maximisation of renewable resource self-consumption. Indeed, the load matching indexes of both configurations show an average of 10% increase in performance - as much as 11% between the generic's without TES and the optimised project's with TES. The capacity factor is on average reduced by a 5%. There is a constant 8% increase in primary energy covered by renewable resources on average between the two system configurations; and finally, the sole presence of TES incurs a massive increase in the probability that grid interaction won't happen - a 42% average.

While the presence and utility of a thermal energy storage is here demonstrated, it also appears how beneficial proper, algorithmic preliminary design can have on the future project's self consumption and TES performance. All the performance indicators tend to show a more potent response when introducing a TES in the optimised project than for the generic/control project. Indeed, the increase in load matching; primary energy covered by RES; and no grid interaction probability; as well as the decrease in capacity factor; are all higher for the optimised project than for the generic one - by 1,2% ; 1,7% ; 1,9% ; and 0,1% respectively. This means that proper preliminary design allows for the water TES to be significantly more efficient and well performing than a similar project's TES not undergoing such preliminary optimisations.

CONCLUSION

In the overall framework of the role and influence of proper, computationally-aided, preliminary design on renewable resource self-consumption potential through water-based thermal energy storages; several conclusions can be made.

First, proper preliminary design allowed for a reduction of overall thermal (heating and cooling) demand of about 9% between an optimised project following such preliminary optimisation process; compared to a generic/control project not following such process. This in turn allowed for a reduction of necessary photovoltaic peak power by an identical 9%. The lower electrical heat pump demand resulted in a lower instantaneous consumption proportional profile - 36,9% vs 40,5% for the optimised and generic/control project's respectively (even though the optimised project's peak power profile was lower, thus counter effecting this phenomena). This in turn allowed for a higher proportion of storable energy, and in effect of a higher tank storage capacity.

From an economic standpoint however, the optimised project's tank size resulted in a non-negligeable decrease in both NPV and payback time - 19€ and 1,8 years respectively (although being criticisable values due to their biased calculation techniques - as discussed earlier). That said, annual expenditures were 15% lower for the optimised project.

In any case, the optimised project's higher proportion of renewable energy self-consumption potential; its 9% lower need of peak power (and thus of photovoltaic carbon-hungry cells); its 4% higher potential for storable energy; and 4% higher avoided consumption due to PV stored; all tend to show the optimised project's configuration's performance superiority.

Indeed, if we look at the more specific - not proportional - energetic demand response as described in the table in the previous pages; total electric consumption appears lower for the optimised project by >250 [kWh]; has a lower demand (but higher proportionally) covered by photovoltaic self consumption; has a 120 [kWh] lower grid coverage necessity; a 40 [kWh] larger amount of stored energy; and finally a significant >100 [kWh] lower amount of photovoltaic energy excess given to the grid - once again manifesting the optimised project's configuration superiority.

These trends where then verified when looking at localised behaviours of both configurations in reference seasonal weeks. Looking at the graphs indeed, we notice how the optimised project's configuration resulted in a higher potential of energetic storability on one end (itself leading to higher levels of self-consumption); while on the other end inducing lower intensity, shorter lived, and less volatile grid supply needs.

Finally, the comparison of both project's configuration - and subsequent differences in preliminary design - showed how beneficial such design process could have on a project's self-consumption and thermal energy storage potential. Under this condition indeed, all performance indicators manifested better performing load matching indexes; no grid interaction probabilities; capacity factors; and proportion of primary energy covered by renewable energy sources; as well as incurring a more potent response (with respect to the studied KPIs) when introducing a TES in an project having undergone such process; than a project that had not.

Although these trends may appear (relatively) insignificant at the scale of a single project, placing them in the perspective of whole neighborhoods - even cities, countries or whole continents - instantly allows us to see how beneficial such preliminary design processes may have on energetic self-sufficiency; load matching and self-consumption optimisation; reductions of unecessary consumption of non-renewable energy; reductions of avoidable grid interactions; and finally reductions of processed materials (cells, electrical batteries, etc) manufacturing pollution. Ultimately orienting us towards net zero energy building cultures; maximised decarbonisation; smarter resource sustainability; energetic independancy and autonomy; as well as individual sovereignty.

ANNEXE 1

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