Designing a neighbourhood energy infrastructure

Applying a novel framework to Lisbon

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July 10, 2020

Abstract

This thesis introduces a novel framework for the fundamental design of energy systems for neighbourhoods. The framework is based on the sequential integration of three software tools: QGIS, City Energy Analyst (CEA) and Urbio. QGIS is used to build the buildings database (construction standards, occupancy types and schedules). CEA is used to model the neighbourhood energy services (heating, cooling, domestic hot water and electricity for other uses, including EVs). Urbio is used to design in an optimized manner the energy infrastructure that supplies the neighbourhood. This framework was successfully used in the case study of the Vale de Santo António, a neighbourhood to be built by the Municipality of Lisbon within the scope of the Renda Acessível (Affordable Rent) program. The results show that the different software can be easily combined, thus demonstrating a flexible approach for planning neighbourhood energy infrastructures.

Acknowledgements

I would like to express my deep gratitude to all the people who have trusted and helped me during this master project. Prof Carlos Santos Silva proposed the challenging task of designing an energy infrastructure for the Vale de Santo António. Ricardo Gomes was always there to attend our weekly Skype calls, point out important aspects of building simulations and share useful documentation. Sébastien Cajot assisted in the initial design of the process and reassured me in moments of distress. Nils Schüler provided continuous backing with Urbio and expended a lot of effort in understanding and correcting the many bugs caused by my data. He adapted his software to respond to my specific project. They were the people I would call for advice when new obstacles arose.

Due to the recent events, my stay in Portugal was upturned and ended up far bumpier than I initially expected. I would like to thank with all my heart Tia Guiga and Zé Gregório for their warm welcome in the Beira Baixa. Surrounded by nature and care, I was provided perfect conditions to continue my work. I would also like to express my gratitude to my grand-father Luis. While being my host, he put a lot of effort in showing Lisbon and introduced me to its musical and culinary delights. Similarly, my stay has enabled me to build deeper connections with my cousins Luis and Maria for which I am grateful. I hope to be able to keep these links intact. Finally, I would like to thank all the people I have met during my project including Pedro and Leonardo without whom my lunches at the IST would not have been the same, Prof Estefânia Alves thanks to whom my Portuguese is now top-notch, and of course Madalena who introduced me to her friends and made me discover new parts of Portugal.

I have come a long way since I left Brussels. I have learned so much, and this would not have been possible without the intense classes I have received at EPFL. While EPFL has taught me how to work, Prof François Maréchal, my project supervisor, has made me discover the world of energy and, more precisely, energy modelling. Since then, I have been passionate about both. Yet, even though this academic learning helped propel me, my short experience in the professional world taught me energy aspects unseen until then. I would like to thank in particular Nicolas Charton and Paul Letainturier from E-Cube. Both have kindly instructed me on the strategical aspects of energy, as well as helped shape my communication and presentation skills. I owe much of my current thought patterns to them. I would also like to thank T4M, and particularly Achille Lecrivain. Together with Achille I visited the undergrounds of many buildings in Brussels. He patiently explained to me the functionning of HVAC systems, what to look after, which parameters were important. This field experience gave me insights that I believe turned out to be valuable for my project.

Finally, I could not forget mention my dear friends. When I was in Lausanne, they never stopped reminding me that I had a home in Brussels. Pierre, Paul, Julien, Eléonore, I know time changes people, but I am happy to see that our friendships have survived the years. Through my many years at EPFL, I have got to know students from many horizons, but few

have influenced me as much as Diego, Yanns, Meril and Paul. They remain today irreplaceable friends whose opinions I highly esteem and respect. Last but not least, I want to thank my family. My brother Tomás has always lent an ear when needed. I hope the current relation we have will last. My father Richard sparked my interest for the outside world and undoubtedly for engineering. His passion for current issues always leads to interesting conversations and inspiring ideas. Finally, my mother Maria has been my fan n°1 since childhood. I love the conversations we have late at night, and I would have never been able to accomplish what I have without her unconditional support.

It is impossible to list all the people who had and still have a lasting impact on my life. Nevertheless, for all the moments we have shared together, I would like to thank them all as well.

Table of Contents

List of Figures

List of Tables

Acronyms and abbreviations

QGIS	Quantum Geographic Information System
CEA	City Energy Analyst
USEM	Urban-Scale Energy Modelling
UBEM	Urban Building Energy Modelling
GHG	Green House Gases
UHI	Urban Heat Island
GIS	Geographic Information Systems
BEM	Building Energy Model
HVAC	Heating, Ventilation and Air-Conditioning
VSA	*Vale de Santo António*
DM	Decision Maker
TMY	Typical Meteorological Year
DHW	Domestic Hot Water
TAC	Total Annual Cost
PEF	Primary Energy Factor
MILP	Mixed-Integer Linear Program
IO	Interactive Optimisation
GUI	Graphical User Interface
CRS	Coordinate Reference System
OSM	Open Street Map
GFA	Gross Floor Area
NZEB	Nearly Zero-Energy Building
DRE	*Diário da República Eletrónico* (Portuguese Decree Law)
TFEC	Theoretical Final Energy Consumption
RFEC	Real Final Energy Consumption
EV	Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicles
BEV	Battery Electric Vehicles

PV	Photovoltaic
ET	Evacuated Tube
FP	Flat Plate
PVT	Photovoltaic-Thermal
COP	Coefficient of Performance
DHC	District Heating and Cooling
CHP	Combined Heat and Power
RES	Renewable Energy Sources
CI	Carbon Intensity
OPEX	Operational Expenditure
CAPEX	Capital Expenditure
RNC	*Roteiro para a Neutralidade Carbono* (Portuguese National Roadmap for Carbon Neutrality in 2050)

1 Introduction

"Everything should be made as simple as possible,
but not simpler" – Albert Einstein[1]

1.1 Context

More than half of the global population lives in cities. The UN forecasts that this number will continue growing at the net rate of an extra 2 million city dwellers per week [1]. Cities are under great stress to house these new people while maintaining proper living and working conditions. Moreover, this urban growth is taking place while cities face the challenge of climate change. The response needs to be twofold. First, cities need to mitigate the effects of climate change. In this regard, special attention is given to the urban micro-climate and the existence of urban heat islands (UHI). Second, they need to transition to carbon neutrality.

No ecological transition can happen without profound changes in the way energy is produced and consumed. On the supply side, decentralisation and efficiency are important. In the context of cities, this implies respectively the on-site exploitation of endogenous resources (waste & renewables) as well as the installation of district-scale energy generation and distribution systems (thermal & electrical grids). On the demand side, experts outline the need for ambitious retrofitting programs, as well as awareness campaigns to counter eventual rebound effects.

In the last decade, new models have appeared that can take advantage of big data and fast computation. These models have proved to be great for simulation, evaluation and forecasting. Their outputs are the basis upon which decisions are taken in varied sectors such as health, energy, economy, etc. Furthermore, at the core of modelling lies a compromise between practicability and reliability. On a daily basis a modeler needs to judge the appropriate level of detail. In order to properly make such decision, a deep understanding is essential. Over-simplification risks delivering results stripped of nuance, while exaggerated complexity can be time-consuming and counterproductive.

To be found at the crossroad of the energy, urban and modelling worlds is the highly specialised, yet profound, diverse and growing field of urban-scale energy modelling (USEM). Within USEM, urban building energy modelling (UBEM) - merging detailed and reliable individual building energy models (BEM) with regional and country-level building stock models - has been gaining ground in energy planning. In contrast to a simple agglomeration of

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[1] It is believed that the statement first appeared in an article published on January 1950 in the New York Times and written by the composer Roger Sessions while paraphrasing Albert Einstein. The discovery of similar aphorisms in Einstein's earlier work support the hypothesis.

individual BEMs, it can account for buildings' cross-influences such as micro-climate, long-range radiation, shade, etc. With the integration of the buildings' geographic location via the use of geographic information systems (GIS), it can realistically gauge potential for shared energy infrastructure. Finally, thanks to a service-based model structure, it can efficiently assess the impact of targeted building retrofits, of heating, ventilation or air-conditioning (HVAC) system upgrade, or of occupant behaviour's change in the buildings' energy consumption. The system of urban buildings becomes greater than the sum of its individual entities.

1.2 Scope and aim of the thesis

An energy infrastructure proposal is designed as part of the updated urban development plan of the Vale de Santo António (VSA), a neighbourhood in Lisbon. The VSA is characterised by a central area devoid of buildings and crossed by a main avenue connecting the upper part of the municipality of the Penha de França to the riverside of the Tejo. The urbanisation plan foresees the construction of mostly residential buildings (80% of floor surface) ranging from single-household villas to multi-storeys buildings with an overall capacity of around 2500 dwellings. A portion of the dwellings are to join the Affordable Rent (Renda Acessível) program. The remaining floor space will be shared between business and public services. In this regard, the construction of a school, a swimming pool and a health centre are planned. Thanks to the reduction of residential and business capacity relative to the previous plan, an area close to 11 of the 29 ha is to be allocated to green and collective spaces.

Figure 1.1 – Urban development plan of the Vale de Santo António

For the purpose of the project, a new framework is devised which relies on three software tools – QGIS, City Energy Analyst (CEA) and Urbio – linked sequentially and enhanced by custom interfaces coded in Python. Within the framework, these tools interact and exchange data in order to output relevant and concisely formatted visualisations, as well as to propose interfaces of the neighbourhood energy aspects with which the decision-makers (DM) can interact. Figure 1.2 presents a conceptual visualisation of the process.

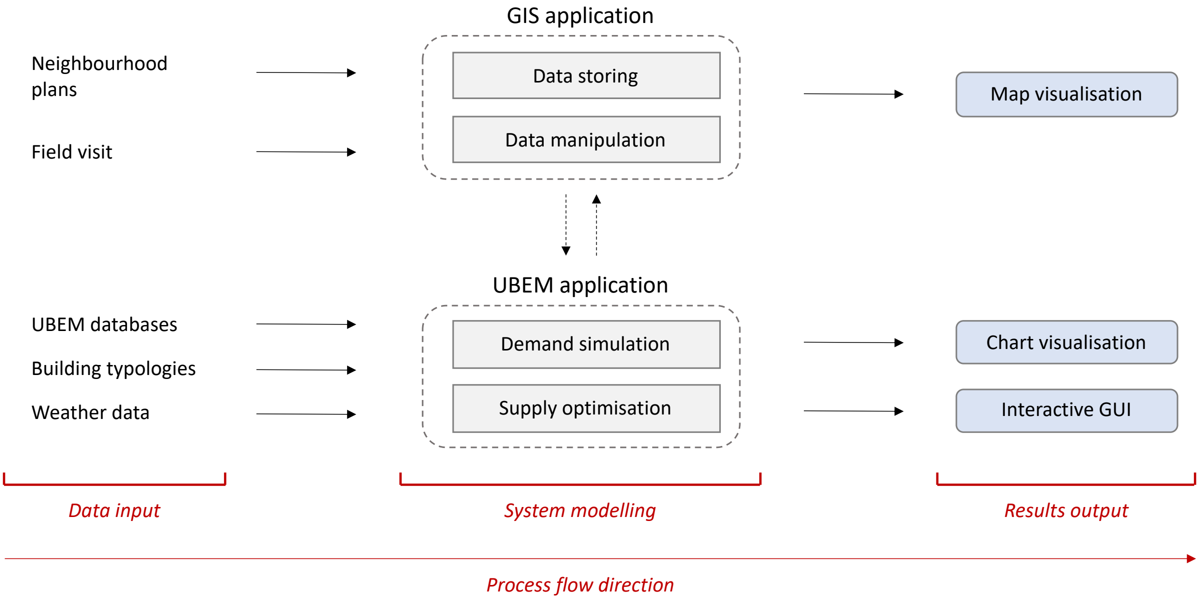


Figure 1.2 – Conceptual visualisation of the process

1.3 Chapters' overview

The report contains 8 chapters, which correspond to the body of the thesis, and a bibliography.

An introductory narrative of UBEM and its applications, informations about the case-study and the selected framework, as well as an overview of the thesis structure are summarised in Chapter 1.

Background information on the evolution of UBEM and the distinctive modules included in its tools are provided in Chapter 2. An explanation with further details on data input, the demand modelling and supply optimisation is given citing existing tools and techniques.

Chapter 3 describes in more detail the framework selected and the ways in which it can be used for energy infrastructure development. The spatial and temporal scales to be considered in the project and the three concrete outputs to support decision making are highlighted.

The building of inputs for the VSA and the use of QGIS for efficiently structuring and storing the data is the focus in Chapter 4, which also illustrates the features in QGIS for presenting information.

Chapter 5 concentrates on the simulation of energy consumption and thermal network layout optimisation with CEA. The demand outputs are analysed per end-use at a building and a district scale. The performance of layouts are compared and an optimised layout is proposed. The potential for fifth generation district heating and cooling is highlighted.

The conversion of CEA outputs to inputs for Urbio software is discussed in Chapter 6. This distinguishes between the data from CEA and the data added externally. It also lists several problems from the conversion process.

The many scenarios generated by Urbio are considered in Chapter 7 to understand the environmental, ecological and social compromises. An analysis is provided on how the scenarios rank against the anticipated future trend of greening the electricity mix and the increase in carbon taxing.

Chapter 8 draws conclusions from the project, the selected framework and the resulting scenarios. It details areas for improvement of the process and for the UBEM tools. It outlines current limitations to the development of UBEM and gives a personal opinion on strategies for decarbonising the building stock.

Due to the open source nature of QGIS, CEA and Python, the thesis will also look at the development of these community-driven software utilities and programming languages, discuss their advantages and disadvantages, and attempt to anticipate their future evolution. Moreover, throughout this report, the reader will notice underlying themes such as the search for efficient data storage, manipulation and presentation, insights on unperceived social aspects and their impact on decision making, the need for global parameter calculation conventions and the challenges of assessing a model's reliability.

2 Background information

2.1 USEM: A urban sub-model ecosystem

The twentieth century has witnessed a population shift from the countryside to the city. Nowadays cities account for two-thirds of world energy use and more than 70% of global CO2 emissions [2]. They are a focus for energy efficiency and emission-reduction programs. In parallel, modelling teams have been building tools to model the existing urban phenomena: microclimate, transporation, energy infrastructure use, building energy consumption, user behaviour, land use, etc. Due to the lack of data and computational complexity, aggravated by an absence of collaboration between teams, these tools have evolved independently with little interoperability.

Sola et al. in a review on simulation tools for USEM [3] noticed that recent years have witnessed the emergence of heterogeneous platforms integrating some of these tools into broad urban energy systems. They distinguish simulation engines capable of simulating a specific sub-part of the urban energy system from the heterogeneous platforms capable of simulating broad urban energy systems often via the integration of the sub-models mentioned previously. Distinction between simulation engines and heterogeneous platforms was not made clear by Allegrini et al. [4], nor was the largest and booming field of urban building energy modelling (UBEM) clearly defined as an entity of a greater USEM ecosystem in previous reviews [5] [6].

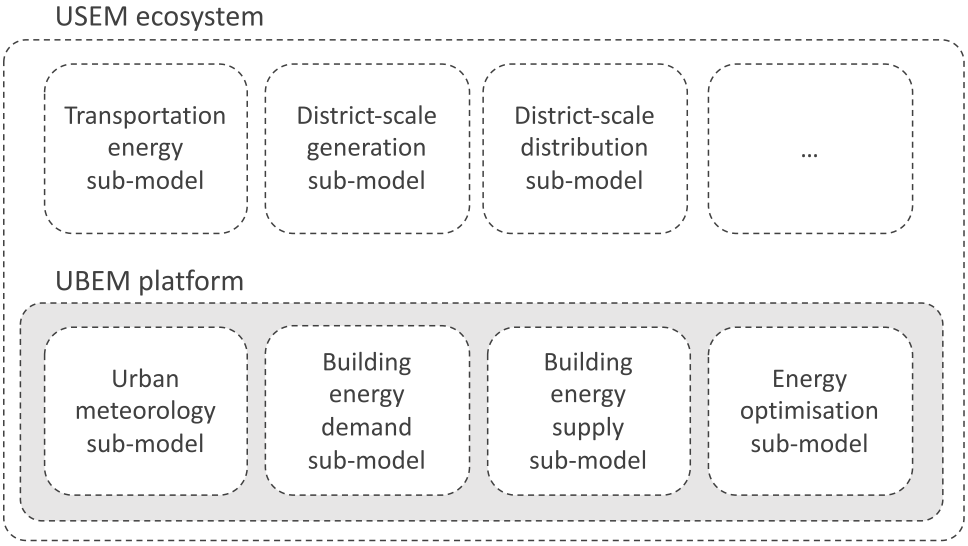


Figure 2.1 – An overview of USEM ecosystem

Heterogenous platforms are structured as workflows using sub-models of the USEM ecosystem following a sequential (preprocessing), co-simulation or integrated architecture [7]. With a sequential architecture, outputs of a sub-model, e.g. the urban meteorology sub-model, are used as inputs for the next sub-model, e.g. the building energy demand sub-model. Instead, the co-simulation architecture uses during runtime and at each timestep the outputs of a sub-model as inputs to another. In cases with strong coupling, the sub-models can follow a reiterative process where they call each other repeatedly until converging with respect to their outputs. Finally, the integrated setup merges features of each sub-model into a unified model.

The areas of research in USEM consits mainly in the coding of new or improvement of existing sub-models (reliability, efficiency) and the efficient integration of isolated sub-models into new or existing heterogenous platforms.

2.2 UBEM: A bottom-up approach

Traditionnally, a top-down approach has been used for energy planning and saving estimates from retrofitting and HVAC upgrade program. Top-down building stock energy models use area-delimited (national, regional, etc.) aggregated energy building consumption statistics and combine them with a model of the building stock categorised into archetypes. The archetypes are designed to represent groups of building with similar construction properties, HVAC systems and operational uses. Energy gains from retrofit programs can be easily estimated by converting a number of buildings from one type to another. This approach has been successfully used for estimating the potential for energy conservation measure in four EU countries [8]. Yet, these models always extrapolate from the current situation, require access to energy consumption statistics and do not perform well when considering integrated energy supply-demand scenarios. Nevertheless, they perform very efficiently, delivering satisfactory result on a regional and national level as well as enabling fast gain/cost estimates.

In the first ever review on UBEM, Reinhart et al. [9] pinpoint the explanation for the growth of UBEM as being due to the merging of regional and country-level building stocks with reliable detailed individual building energy models such as EnergyPlus [10], DOE-2 [11] or TRNSYS [12]. The use of physics-based BEM for the building energy demand modelling contrasted with the previously used top-down approach in that the energy demand estimate of a building was not a statistical result, but rather was directly generated from the building's climate, construction properties and uses. The bottom-up approach, on top of clarifying the energy services and their corresponding end uses that underpin the energy demand of a building, was found to be better suited to end-user needs [13]. Indeed, it can uniquely adapt its results to climate change [14] or measure the impact due to change in occupant behaviour [15]. Finally, the bottom-up approach was also found to perform better for the identification of possible improvements in the building sector level at urban and regional levels [16].

The standard workflow first tested by Shimoda et al. [17] on Osaka city and described by Reinhart et al. can be divided into three subtasks: simulation input organisation (data input), thermal and electrical demand model generation and execution (demand modelling) and result validation (validation). This workflow does not change with the nature of the project. However, the aim may not be the same if, for example, the buildings modelled already exist (brownfield neighbourhood) or are to be built (greenfield neighbourhood).

2.3 Data input

Data is an important feature, but unfortunately can often be hard to access. To help modelling teams, many cities have been setting up open data portals in recent years. However, the data often lacks standardisation which complicates automated data processing. Consequently, the use of different data sets often requires time-consuming data cleansing. In case of UBEM, the data inputs are of three types: climate, geometric and non-geometric data.

2.3.1 Climate data

The climate data is now widely accessible with, among others, typical meteorological year weather (TMY) files for more than 2100 cities available under the EPW format of EnergyPlus [18]. The meteorological data contains, for instance, monthly measurements of ground temperatures, and hourly measurements of air temperature and humidity, which can be useful for computing ground source heat pump efficiency or for quantifying heating and cooling needs. Geometric and non-geometric data are both building-specific and can be built from real measurements or deduced from archetypes.

2.3.2 Geometric data

The geometric data contains information about the shape of the buildings and the terrain elevation. The shape of the buildings is primarily stored in GIS formats such as the ESRI Shapefile/FileGDB [19] [20], GeoJSON [21] or CityGML [22]. These formats usually combine the 2D footprint information of each building with a height (above and sometimes below ground) attribute enabling a “2.5 D” representation of the building. CityGML – an open data model to represent and exchange digital 3D models of cities and landscapes – allows for a flexible representation of buildings and landscapes at various level of detail (LoD). In the case of building shape, LoD0 is limited to the 2D footprint of the building while LoD4 contains the detailed inner and outer 3D structure of the building with distinction between the types of surfaces. The use of LoDs for building representations is crucial to adapt to the varying levels of data availability and quality of the building stock. The terrain data can be implicitly contained as an elevation feature for each building, or stored in a separate file as a geo-referenced matrix of terrain parcels of different altitudes.

2.3.3 Non-geometric data

Non-geometric data consists of all the other parameters necessary for the energy demand modelling of the building. It varies depending on the model requirements, but usually consists of the building envelope properties (thermal coefficient, window ratios, glazing coefficient, etc.), the building HVAC system (type, efficiency, fuel) and the occupant behaviour (thermal comfort requirements, internal gains and presence schedules). Due to the large amount of data required per building and the lack of complete and detailed studies or the prevention of access for privacy concerns, assumptions are made and the properties are deduced from archetypes of groups of similar buildings for which the access to the missing data was possible. The design of these archetypes follows two steps: first the segmentation, then the characterisation.

2.3.3.1 Archetypes for the building stock

Archetypes have two advantages. First, they provide a solution to the automation of the heavy task of input preparation as seen in the use of BEM for individual building, and, second, they compensate the knowledge gaps for a specific building stock. Due to their scale, UBEM projects require the form of abstraction for the building stock that archetypes provide.

When building archetypes, the first step is to divide the entire building stock with respect to segmentation parameters. These parameters tend to be available for the entire building stock and are suggestive of similarity in construction standards and operational use. In the same way, as there can be varying levels of segmentation, the set of parameters can include as many parameters as necessary. The usual parameters are the building shape, age, use, HVAC system and the climatic region in which it is located. The optimal parameter selection is the outcome of trials and depends on the characterisation process.

The characterisation of an archetype can be based on a sample building of the segmented set (documented by an audit) or on a *virtual* building built from the statistical data of the segmented set and/or expert opinion. The characterization can take place separately for the building typology (construction standard, HVAC system) and the use type (occupant behaviour).

Nowadays, the design of archetypes for urban building databases (UBD) – building archetype repositories - is a process well known by the UBEM community. In the EU, the Energy Performance of Buildings Directive, legislating on the issuance of energy performance certificates for selling or renting buildings, and the TABULA project [23] have incentivised the definition of building typologies per country [24] [25]. Similar characterisations have been applied to Portugal [26] [27] and to Lisbon [28]. Figure 2.2 illustrates the generation of data inputs in a UBEM framework with little information about the building stock, and a UBD.

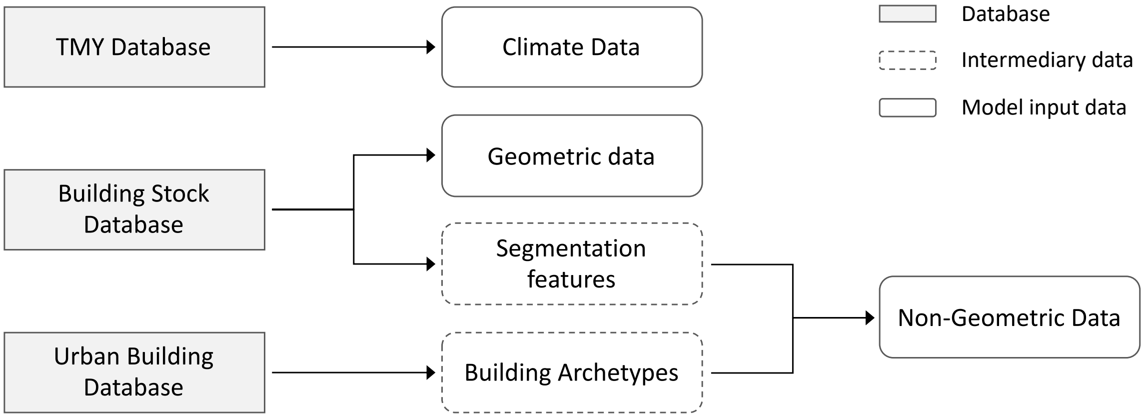


Figure 2.2 – Data input generation for UBEM

2.4 Energy demand modelling

Energy demand modelling can be used to estimate the demand of existing or future buildings. In the former case, its aim can be a better understanding of the underlying energy services provided to the building. For the latter, a demand estimate is necessary for designing an adequate energy supply sytem.

The inputs are used to model the energy demand for the heating, cooling, domestic hot water (DHW), ventilation, lighting and electric appliances. The energy demand modelling for DHW, ventilation, lighting and electric appliances is based on the presence schedules of the user as well as the intensity of use. The heating and cooling demand depends also on the climatic conditions. The demand models can be classified depending on their complexity.

2.4.1 Single or multi-zone model

A single-zone model assumes a single use of the building. A single-zone model admits only unique thermal comfort conditions for the building, e.g. minimum and maximum acceptable temperature, and a homogeneously spread thermal output by the users and machines present in the building. On the contrary, multi-zone models convert the massing model into a network of volumetric thermal zones, each holding their own thermal comfort conditions and thermal output intensity. In such cases, in addition to the interaction with the climate, each zone interacts with other connecting zones for thermal exchanges. Multi-zone models are important when investigating detailed urban models containing mixed-use buildings.

2.4.2 Steady or dynamic-state model

A steady-state model aims to solve the thermal balance at each time-step in order to respect the thermal comfort conditions, e.g. maintain indoor temperature in the acceptable range. Steady-state models represent an idealistic “design” situation where inner dynamics of HVAC systems, thermal inertia of the envelope, etc. do not influence the values of key parameters of the energy demand calculation. Dynamic-state models follow the same physical principles as steady-state models but acknowledge the dynamic nature of processes. The admission of kinetics in the model leads to parameter variation with respect to time. The main BEM tools (EnergyPlus, DOE-2, TRNSYS, etc.) use dynamic-state models, and, while no major differences have been found for the computation of heat loads, dynamic-state models have been shown to perform better in simulations involving high cooling needs [9].

2.4.3 Interaction with surrounding buildings and the local micro-climate

When considering no interaction, the demand modelling can be limited to the use of a sample building of each archetype. To obtain aggregated demand for the entire stock, each demand is then multiplied by the number of buildings corresponding to this archetype, or by a floor-area weight function. In case of high geometry variation between buildings of the same archetype, each building can be simulated separately.

In urban areas, the shading caused by surrounding buildings is computed first. For dense urban areas, the effect of surrounding buildings on local wind patterns or the emission of long-range radiation can be significant, and demand models integrating computer fluid dynamics (CFD) are necessary. The coupling effect of heat emissions from buildings heating up the local micro-climate further influences the building energy demand and is currently not considered by the most widely-used UBEM tools (CEA, UMI, CitySim, Teaser) [29].

2.4.4 Deterministic or stochastic presence schedule

The most popular modelling approach is space-based, i.e. the occupancy and its corresponding occupant density is a feature of the building with regard to time. In such a case, a deterministic presence schedule assumes no randomness regarding the arrival and departure times of the users in the building. On the other hand, stochastic models sample from statistical distributions to predict the likelihood of user presence in the building. First-order Markov chain techniques are then used to transform these likelihoods into a schedule of presence for the entire time range of the simulation [30].

When considering aggregated annual energy demand values and the gains from retrofitting programs, these two approaches differ little. However, a stochastic method becomes necessary when working on planning and optimisation of urban energy supply systems. Indeed, deterministic approaches fail in properly simulating peak loads, hampering the consideration of demand-control techniques such as peak shaving and load shifting, and in providing realistic spatio-temporal constraints necessary for district heating or cooling-network design [31].

Finally, in dense urban areas people interact with various buildings on a daily basis. Each person interacts with the building appliances depending on their activity and their personal thermal comfort requirements. In such cases, a stochastic person-based approach allocating an agenda to each user might be needed instead of space-based approach.

2.4.5 Accelerating the modelling process: parallelisation and order reduction

As models become more complex in a quest for greater fidelity, so does the computational cost. While acceptable for single BEMs, such costs can become significant when working on UBEM projects requiring the simulation of thousands of buildings. Fortunately, the modelling process can be fully parallelised via cloud computing. This means that the demand simulation of separate buildings can be handled by separate processors, once the cross-influence of buildings and the characteristics of the micro-climate have been computed. Additionnaly, there are methods to reduce the computational complexity of the model without altering the reliability of the results. One of these is the use of reduced-order calculation methods. Instead of using physics-based simulations which rely on the complete simulation of the physical processes, reduced-order models use normative calculation methods, similar to the methods used in the energy performance ratings of European countries [32]. These methods have the advantage of being simple, transparent and robust, and are used in tools like SimStadt [34].

2.5 Energy supply systems modelling

Depending on whether the project is of a brownfield or greenfield neighbourhood, the model will consider an existing energy infrastructure. The energy supply system usually consists of a thermal network equipped with conversion and storage units and distributing heat and cold to its set of connected customers. There may be a collection of decentralised energy generation, conversion and storage units installed in separate buildings. The energy supply system proposed by the model is normally the result of an optimisation process.

2.5.1 A multi-objective problem

The objectives of the analysis can vary from the minisation of the total annual cost (TAC), of the GHG emissions or of the primary energy factor (PEF), to the maximisation of the use of renewable energy during operation. Other objectives can also be considered depending on the preferences of the decision makers (DM). Multi-objective problems, by the inclusion of potentially conflicting objectives, do not result in a unique optimal configuration, but instead in a set of equally interesting solutions called Pareto-optimal. These Pareto-optimal solutions cannot be modified to make any preference criterion better without making at least another preference criterion worse. The set of Pareto-optimal configurations define the Pareto-front.

2.5.2 Optimisation techniques

Finding the true Pareto-front is often difficult. Given a fixed amount of time, all optimisation methods can at best give an approximation. Indeed, an analytical solution for the multi-objective and multi-period (hourly) optimisation might not exist. However, there are techniques to accelerate the process and improve the quality of the approximation.

More than one technique can be used in the process. For instance, CEA uses a heuristic technique for the design of the thermal network layout [33]. Then, to define the optimal configuration of decentralised units, it relies on evolutionary algorithms – a meta-heuristic technique. Evolutionary algorithms mimic natural phenomena of a population's evolution such as crossover, mutation and selection. At each generation, the candidate solutions to the optimisation problem are evaluated based on one or more fitness functions. The best candidate solutions serve as a basis for the building of the next generation. The evaluation of individuals can be distributed to multiple processors that send back the evaluation result of the given individual to the main processor. This master-and-slave routine is also an efficient distribution technique of taks between processors for a faster exploration of solutions [35].

Depending on the construction of the model, the multi-objective problem can be a mixed-integer linear programming (MILP) task. Urbio maintains only one objective function using the ε-constraint method to convert the remaining functions into controlled constraints. It also defines decision parameters (parameters under control of the planner) from the set of variables, building up a multi-parametric MILP. The remaining variables represent decisions taken in a latter stage of the planning and are optimised in accordance to the MILP defined by the decision parameter's values. The MILP optimisation problem changes when varying the decision parameter values. If this variation is guided by a Sobol sequence or a systematic approach, various scenarios can be tested, and the decision space can be explored. The performance factors of each scenario are returned. In contrast with CEA, the goal is not to compute an approximation of the Pareto-front, but rather to probe quickly the decision space gaining sufficient insights for the restriction of the search space to the most relevant areas [36].

2.5.3 The decision processes

The entities of the Pareto-fronts are the result of optimal tradeoffs between multiple objectives. To select the most satisfactory solution, the DM needs to articulate the preferences. These preferences include acceptable ranges, tradeoff information, relative weights of objectives, etc. These need to be sufficiently specific to result in a single solution and can be declared at different times during the process [37].

The first option is to declare these preferences *a priori*. This is by far the most efficient process as it computes a single solution. Yet, it requires a complete prior knowledge by the DM of the preferences and the tradeoffs in the optimisation, which is highly unlikely when considering a complex and interdisciplinary problem such as energy supply system modelling.

A more common method is to declare the preferences *a posteriori*. This allows the DM to have a complete view of all solutions. However, the computation of all the solutions can be a lengthy process depending on the size of the solution space and the expected resolution (density of solutions). Moreover, once all the solutions are computed, these can be hard to interpret and understand, thus compromising the trust of the DM. Finally, when more than three objectives are selected, the tradeoffs are hard to present.

Adapting to the limitations of the aforementioned method, CEA limits the number of solutions (customisable by the user) and sets the objectives to be considered (minimisation of the TAC, GHG emissions and PEF). After presenting the resulting Pareto-front, it uses a decision module to grade the configurations with respect to the user preferences [33]. However, it does not permit the computation of new scenarios integrating the preferences of the DM.

A response to the limitations of both approaches would be an interactive optimisation (IO) [37]. IO enables the user to learn from the solutions as they are generated. By visualising the tradeoffs, the user can refine the preferences and communicate those to the scenario generator. In accordance with these newly stated preferences, the generator steers its search to the most relevant areas of the solution space. This information-sharing cycle In addition to avoiding the computation of numerous solutions of little interest (and thus saving time), the IO human-computer interaction improves the understanding of the DM of existing tradeoffs; this ultimately helps build trust and confidence in the final scenario.

Schüler defines urban planning as the improvement of the status quo, and not the computation of an optimum scenario [38]. Following that philosophy, Urbio's technique of probing the decision space is combined with an intuitive visualisation of the scenario's performance factors and an interface for the user to update his preferences as the generator adapts accordingly.

3 Designing a comprehensive framework

3.1 Important features of the case-study

The VSA neighbourhood is situated in Lisbon, Portugal. Due to the composition of the neighbourhood, the nature of the project and the host country, there are features that are important to take into account. These will have an impact on the aims and objectives of the project, as well as influence the initial assumptions about the way of living of the inhabitants.

The latest report by the EU Energy Poverty Observator included mixed results for Portugal on the fulfilment of citizen energy needs [39]. For instance, it states that in 2017 around 20% of households were not able to keep their home adequately warm. These situations occur with higher frequency in social housing, and the data pinpoint households in urban areas as being most susceptible to energy poverty. Likewise, scientific work focusing on the energy gaps in Portugal - the difference between estimated and real energy consumption – have concluded that the reference conditions assumed by the energy certifications overestimate the heating and cooling consumption of Portuguese inhabitants, reflecting unmet thermal comfort needs, but also culturally distinct heating and cooling traditions [27] [13].

Due to its particular terrain, the VSA has suffered from an uncoordinated development of its peripherical neighbourhoods. This chronic disconnection has been aggravated by the absence of mechanisms that ensure mobility and access, along with the disregard of the central area of VSA, an unoccupied hill. The urban development plan aims at introducing coherence between these construction lots in order to benefit both existing and future inhabitants. Moreover, a number of the appartments will form part of the Affordable Rent Program that introduces rent controls and allocates appartments to families with lower revenues to increase the social diversity in the neighbourhood.

3.2 Motivation

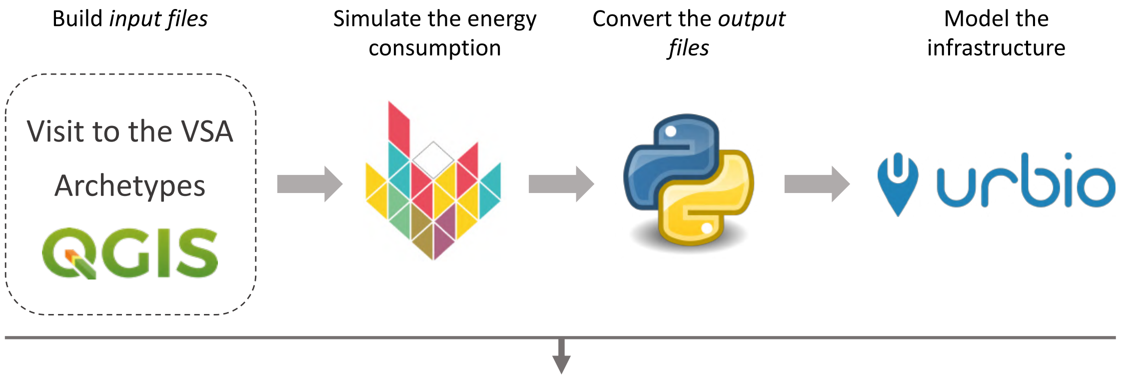
The aformentionned special features for Portugal and the VSA guided the aims of the project:

1. **To investigate** different scenarios of energy supply systems
2. **To understand** the economic, social, environmental and technological trade-offs
3. **To take advantage** as much as possible of open source softwares

When designing the energy supply systems for the new VSA urban area, special attention should be given to inclusion of the peripheral buildings. Ideally, the energy supply system should be able to extend its distribution area to the rest of the VSA and to adapt to the expected evolution in energy consumption. Special concern should be given during the design process to ensure that the energy supply system minimises its environmental impact, while remaining within budgetary limits and accounting for local realities.

3.3 Method and tools

To design an energy supply system, the tools require specific data to be fed to their algorithms. This information often does not exist as such and must be either collected from varied databases or, if inexistent, generated via another tool. Only then is it transformed to correspond to the tool-specific data format. To compensate for the recurrent unavailability of neighbourhood-specific data, the tools often provide default parameter values. Though useful, these default values are more or less accurate depending on their source and on the building stock they are expected to represent. In the scope of the project, three tools – QGIS, CEA and Urbio – were used sequentially. This novel framework designed specifically for the VSA project aims, among other things, to respond to the lack of data by generating as faithfully as possible all the missing inputs for the modelling of the energy infrastructure.



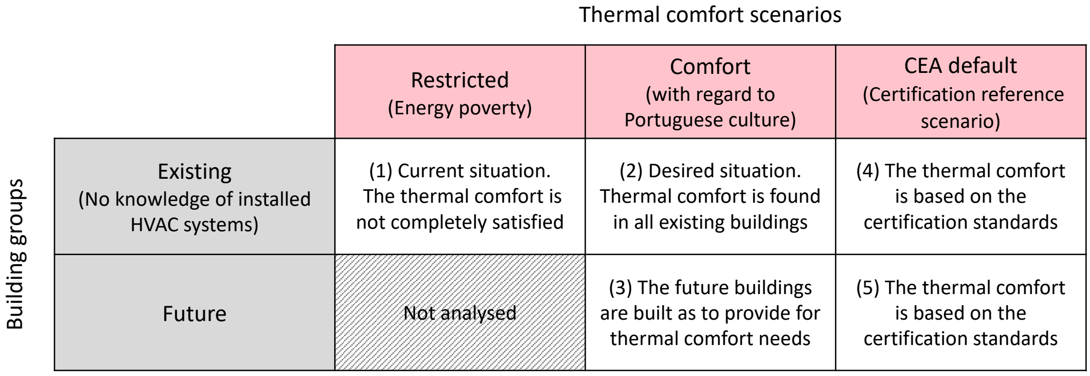
Scenarios of energy infrastructure **at the intersection of spatial and temporal groups: Existing** and **planned buildings**, **current** and **future consumption patterns**

Figure 3.1 - The entire framework

The three tools are complementary. QGIS is used for storing the GIS-based data such as the terrain information, the road network and the building stock features. Its Geopackage format is an efficient way of condensing all the layers into a single file facilitating the sharing of information among modelers and project stakeholders. CEA is a heterogeneous platform for simulating energy demand and designing energy supply systems. It possesses other features for evaluatimg the endogenous potential of resources, life cycle analysis, thermal network design, etc. In the scope of the framework, it is only used for its energy demand capability. Python is an open source programming language. It offers a wide array of useful libraries coded by its community of programmers enabling the user to work on high-level programs. Urbio is an energy infrastructure optimiser. It differs from other tools in its use of interactive optimisation and its fast generation of scenarios for exploring the decision space. The user-friendly interface makes it a good tool for group work with other stakeholders. Selected scenarios can be discussed with respect to their relative scores on performance indicators. Input data can be altered to study the scenario sensitivity to certain assumptions.

3.4 Expected outcomes

From a modeler's perspective, the VSA project can be divided with respect to the building stocks and occupant behaviour. Firstly, the VSA is composed of existing and future buildings. On the one hand, the existing buildings possess unknown construction properties. Furthermore, some are already provided with heating and/or cooling systems, while others not. On the other hand, the envelope properties of future buildings are yet to be decided, while the energy supply system is to accommodate for all user end-use energy needs. Secondly, the existing buildings are expected to witness a change in energy consumption as a consequence of increasing financial capabilities and living standards, closing the present energy gap. If a district-scale generation and distribution thermal supply system is to be designed for the existing and future buildings, it must be able to provide for current, but also future energy demand. A division of the building stock and the studied thermal comfort scenarios is presented in Figure 3.2.



Thermal comfort scenarios

Building groups	Restricted (Energy poverty)	Comfort (with regard to Portuguese culture)	CEA default (Certification reference scenario)
Existing (No knowledge of installed HVAC systems)	(1) Current situation. The thermal comfort is not completely satisfied	(2) Desired situation. Thermal comfort is found in all existing buildings	(4) The thermal comfort is based on the certification standards
Future	Not analysed	(3) The future buildings are built as to provide for thermal comfort needs	(5) The thermal comfort is based on the certification standards

Figure 3.2 – Building stock and thermal comfort scenarios' overview

Based on the current state of knowledge about VSA and the capabilities of the proposed framework, three outputs are defined. As a whole, they offer well-founded and diverse information to the stakeholders for their final decision making concerning the energy supply system to be installed in the VSA. These outputs are:

1. **Comparison of energy demand with CEA** between restricted, comfort and CEA default scenarios for the existing and future buildings: (1) & (2) & (5), (3) & (5)
2. **Comparison of thermal network designs with CEA** for future buildings: (3)
3. **Energy infrastructure scenario with Urbio** for the future buildings: (3)

4 QGIS – Build GIS input files

4.1 Geographic Information Systems and QGIS

With regard to its latest developments, Geographic Information Systems (GIS) can be considered a young field though it began in the 1960s. As information becomes increasingly spatially aware, the use has been spreading. A fundamental feature of GIS is the ability to associate information (non-geographical data) with places (geographical data). By relating, integrating and analysing information from different themes (or layers) of spatial information, GIS can display the spatial data or exploit it to gather insights. Nowadays, it is used for mapping (resources, properties, land use, etc.), for monitoring (disease, fire, invasive species, etc.) or for spatial analyses (indundation risks, customer targeting, route finding, etc.).

There are many existing tools able to fulfil some or all commonly used GIS functions. QGIS distinguishes itself by being an open-source GIS application supported by a large community of users and developers who constantly enrich capabilities via the coding of plug-ins. Its user base has increased thanks to its cross-platform nature and the integration of other open-source GIS packages such as PostGIS, GRASS and SATA. Moreover, it supports numerous file formats (shapefiles, dxf, etc.) and can connect with web services to query spatial data from external sources.

4.2 Terminology

GIS have their own set of terms:

- *Layers.* They are the means by which spatial information is structured and represented in GIS. Each layer contains a unique type of spatial data and represents something in the real world, e.g. a terrain elevation layer, a road network layer or a building shape layer. They are stacked following a natural order usually starting with raster data (continuous information) then followed by vector data (discrete objects).
- *Raster data.* Raster data is used to represent information that is continuous across an area. It consists of a matrix of pixels, called cells, each containing a value that represents the conditions for the area covered by the cell. For instance, the elevation of a terrain can be discretised into a grid of cells defining the average altitude of the parcel.
- *Vector data.* In contrast with raster data, vector data is used to represent real world features. An object represented as vector data is called a *feature*. A feature has its shape represented using a geometry. There are 3 main geometries in GIS: *point* (a single vertex), *line* (2 or more vertices where the first and last vertices are not equal) and *polygon* (4 or more vertices where the first and last vertices are equal). The choice of geometry sometimes depends on the scale, e.g. representing a city by a point on a

world map and by a polygon on a regional map. Furthermore, a feature also has *attributes* associated with it. They are its characteristics, e.g. the height of a building. In a layer, there can be many features, all necessarily possessing the same geometry type. Their attributes define the *attribute table* where each feature corresponds to a row of table called a *record*, while all the attributes of the features are distributed into columns called *fields*. Each field allows one type of data: numeric, text or date.

- *Projections*. A projection is a set of equations that define the transformation of a 3D reality to a 2D model for representation purposes. Since no transformation exists that could represent all geometric metrics correctly, transformations can be classified with respect to their suitability at different scales and their corresponding performance in maintaining angular, distance or area conformity.
- *Coordinate Reference Systems (CRS)***.** A CRS is the coordinate system used for relating the projected places to their real word locations. A *Geographic Coordinate System* uses latitude and longitude values for defining positions, whereas a *Projected Coordinate System* adopts x and y (and optionnally z) coordinates. In the former case, map units would be degrees, minutes and seconds, while in the latter, map units would be meters or similar.

4.3 Georeferencing urbanistic plans

A large amount of urban GIS data is available and accessible from open data sources such as the Open Street Map (OSM). However, when working with urban development, information must sometimes be extracted from plans. For the VSA neighbourhood, plans about future building and road network layouts had first to be georeferenced and then manually drawn over.

Figure 4.1 - Georefencing urbanistic plans

4.4 Terrain layer

The terrain layer contains information about the elevation at all locations of the simulated area. The altitude of a building can strongly influence the solar radiation calculation and is important for districts located in hilly areas. The terrain elevation can be implicitly expressed via the definition of elevation attributes for the building features or explicitly if a terrain raster layer is built.

In the VSA, the terrain layer was interpolated from point measurements. In GIS applications, interpolation methods have been designed to support transformations between different discrete and continuous representations of spatial fields, typically to transform irregular point or line data to raster representation [40]. A popular interpolation method was used: Triangulated Irregular Network (TIN) for which a common algorithm is the Delaunay triangulation. It tries to create a surface formed by triangles of nearest neighbour points. To do this, circles around selected sample points are created and their intersections are connected to a network of non-overlapping (as compact as possible) triangles.

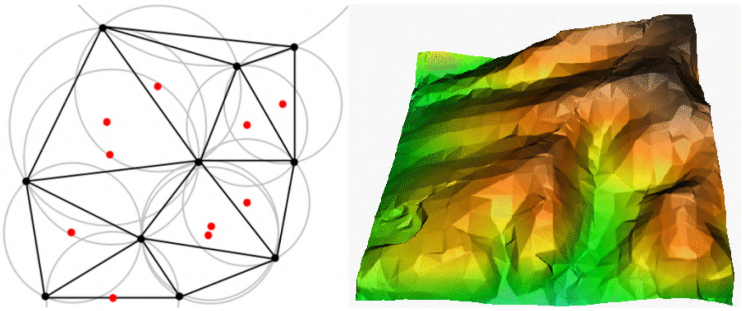


Figure 4.2 – Delaunay triangulation interpolation example [40]

The following steps were executed to obtain a raster layer of 5x5m cells: vertices extraction, triangular interpolation, and raster extension to embrace the surrounding buildings outside of the VSA. Figure 4.3 highlights the steepness and elevation range of the neighbourhood.

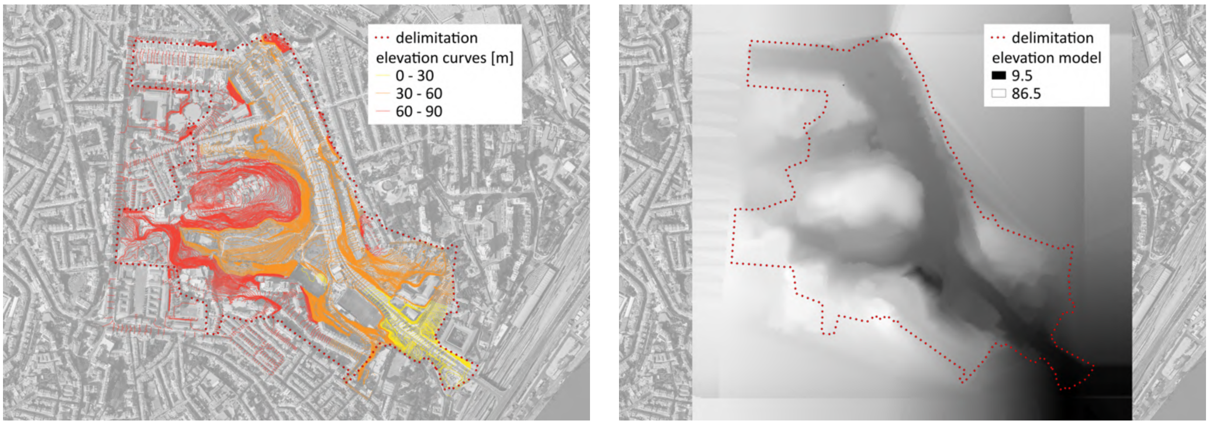


Figure 4.3 - VSA TIN interpolation

4.5 Road network layer

The road network layer defines the layout of all the paths of the neighbourhood. It can be composed of a single polyline feature or a set of polylines features whose attributes can define the type of road, the width, the material, etc. In the modelling of energy supply systems, the road network serves as the basis for the piping layout design of the thermal networks. For the VSA, the road network was manually built from the circulation plans.

Figure 4.4 - Building the road network

4.6 Buildings' layer

The building layer is divided between the VSA buildings and the surrounding buildings. The geometry of all the buildings is required to compute shading. The VSA buildings, whose energy demands are to be simulated, require additional information, i.e. the building standard and the use type. This data is either based on real measurement or, in the absence of data, on educated guesses via the use of archetypes. To select the surrounding buildings, a buffering zone of 50 m around the VSA delimitation was drawn.

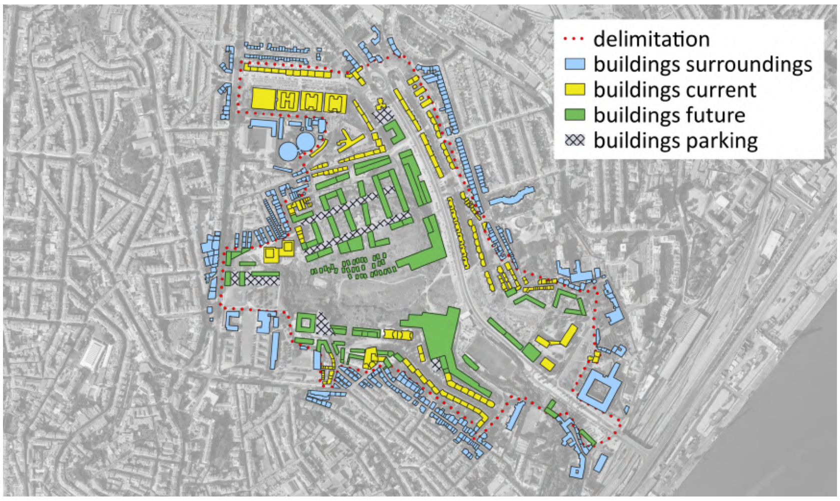


Figure 4.5 – VSA buildings layer

4.6.1 Building geometry

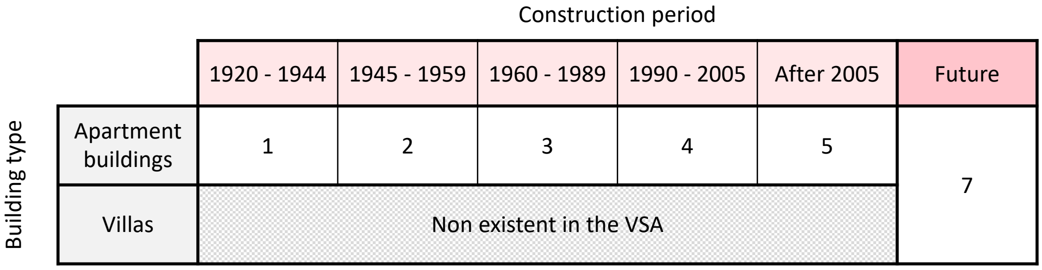
In addition to the footprint, the height attribute for the buildings is needed to complete the geometry. The name field identifies individually the buildings simulated. The height above and below ground permits a 3D description for the building. If a building is divided in zones of different height, distinct features must be built and assigned a similar root name to signal their capacity to share HVAC or in-city generation infrastructure during the energy supply system modelling. Finally, the internal loads computation requires the number of floors in the building.

Field name	**Format**	**Unit**
Name	text	-
Height above ground	integer	meter
Floors above ground	integer	-
Height below ground	integer	meter
Floors below ground	integer	-

Table 1 - Geometry fields' description

4.6.2 Building typologies

The remaining attributes that define the technical and occupational characteristics of the buildings are abstracted by the use of archetypes. These attributes are grouped into two families of archetypes: the construction standard and the occupancy type. The construction standard defines the envelope characteristics, the HVAC systems, and its corresponding supply, for the building. In the case of VSA, five construction standards were defined for the existing buildings depending on their construction year, while a unique construction standard was selected for future buildings. The building stock's segmentation is shown on Figure 4.6.



	Construction period					
Building type	1920 - 1944	1945 - 1959	1960 - 1989	1990 - 2005	After 2005	Future
Apartment buildings	1	2	3	4	5	7
Villas	Non existent in the VSA					

Figure 4.6 - VSA construction standards segmentation

The occupancy type defines the indoor comfort, the internal loads, the presence schedule of occupants, and the HVAC operational modes. In the scope of the VSA, five occupancy types were defined. The occupancy types for school, swimming pool and restaurants represent less than 5% of the ground floor area (GFA). For simplicity, it is assumed that since these buildings provide services, their thermal comfort can not be impaired, and thus no other thermal scenario is simulated other than a standard default scenario. As for the residential buildings, the occupancy type is distinguished between single and multi-dwelling buildings because of the influence on internal loads of varying occupancy density.

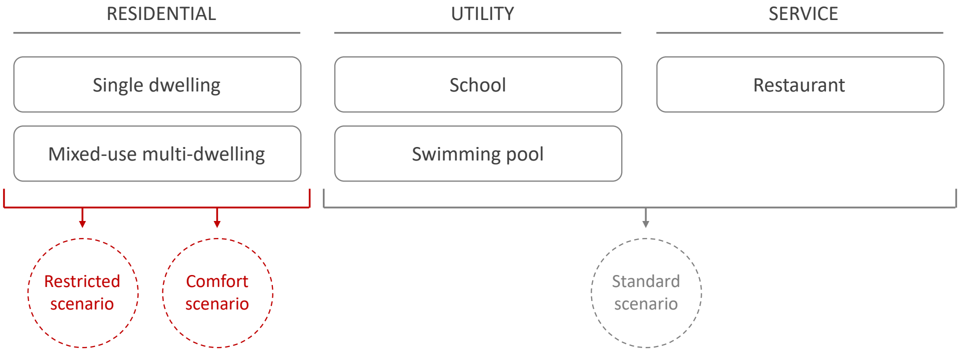


Figure 4.7 - Occupancy types overview

The consumption patterns of the residential sector represent around 95% of GFA, essentially driving overall energy demand of the VSA. Two thermal requirement scenarios were defined for the VSA. The comfort scenario aims at simulating the heating and cooling conditions and schedules to provide thermal comfort for the inhabitants in Lisbon. The comfort scenario is used for existing and future buildings. On the other hand, the restricted scenario is used for modeling the common Portuguese heating and cooling conditions as defined by Palma et al. [41]. The cause of energy poverty is most often due to poor insulation which causes an unaffordable increase in energy demand for an equal level of thermal comfort, along with the lack of efficient equipment for heating and cooling. The future buildings will satisfy the highest standards of thermal insulation and be fully equipped with space heating and cooling systems. Consequently, the application of the restricted scenario is limited to the existing buildings.

In the case of mixed-use buildings, different shares of the building floor area can be assigned proportionately to the relative importance of each occupancy type. To take into account the difference in behaviour between active and inactive residents, mixed-use buildings were used for the multi-dwelling units. The share in GFA corresponding to active and inactive residents is based on the ratio of 15 – 64 years to 65+ years old inhabitants in Penha de França [42].

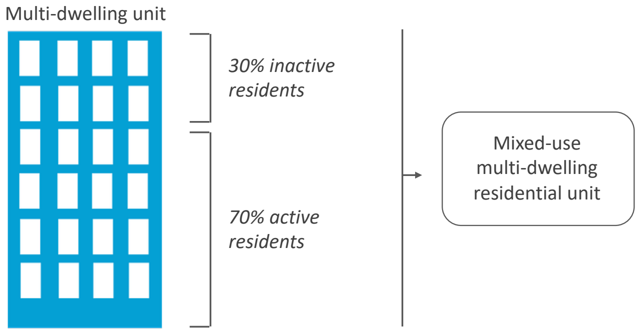


Figure 4.8 - Mixed-use multi-dwelling simulation

For the building typologies, the use of two families of archetypes enables a clear separation between the building as an object and the building as a program. The physical body of the building is slow to change and depends on retroffiting and technology upgrade. On the other hand, the program of a building is ephemeral and depends on its function and on the lifestyle of the occupants [43]. Together, the construction standard and the occupancy type determine the typology of the building. As shown in Table 2, in the building layer, each building record is assigned a construction standard and one or more occupancy types depending on whether the unit is single-use or mixed-use.

Field name	**Format**
Name	text
Construction year	integer
Construction standard	text
1st / 2nd / 3rd occupancy type	text
1st / 2nd / 3rd occupancy type rate	float

Table 2 - Typology fields' description

Therefore, separate processes were applied to assign both archetypes to the existing and future building stock. A visit to the VSA served as a basis to determine the construction period for existing buildings and their construction standard. This first draft assessment was later reviewed and corrected by the VSA urbanists. The occupancy types were distributed based on information collected on Google Maps for the existing buildings and in the VSA urban development plan for the future buildings. The distribution of the two families of archetypes along the building is shown on Figure 4.9.

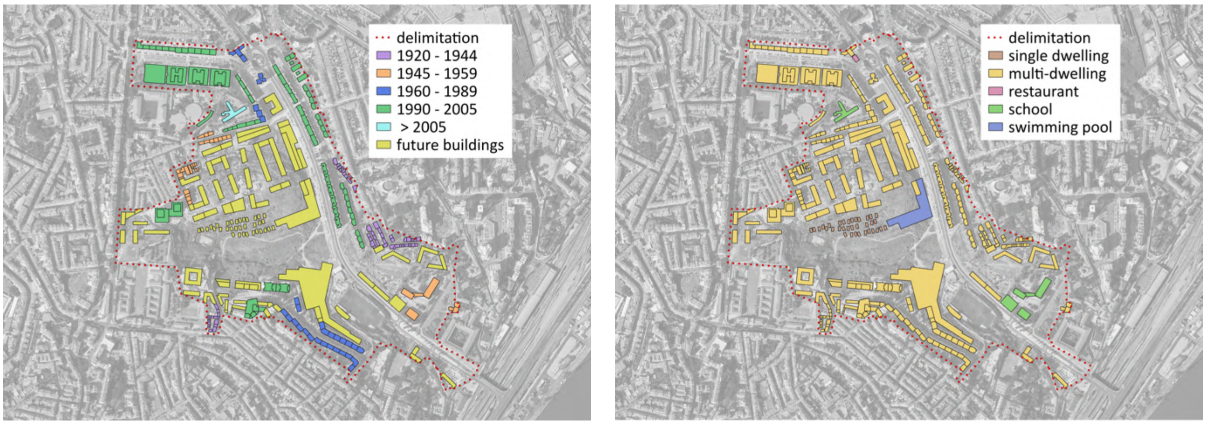


Figure 4.9 - VSA building typologies

4.7 Geopackage format

QGIS offers an efficient format for storing all the layers in a single file, Figure 4.10. The neighbourhood GIS information can then be easily shared with other stakeholders for urban planning using a unique Geopackage file, instead of multiple ESRI Shapefiles. Moreover, the Geopackage can also contain a project for visualising the layer and can thus be self descriptive. In the scope of the VSA, a Geopackage file was used to store, structure and share the GIS data for the VSA.

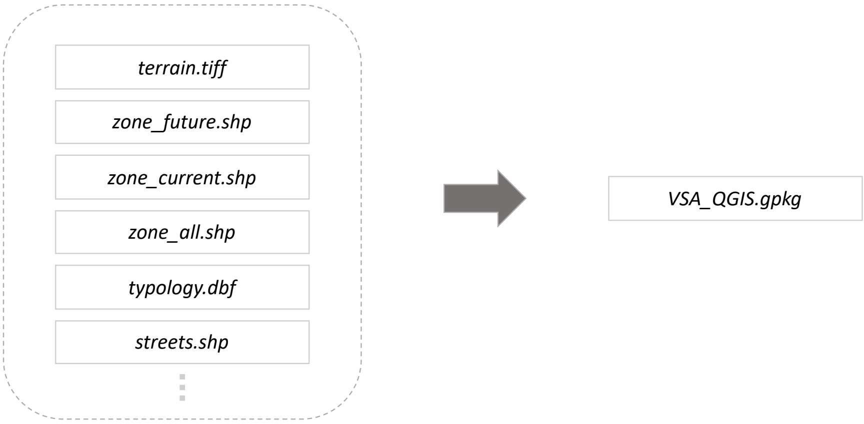


Figure 4.10 - Geopackage storing capacity of multiple layers

5 CEA – Simulate energy consumption

5.1 A brief overview of CEA

CEA is an open source computational framework for the analysis and optimisation of energy systems for urban districts and neighbourhoods. CEA follows a sequential structure integrating the simulation of the district energy demand, the design of its optimal energy supply systems and their following comparison and benchmarking relative to international indicators such as the 2000W-society. Thanks to the improvement from its multi-discplinary team of researchers, as well as the feedback and code development from its community of followers, CEA has witnessed a significant increase in the number of analysis and design plug-ins, along with an improvement in visualisation capacities.

An urban database facilitates the feeding of inputs for the energy demand simulation by querying information to open external sources such as OSM for the building geometries and street layout or to EnergyPlus for the TMY weather data. Moreover, default archetypes are accessible for the Swiss and Singaporean context, although the developers recommend the use of locally designed archetypes to respect the specific details for any project. These features enable the modeler to build a first model of the neighbourhood with little to no data. Afterward, depending on the desired level of reliability, the default inputs can be replaced by imported files. The energy demand simulation provides a spatio-temporal distribution of energy consumption for buildings with respect to their end-use.

The energy supply systems can be defined by the user at the start or can be locally conceived and optimised via CEA. To do so, CEA integrates a bi-level evolutionary algorithm to design optimal distribution, conversion and storage systems. These include, for example, the design layout of thermal networks, the selection of HVAC systems and the exploitation of endogenous energy resources. The generated scenarios can be assessed on their environmental, energetical and economical performance. Pursuing a holistic approach, CEA builds on peripheral units for the life-cycle analysis, embodied energy estimates, and capital and operational costs calculation for the infrastructure. A decision module enables the DM to select between the scenarios according to preferences.

Finally, CEA is provided with a multi-scale and multi-dimensional visualisation tool. Estimates of the energy demand and GHG emissions can be aggregated following different spatial scales (i.e. building or district) and temporal scales (i.e. hourly to annual).

Within the VSA project, CEA was used to simulate the energy demand of the neighbourhood. To do so, the existing and future buildings were assigned construction standards. Likewise, each building was assigned an occupancy type determining the building function, but also describing the behaviour of its occupants. Taking account of uncertainty regarding the current state and future evolution of the space heating and cooling conditions for residents, two different thermal comfort scenarios were designed and tested on the existing residential buildings: the restricted and the comfort scenario. As a consequence of a predicted increase in heat waves from climate change, and the continuous decrease in energy poverty, the comfort scenario is a probable and desirable future scenario for VSA residents. The visualisation tools were used to present and gather insights on the dependence of energy demand with respect to the scenarios. The Thermal Network tool also enabled the optimal design of a thermal network layout for the entire neighbourhood. Finally, the energy end-use demand estimates provided by CEA were processed and fed to URBio for the design of the energy infrastructure.

Figure 5.1 - Visualisation in CEA of the VSA neighbourhood

5.2 Construction standards

As explained in Section 4.6.2, the construction standards for existing buildings are segmented following their estimated construction years. A unique construction standard was defined for future buildings.

The characterisation of the construction standards for the existing buildings is based on works led by C. Sousa [44], by J. Gouveia et al. [45], A. Vasconcelos et al. [26] and A. Pinto [46]. None of these authors published complete archetypes with regard to the modelled parameters or to the building stock considered. Sousa and Gouveia defined archetypes for the city of Lisbon. Their segmentation features are the construction year and the building type. Considering that the existing buildings are composed mostly of appartment buildings, the villa construction standards were discarded. Pinto's study of air tightness is the basis upon which a probable evolution of the "n50" factor was established in the VSA archetypes. He observes a wide variation in air tightness measurements from which he detects significant differences between appartment buildings and villas. Vasconselos et al. characterised a reference Portuguese residential edifice for the 1961 – 1990 period. The estimated values for shading coefficients and window glazing factors are used. Finally, CEA default archetype parameters are used to compensate gaps in knowledge for less important or non context-dependent building parameters.

In recent decades, new materials and construction techniques, as well as innovative technologies, have enabled engineering teams to design energy eficient building envelopes. In accordance with this aim, the Portuguese regulators have implemented ever stricter minimal accepted thermal coefficents for new construction and renovation. The estimation of the future building envelope characteristics is based on the latest regulations [47]. To benchmark the resulting archetype with the state-of-the-art in building envelopes, the field of Nearly Zero-Energy Buildings (NZEB) was researched. The insights obtained from H. Erhorn's detailed reports on examples of NZEB in the European Union [48] and from the SOLARXXI - the first NZEB in Portugal - case-study [49] validated the chosen parameter values.

5.2.1 Envelope characteristics

The envelope characteristics are defined per construction, per surface type or per surface direction. The surface types are party wall, external wall, windows, roofs and slabs/floors in contact with the ground. The directions are the four cardinal points. Table 3 describes the parameters defining the envelope characteristics and indicates their values for all constant parameters.

Parameter	**Format**	**Unit**	**Distribution**	**Value**	**Reference**
Construction weight	integer	kg/m^2	construction	165	[26]
Window shading coefficient	float	-	construction	0.29	[26]
Air exchange rate at 50 Pa (air tightness)	integer	1/h	construction	-	[46]
Fraction of GFA with electrical demand	float	-	construction	0.82	CEA
Fraction of GFA air-conditioned	float	-	construction	-	[41]
Fraction of net GFA	float	-	construction	0.82	CEA
Thermal transmittance coefficient U	float	W/m^{2}K	surface	-	[45], [44], [47]
Glazing factor	float	-	surface*	-	[26], CEA
Absorption factor	float	-	surface*	-	CEA
Emission factor	float	-	surface*	-	CEA
Reflection factor	float	-	surface*	-	CEA
Window-to-wall ratio	float	-	direction	0.21	CEA

* *required only for certain surfaces*

Table 3 - Envelope characeteristics' description

Most parameter values are taken from CEA's inventory. Following Vasconcelos et al., medium weight construction and single glazing windows are assumed for all existing buildings. Constant values are given to the net GFA and the GFA fraction with electrical demand. On the contrary, the fraction of air-conditionned GFA is subjected to the considered thermal scenario. The absorption, emission and reflection factors for the window, roof and windows are copied from CEA's default database for construction standards of corresponding construction period.

For the existing buildings, to reflect the Portuguese context, the air tightness is based on real measurements and venetian blinds are selected as shading systems from which the window shading coefficient is computed. Furthermore, to reflect Lisbon's context, the thermal transmittance coefficients U are computed as averages of Sousa and Gouveia's Lisbon archetypes. As no distinction is made between external and party walls, they are assigned the same thermal coefficients. A probable air tightness evolution is deduced from Pinto's measurements.

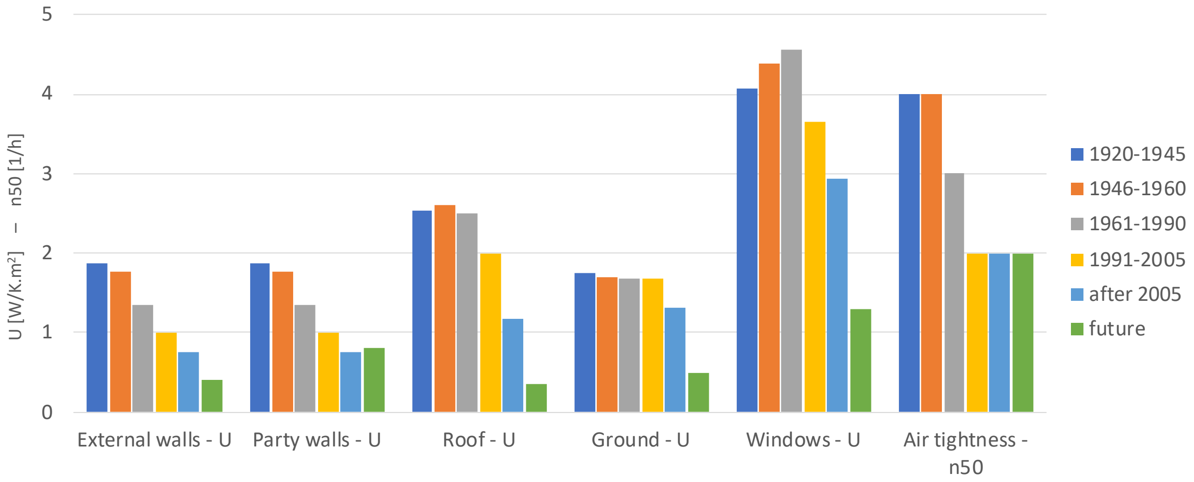


Figure 5.2 – U values and air tightness for existing and future buildings

For future buildings, the thermal transmittance coefficients are taken from the public dispatch [47], except for the windows. Instead, a double-glazed window with argon filling – a mature technology – is assumed and taken from CEA's database. This new technology reduces at little cost the heat loss during winter due to thermal conduction and the heat gain during summer due to radiation from the sun.

5.2.2 Air-conditionning systems and supply assemblies

Heating and cooling seasons were implemented to account for real operation of HVAC systems in buildings. Space conditioning is considered null outside of its corresponding season.

HVAC period of use	Start	End
Heating season	16/09	15/05
Cooling season	15/05	15/09

Table 4 - HVAC period of use

Correspondingly to cultural patterns, a natural ventilation system consisting of window opening is considered [50]. Similarly, no control systems are considered for existing buildings. Still, a room temperature control system is selected for future buildings. For simplification, it is assumed that the choice of supply technologies (heating, cooling and DHW) does not affect the useful energy demand. Consequently, to estimate the end-use energy demand, standard supply assemblies and air-conditioning systems are assumed, based on the most popular HVAC systems in existing buildings and the expected technologies for the future buildings.

Service	**Existing buildings**	**Future buildings**
Heating	Low temperature radiator (70 °C)	Low temperature radiator (70 °C)
Cooling	Mini-split AC	Central AC
Domestic Hot Water	Medium temperature water (45 °C)	Medium temperature water (45 °C)
Ventilation	Natural (window)	Natural (window)
Control system	None	Room temperature control

Table 5 - HVAC assembly definition

5.3 Occupancy type

The characterisation of the occupancy type depends on the relative importance of each archetype. The VSA is largely composed of residential buildings. The three non-residential occupancy types – swimming pool, school and restaurants – represent less than 5% of the total GFA of the neighbourhood. Therefore, the default CEA occupancy types were used in order to focus on a more realistic representation of the residential energy demand. The residential occupancy types can be divided between single and multi-dwelling mixed-use archetypes.

5.3.1 Occupancy schedules

In CEA, the occupancy type defines the internal loads, the indoor comfort and the schedules of occupancy, but also of the use and operation of the HVAC systems and other appliances. The internal loads depend on the presence schedule and are not context dependent. However, the real occupancy schedule fo a building is inherently stochastic, and CEA enables the user to integrate randomness in the mapping from the occupancy schedules to the buildings.

5.3.2 HVAC operation mode

The indoor comfort and operation schedules of the HVAC systems depend on the thermal scenario. Both thermal scenarios are illustrated in Table 6. These scenarios are based on P. Palma's research on the energy gap in Portuguese households [41] and are specific to the winter and summer climatic zones of the city of Lisbon.

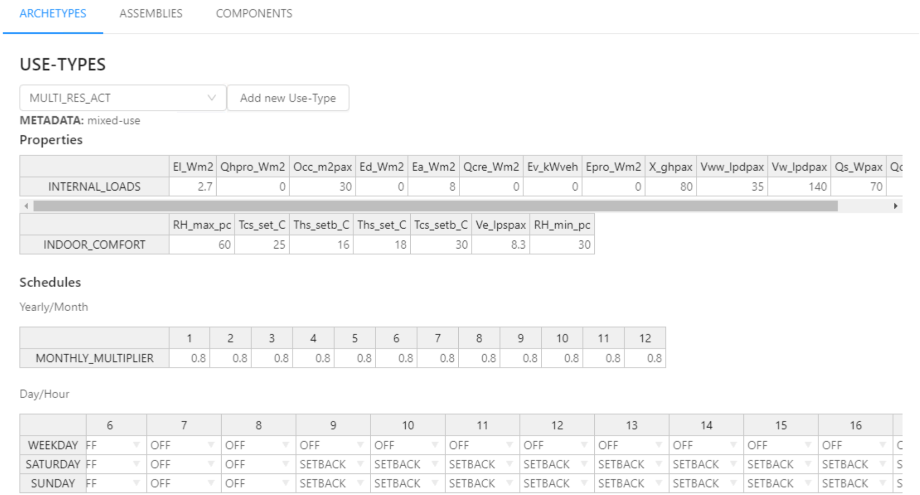
P. Palma tested various scenarios of thermal comfort on the entire building stock of Portugal. The simulations of energy demand for the scenarios and the subsequent comparisons of the theoretical final energy consumptions (TFEC) with the real final energy consumptions (RFEC) per council enabled the definitions of the strict and the conservative scenario. In the most thermal-comfort-deprived councils, the strict scenario's TFEC matched the RFEC. However, for certain councils, the TFEC from the conservative scenario provided a good approximation.

	Strict scenario		Conservative scenario	
	Heating	Cooling	Heating	Cooling
Temperature	18°C	25°C	18°C	25°C
Daily duration	3h	4h	6h	8h
Conditioned area	12,5%	12,5%	25%	25%

Table 6 - P. Palma's thermal comfort scenarios

Another dimension resides in the equipment rate of households. Currently, in Lisbon, most households (90%) are expected to be equipped with a heating system as shown by the enquiry led by M. Ferreira [51], while the penetration rate of cooling system is much lower (20%). This reflects an EU and a Portuguese characteristic, i.e. low mechanical air conditioning penetration when compared to Japan and the United States, and the use of natural ventilation and other passive measures as cooling strategies. Due to climate change and the exposure of the Iberian peninsula to summer heat waves, these characteristics may change and lead to a higher adoption rate of air conditioning systems.

CEA incorporates a higher-level of detail than Palma et al. simulations. Indeed, CEA requires schedules of heating and cooling. These schedules attribute one of 3 modes separately to the heating and cooling systems: setpoint, setback and off. The setpoint mode ensures the respect of a stricter range of temperatures compared to the setback mode. The off mode corresponds to the disconnection of the system. Such level of detail enables the user to simulate differences in behaviour between active and inactive residents, but also implies an adaptation of scenarios.



USE-TYPES

MULTI_RES_ACT

METADATA: mixed-use

Properties

	El_Wm2	Qhpro_Wm2	Occ_m2pax	Ed_Wm2	Ea_Wm2	Qcre_Wm2	Ev_kWveh	Epro_Wm2	X_ghpax	Vww_lpdpax	Vw_lpdpax	Qs_Wpax	Qc
INTERNAL_LOADS	2.7	0	30	0	8	0	0	0	80	35	140	70	

	RH_max_pc	Tcs_set_C	Ths_setb_C	Ths_set_C	Tcs_setb_C	Ve_lpspax	RH_min_pc
INDOOR_COMFORT	60	25	16	18	30	8.3	30

Schedules

Yearly/Month

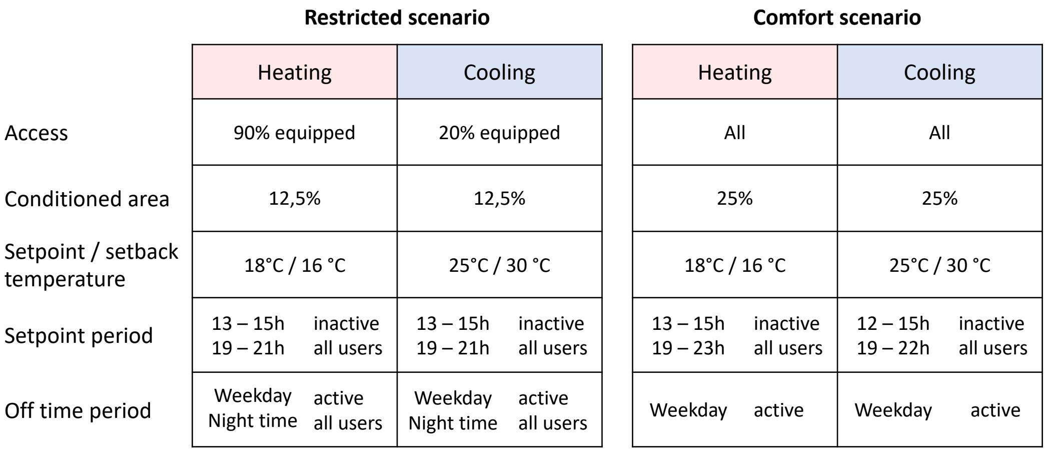
	1	2	3	4	5	6	7	8	9	10	11	12
MONTHLY_MULTIPLIER	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Day/Hour

	6	7	8	9	10	11	12	13	14	15	16	
WEEKDAY	FF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	C
SATURDAY	FF	OFF	OFF	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	S
SUNDAY	FF	OFF	OFF	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	SETBACK	S

Figure 5.3 - Defining an occupancy type on CEA

Therefore, in the light of these Portuguese conditions and the desire to prepare for higher adoption rates of cooling (and heating) technologies, two new scenarios were defined for the VSA to be simulated in CEA: the restricted and the comfort scenario. A more extreme setback temperature is defined in order to simulate the tolerance to more extreme indoor temperatures. In this case, the energy poverty is defined by the lower adoption rate of heating and cooling technologies, by a smaller conditioned area, by a shorter setpoint period and by the switching off of HVAC system (no matter the temperature) at night time for all user profiles. The remaining hours are assigned the setback mode. The simulation of both scenarios helps understand how the total energy demand might change if the thermal comfort for all buildings in the VSA is to be met.



	Restricted scenario		Comfort scenario	
	Heating	Cooling	Heating	Cooling
Access	90% equipped	20% equipped	All	All
Conditioned area	12,5%	12,5%	25%	25%
Setpoint / setback temperature	18°C / 16 °C	25°C / 30 °C	18°C / 16 °C	25°C / 30 °C
Setpoint period	13 – 15h 19 – 21h inactive all users	13 – 15h 19 – 21h inactive all users	13 – 15h 19 – 23h inactive all users	12 – 15h 19 – 22h inactive all users
Off time period	Weekday Night time active all users	Weekday Night time active all users	Weekday active	Weekday active

Table 7 - Final thermal scenarios for the VSA

5.4 Electrification of mobility

5.4.1 Overview

The municipality of Lisbon has been pushing for the electrification of mobility. Several steps have been taken in that direction: the replacement of old buses with electric buses [52], the use of electric trucks for waste collection, the implementation of a public network of electric bikes [53], the planned installation of a Reduced Emission Zone in the city center inaccessible to old cars [54], etc. Naturally, the future buildings in the VSA should be capable of managing the transition to electric mobility and correctly equipped to charge privately owned electric cars. Hence, the need to take into account this source of energy consumption.

Predicting the speed of electrification of the private car fleet is a complex and speculative task. What makes it particularly harduous is that the integration of electric vehicles (EV) is highly dependent on the local context as a consequence of political decisions, changes in user habits and economic incentives. The local contexts are at the root of the current difference in EV fleet percentage between fast transitioning countries such as Norway (12.5% in 2020) and slow transitioning countries such as Spain (0.22% in 2020) [54], but also between regions in a same country. In 2020, over 0.6% of the Portuguese passenger fleet was electrified, of which half represented plug-in hybrid electric vehicles (PHEV) with a battery and an electric motor for short distances (the combustion motor is turned on once the battery dies out), while the other half were battery electric vehicles (BEV) only equipped with an electric motor and a battery able to sustain 200 to 300 km before charging. As shown on Figure 5.4, the trend is similar to the one found in the 28 European countries.

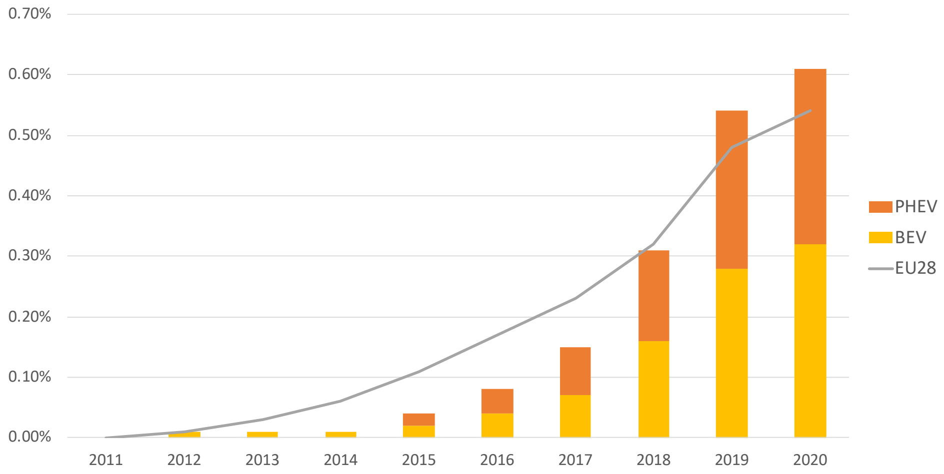


Figure 5.4 - EV spread as percentage of overall fleet in Portugal and in EU28 [55]

5.4.2 Methodology

In predicting the electric demand due to the EV passenger fleet for the VSA future buildings, many assumptions must be made. First, correspondingly to the rapid evolution, more and more parking spaces will have to be equipped. As an arbitrary decision, the electric demand is dimensioned for the year 2030.

By 2030, the world EV passenger fleet is forecast to grow from 16 million vehicles to 210 million vehicles divided one third PHEV and two thirds BEV [55]. Such an increase would correspond to a total penetration of 7,5% for a fixed-size fleet in Portugal. A similar ratio of BEV and PHEV is assumed.

Secondly, it is assumed that the daily distance per car is 40 km for residents of Lisbon [56]. Obviously for the BEVs, the entire distance is supplied by electricity. Yet, for the PHEV, this share is assumed to be only of 50%.

Thirdly, even though the efficiency per km differs between PHEV and BEV due to the respective sizes of batteries and motors, a unique efficiency of 0,2 kWh/km is assumed for all EV cars. This efficiency corresponds to the average efficiency stated by the models currently being sold [57].

Finally, electric chargers installed in the VSA future parking lots are assumed to supply electricity at 3,7 kW, which corresponds to the standard electric power supplied by domestic chargers.

5.4.3 Outcomes

In the urban development plan, one parking place is attributed per household. Additionnal parking spots are built for the service and utility sectors, however these are not considered in the computation as charging is assumed to take place at home. By precaution, it is assumed that each parking place correspond to a resident's car. The electric load is allocated during the file conversion to Urbio to each building with regard to its estimated number of EV cars. Table 8 summarises the main outcomes.

Parameters	**Value**
Residential cars	2'466
BEV cars	123
PHEV cars	62
Total daily electrical demand [MWh/d]	2,2
Total annual electrical demand [MWh/y]	810

Table 8 - VSA estimated EV charging requirements for 2030

5.5 Solar radiation

Before simulating the energy demand for the neighbourhood, CEA computes the hourly solar irradiation per surface per building for the entire year. This solar radiation integrates shading and reflection of nearby buildings. Then, the computed solar radiation is included as an external load when computing the hourly thermal energy balance. It is also used to estimate the solar potential for the buildings and the neighbourhood as a whole. In the case of VSA, the solar potential is strong and well spread. Less than 2% of the buildings possess annual solar radiation intensity below the 800 kWh/m^2.yr considered as a minimum threshold for the installation of solar technologies [33].

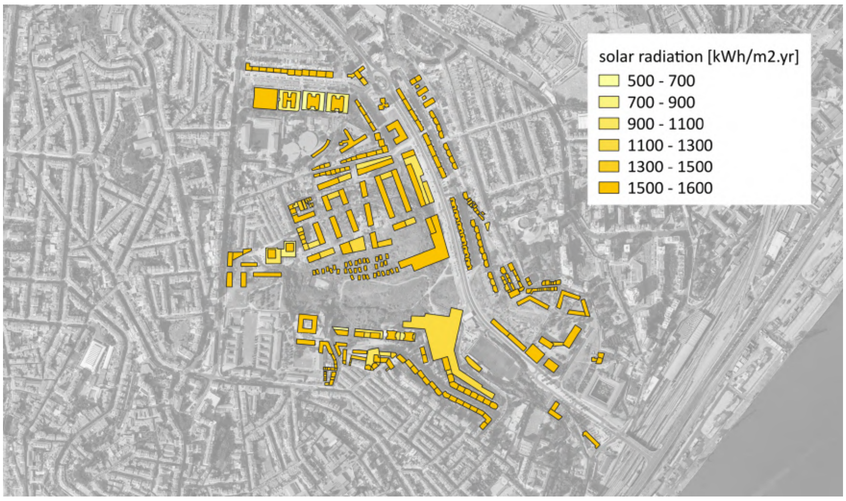


Figure 5.5 - Solar radiation intensity per building

The solar technologies can be categorised depending on whether the energy is supplied as electricity, as heat or as a mix. For that purpose, the available technologies are respectively photovoltaic (PV) panels, solar collectors with evacuated tubes (ET) or flat plates (FP), and photovoltaic-thermal (PVT) panels. The potential energy generation in the VSA for the referred solar technologies is compared in Figure 5.6. The potential for heat generation is significantly greater than for electricity. However heat is an energy vector whose energy is dependent on temperature with respect to the surrounding environment. For instance, CEA analysis shows that PVT panels have a higher total thermal energy output than solar collectors but delivered at a variable and lower temperature output. In this context, solar technologies producing low-temperature heat may not be efficient as they do not comply with the minimal temperature requirements of the heating or DHW systems. Moreover, heat distribution involves proportionately greater losses than for electricity.

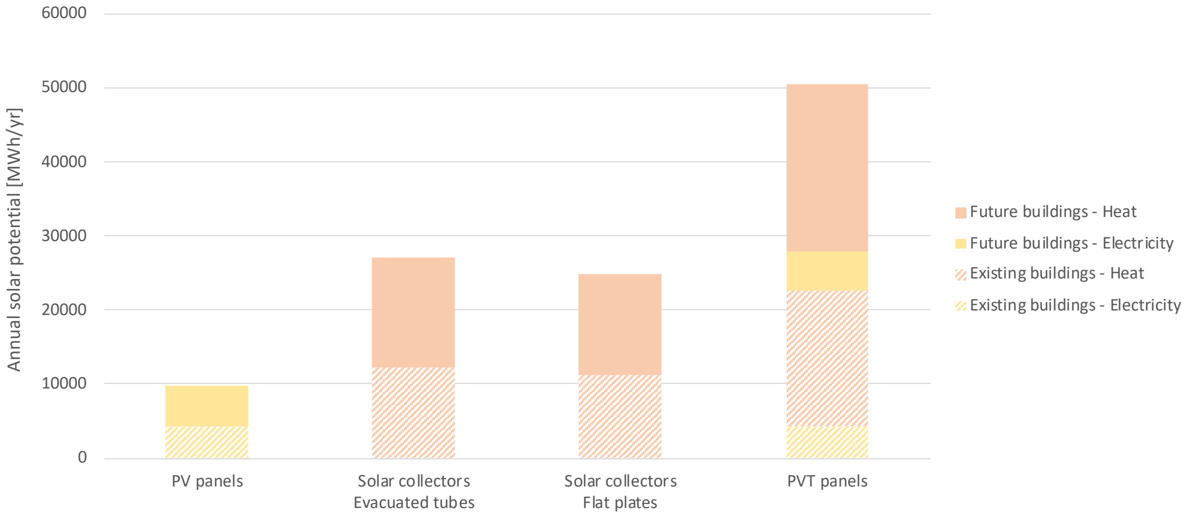


Figure 5.6 - Potential energy generation for various solar technologies

5.6 Energy demand simulation

The energy demand was simulated following the needs laid out in Section 0. The existing and future buildings were simulated together using the context-specific comfort scenario. Furthermore, the context-specific restricted scenario was applied to the existing buildings. To finish, both building stocks were simulated using CEA's Swiss default occupancy types in order to enrich the comparisons.

When comparing scenarios for the VSA, there exist two main spatial scales. Firstly, the scenarios can be compared at the building level. At such level, it is easier to gain a rapid understanding of the interaction between the building characteristics and the scenarios. The method benefits from comparing the effects of the scenarios on buildings with varied characteristics. Once these insights have been gathered, the user can better perceive the underlying phenomena at the scale of the district.

5.6.1 Building level comparisons

5.6.1.1 Residential buildings

The data of interest to be transferred to Urbio is the energy demand per end-use, i.e. space heating, space cooling, DHW and electrical demand from lighting, appliances and auxiliary machines for the HVAC systems. The energy demands simulated in CEA are classified likewise. Two existing buildings and a future building have their energy demand compared for each scenario. Only buildings equipped for space heating and cooling are selected.

Characteristics	**Building IE092**	**Building IE206**	**Building B1.2**
Building stock	Existing	Existing	Future
Number of floors	1	15	8
Construction period	1920 - 1945	1990 - 2005	-

Table 9 - Sample buildings characteristics

The main building characteristics are the construction period and the number of floors. The construction period directly defines the thermal properties of the building's envelope via the construction standard. As for the number of floors, it indirectly influences, through the resulting geometry of the building, the thermal balance per dwelling at the envelope interface.

The IE092 is a single-dwelling building. The total energy demand is highly impacted by the space heating and the thermal comfort scenario it satisfies. The CEA default scenario depicts an unrealistic situation where 75% of the end-use energy demand is related to space heating. Depending on whether the comfort or restricted scenario is considered, this percentage is reduced from 40% to less than 20%. Figure 5.7 includes the energy demand from a fictitious reference Portuguese dwelling built from the estimated energy demand per dwelling in 2013 [59] divided proportionately into the end-use shares of the Portuguese residential sector [60]. Assuming that the end-use demand from the kitchen (fridge, freezer, oven, etc.) is integrated in the electricity demand (electrical appliances), CEA slightly understimates the cooking demand and overestimates the DHW demand. Yet, the restricted and comfort scenarios represent realistic lower and upper bounds for the buildings in the VSA.

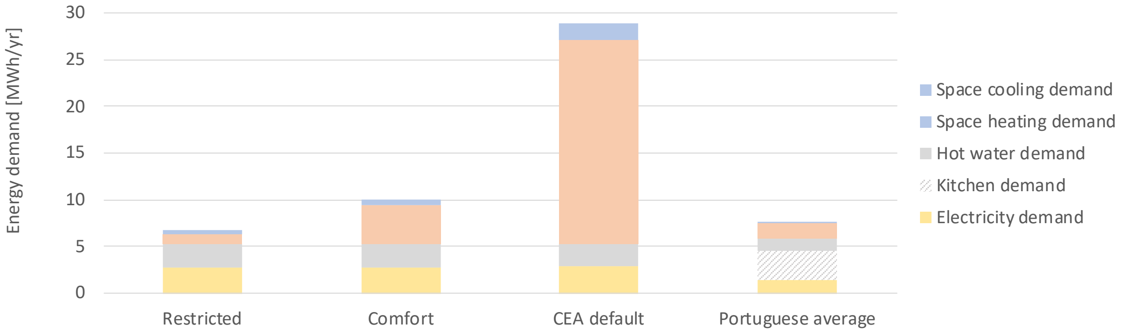


Figure 5.7 - IE092 energy demand per end-use

The energy intensity demand stands as a normalising measure to compare the energy demand of buildings with different areas and heights. As demonstrated in Figure 5.8, the effective impact of insulation on energy demand reduction for space heating accounts for most of the difference in energy demand intensity between IE092, and IE026 or B1.2. Indeed, both buildings attribute significantly lower shares of their final energy demand to space heating in the comfort scenario. Interestingly, space cooling follows a similar trend, but with a smaller extent. As a consequence, space cooling can end up representing a higher share of energy demand than space heating for well-insulated buildings. This is the case for the future building B1.2 for which space cooling represents five times the energy demand for space heating. On the contrary, for IE206 the energy demand share for space cooling remains lower.

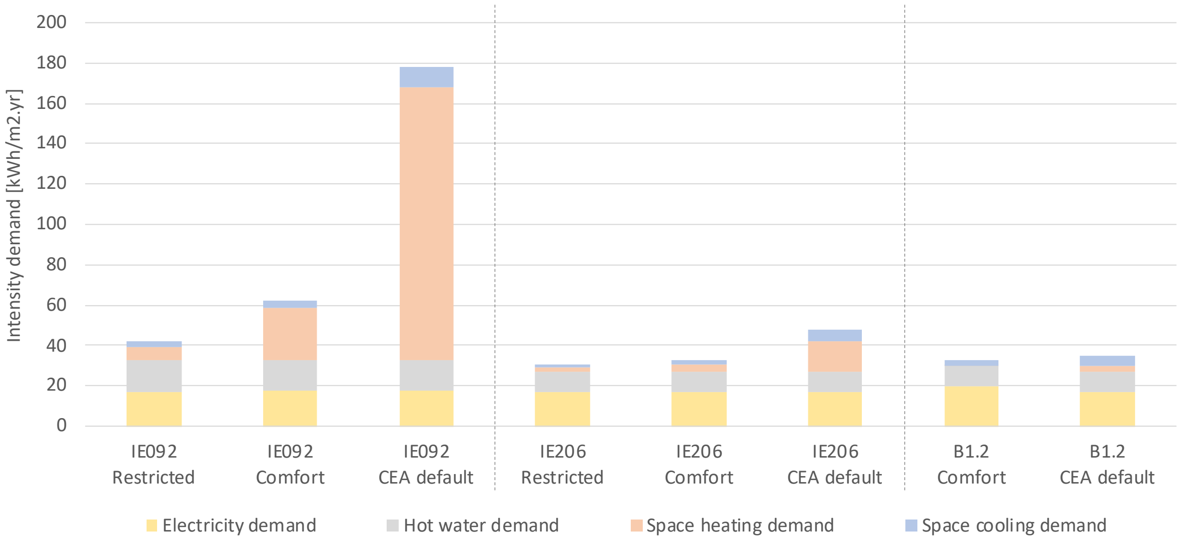


Figure 5.8 - Energy demand intensity per end-uses for selected buildings

To conclude, renovation of the envelope of an antique building to current standards seems, from the simulation results, to reduce by about 15% the total energy demand of the buiding, while simultaneously improving the thermal comfort of its inhabitants. This result has been documented and observed in different EU countries [60] [61]. Studies show how occupants adapt their thermal comfort requirements depending on the level of building insulation, translating into an underconsumption before building renovation and a subsequent increase in comfort standard afterwards. This behavioural pattern has strong impacts when estimating the future energy gains following renovation programs.

Also, as a consequence of improved thermal performance of the building envelope, it becomes increasingly important to properly characterise the energy demands for end-uses not related to space conditioning: DHW, electrical appliances, cooking, etc. In that respect, CEA could shift from the definition of general occupancy types using energy demand intensities per floor area as parameters, towards a hybrid method allowing for the definition of energy demands per dwelling or person, as there are end-uses whose intensity can be better described by the number of residents rather than by the size of the apartment or building.

5.6.1.2 Swimming pool

The VSA urban development plan includes the construction of a municipal swimming pool for residents. The swimming pool represents close to 25% of the DHW demand for the future buildings. Consequently, it is important to characterise it properly and calibrate CEA default scenario for swimming pools. Based on Zuccari et al. analysis of Italian swimming pools [63], the scenario was adjusted in order to obtain a realistic energy power consumption for pool heating of 150 kW, corresponding to the standard heating demand for a pool of 50m x 12.5m. The remaining DHW demand is caused by the existence of other services (showers, lavatories, etc.). Figure 5.9 exemplifies the power consumption variation along a typical week of March.

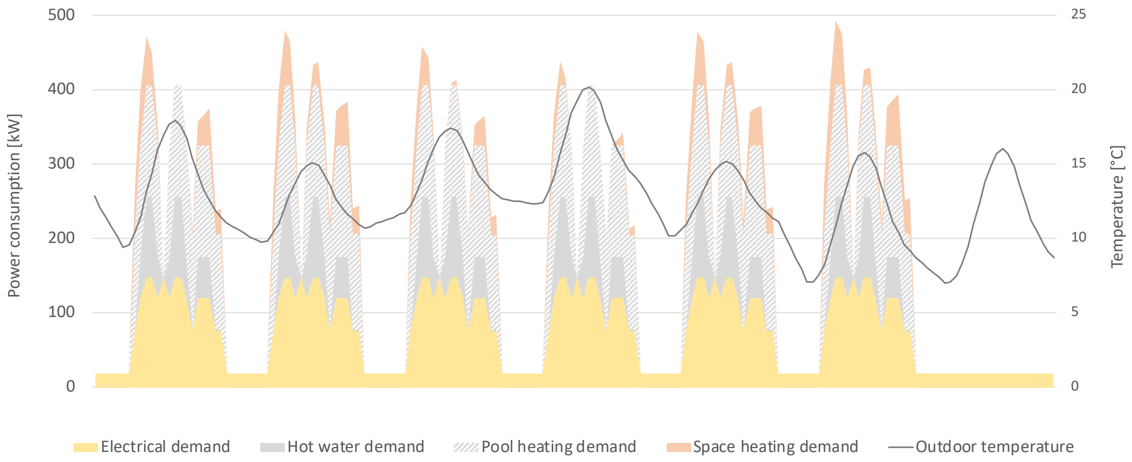


Figure 5.9 - Swimming pool load curve

Swimming pools require a lot of energy to operate. Indeed, in addition to energy needs that are common to all types of sport facilities (space heating, lighting, etc.), they also have particular requirements such as water heating, filtration and water replacement. However, they also withhold a potential for considerable decrease of their final energy demand through the reduction of heat losses, the recycling of heat and the implementation of renewable technologies to supply the residual demand.

For instance, Zuccari et al. have shown that using thermal swimming pool covers during the night-time and other closing hours can help reduce about 12% of the total heating needs. Such measure can be easily implemented in swimming pools regardless of their construction year. Also, swimming pools expel on a daily basis around 5% of their total volume of water. The heat contained can be recovered for preheating the fresh water feed through heat exchangers or via heat pumps, respectively recovering 60% to 80% of the heat. Finally, high efficiency systems can supply residual demand for pool heating. These include air/water source or geothermal heat pumps with coefficients of performance (COP) equal or greater than 5. The low temperature requirements also enable the use of non-glazed solar collectors compared to the more expensive standard panels, and with higher performance at these operating temperatures.

5.6.2 District level comparison

For existing buildings, the space heating accounts for 10% to around 50% of total energy demand depending on the scenario considered. However, for space conditioning end-uses, the relative increase in energy demand from the restricted to the comfort scenario is greater in space cooling than space heating, as explained by the low adoption rate considered for cooling technologies (20%) compared to heating technologies (90%) for the restricted scenario.

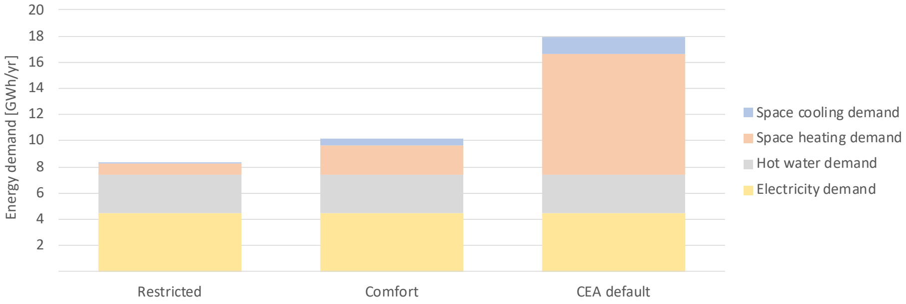


Figure 5.10 - Existing building stock energy demand per end-use for all scenarios

For future buildings, the EV demand in 2030 represents little more than 10% of the electricity demand for future buildings. The EV demand can in the future represent flexible demand whose power consumption can be adapted depending on generation from renewables. The district level comparison between existing and future buildings show the same trends concerning space conditioning and the relative increase in share of electricity and DHW demands. The significant decrease in the space heating share of energy shown for future buildings emphasizes the importance of selecting efficient materials and technologies for building envelopes. Two synergies should be underlined. First, the pool heating occurs during the day while residential DHW demand takes mostly place early in the morning or at night. Secondly, since the space cooling demand occurs during summer while DHW demand happens all year round, it can be expected that the cold and heat supply balance out on a daily basis during summer. Both synergies should be taken into account when designing the thermal supply systems, particularly when considering district-scale supply systems.

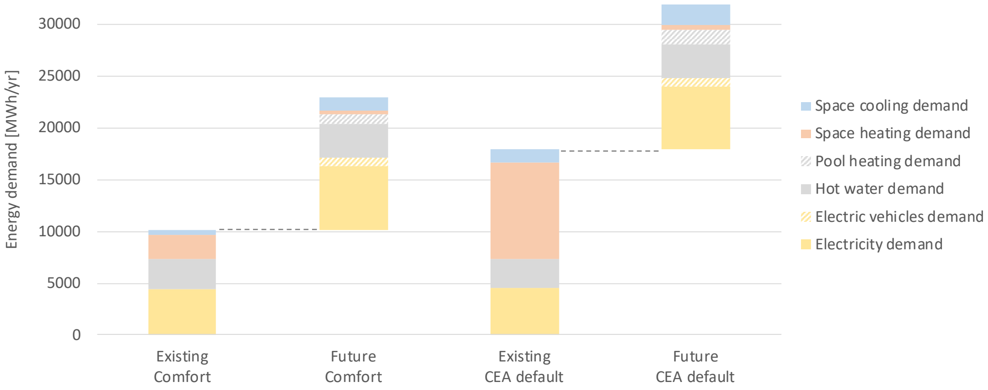


Figure 5.11 - VSA energy demand per end-use for comfort and CEA default scenarios

5.7 Thermal network layout

Until recently, thermal networks were uniquely applied for district heating purposes. Nowadays, district networks are also being built and used for district cooling, although they remain marginal compared to district heating systems. Together, they form the family of district heating and cooling (DHC) applications.

For many years, the fundamental idea of district heating was to "*use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a distribution network of pipes as a local market place*" [64]. The excess heat sources were found in combined heat and power (CHP) plants, waste-to-energy plants and industrial processes. However, in recent decades, renewable heat sources such as geothermal wells, solar collectors and biomass fuels have been used singlely or as a complement to the traditional heat sources to supply heating networks. Today, district heating systems are being built for their ability to supply many societal heat demands with a lower primary energy supply and at a lower environmental cost than decentralised heating systems [65].

Being an alternative to the generic decentralised boilers, district heating implementation rates have depended significantly on the historical evolution of fuel prices, as well as the presence of local heat sources in dense urban areas with concentrated heat demands. However, these factors can not account for the high variation in the implementation rates between countries. For instance, while the share of heat delivered by district heating in Europe has hovered for years around 13%, there are northern and eastern countries whose shares are higher than 50%. In these cases, district heating systems have been backed up either by awareness with regard to its benefits, by an internalisation of climate impact damage costs into national taxes or fees, or by favourable national heat plans.

Since its beginnings, district heating has gone through major changes. The first systems used steam as a heat carrier. They were quickly replaced by a second generation based on water, considered more efficient with regard to heat losses and requiring less maintenance cost. The third generation introduced more lean technology with prefabricated pipes and substations, enabling a wider industrialisation and faster production of the basic components. The three generations have in common their fossil supply and their high heat demands. As for the fourth generation, its main challenge will be to supply heat from local and renewable heat sources, whose power generation is variable, and distribute it to a set of connected buildings with lower heat demands. Low temperature fluids appear to be a main feature of these future networks.

When choosing its cold sources, district cooling can use a logical merit order favouring natural and excess cold resources (through heat exchangers) first and then absorption chillers from excess heat resources, mechanical chillers or cold storages. District cooling stands apart due to its small temperature difference between the supply and return pipes. On the one hand, it calls for heat exchangers with longuer thermal lengths and a network with wider pipes than used for district heating systems with similar capacity. On the other hand, it enables temperatures closer to the ground temperature, thus reducing the thermal losses ensuing from distribution.

5.7.1 Designing the network layouts

In Europe, most customers are connected by substations to the primary network that supplies the same temperature to all customers. Each substation possesses control systems to manage the local heat demand and flow. The substation can also contain heat meters to measure the heat deliveries. As for the heat supplier, this maintains the centralised differential pressure in the network and regulates the supply temperature. Different applied temperature levels, insulation standards and linear heat densities (heat sales per route length) generate inevitable heat losses between 5 and 35% [64].

CEA enables the design of thermal networks for a set of buildings. It uses a heuristic method to connect the buildings. First, it locates the building with the highest heat consumption (anchor load) and defines it as the host for the DHC supply system. From that starting point, it connects the buildings depending on their consumption and proximity. Since the heat delivered is the product of flow and the temperature difference between the supply and return pipe, prioritising building connections with regard to their heat demand helps reduce pumping costs and thermal losses, while minimising the size of heat exchangers in the main consumer substations via the supply of higher temperature water. A network layout can be branched or looped. A branched layout defines a unique route from the heat supplier to the consumer substation avoiding the installation of redundant pipelines. On the other hand, a looped layout possesses a greater number of interconnections between substations, thus enabling the optimisation of the supply route during operation, but at a greater initial capital expenditure. It becomes pertinent to build a looped network once more than one heat or cold production sites exist. A well interconnected network structure is said to be meshed [65].

Figure 5.12 - A branched and a looped structure for the northern layout

In the scope of the VSA, three sets of buildings were defined to build and analyse DHC network performance: the northern layout, the southern layout and the future layout. The northern area only possesses the northern fraction of future buildings. They constitute a dense urban area of tall residential buildings and include the swimming pool. On the other hand, the southern layout contains the remaining buildings and is supplied by the I3 building. Finally, the future layout comprises all the future buildings. Once the layouts are designed, they are simulated for an entire year and their performance compared with respect to pumping power and thermal losses. In the absence of a functionning thermal network optimisation module, this three-layout methodology aims to provide the DMs with preliminary information about the existing alternatives for layout and building connections in the VSA. A deeper analysis should be made for the inclusion of the existing buildings in the networks in the future.

The network designs possess two characteristics that suggest looped networks to be unsuitable. First, for each network, only a single building is considered for supplying the heat and cold to the DHC network. Second, excluding the swimming pool, the VSA is essentially a residential neighbourhood, and thus the connecting buildings present very similar demand patterns. Consequently, the spatial distribution of heat or cold consumption during the day does not change. Hence, only the branched layouts are considered for analysis.

Figure 5.13 - Branched structure for the southern and future layouts

CEA's design results for the layouts are equal for heating and cooling purposes as a result of both demands being proportional to the GFA of the buildings. Figure 5.14 demonstrates that the layout north reaches the highest linear heat density, i.e. the total heat demand divided by total length of pipes. The southern layout requires many pipes for only a small energy supply. For comparison, the expected properties of a layout for all buildings in the VSA are included.

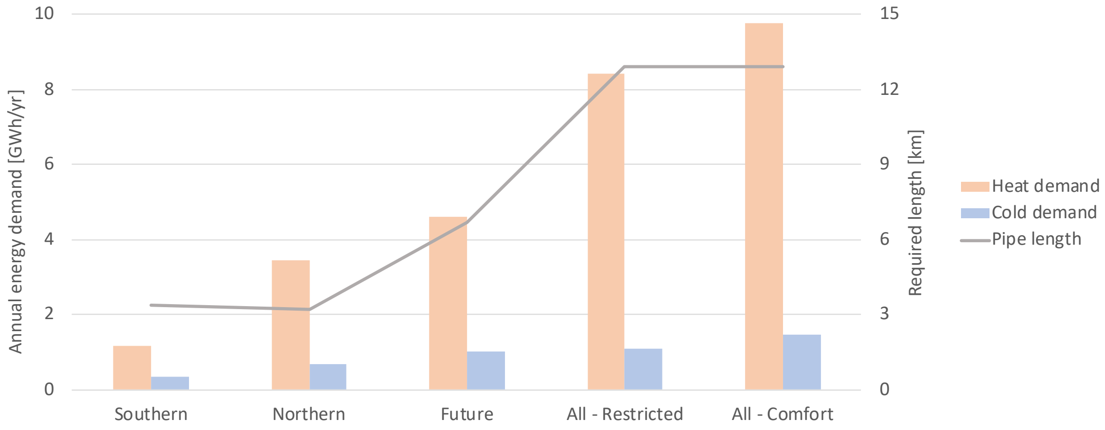


Figure 5.14 - Layout demand and pipe length per building set

5.7.2 Comparing the performances

Selecting the optimal perimeter for the DHC network resides essentially in finding the right balance between economies of scale and production advantages from having DHC systems, and dis-economies of scale from requiring a distribution network [66]. Indeed, as a network increases and a single plant site is maintained, the latter outgrows the former due to the increasing cost of pumping the network fluid from the supply to the consumption site. This trend is even more accentuated when the network expansion involves a lower linear heat density. Therefore, in the scope of the VSA, the objective is to gather insights on the optimal size of the network(s).

While testing simulations, the results have shown the limits of the parametrisation used to define space heating and cooling for the buildings in the VSA. Indeed, the definition of the future buildings as being uniquely residential omits the actual share of 20% of GFA assigned to business, thus disregarding the synergy in demand. Secondly, the use of a unique set of schedules for the activation of the setpoint mode for the space conditioning HVAC technologies, instead of a variety of schedules that represent the diversity in uses and are in accordance with the restricted and comfort scenario, result in identical temporal demand constraints for all buildings. These simultaneous heat and cold demands cause periods of high activity with an important pumping consumption and periods of stoppage where the thermal losses increase. For the above-mentioned reasons, the simulation results can not be considered as representative of a future behaviour of a district heating system, though they can still provide clues for the purpose of defining optimal network sizes.

For simplification, only the district heating networks are simulated and their performance compared. In addition to providing heat for the consumer, the plant needs to provide the pumping power that moves the water within the network and needs to compensate for the thermal losses inherent to the functionning of a district heating network. Spikes in heat demand can lead to unrealistic and sometimes unexplainable increases in the required pumping power, as shown on Figure 5.15, while thermal losses are constant.

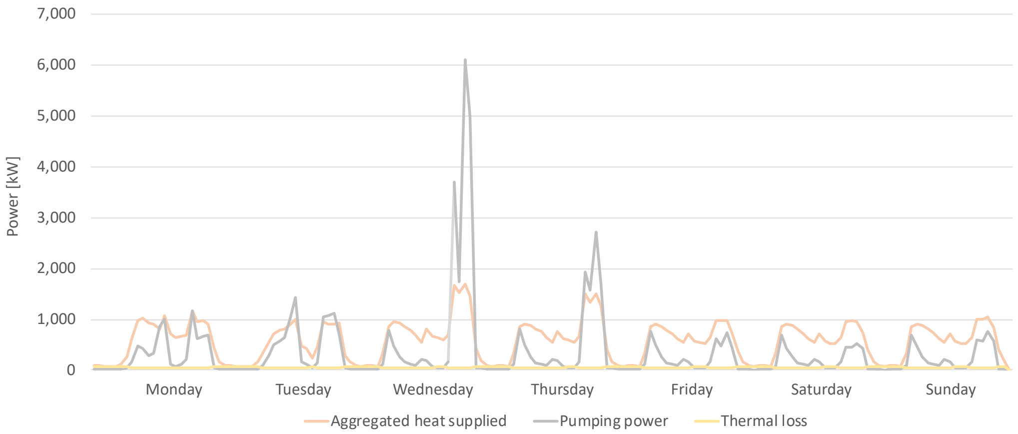


Figure 5.15 - Load curve during a typical January week for the future layout

The networks performances are compared on a yearly basis. The simulations parameters do not vary between simulations. The yearly consumption per layout, including the combined consumption of the northern and southern layout, is compared on Figure 5.16. The results show that the future layout with only a single plant site requires more pumping than a two-layout structure made of the northern and southern network. The assigned shares for each type of energy consumption vary between the simulations. In the case of the southern layout, there is close to no pumping demand. In the case of the northern layout, the pumping demand is greater than the thermal losses. The performance comparison demonstrates that in the case of the future layout there is a high pumping demand due to diseconomies of scale. A solution to the problem would be to invest in two separate layouts each supplied by a different plant.

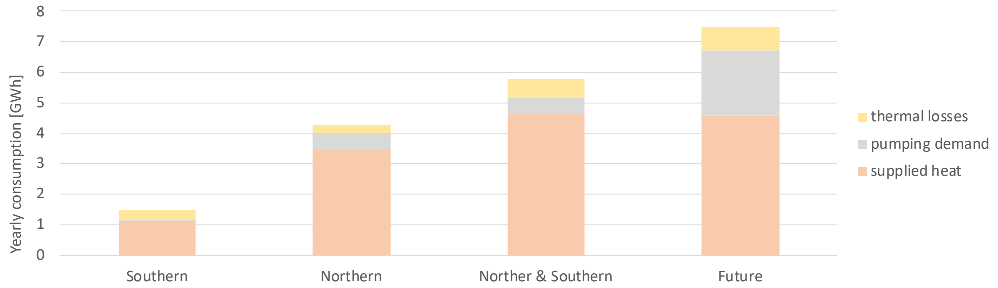


Figure 5.16 - Network-layout performances' comparison

5.7.3 Optimising the perimeter

There is a strategic interest in opting for a two-layout structure rather than a single layout. The swimming pool and the I3 building are located in proximity with unconnected existing buildings. As part of a renovation program, both networks could be extended to supply the existing buildings. However, in the case a single network was installed, extending the network would probably aggravate the pumping demand.

As shown in Figure 5.14, the southern layout registers a low linear heat density. This is due to its connection to distant and isolated buildings. Besides requiring higher investment in the thermal network, the extended network causes high thermal losses. Therefore, a new network including the northern layout and a more concentrated southern layout was tested.

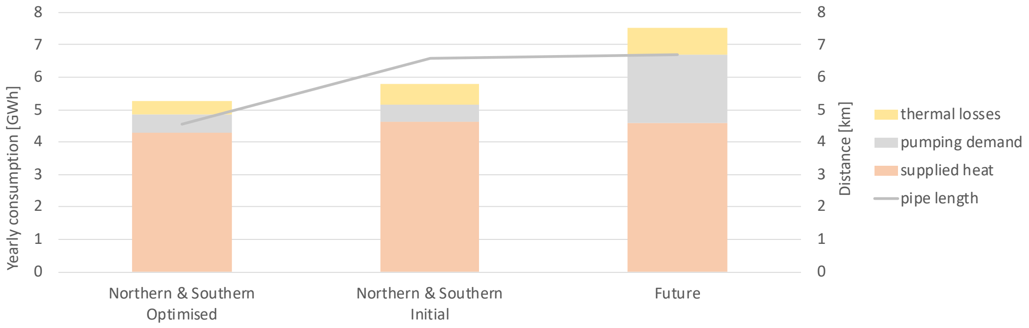


Figure 5.17 - Comparison of the optimised layout

The optimised layout reduces by over a third the pipe length with little impact over the heat supplied. Naturally the thermal losses also decrease. The southern layout possesses a lower heat demand from the future buildings. Yet, it possesses also a higher potential for expansion comprising the existing buildings within and outside of the VSA perimeter. An optimised two-layout structure is illustrated in Figure 5.18. The pipe diameters are included.

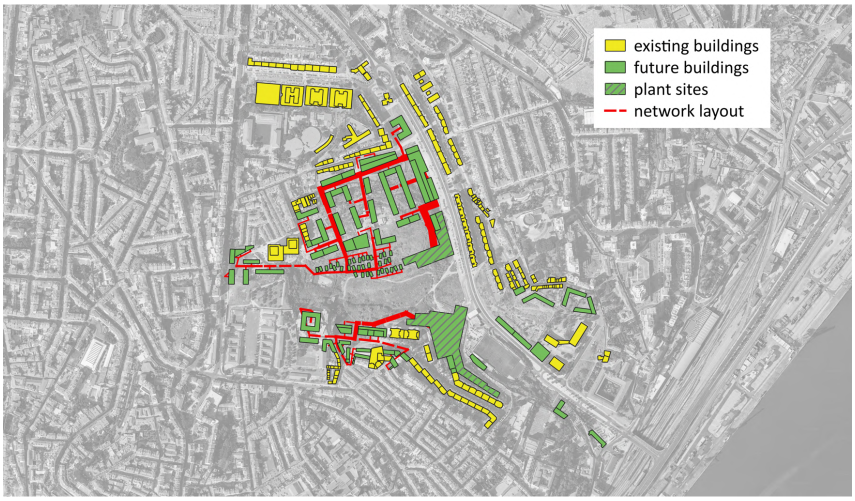


Figure 5.18 - Optimised two-layout structure

5.7.4 Exploring the fifth-generation district heating and cooling potential

The fourth-generation district heating system provides an alternative to the traditional system with centralised power stations supply high temperature water. Such systems incur high losses, particularly in summer when they operate only to meet DHW demand. As for the fourth generation, via its lower network temperature it is able to take advantage of a greater share of endogenous resources for heat recycling and to integrate renewables in the heat production. However, the pipes are not designed to provide both heating and cooling services.

Buffa et al. advocate for a fifth generation of district heating and cooling (5GDHC) system able to provide heat and cold to all its connected buildings using a unique network [67]. They examined 40 thermal networks in Europe corresponding to their definition of 5GDHC and estimated a growth rate of 3 systems per year. A 5GDHC system relies on decentralised water source heat pumps connected to a network of flowing water whose floating temperature ranges between 0 and 30°C.

A distribution temperature close to the ground minimises the heat losses, while enabling the heat recycling from low temperature endogenous heat sources such as sewage water or the integration of low enthalpy renewable energy sources like solar collectors. Moreover, it provides the same advantages as a ground-source heat pump compared with an air-source heat pump, which include a higher temperature when acting as heat source and a lower temperature when acting as a heat sink. With a network water temperature that is more stable than the ambient air results in a higher efficiency for the distributed heat pumps and enables them to work independently in heating and cooling mode. Moreover, by sharing a single network helps opposing demands (heating or cooling) complement each other, and the excess heat emissions or absorptions balance out at the entire network-scale. To compensate for uneven periods, a central thermal seasonal storage can be used.

On the downside, 5GDHC systems call for a higher initial investment from the heat pumps and the need for individual DHW tanks at the substations. Moreover, the system requires more electricity for the heat pumps at the substations, though it saves energy through the absence of a centralised heat supply system and the operation of a single network. Finally, the low temperature difference between the supply and return pipes (such as with district cooling system) leads to larger pipes and thus more pumping energy. Hence, a 5GDHC network make sense only if it combines the functions of a district heating and a district cooling network, not acting as a mere substitute for a fourth-generation district heating system.

The VSA possesses many characteristics that would suggest 5GDHC network to be a viable and promising option to supply heat and cold in the neighbourhood. Firstly, synergies have been found for the time of usage between the swimming pool and the residential buildings, but more importantly between complementary heating and cooling demands during the summer, when the heat demand for DHW is expected to exceed the cooling demand, thus enabling an almost perfect recycling of the heat emissions from the chillers by the heat pumps for DHW demand.

Secondly, even though the future buildings could be equipped with unconnected ground-source heat pumps, it becomes complicated to introduce such systems into existing buildings. In this case, a 5GDHC system can overcome such problems, as well as compensate the ensuing impossibility for the existing buildings to obtain seasonal heat storage from increased capacity in one or several centralised heat storage systems. For instance, such systems could store heat underground or in large water tanks during summer, a period of low heat consumption and high solar energy production, to be used during the next winter. A 5GDHC network allows the capacity to be extended in a second stage to the existing buildings as part of an integration process of future buildings to existing buildings with envelope renovation, and new, efficient and sustainable HVAC systems.

Finally, the 5GDHC technology is integrated within two major technological trends. Just as the spread of EV announces the upcoming electrification of the mobility sector, the 5GHDC technology accompanies the sustainable and rational electrification of the thermal sector in urban areas. Furthermore, the cluster of water-source heat pumps are part of the smart thermal grid concept, enhancing the sector coupling between electrical and thermal grids. The adoption of decentralised active substations paves the way for a new vision of DHC networks from the traditional production-centric understanding to a more consumer/prosumer-centric perspective.

6 Python – Convert files

6.1 Why Python?

Python is an open-source programming language that has been increasingly widely used in the last decade. Its success is mostly due to its construct that emphasises code readability and to its architecture that combines a small core language with a large standard library thus making it highly extensible. These two characteristics account for the success encountered with novices and seasoned programmers alike.

Python being an interpreted language (it is interpreted into computer-understandable code before compilation), enabled its developers to be less constrained in the application of the Python philosophy as described by the *Zen of Python* [68]. The small poem summarises the essence of Python as being about simplicity, explicitness, readability and understandability.

6.2 Conversion methods

The main purpose of the conversion code is to transfer the data contained in CEA scenario files to files whose format and content match Urbio requirements. In addition, special attention was given to code automation, as a way to reduce the need for user inputs and intervention in the face of changing scenarios, and to increase the code clarity. A Python class was created to facilitate the access to the paths of the files contained in CEA's scenario structure. These path collections followed a network structure and implemented methods for obtaining a file's absolute path from its name or for iterating on all files in a folder.

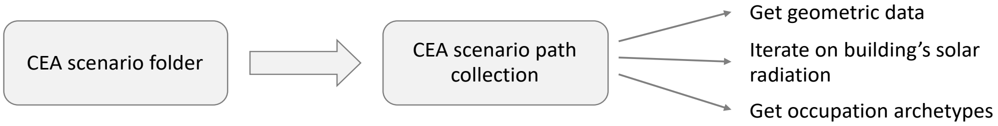


Figure 6.1 - The path collection's methods

Python is inherently a readable programming language, however a standard Python file remains limited by its inability to include rich text or images, as well as to print and present intermediate results. Therefore, a Jupyter notebook served as a template for the conversion code. Although they can effectively enhance the user comprehension of the code, they require each cell to be run separately, thus preventing their use in wider architectures.

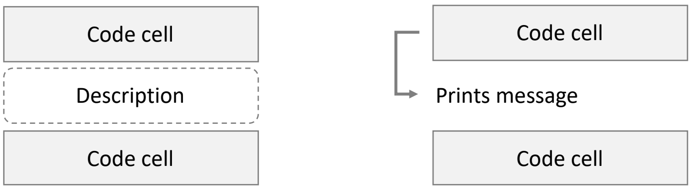


Figure 6.2 - Relevant Jupyter notebook's features

6.3 Data transfer

As far as possible, data is sourced from the CEA project folders, where much of the data from external documents is also stored. The data from CEA includes geometrical data on the buildings and the streets, climate data on the external and ground temperatures, and attribute data about energy demands, solar radiation and installed HVAC systems for the existing buildings. As for the data from external documents, it defines properties of the fuels. In summary, CEA and the external documents provide respectively neighbourhood and Portugal-specific information.

6.3.1 CEA information

In addition to the time series of external temperatures for a TMY, the EnergyPlus weather file provides, for instance, monthly measurents of the ground temperature at different levels of depth or ASHRAE standard temperatures for the design of heating and cooling systems [69]. Ground temperatures are required to compute the COP in heating and cooling mode for ground source heat pumps. As for solar radiation, the values are summed up for the entire year from the irradiation estimated and used in CEA energy demand simulation.

In addition to the geometrical, solar radiation, and energy demand data for the buildings, the conversion program converts the building occupancy type into its CityGML correspondent [22]. The CityGML data framework developed by the Open Geographical Consortium is already supported by several UBEM tools enabling the easy integration of distinct tools for a single project.

During the code writing, it was notrd that a limitation for data transfer between CEA and Urbio was the loss of information resulting from differences in their underlying data structure and requirements. Indeed, the information in the CEA scenarios cannot be fully transferred to Urbio, and likewise Urbio's data requirements can not be fully fulfilled by CEA. Moreover, the terminologies differ in some cases, and perfect correspondence can not be reached as with the types of installed HVAC technologies.

Another drawback of any conversion code is its limited validity period. Both softwares evolve independently, and previously existing compatibilities can disappear with subsequent updates. Hence, maintenance efforts are regularly required to ensure a lasting functionning of the code.

6.3.2 External information

Data more specific to the optimisation process energy infrastructure not included in CEA was collected and stored in external documents to which the conversion code referred. This external information was specific to Portugal and contained values for the prices, the renewable energy source (RES) share, the carbon intensity (CI) and the PEF of the fuels. The RES share asserts the percentage of the energy from renewable energy sources for each fuel. The CI estimates the amount of emissions per unit of embodied energy for each fuel. The PEF defines the ratio between primary and final energy.

At the time of this thesis, Urbio did not include models of district cooling networks. Consequently, the fuels considered are electricity, natural gas, hot water via district heating, and wood chips (pellets). Wood chips are the only fuel whose default price is maintained. The electricity and natural gas prices were taken from the national database *Pordata* [70] [71]. The selling price for electricity produced by the consumer is picked from the Portuguese legislation [72]. The hot water price is based on the fare applied by Clima Espaço, the only existing commercial heating network in Portugal [73]. All prices include taxes.

Electricity, natural gas and hot water demand final price possess a fixed component proportional to the power signed up for and a variable component proportional to the total consumption. Urbio and other optimisation tools account singlely for the variable component, thus leading to an approximation of reality. Moreover, in case of electricity and natural gas, EDP and other energy providers propose a state-subsidised social fare for low-revenue households which might apply to certain households moving into the VSA as part of the *Renda Acessível* program. For simplification, one standard fare per fuel was taken into account.

Carrier	**Unit**	**Value**	**Reference**
Electricity (buy)	€ / kWh	0.215	[71]
Electricity (sell)	€ / kWh	0.095	[73]
Natural Gas	€ / kWh	0.091	[72]
Hot water	€ / kWh	0.039	[74]
Wood chips	€ / kWh	0.061	-

Table 10 - Energy carrier prices

The RES share, the CI and the PEF of fuels touch different aspects of a sustainable neighbourhood energy infrastructure. Indeed, they emphasise different objectives, i.e. the maximisation of renewable energies, the minimisation of emissions or the optimisation of energy efficiency. Though these characteristics are decisive for the design process and building certifications, the methodology used to calculate their values still depend on countries such as for the PEF in Europe [75]. It is crucial to establish a common framework for the computation of these values in order to enable cross-country assessment and build common databases. When available, the values were taken from the national department for energy [76].

Carrier	**PEF [-]**	**GHG emissions [kgCO2eq/kWh]**	**RES share [%]**	**Reference**
Electricity	2.5	0.144	52	[76] , [77]
Natural Gas	1.11	0.202	0	[76]
Wood chips	0.06	0.0108	100	[76]

Table 11 - Fuel characteristics

7 Urbio – Develop infrastructure scenarios

7.1 A brief overview of Urbio

Current energy infrastructure designs invariably incorporate multiple criteria such as the operational and/or investment cost, GHG emissions, RES share, primary energy, etc. Hence, no optimal solution exists *per se*, but rather a group of equally optimal solutions with regard to the objective functions selected and representing varied compromises. The DM makes the final choice depending on the scenario performance with regard to the objectives and additional indicators.

Urbio models urban energy infrastructure design as a suite of decisions with regard to the type and dimension of the infrastructure. As the planning process goes ahead, the margin for flexibility diminishes, and the remaining decision outcomes are the logical results of previous decisions. Accordingly, Urbio variables are categorised as decision variables, i.e. decisions taken by planners at an earlier stage of the process and applied to a larger scale, and as follower variables, i.e. later local decision that represent logical consequences of the decision variables.

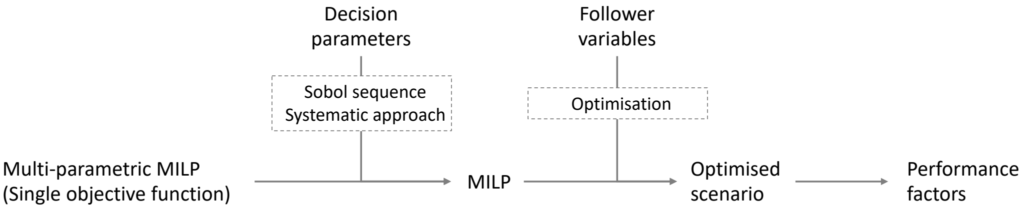
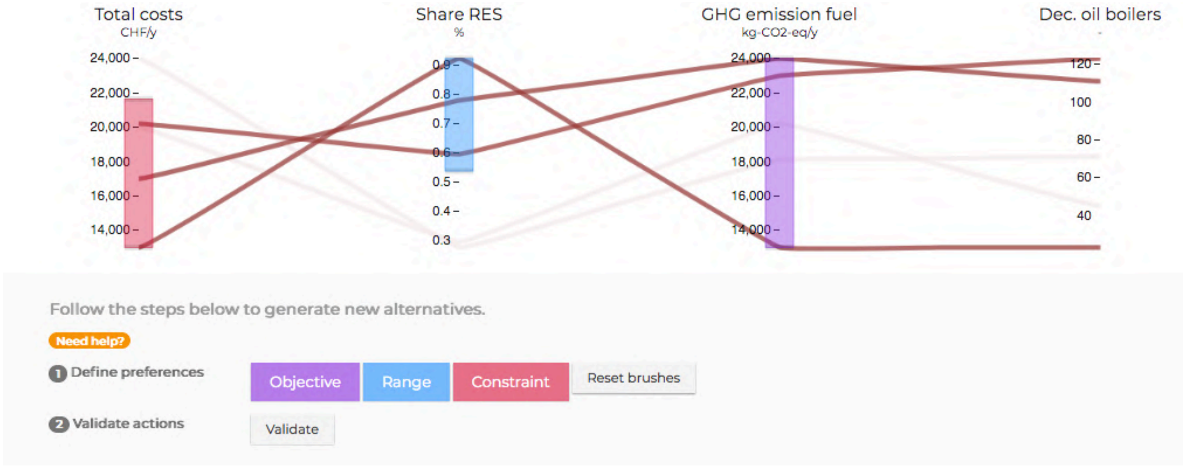


Figure 7.1 - Urbio workflow

Sampling techniques vary a parameter in order to capture the decision space within its exterior bounds and interior stable regions and tipping points. The DM can define range of objective or indicator values to explore, thus promoting a deeper understanding of the way these parameters affect the principal objective. A systematic approach ensures that equally distant values are chosen for the parameters in order to rigorously map the entire decision space. On the other hand, a Sobol sequence emphasises the selection of groups of values that promote a marked difference in outcomes.

A fundamental difference between Urbio and other neighbourhood energy infrastructure design tools is its use of interactive optimisation (IO) versus *a posteriori* decision making. IO methods favour the fast computation of a small number of solutions from which the DM can gain insights and restrict the search space. Similarly, fast computation enables fast testing of hypotheses on the values of parameters. This can be useful when optimising based on parameters whose future evolution is uncertain. In the case of urbanism, these can include, for instance, the price and carbon intensity of fuels or the efficiency of technologies.

Urbio is equipped with a web platform for directing the optimisation process and visualising the scenario performances. The GUI possesses a customisable array of axes: one per variable of interest picked by the user from a large list of available variables. These axes are used to assign the objective function, ranges and constraint intervals. In addition, once the optimisation is completed, the solutions are loaded, and their position on each axis enhances understanding of the compromises inherent to the project and the interconnexions between variables.



Follow the steps below to generate new alternatives.

Figure 7.2 – Urbio's polyline chart

In addition to the polyline chart, Urbio provides access to a scenario board where the most interesting scenarios can be stored, compared and classified with respect to their total score. Furthermore, the technology selection and dimensioning of the scenarios can be displayed on maps for more detailed analysis. For example, the color of a circle defines the energy conversion system installed and the size of the circle corresponds to its capacity relative to identical systems installed in other buildings in the neighbourhood. Finally, the data for each alternative energy infrastructure can be exported as shapefiles and further explored in GIS applications such as QGIS.

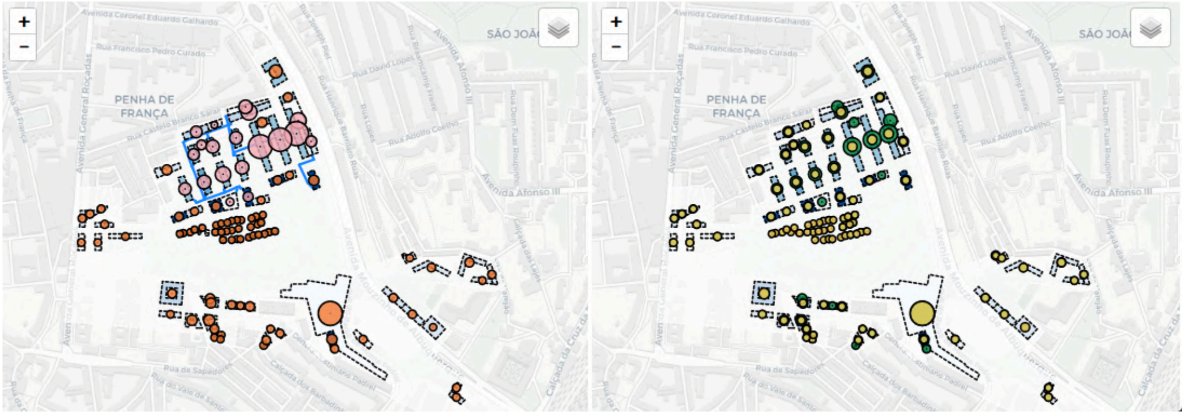


Figure 7.3 - Displaying the scenarios on map

7.2 Guiding the optimisation

In the scope of the VSA, Urbio is first used to propose infrastructure solutions to the DM with additional information about their performances with respect to economical, ecological and energetic variables. In the spirit of designing a sustainable neighbourhood, the energy supply systems will be optimised with regard to the GHG emissions for different TAC.

The economical variables considered are the TAC, the annualised operational expenditure (OPEX) and the annualised capital expenditure (CAPEX). Though given on a yearly basis, the CAPEX represents the initial investments to be made in the energy supply systems. As for the OPEX, it represents annual costs related to the operation and maintenance of the supply systems. The ecological variable is the operational GHG emission level, while the energetic variables include the RES share and the annual primary energy consumption.

The selected scenarios are then tested with regard to their performance in a future context. Indeed, even if the scenarios are adapted to today's situation, it is even more crucial to assess whether they remain suitable in the changing context. In this respect, a neighbourhood energy supply system should be designed with the future in mind in order to avoid stranded assets.

Two major trends are taken from the strategy plan drawn up by the Portuguese government in the *Roteiro para a Neutralidade Carbono* (RNC) [78]. The RNC foresees an increasing share of renewable energy in the electrical mix with a target of 100% by 2050. Moreover, it underlines the need for green taxation that penalises fossil fuels while promoting clean technologies.

In its 2019 report on carbon pricing, the World Bank explained that around 30% of Portugal's emission were covered by a carbon tax [79]. The carbon tax averaged 12,5 €/tCO_2 – eq when it was estimated that to reach the Paris agreement, the minimal range for carbon taxing should be between 35 and 70 € / tCO_2 – eq in 2020. As Portugal pushes for more sustainability, it is likely to implement higher taxes on all fossil fuels including natural gas. In the scope of this project, it is conservatively assumed that by 2030 Portugal implements a carbon tax of 35 € / tCO_2 – eq and increases it to 70 € / tCO_2 – eq by 2040.

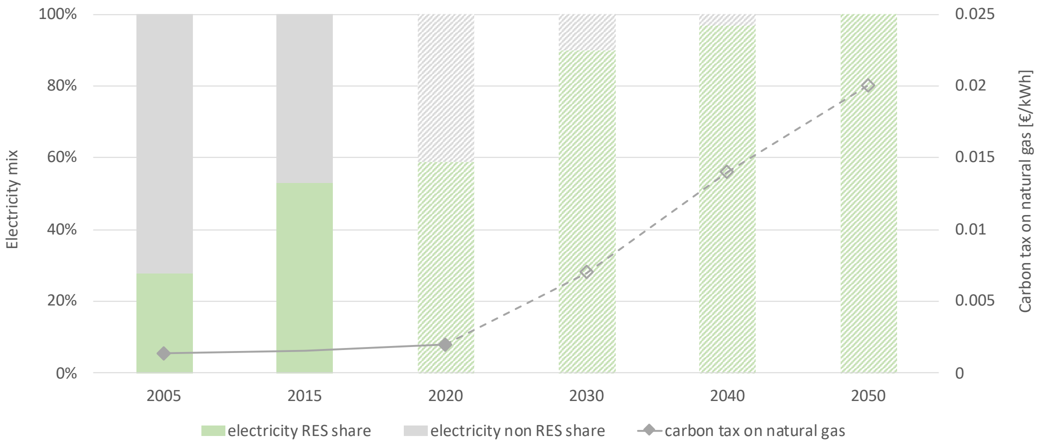


Figure 7.4 – Future trends for the energy context

7.3 Proposing scenarios

The infrastructure scenarios generated by Urbio define energy flows for the entire neighbourhood. The energy flows follow an ordered sequence of stages. The stages can be divided in types and in perimeters. The types refer to whether the stage involves the distribution of the energy vector or its conversion into another energy vector. In that sense, each type has its own infrastructure with its investment cost, as well as its distribution losses or conversion efficiencies. As for the perimeters considered, they can be classified as the city, the neighbourhood and the building. Each perimeter is managed by a different entity: the national provider, the local provider and the building owner. The building owner owns the decentralised energy systems. The local provider sells energy services such as heat and cold, while managing the local distribution of the energy fuels. Finally, the national provider guarantees the connection of the neighbourhood to the national grid through which energy is bought and sold. The distinction between local and national providers depend on the countries and on the energy vector. For instance, in the case of Portugal, there exist no local providers of electricity. Therefore, in contrast with Switzerland, the electricity exchanges take place directly between the building owner and the national provider. It should be emphasised that the chosen terminology blurs the distinction between energy providers and energy distributors.

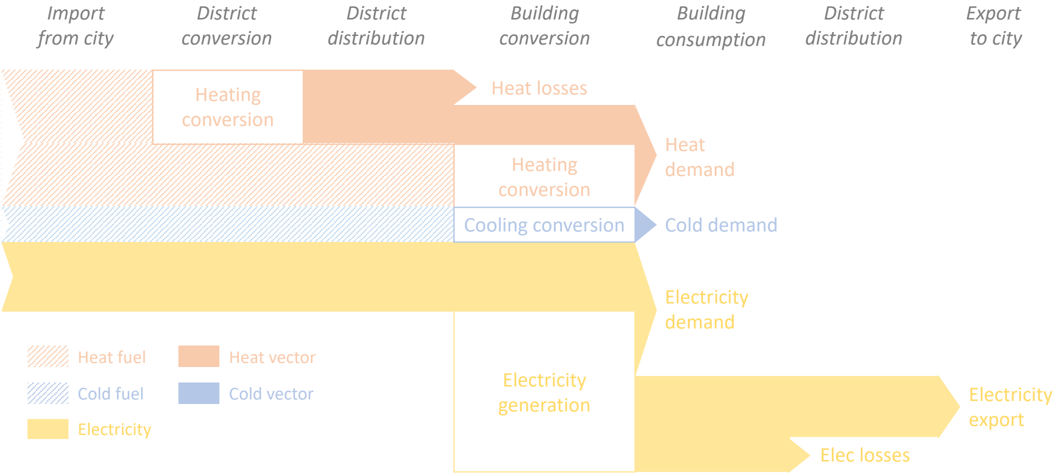


Figure 7.5 – Standard energy flows in a neighbourhood

The considered energy flows are shown in Figure 7.5. The possible heat fuels are oil, natural gas or wood to generate heat via boilers, and electricity used via electrical heaters and air, water or ground source heat pumps. On the other hand, electricity is the only possible fuel for generating cold via chillers. Currently, only heat can be centrally generated and then distributed. In this regard, further areas of research could include the analysis of cooling networks or centralised PV plants for the local provider. The figure does not illustrate properly how the local provider resells PV electricity between buildings, nor does it show, for instance, how a central CHP plant managed by the local provider can supply both heat and electricity to the buildings in and outside of the neighbourhood.

7.3.1 Maximisation of the PV production

The price of PV panels has been steadily decreasing during the last decade. Nowadays, the local conditions - solar radiation, electricity selling price - in Lisbon provide an economic incentive to maximise the electric production from privately-owned PV panels. In the case of the VSA, even though around 50% of the PV production is sold to the local provider at discount, the maximisation of PV production helps reduce by 25% the total annualised cost of the energy infrastructure as illustrated by Figure 7.6. Moreover, it reduces the operational GHG emissions by around 1'000 kg CO_2 – eq per year which corresponds to a 66% reduction compared to the scenario without PV. Since CEA estimates a lower solar potential than Urbio, and because there may be an incentive not to recover the entire roof area of the VSA with PV panels, the electricity production from PV for the following scenarios was set to 6 GWh/y, thus lower than the estimated 7 GWh/y of initial electric demand from the VSA.

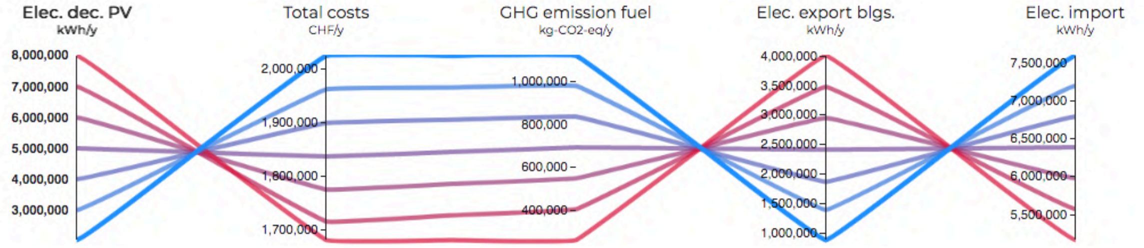


Figure 7.6 - Optimising the installation of PV

7.3.2 Comparison of decentralised heating systems

The type of heating technology represents the only degree of freedom when considering the decentralised energy conversion systems. For most buildings, gas boilers and air-source heat pumps are usually preferred by Urbio. Such preference makes sense in light of the current state of knowledge. Oil is the most polluting fuel for heating purposes and should therefore be excluded. As for wood, though it is an entirely renewable and low-emitting fuel, its stock is slow to regenerate, and therefore should be kept for buildings in the countryside where it can be locally supplied. On the other hand, electrical heaters were sometimes proposed, but only for buildings with low heat demand such as the villas. The compromise between economic and ecological criteria is shown in Figure 7.7. The installation of gas boilers instead of air-source heat pumps for the VSA can help reduce the TAC by 33%, but at the expense of doubling the operational GHG emissions.

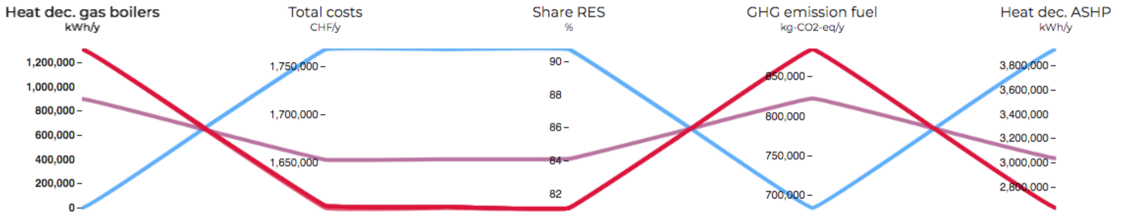


Figure 7.7 – Pareto-optimal decentralised heating systems

7.3.3 Comparison of centralised heating systems

Concerning the analysis of the installation of a heating network, the task is made difficult by the multiple degrees of freedom with regard to the mix of technology installed at the plant site, and the perimeter of the network. In that task, Urbio has not performed well, and only a limited portion of the decision space was made explorable. The objective would have been to research optimal perimeters and technology mixes for the heating network. Moreover, it would have been interesting to dig further the relation between the electricity mix and the installation of a CHP plant. A sample of polylines with heating network are illustrated in Figure 7.8.

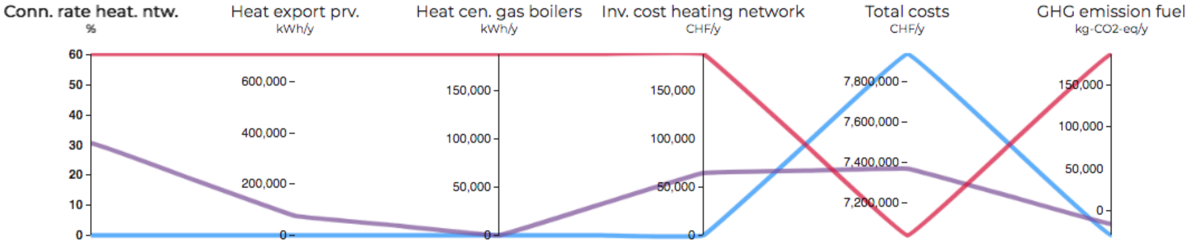


Figure 7.8 - Variation in network connection rates

7.3.4 Potential improvements for Urbio

Urbio swiftly generates diverse scenarios following general guidelines set by the DM. Yet, reached a certain stage, it becomes necessary to understand the impact of specific decisions, e.g. whether to install a heating network, on the performance indicators. Consequently, it is essential to provide the user with the ability to set infrastructure characteristics, thus reducing the degrees of freedom available to the scenario generator and shedding light on the existing interrelations. By means of such a feature, the user could control the level of randomness allowed in the search-and-probe process.

Similarly, the generation and analysis phase should be clearly differentiated. During the generation phase, the user probes the decision space and increasingly directs the search until obtaining a satisfactory scenario, then during the analysis phase he compares the performances of the most promising scenarios. Currently, it is impossible to store scenarios of interest for later comparison. An option would consist on defining a higher-level class linking all the projects based on the same initial data and perimeter in the same vein as the project and scenario differentiation in CEA. At a later stage, during the analysis phase, scenarios could be fetched from the pool of saved scenarios. The selected scenarios could be compared with respect to expected future changes. Alternatively, the analysis phase could serve to perform a sensitivity analysis with regard to important parameters whose values are uncertain.

7.4 Testing two possible pathways

Two scenarios were exported from Urbio. They serve to exemplify two possible pathways for supplying heat to the buildings: the decentralised electrical pathway and the centralised gas pathway. The former considers the installation of decentralised air-source heat pumps, while the latter explores the integration of a heating network supplied by a central CHP plant for providing part of the heat demand. Both scenarios are equally equipped in chillers and PV panels generating 6 GWh/year of electricity. The distribution of technologies with respect to the amount of heat supplied is illustrated for each pathway in Figure 7.9.

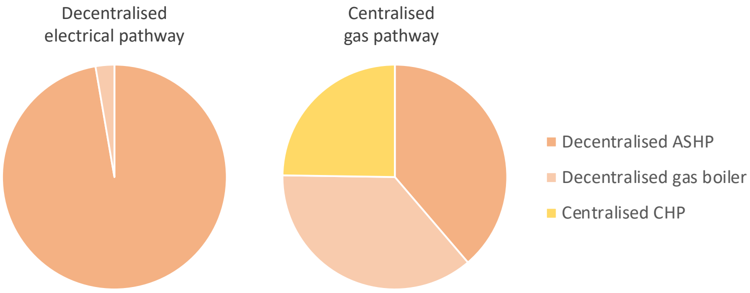


Figure 7.9 - Share of heat conversion systems

The cost structure is shown in Figure 7.10. The first chart accounts for all costs, whereas the second chart accounts uniquely for the costs related to the heating services. The expenditures are classified with respect to their type: operational or investment. The revenues comprise the monetary savings from not importing electricity – PV autoconsumption and CHP generation – and from exporting electricity. The costs are also classified with regard to the corresponding energy conversion system. In the second chart, the revenues from CHP electricity generation were substracted from its operational expenditures for greater clarity.

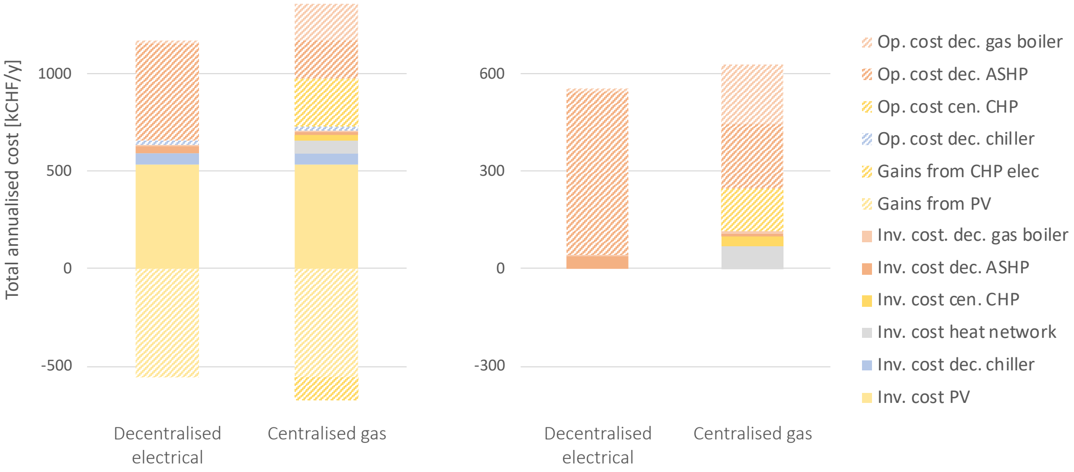


Figure 7.10 - Cost structure of the pathways

The heating technologies represent by far the biggest share of the total annualised cost. The savings and revenues from the PV electricity autoconsumption and export balance out entirely the high investment cost. The chillers require high initial investments but are cheaper to run than the heating systems. Concerning the heating services, both pathways present high operational costs relative to the investment costs. In this regard, electricity represents the totality of operational costs for the decentralised electrical pathway, whereas it represents less than half of the operational costs for the centralised gas pathway. The heating network corresponds to more than half of the total investment costs for the centralised gas pathway. Finally, the electrical decentralised pathway appears to offer the cheapest infrastructure. However, a more realistic distinction of energy prices between the local provider and the building owner would have reduced the average cost of the energy imports for the centralised gas pathway, thus turning both scenarios more competitive.

When computing the GHG emission from the energy infrastructure operation, it is necessary to include only the energy consumption. Indeed, the electricity export from the PV production can not be used to compensate consumption emission. Instead, it participates to the greening of the national electrical grid, thus helping other neighbourhoods turn more sustainable. The ecological performance of both pathways is compared in Figure 7.11. In order to distinguish properly the impact of each conversion system type, the electricity generation and consumption on-site was substracted uniquely from the neighbourhood initial electrical demand, i.e. the electrical demand for end uses not related to heating or cooling.

It can be analysed that although the electricity production from the CHP plant helps reduce the residual electrical demand, this reduction is surpassed by its operational emissions. In that respect, it can be concluded that conversion systems reliant on gas are more polluting than electricity because the higher emission rate per energy embodied of gas and because of the unbeatable efficiency of heat pumps (COP > 1) when compared to standard conversion systems. Finally, it is logical that an energy system reliant in part on non-renewable fuels such as gas performs worse than scenarios that rely uniquely on electrical systems for heating.

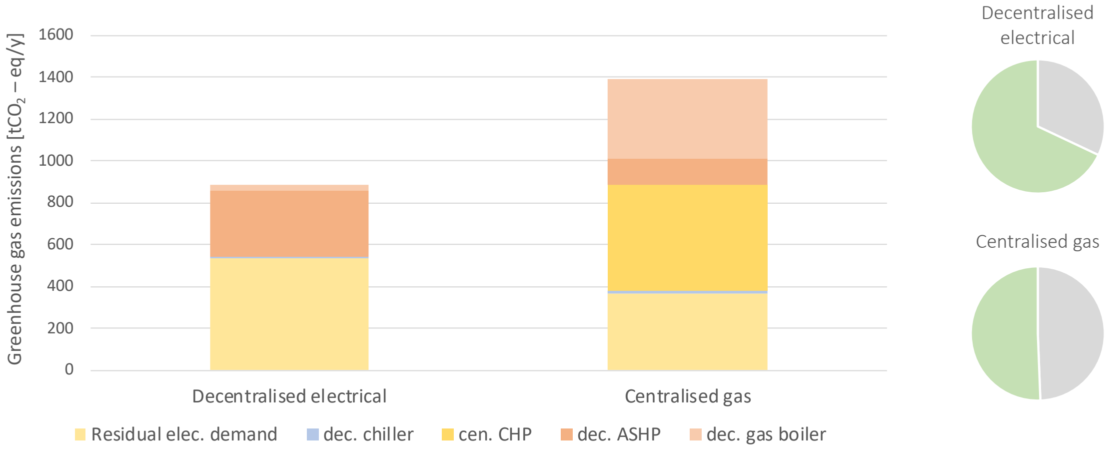


Figure 7.11 - Ecological performance of the pathways

7.4.1 Future evolutions of the pathways

Two future evolutions were described in Section 7.2 : the taxation of greenhouse gases and the greening of the grid. For simplicity, the taxation of greenhouse gases is only measured on the gas price. Moreover, it will also be assumed that the greening of the grid will be accompanied by a proportional decrease in the electricity GHG emission rate.

The evolution in cost and in GHG emissions, as well as the RES share in 2050, are shown in Figure 7.12. The clustered columns show the evolution of the decentralised electrical pathway (left) and of the centralised gas pathway (right) with respect to each criterion. Concerning the cost evolution, only the operational cost of the heating systems is considered. The operational cost is the only expense affected by a changing context, and the heating systems is the only type of energy conversion system fed by natural gas. Concerning the GHG emissions, the entire emissions of the neighbourhood are included. The lower emissions for the year 2020 with respect to Figure 7.11 are due to the RNC estimation of the RES share being greater than the real RES share witnessed in 2020. Yet, for consistency, the values given by the RNC were also used for 2020.

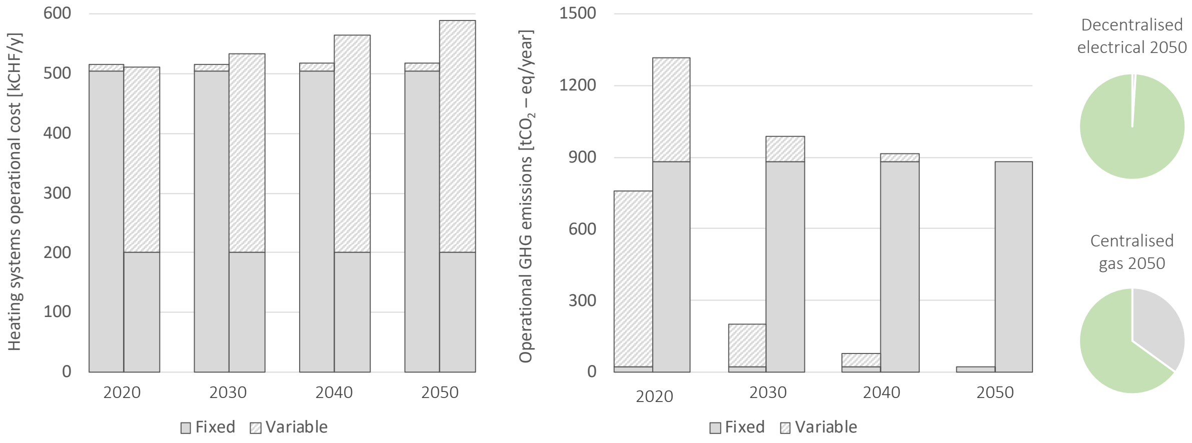


Figure 7.12 - Impact of future trends on the scenarios

In both charts, the bars are divided in a fixed and variable portion depending on whether they represent conversion systems affected or not by the trend. With regard to the future trend researched, the decentralised electrical pathway performs better as it is little sensitive to an increase in the natural gas price from a carbon tax, while it is capable of taking advantage of the greening of the electrical grid. On the other hand, the centralised gas pathway fares worse due to its significant import of emitting natural gas. The difference in RES shares achieved in 2050 by both energy infrastructures demonstrates the ecological limitation of supplying heat from a fossil fuel. It can be concluded that when both options are available, it is better to opt for the electrical pathway as its economical and ecological performances, already competitive, improve along with the years when compared to the gas pathway.

Two things should be highlighted. Firstly, the analysis does not question the pertinence of installing a heating and/or cooling network, but rather its supply with natural gas. For lower emissions and higher share of RES, it could be supplied with biomass, though such alternative brings its own set of problems as discussed in Section 7.3.2 Secondly, the sensitivity analysis does not account for the replacement of gas by other more sustainable gaseous energy vectors such as hydrogen produced from renewable electricity or gas from biomass or waste. Moreover, the evolution in the electricity mix foreseen by the RNC was taken unquestioned. It is difficult to predict the impact of such drastic changes on other parameters such as the price. Moreover, the issues linked to storage and management of intermittent renewable energy production was not addressed.

8 Conclusion

8.1 Application of a novel framework

The initial objective was to demonstrate how independent tools could be combined sequentially in a comprehensive framework for the design of neighbourhood energy infrastructures. However, during the project, it was shown that the tools performed best when interconnected. At this stage, this was shown to be especially true for CEA and Urbio. CEA provides fast and detailed estimations of a building stock's energy consumption. As for Urbio, it enables a swift exploration of the decision space and provides a deeper understanding of the supply alternatives, and how they relate to external conditions such as fuel prices or carbon intensity, but also to urban parameters such as the distribution of GFA between occupancy types. From these new insights, the energy modeller can adapt the existing model and resimulate its functionning in CEA. Once a definitive model is reached, CEA can be used for optimising infrastructures such as DHC networks capable of taking advantage of the energy potentials inherent to urban areas.

The project also presented ways to include energy considerations into urban development. Besides being a reliable repository of input and output GIS data, QGIS proved to be succesful in concisely presenting relevant information such as spatial distributions of energy demand and potential, geographical constraints for distribution networks, etc. Moreover, QGIS includes features for changing data, acquiring statistical information or extrapolating models from point measurements. The mapped information combined with charts plotting load curves or aggregated demands per end-use helped communicate the insights gathered by the energy modeller to the other stakeholders. Similarly, Urbio's model of fast generation of energy supply infrastructure provides a complementary method for the DMs to witness directly the inherent compromises of neighbourhood energy infrastructures. In the end, this first-person interaction with the models helps build trust and confidence in the energy design process.

In the scope of the VSA, the goal was to provide diversified information comprising all aspects of a neighbourhood energy infrastructure design. Firstly, it was demonstrated that the challenges for the existing and future building stocks are different. The buildings constructed before the 1990s feature leaky and conductive envelopes. These building characteristics induce unaffordably high energy consumptions to maintain comfortable indoor temperatures. Though documented, prebound effects where occupants reduce their thermal comfort for financial reasons can lead policymakers to overestimate gains from renovation. In that sense, it was shown that the renovation program could help reduce by 15% the total energy demand while simultaneously improving the comfort conditions for residents.

Concerning the future buildings, it was noticed that heat - mostly for DHW demand - continued to represent a high share of the end-use energy demand, while the demand share of electricity had grown. Moreover, future buildings were designed to provide for space cooling.

As heat waves are expected to become more frequent in the Iberian Peninsula, it will become necessary to have access to space cooling services during the summer. In this respect, it was shown how low-tech equipment such as venetian blinds or swimming pool covers could be exploited to reduce energy losses and gain a greater control on the indoor temperature at no additional energy cost, thus emphasizing the importance of an education on energy use. Conversively, it was also demonstrated how such diversity in end-uses can present new challenges and opportunities for sustainable supply systems. Variable production from renewables can be compensated by smart storage and demand flexibility, while low-temperature district networks can enable heat recycling from by-products of the neighbourhood such as sewage water while taking advantage of synergies in demand by centralising the supply capacity.

CEA was used to test various layouts for the DHC networks. Initially, it was planned to build a single layout for connecting all the future buildings. However, it was shown that not connecting the most isolated buildings and opting for a two-layout structure provided a significant reduction in pipe length (and thus capital investment) and considerably improved the overall performance. Moreover, it was shown that each network had a potential for expansion to the existing buildings as part of a renovation program. In this respect, the possibility of installing a 5GDHC network was presented for its specific suitability to the neighbourhood and its interest in being part of two major trends described in the RNC: electrification of the energy services and the set-up of a prosumer-centric system. The VSA represents to this end a great opportunity for testing a promising technology for Portugal.

Finally, Urbio was used to propose specific energy infrastructure scenarios for the future buildings. Insightful relations were outlined for the installation of PV panels and for the choice of decentralised heating systems. No visible conclusion was possible with regard to the mix of supply technology and the perimeter of a heating network. Two scenarios were exported from Urbio that illustrate possible pathway types: centralised vs. decentralised and electrical vs. gas. They were confronted by two future trends: the increase in RES share of the electricity vector (and corresponding reduction in carbon intensity) and the increase in carbon taxation for fossil fuels such as natural gas. In the case of the VSA, it was shown that an electrical decentralised scenario adapted better to the future trends than a centralised gas pathway, though shortcomes in the analysis were presented.

Looking back at the work accomplished, it is easy to identify possible improvements. First, certain assumptions and simplifications have led to unrepresentative results. Instead of uniquely applying residential occupancy types, the models defined in CEA should have included the GFA share assigned to business. Similarly, different schedules compatible with the comfort scenario should have been applied in order to simulate the diversity in consumption patterns. Secondly, it was seen that for future buildings, space conditioning represents a low share of end-use demand. More time should have been set aside for a thorough research on DHW and electricity consumption in Portugal.

The level of detail of the models depends on the planning stage. As the decision on the supply systems are taken, it would be worth studying the HVAC systems capable of using more neutral temperatures. Indeed, heating and cooling systems possess their own constraints. For instance, a floor or ceiling heating system may be able to use lower-temperature fluids. On the other hand, it should be verified whether their application perimeter can be restricted to specific areas in the flat, a key parameter when computing the building's energy demand.

The VSA illustrates an interesting example of integration of new buildings within an existing neighbourhood. Further research is needed to evaluate targeted programs for renovation and integration of the existing buildings in the district-scale energy supply systems. Urbio can integrate such programs in its computation, however, to be useful, more information is required. What are the installed HVAC systems? What are the real envelope characteristics of the buildings? How to account for prebound and rebound effects? These questions add up to the complex task of comparing renovation measures for buildings with different initial characteristics: geometries, height, envelope U values, etc. Simplifying assumptions enable faster decision-making at the risk of being sub-optimal or inappropriate for the real context.

8.2 The future of UBEM

UBEM tools have witnessed an important boom in the last decade thanks to the advent of fast computation and the spread of GIS data. Together, they have enabled the analysis of neighbourhood energy consumption and the simulation of infrastructure alternatives. As much as they have improved in the last years, there remains untapped potential.

Adopting a service-based vision is one key in understanding energy consumption better and the impact of renovation measures, behavioural changes or HVAC system upgrades. It can also help estimate the demand flexibility potential of the energy demand. For example, there is no need to charge directly a BEV that will be plugged the entire night. Similarly, a certain amount of flexibility can be found in space heating demand where a range of indoor temperatures can be accepted.

For the design of optimal energy infrastructure, more technologies should be included in the databases of the tools. Indeed, there is risk that these tools may hamper the innovation in energy infrastructure if used blindly. In order to avoid this, stakeholders should allow themselves to look outside of the technology database.

There exist current limitations to the spread of UBEM tools in the wider professional world. First, predicted energy consumptions do not always correspond to reality. In this respect, P. Wilde discussed the need for a broad and coordinated approach to understand the causes of these performance gaps and improve the modelling tools [79]. More precise urban building databases are needed for the current building stock. To democratise UBEM tools, these databases should be available to the public. To validate the models, access should be granted to end-use energy consumption data at a building level. This information currently held by energy providers would help refine the models with regard to hourly and total consumption, as well as test their performance with respect to different construction standards. For UBEM tools, district or national-scale energy consumption data provides little help, and instead the impetus should be set on finding a way to make real and detailed data openly available to the researchers and programmers without breaching user privacy.

8.3 Decarbonation of the building stock energy consumption

A methodical approach is necessary to take advantage of all opportunities for an optimal decarbonisation of the building stock energy consumption. This methodological approach can be summed up in three steps: demand reduction, energy recycling, and efficient and renewable energy supply. The insights acquired through this thesis are summarised below.

Demand can be reduced by the implementation of energy saving measures. In the case of existing buildings, renovation of the envelope can help diminish the heat loss to the environment. Besides reducing energy losses, the user can be made aware of how to consume energy efficiently, stop energy waste and make personal savings. Behavioural changes are necessary for an energy-conscious future.

Energy can be recycled to reduce waste. Often as a heat vector, energy can be reused for consumption on-site or by the neighbourhood. For instance, swimming pools can recycle the heat contained in the expelled water to preheat the fresh water. On a larger scale, heat from industrial processes or sewage water can be used, directly or as heat-pump sources respectively, for preheating district heating networks.

The remaining energy demand needs to be supplied efficiently and be based on renewable energies. New renewable technologies are able to supply electricity and heat at low cost. However, seasonal storage solutions are necessary to accommodate the unmatching peaks in energy production and consumption. Where appropriate, underground thermal storage solutions can be explored. For urban areas in southern countries, PV panels and heat pumps have strong potential.

The goal set by the European Union to reach carbon neutrality by 2050 is a big challenge. For this reason, no solution, measure or method should be ignored. Concerning urban development, basic components of district development plans such as the street layout, the land use and the building densitiy distribution have been shown to determine the efficiency of the energy supply systems. Since these parameters are decided at the start of the design process, urban planners must include energy considerations in their decision-making right from the start. Such changes, among others, are necessary for the transition from generic fossil technologies to context-specific technologies that tap local conditions for efficient and renewable supply.

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