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An energy efficiency driven algorithm for filtering and sizing HVAC system layouts for building retrofit

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Abstract

As reported in many sources, buildings consume over 40% of end-use energy worldwide, the quasi-totality destined for Heating, Ventilation and Air-Conditioning (HVAC) systems. Several studies dealt with the topic, developing new methods for the optimization with statistics, cost-optimal building design or through Multi-Criteria Decision Making. Inspired by the objectives of the European project Heat4Cool, I wanted to create a general algorithm for the pre-design of HVAC rehabilitation, i.e. a program for filtering all the possible solutions, size them and evaluate their performance. My work starts with the analysis of the building models which can be adopted for the purpose, looking at qualities and criticalities of the hourly static energy balance compared with TRNSYS dynamic simulation. Once defined this theoretical base, it is written with MATLAB a program that individuates some simple rules guided by standards and technical literature, in an ample engineering spectre, from mechanical to hydraulic and energy aspects. The filter and sizing are governed by the external inputs coming from an auxiliary front-end program, following a precise path in function of the interconnection of HVAC equipment. The rendering of the results is entrusted to a program which translates the HVAC layout into an energy rating index, the Primary Energy (PE) demand. It contains and applies the PE factors for the conversion of the annual energy need of the building system configurations, computed with reference to the machineries performance maps. I tested the program on a reference framework, placed in three different European climates, varying the envelope performance. The results confirm the expected energy savings earned with advanced HPs, solar plants and PCM: they are shown the PE demand profiles of HVAC solutions, the possibility or impossibility of the achievement of NZEB status and the relative importance of each component of the retrofit. Results demonstrate that the algorithm reads with precision the variations of boundary constrains, giving a comparative tool for the optimization of dynamic models or a replicable module for multi-variable analysis.

Sintesi

Come riportato in molte fonti, gli edifici consumano oltre il 40% dell'energia prodotta, la quasi totalità della quale destinata ai sistemi HVAC. Diversi studi hanno sviluppato metodi per l'ottimizzazione impiantistica, con metodi statistici, modelli economici o attraverso processi decisionali multi-criterio. Prendendo spunto dagli obiettivi del progetto europeo "Heat4Cool", ho voluto creare un algoritmo di pre-progettazione del riammodernamento dei sistemi HVAC, ossia un programma in grado di filtrare le soluzioni significative, dimensionarle e valutarne le prestazioni. Il mio lavoro inizia con l'analisi dei modelli dell'edificio adatti allo scopo, studiando qualità e criticità del bilancio energetico statico orario rispetto alla simulazione dinamica di TRNSYS. Una volta definita questa base teorica, con MATLAB è stato scritto un programma che individua semplici relazioni, rielaborate da normative e letteratura tecnica, in un ampio spettro ingegneristico, dalla meccanica all'idraulica all'energetica. Filtraggio e dimensionamento sono guidati dagli input esterni di un programma front-end, seguendo un percorso preciso in funzione dell'interconnessione delle apparecchiature. Il rendering dei risultati è affidato a un programma che traduce le soluzioni HVAC in un indice di valutazione, ossia la domanda di energia primaria (PE). Il programma contiene e applica i fattori di PE per la conversione del fabbisogno energetico delle configurazioni impiantistiche, calcolato in riferimento alle efficienze dei macchinari. Ho testato il programma su un edificio di riferimento, collocato in tre diversi climi europei, variandone le prestazioni dell'involucro. I risultati confermano i risparmi energetici previsti da PdC d'avanguardia, impianti solari e PCM: si mostrano i profili del fabbisogno energetico delle soluzioni HVAC, la possibilità o meno dell'ottenimento di NZEB e l'influenza di ciascun componente nella riqualificazione. I risultati dimostrano che l'algoritmo legge con precisione le variazioni delle condizioni al contorno, fornendo uno strumento ausiliario per l'ottimizzazione di modelli dinamici ovvero un modulo replicabile per l'analisi multi-variabile.

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Nomenclature

A	Area	[m^2]
α	Global gain factor	[W/m^2]
β	Slope of the tilted surface	[°]
C	Thermal capacity	[J/K]
COP	Coefficient Of Performance of the Heat-Pump/Chiller	[-]
$c_{p,a}$	Isobaric specific heat of air, in standard conditions is equal to 1.0005	[kJ/(kg·°C)]
$c_{p,v}$	Isobaric specific heat of water vapour, in standard conditions is equal to 1.95	[kJ/(kg·°C)]
$c_{p,w}$	Isobaric specific heat of liquid water, in standard conditions is equal to 4.186	[kJ/(kg·°C)]
γ	Azimuth angle	[°]
d_p	Duration of the peak demand	[h]
δ	Solar declination angle	[°]
E	Thermal energy	[kWh]
g	Solar factor of the window	[-]
GUE	Gas Utilization Efficiency of the Heat-Pump/Chiller with natural gas support	[-]
h	Superficial heat transfer coefficient through convection	[W/(m^2·K)]
h_a	Specific enthalpy of moist air	[kJ/(kg·K)]
H_T	Heat transfer coefficient for transmission through the envelope	[W/K]
H_V	Heat transfer coefficient for ventilation	[W/K]
η	Efficiency of the boiler	[-]
θ	Zenith angle	[°]
I_S	Solar radiation	[kW/m^2]
K_{pk}	Peak power coefficient of the photovoltaic module	[kW/m^2]
λ	Thermal conductivity	[W/(m·K)]
λ_{LV}	Latent heat of vaporization of water, in standard conditions is equal to 2501	[kJ/kg]
$\dot{m}_a$	Air mass flow	[kg/s]
n_p	Occupancy rate	[pers./m^2]
p	Pressure	[Pa]
PE	Primary Energy	[kWh]
PEf	Primary Energy factor	[-]
P_p	Domestic hot water pre-heating period	[h]

$\dot{q}$	Specific thermal power	[kW/m^2]
$\dot{Q}$	Thermal power	[kW]
R_b	Beam radiation ratio with respect to the total horizontal radiation	[-]
ρ	Density	[kg/m^3]
ρ_a	Air density, in standard conditions is equal to 1.225	[kg/m^3]
ρ_g	Albedo coefficient	[-]
ρ_w	Water density, in standard conditions is equal to 1000	[kg/m^3]
s	Thickness	[m]
t	Time	[s]
T	Temperature	[°C]
U	Thermal transmittance	[W/(m^2·K)]
v_{DHW}	Domestic hot water peak demand	[l/h]
V	Volume	[m^3]
φ	Latitude	[°]
X	Absolute humidity of air	[g_w/kg_a]
ω	Solar hour angle	[°]

1 Introduction

The inspiration of this thesis comes from Work Package 2 in Heat4Cool project. It deals with the design of the web-tool for retrofit named "RetroSim", developed by a design team constituted by four partners who interact on its different aspects.

Chapter 1 briefly describes the whole project and the package, with a view to its primary objectives and the driving philosophy.

1.1 Summary of the project Heat4Cool

Heat4Cool proposes an innovative, efficient and cost-effective solution to optimize the integration of a set of rehabilitation systems in order to meet the net-zero energy standards. The project develops, integrates and demonstrates an easy to install and highly energy efficient solution for building retrofitting that begins from the Heat4Cool advanced decision-making tool (which addresses the building and district characteristics) and leads to the optimal solution combining:

- gas and solar thermally driven adsorption heat pumps, which permits the full integration with existing natural gas boilers to ensure efficient use of current equipment;
- solar PV assisted DC powered heat pump connected to an advanced modular PCM heat and cold storage system;
- energy recovery from sewage water with high performance heat exchangers.

"The project will implement four benchmark retrofitting projects in four different European climates to achieve a reduction of at least 20% in energy consumption in a technically, socially, and financially feasible manner and demonstrate a return on investment of 8 years. The Heat4Cool consortium will ensure the maximum replication potential of the Heat4Cool solution by a continuous monitoring of technical and economic barriers during the development and validation phases in order to present the building owners and investors with clear energy and economic evidence of the value of implementing Heat4Cool solution."[1]

1.2 Description of Work Package 2

The objective is to develop a reliable design tool that will allow the simulation of the combination of different retrofitting measures (including HVAC, RES and BEMS measures) assessing the energy savings and the cost-effectiveness of the solutions and thus supporting the retrofitting decision making.

- Provide a mapping of existing buildings and districts energy performance
- Identification of needs and constraints for the selection of most suitable retrofitting measures.
- Creation of a retrofitting tool kit Dataset with technological solutions and legislative requirements
- Definition of the specifications of the design tool
- Definition of the algorithms that will allow assessing the most cost-effective retrofitting measures combination
- Implementation of the tool "RetroSim"

[1] European commission, Directorate-general for research & innovation, #723935 - Heat4Cool: Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system

The specific description of the work is divided into five tasks.

Task 2.1.

Mapping of European building stock (identifying needs and constraints).

Task 2.2.

Creation of the Heat4Cool Retrofitting tool kit Dataset

It deals with two kinds of data:

- technology data: retrofitting measures will be collected, focusing on HVAC, RES integration, BEMS, and their interconnection. The technologies will be described with all the required information needed for the optimisation algorithms. Moreover, special requirements of each of them and of the interconnection between them will be included. The cost of each technology will be included for the cost-effectiveness analysis.

- Regulatory data: most relevant regulation will be identified in order to ensure the applicability of the proposed retrofitting solutions.

The toolkit data set will be a repository of technological solutions that will be open to updates.

Task 2.3.

User requirements, technical specification and architecture design

The core functionalities will be defined, indicatively including functionalities such as

i) analysis of building/district characteristics,
ii) modelling of available retrofitting solutions including control systems
iii) energy efficiency estimation
iv) retrofitting cost estimation
v) validation of suggestion based on applicable regulation
vi) data management
vii) user interface front-end.

Task 2.4.

Creation of the optimisation algorithm for the solution set

The task leader along with the involved partners will build an optimisation model to provide a retrofitting solution set determined on the inputs from building characteristics (Task 2.1), technology options (Task 2.2) and user requirements (Task 2.3).

The optimization technique is constraint-based and will provide solutions with respect to Energy consumption, Carbon emissions, Payback period (PBP) and Life-Cycle Cost Analysis (LCCA). The constraints and objectives are based on the user information entered via the web portal and the constraints that have been collected about National Building Codes, HVAC functional and non-functional requirements and user specifications. The optimization tool will ensure the best retrofitting choice in terms of typology, resources and size for each demo case, orienting to the end user as decision support platform in HVAC retrofitting design.

Task 2.5.

User Interface Design and tool integrated development (web platform integration).

1.3 Connection between the project and the thesis work

Heat4Cool is a pluriannual project which aims to diffuse some retrofit solutions for European buildings. Part of its work is the development of the webtool RetroSim from which I took inspiration for my thesis. The design layout[2] of the tool is represented in Figure 1.1.

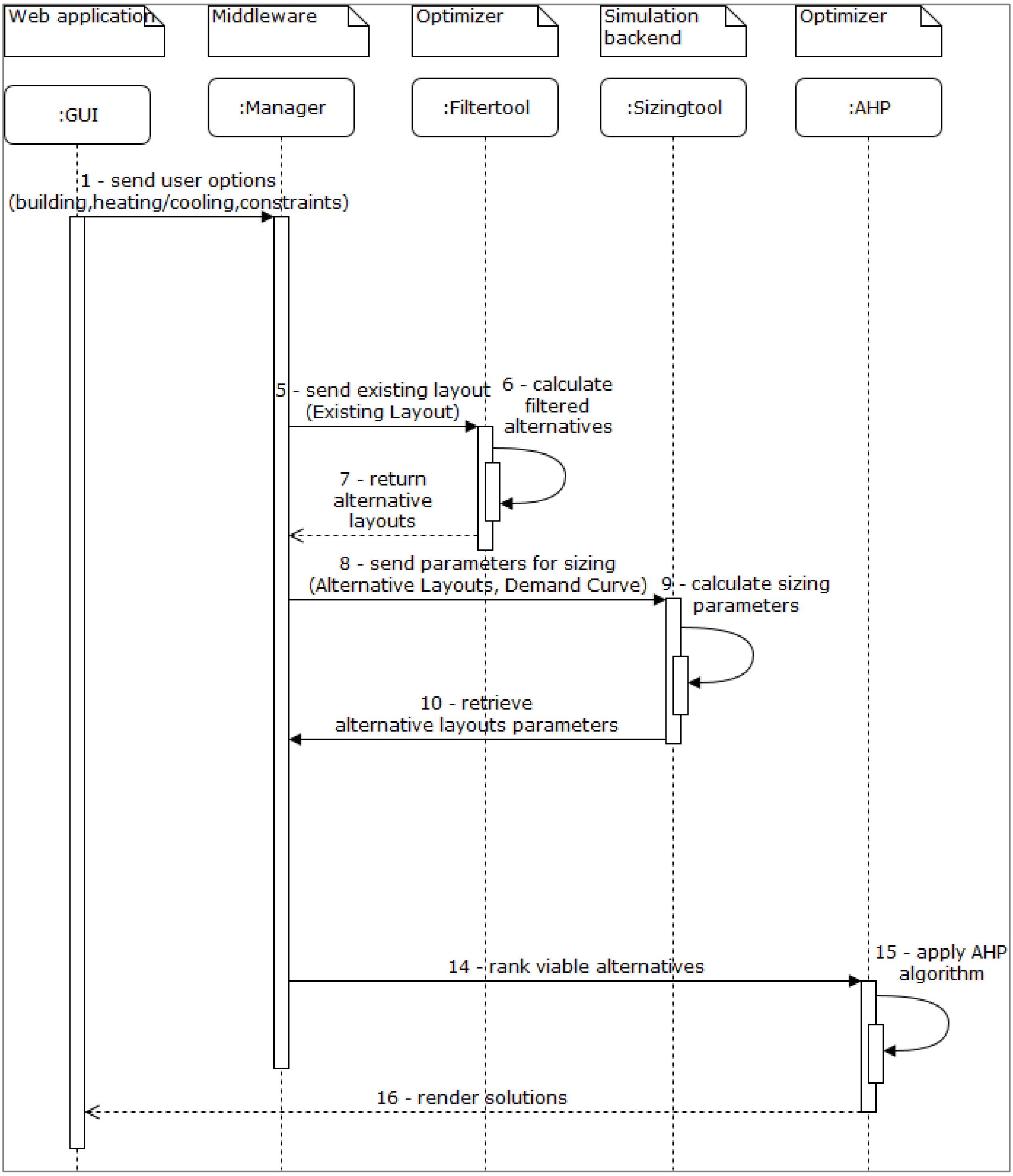


Figure 1.1 - RetroSim layout with definition of the different phases of the simulation

2 Heat4Cool - Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system.
Task 2.5 - User Interface design and tool integrated development.

The primary objective of my thesis is the achievement of a set of simple rules that build an algorithm for the filtering of all the possible retrofit solutions that nowadays can be encountered on the market. This derives from the necessity, in RetroSim, of an instrument, called "Optimizer", which can select just few interesting HVAC layouts for its dynamic simulation.

The first part of the work is the design of some substitutive program which can perform the computation of the energy balance of the building and the dialogue with the user, for the acquisition of the fundamental inputs for the optimization.

My work started with the analysis of the different models which can be adopted for the study of the building, looking at their qualities and criticalities, analysing especially the reliability of the assumptions made for the obtainment of a tool which can be in the same time efficacious and not burdensome. I compared the results coming from annual static simulations and the outputs of a reference dynamic simulation software (TRNSYS).

Once known the different aspect of the adopted model, I wrote on MATLAB an auxiliary front-end and only at this point I could write the actual rules and the logic of the filtering tool. The program is based on several rules I could find in the technical literature, guided by the experience I acquired in these years on building systems and its machineries. I looked at the topic in an ample spectre, from mechanical to hydraulic and above all the energy engineering.

I decided to differentiate my approach from the one chosen in Heat4Cool project for the tool RetroSim, because it was focused on some reference HVAC system layouts based on the most strong and modern technologies involved in the project (DC heat-pump, adsorption heat-pump, PCM storage), while, on the other hand, I preferred to leave this constrain, in order to attain a more general algorithm which can be replicated for different purposes out of the project Heat4Cool. It is important to underline, anyway, that the results of my thesis also confirmed the validity of the choice made by Heat4Cool team.

The sizing program checks the performance of the equipment against the building energy demand, together with some assessments also on the commercial aspects of the size of the generators. Once again, I referred to the available literature and the standards that rule the subject.

For the obtainment of a visualization of the outputs, I wrote a program which translates the set of HVAC system layouts into a rating index. I decided to do so with the Primary Energy demand, that is the most used parameter for the evaluation of the energy performance of buildings. The program explores the necessary information in some selected performance maps which let me render the hourly HVAC need of the building with the Primary Energy demand of the building system.

This last program rates the retrofit solutions from the energy point of view, but this is not the only topic that has to be evaluated in the design. RetroSim project adopts a multiple rating of the most interesting solutions, after its simulation engine analyses the building energy balance in its differential form that permits to study also the internal temperature profiles, hence the comfort of the users and the control of the emission subsystem. My program "PE_demand" could be seen as the module for RetroSim multi-criteria evaluation, with the AHP (Analytical Hierarchy Process) that translates the preferences of the users and can satisfy them in a wider way.

The thesis finishes with the run of the program on the reference framework adopted, obtaining the expected results and looking at the fact that algorithm can read with precision the different behaviour of the building in the different European climates. In the end the program resulting is a pre-desing tool for HVAC retrofit, whose greatest potential comes out together with a dynamic simulation of the outputs and multi-criteria decision analysis.

2 Analysis of the building model adopted in the algorithm

My program bases its calculation on the building energy model commonly used in classical thermodynamics, whose the cardinal principles are recapitulated and extending step by step the analysis of its quantities. In Chapter 2 I also introduce the reference building for my studied and analyse the main features of the building model I decided to adopt for the algorithm.

2.1 The building energy model

From Building Physics theory, I can express the energy balance of a building as the sum of the heat flows ingoing, outgoing and produced inside the system.

The global expression of the energy balance of the system is the result of Figure 2.1[3].

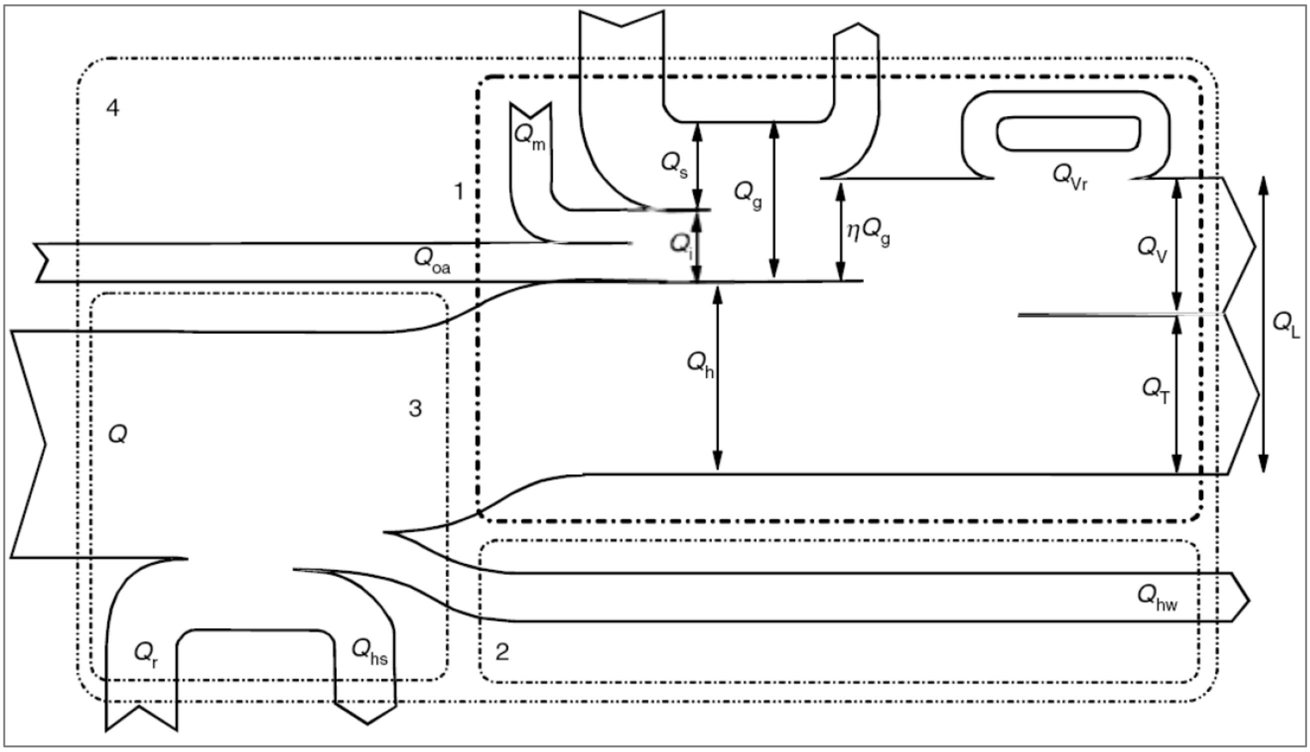


Figure 2.1 - Global scheme of the building energy balance

Heat losses

QT: heat flow for transmission

The transmittance (U) is the heat flow rate per m^2 through an element for each degree of temperature gradient between its two faces.

I can express the total heat flow across the envelope for conduction as:

$$\dot{Q}_T = \sum_i A_i \cdot U_i \cdot (T_{ext} - T_{int}) \quad \text{[kW]}$$

The envelope exchanges heat with the environment through its *i* components, divided in:

- Exterior walls

[3] ISO 13790:2008 - Energy performance of buildings. Calculation of energy use for space heating and cooling

- Windows
- Ground floor
- Roof

The amount of heat flow depends at first on the geometry of the hull. In winter the resultant is a dispersion of thermal energy, while in summer the flow is inverted producing an ingress of heat from outside; in both cases it is valuable the insertion of an appropriate insulating material between the envelope layers.

Q_V: heat flow for internal ventilation

In order to guarantee the comfort of the users, it is required an air exchange rate per hour. It can be performed via natural ventilation, artificial mechanical ventilation and infiltrations. The presence of a heat recovery is very influential for the reduction of these heat losses.

This air replenishment constitutes a large heat exchange with the external environment, both sensible and latent. Expressing the air exchange rate V_a in m^3/h, I can calculate them with technical relations.

$$\dot{Q}_{V,s} = \dot{m}_a \cdot c_{p,a} \cdot (T_{ext} - T_{int}) = 0.334 \cdot \dot{V}_a \cdot (T_{ext} - T_{int}) \quad [W]$$

$$\dot{Q}_{V,l} = \dot{m}_a \cdot h_a \cdot (X_{ext} - X_{int}) = 0.857 \cdot \dot{V}_a \cdot (X_{ext} - X_{int}) \quad [W]$$

Heat gains

Q_S: heat flow for solar radiation

Solar radiation is a considerable source of heat. It depends on the envelope aperture ratio, i.e. the number and size of the windows, and the transparency, i.e. the presence/absence of shading system or obstructions.

I defined with g the solar factor of the window, i.e. the percentage of solar radiation passing through its transparent part. It results so:

$$Q_S = g \cdot A_w \cdot I_S \quad [kW]$$

Solar gains are a positive source of heat in winter, while in summer they become an additional heat load to deal with. They can be faced with the optical features and energy characteristics of the windows.

Q_P: heat production from internal occupancy

Each person produces heat because of its metabolic rate, both sensible and latent.

The specific rates depend on the activity done inside the building, with its characteristic values of heat production (q_P) and water production ($m_{P,w}$). In relation of the activity depends also the number of people inside the internal space per m^2 (n_P).

$$\dot{Q}_{o,s} = A \cdot n_p \cdot \dot{q}_o \quad [kW]$$

$$\dot{Q}_{o,l} = A \cdot n_p \cdot \dot{m}_{p,w} \cdot h_w \quad [kW]$$

Q_m: heat production from internal machineries

All electrical devices are sources of heat. The specific rate depends on the activity done inside the building, with its characteristic values (q_m).

$$\dot{Q}_m = A \cdot \dot{q}_m \quad [kW]$$

2.2 Building dynamic simulation

The remaining parameters of the model adopted in ISO 13790, the utilization factor η_U, aims to evaluate the dynamic behaviour of the building. It expresses the velocity of heat accumulation, which determines a better distribution of the heat gains and avoids overheating; it depends also on losses in the heat production and distribution, together with heat recoveries in the heating plant, which reduce the total amount of heating power introduced into the thermal zone (Q_H).

Thus, the expression of this last quantity is:

$$\dot{Q}_H = \left[\left(\dot{Q}_T + \dot{Q}_V\right) - \eta_U \cdot \left(\dot{Q}_S + \dot{Q}_o + \dot{Q}_m\right)\right] \qquad \text{[kW]}$$

Last, the energy need is usually evaluated in terms of Primary Energy, i.e. "energy that has not been subjected to any conversion or transformation process"[4]. For the computation of this quantity, the total energy demand is multiplied by the appropriate conversion factors in relation to the type of fuel adopted for the energy production. For the annual Primary Energy need the expression is:

$$PE = \dot{Q} \cdot PEf \cdot \Delta t \qquad \text{[kWh]}$$

It is important to underline that ISO 13790 approach does not aim to obtain the exact amount of energy demand of the building. It is in fact a quasi-steady-state model: it has a good reliability for the heating energy need in winter period, which is often the most onerous component of the energy demand, but in summer the oscillation of the outside temperature produces a frequent inversion of the heat flow through the building envelope and the dependability of the quasi-steady-state model is heavily undermined.

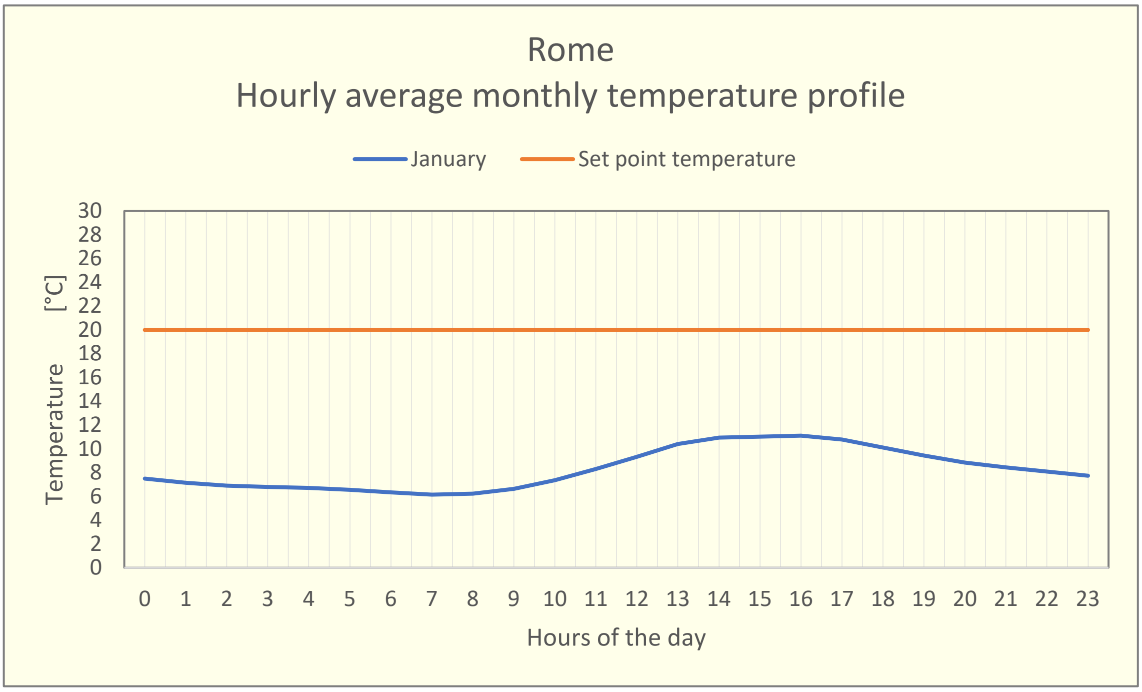


Figure 2.2 - Typical profiles of internal and external temperature in winter

[4] EN 15316-1:2007 - Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 1: General

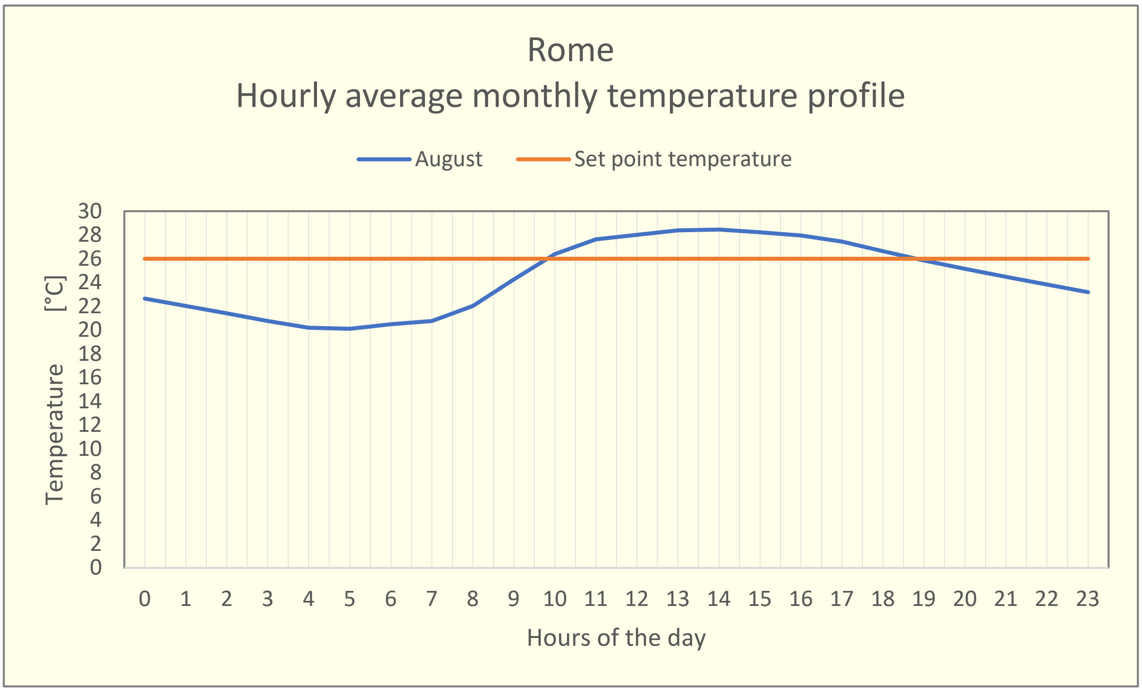


Figure 2.3 - Typical profiles of internal and external temperature in summer

Figure 2 and Figure 3 are placed in Rome, so that the reader can understand the limits of a quasi-steady-state model. In winter the average temperature is constantly below the conventional heating set-point temperature (20 °C); on the other hand, this is no longer true in the cooling season, when the external temperature oscillates above and below the set point temperature (26°C) and the flow direction is more dynamic.

For this reason RetroSim is integrated with a dynamic building simulation. This part of the tool is destined to the differential calculation of the energy balance of the building with the components defined in Chapter 2.1, in the progression of every hour of the year. In this it can fix the mistake in the cooling evaluation, providing a more precise estimation of the energy demand. My program will make use of a substitutive version of the simulation backend, for the calculation of the energy demand of the existing layout and for the energy performances of the retrofit alternatives.

I decided to validate this approach through the comparison of its results with a reliable software coming from the experience and the technical knowledge in the field. This validation tool has been individuated in TRNSYS dynamic simulation. TRNSYS is a simulation program for energy engineering and building dynamic simulation, primarily for passive as well as active solar design, developed at the University of Madison-Wisconsin. The building and its plants are analysed through their main active components, describing, connecting and studying their dynamic performance. I used the software to make a comparison between the outputs coming from two different models:

- "Type 88 - Lumped capacitance building with internal gains", which follows the assumptions employed in RetroSim and in my algorithm
- "Type 56: Multi-Zone Building", the most sophisticated dynamic model inside the software.

I tested a standard building in three different climates, in regard to understand and validate the behaviour of Heat4Cool model under all possible external conditions.

2.3 Description of the reference building

The building I simulated is the Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 (Figure 2.4[5]), in three climates: warm in Athens, cold in Helsinki and Strasbourg as average continental climate.

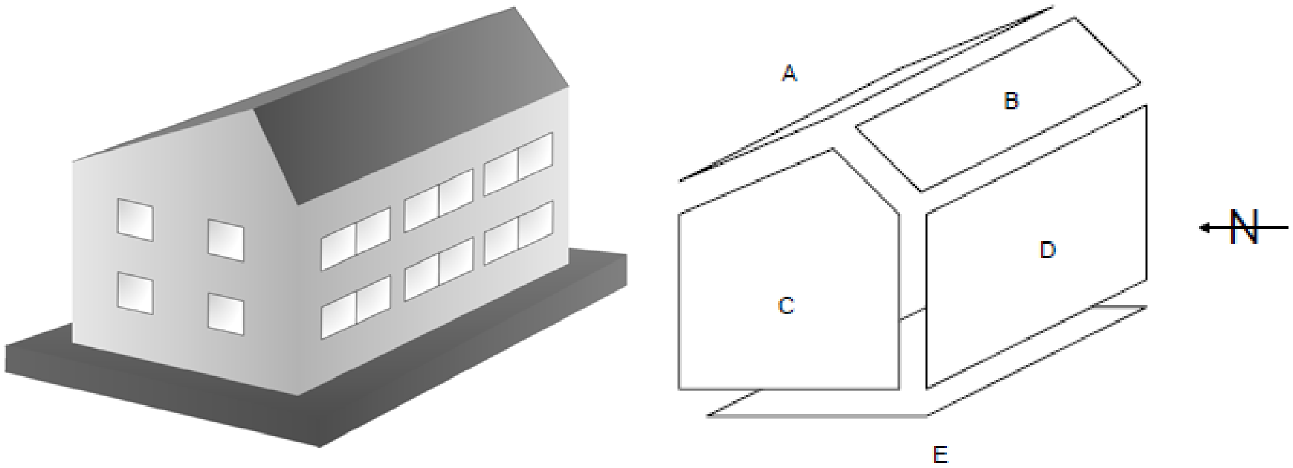


Figure 2.4- Building general view

Table 2.A - Measures of building external surfaces

Surface	A	B	C	D	E
Net area [m^2]	54.6	26.4	45.7	56.0	70.0

Table 2.B - The three different prototypes of building

	Code	Heat exchange area	Air zone volume	Infiltration rate
Old Building	SFH 100	394.3 m^2	389.45 m^3	0.4 V/h
Reference Building	SFH 45	409.8 m^2	389.45 m^3	0.2 V/h
New Building	SFH 15	420.8 m^2	389.45 m^3	0.1 V/h

All of the three buildings are sharing the same geometry. Their main difference is in the insulation layer thickness, hence the heat load. The houses of Table 2.B are named SFH (Single-Family House) 15, 45 and 100.

- SFH15 represents an actual building envelope with very high energetic quality. It fits the Swiss Minergie-P (Minergie 2010) and German Passivhaus (Feist 2005) requirements;
- SFH45 elements are constructed, such that they are oriented at actual legal requirements or represent a renovated building with good thermal quality of the building envelope;
- SFH100 represents a non-renovated existing building.

The orientation is represented by the arrow indicating the North. The common geometrical structure of the buildings is fixed by inside measures, summarized in the Table 2.C.

[5] R. Dott, M. Y. Haller, J. Ruschenburg, F. Ochs, J. Bony - The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38. Part B: Buildings and Space Heat Load

The building is studied as one common thermal zone. Differently from the IEA work and my program, on TRNSYS internal walls and floors play an active role in the simulation (internal heat capacities). Simulation is based on external measurements in Table 2.A, no additional thermal bridges are considered.

Table 2.C - Constructive characteristics of the building

	Layer	s [m] SFH 15	s [m] SFH 45	s [m] SFH 100	ρ [kg/m³]	λ [W/m·K]	C [kJ/kg·K]	U [W/m²·K] SFH 15	U [W/m²·K] SFH 45	U [W/m²·K] SFH 100
External wall	Inner plaster	0.015	0.015	0.015	1˙200	0.600	1.000	0.200	0.333	1.292
	Brick	0.210	0.210	0.210	1˙380	0.700	1.000			
	EPS	0.200	0.120	0.040	17	0.040	0.700			
	Outer plaster	0.003	0.003	0.003	1˙800	0.700	1.000			
Ground floor	Wood	0.015	0.015	0.015	600	0.150	2.500	0.201	0.414	1.124
	Flooring plaster	0.080	0.080	0.080	2˙000	1.400	1.000			
	Sound insulation	0.040	0.040	0.040	80	0.040	1.500			
	Concrete	0.150	0.150	0.150	2˙000	1.330	1.080			
	XPS	0.220	0.160	0.080	38	0.037	1.450			
Roof ceiling	Gypsum board	0.025	0.025	0.025	900	0.211	1.000	0.180	0.510	0.908
	Plywood	0.015	0.015	0.015	300	0.081	2.500			
	Rockwool	0.200	0.160	0.040	60	0.036	1.030			
	Plywood	0.015	0.015	0.015	300	0.081	2.500			
Int. wall	Clinker	0.200	0.200	0.200	650	0.230	0.920	0.964	0.964	0.964

Table 2.D – Orientation and measure of the windows of the building

Orientation	North	South	West	East	Total
Window area	3 m²	12 m²	4 m²	4 m²	23 m²

Table 2.E - Thermal and optical characteristic of the windows

	Frame percentage	Solar factor	Transmittance
SFH 100	0.15	0.755	2.830 W/m²·K
SFH 45	0.15	0.622	1.270 W/m²·K
SFH 15	0.15	0.585	1.100 W/m²·K

I used a total heat transfer coefficient h_i=7.69 W/m²·K to the inside and h_e=25.0 W/m²·K to the outside (ambient).

The detail of the computation of the building parameters in Table 2.F are reported in Annex I.

Table 2.F - Resume of the global building parameters

SFH 100 - OLD BUILDING	
Heat transfer coefficient	450 W/K
Heat capacitance	116˙000 kJ/K
SFH 45 - REFERENCE BUILDING	
Heat transfer coefficient	160 W/K
Heat capacitance	99˙000 kJ/K
SFH 15 - NEW BUILDING	
Heat transfer coefficient	90 W/K
Heat capacitance	120˙000 kJ/K

Internal gains are scheduled with the profiles in Table 2.G, with sensible heat production per person equal to 60 W and latent heat coming from a moisture hourly rate of 0.059 kg/pers.

Table 2.G - Profiles of the internal gains

Starting time	Electricity gains [W]	Occupants
0	105	4
1	55	4
2	55	4
3	55	4
4	55	4
5	55	4
6	392.5	2
7	457.5	3
8	420	2
9	55	0
10	55	0
11	250	1
12	55	3
13	120	2
14	120	1
15	120	0
16	120	0
17	170	1
18	170	2
19	615	2
20	420	4
21	420	3
22	442.5	4
23	355	4

2.4 Dynamic simulation of the reference building with TRNSYS models

The most valid method to model a building on TRNSYS is through the Type 56 - Multi-Zone Building, "models the thermal behaviour of a building having multiple thermal zones. The building description is read by this component from a set of external files. The files can be generated based on user supplied information by running the pre-processor program called TRNBuild."[6]

Nevertheless, on TRNSYS exists also Type 88 - Lumped capacitance building with internal gains, "models a simple lumped capacitance single zone structure subject to internal gains. […] it neglects solar gains and assumes an overall U value for the entire structure. Its usefulness comes from the speed with which a building heating and/or cooling load can be added to a system simulation." Its approach is very similar to the adopted one for the simulation tool, out of the fact that the project tool does not neglect the solar gains.

The final goal of Chapter 2 is the comparison of the outputs coming from an extensive al building envelope modelling, through the Type 56, with the ones from the simplified Type 88, adding the solar gains.

The main approximation deals with the impact of the effective capacitance of the building: in Type 88 is equal to the theoretical capacity, merged in a single node, analysing the heat flow as a one-dimensional flux through the envelope; on the other hand, with Type 56 building thermal capacity is treated through a network of points.

Both models are simulated in the same TRNSYS file, through the architecture of Figure 2.5.

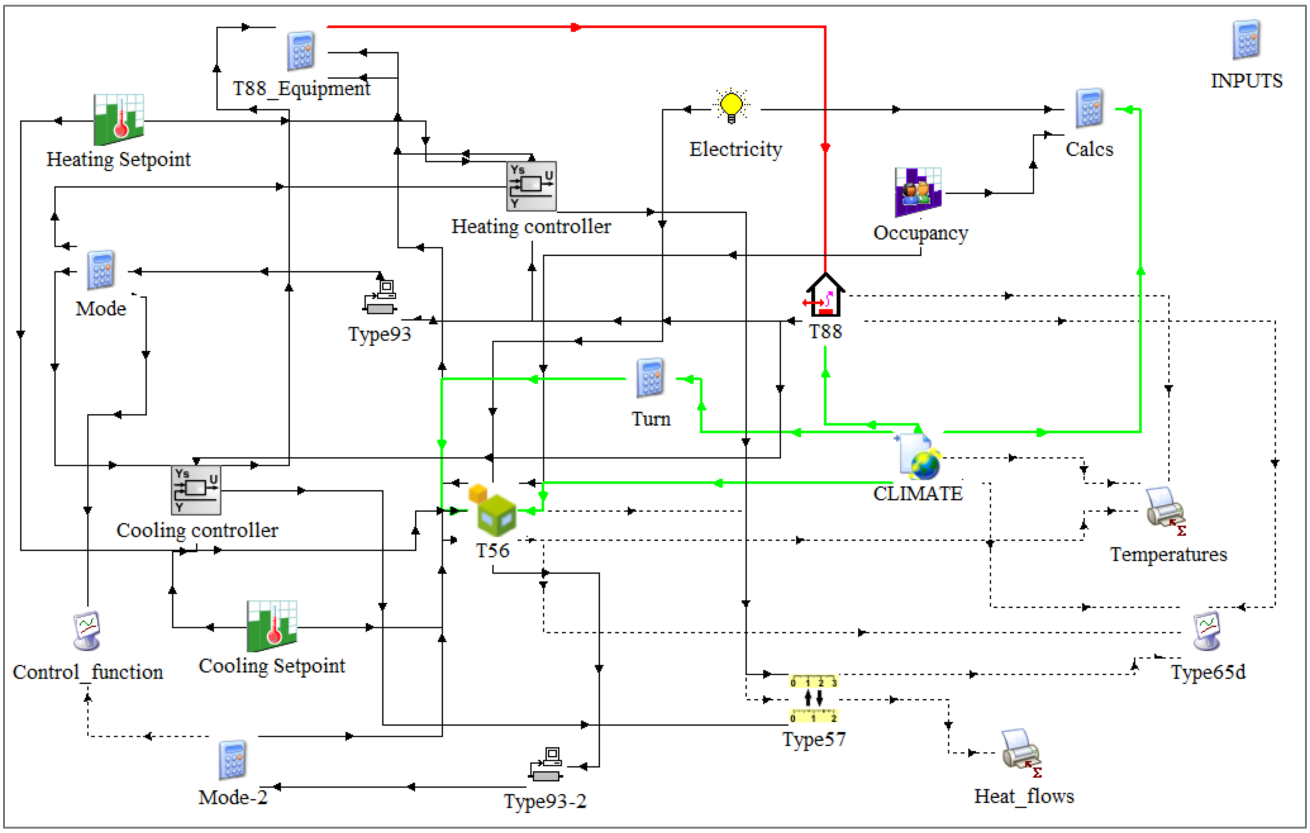


Figure 2.5 – TRNSYS network used for SFH 45 case in Strasbourg

[6] Solar Energy Laboratory, University of Madison-Wisconsin - TRNSYS 17 a TRaN sient S Ystem Simulation program - Volume 4, Mathematical Reference

Figure 2.5 contains all the TRNSYS components (types) necessary to design the two aimed simulations. It follows a brief explanation of its various parts. For a more detailed account of the whole model, Annex II reports TRNSYS deck file for SFH 45 in Strasbourg; the other cases follow the same logic.

This layout was run for all the three building references (SFH100, SFH45 and SFH15) in the three climates (Strasbourg, Athens and Helsinki), defining it through "CLIMATE" (Type 15) and "Turn" calculator, where I evaluated the solar gains.

First, I designed the building with Type 88. It studies building behaviour merging its complexity into one single resistive-capacitive node: all the geometrical and constructive characteristics are summed into two parameters, the "Building loss coefficient" and the "Building capacitance". These values are shown in Table 2.F for each of the three constructive typologies and I provided them through the calculator "Inputs". Building's passive component is finalized providing the internal gains quantity and profiles with "Occupancy" (Type 14a) and "Electricity" (Type 14d), as shown in Table 2.G.

Type 88's HVAC plant is defined with an ideal system with infinite power, "T88_Equipment". Its operation is governed through "Heating controller" and "Cooling controller" (Type 22), two iterative feedback controllers which compare the internal temperature with the seasonal set-point and set-back I provide with "Heating Setpoint" and "Cooling Setpoint" (Type 14). I adopted the standard values of 20°C for winter season and 26°C for summer.

I designed the same building with Type 56 - Multi-Zone Building. It models the building as network of elements, studying the thermodynamics of the building through the heat exchange between them. It is a much more sophisticated instrument for building energy modelling, but in the same time it was developed for this purpose so, through TRNBUILD extension, the building can be defined with a much more intuitive front-end. I show an example of this in Figure 2.6.

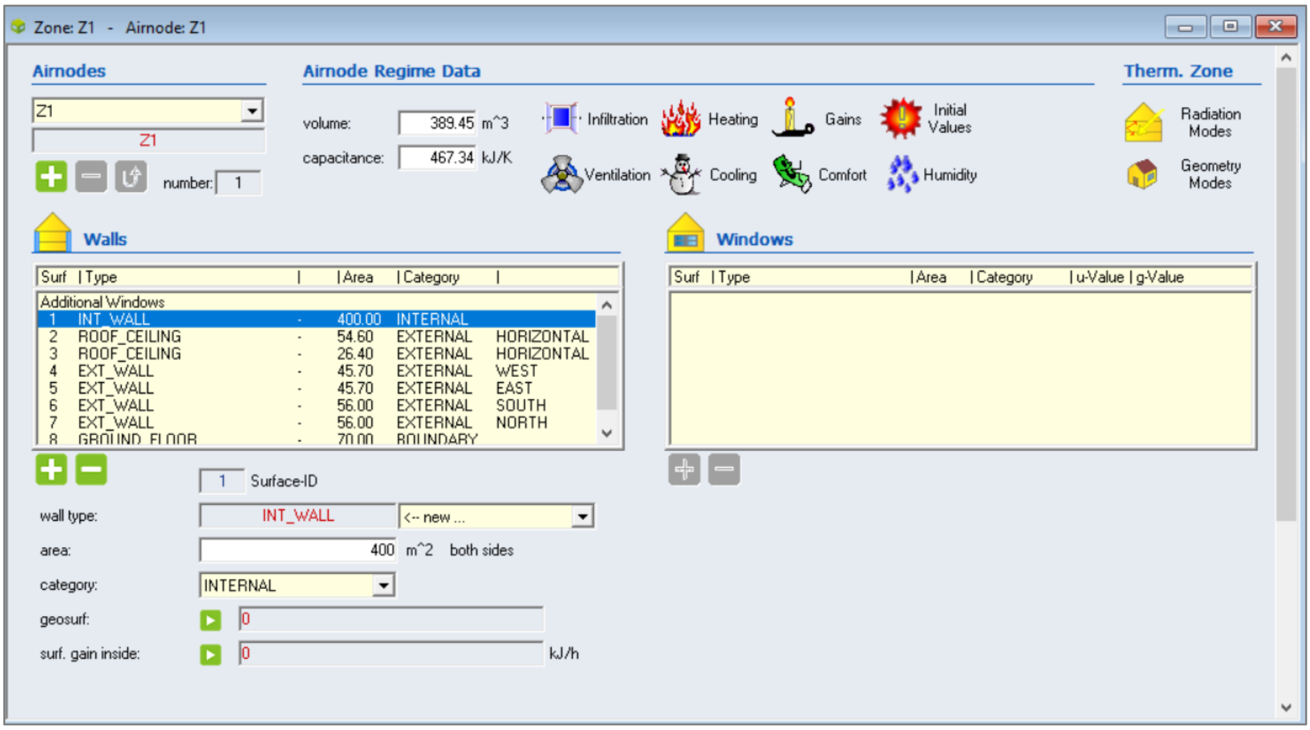


Figure 2.6 - TRNBUILD configuration used for SFH 45 case in Strasbourg

The reader is invited to observe I provided the exact same inputs I just illustrated also to this Type, which explains the tangle of connections between all the types in the global model.

2.5 Results and comments

In the next figures and tables I resume the main information coming from the comparative analysis. The complete collection of the output here analysed are presented in Annex III.

Table 2.H - Average monthly difference between Type 88 and Type 56 output temperature in free floating conditions

	Strasbourg SFH 100	Strasbourg SFH 45	Strasbourg SFH 15	Athens SFH 100	Athens SFH 45	Athens SFH 15	Helsinki SFH 100	Helsinki SFH 45	Helsinki SFH 15
Jan	1.34 °C	1.37 °C	2.43 °C	0.91 °C	1.71 °C	2.25 °C	1.87 °C	1.54 °C	3.13 °C
Feb	0.73 °C	1.48 °C	2.56 °C	0.56 °C	2.30 °C	4.27 °C	1.09 °C	1.66 °C	2.78 °C
Mar	0.65 °C	1.86 °C	3.22 °C	0.59 °C	1.97 °C	4.12 °C	0.67 °C	1.77 °C	2.75 °C
Apr	0.63 °C	2.00 °C	3.76 °C	0.65 °C	2.40 °C	4.74 °C	0.66 °C	2.15 °C	3.73 °C
May	0.63 °C	2.02 °C	4.59 °C	0.58 °C	2.18 °C	5.08 °C	0.82 °C	2.27 °C	4.71 °C
Jun	0.63 °C	2.09 °C	4.85 °C	0.46 °C	2.29 °C	5.28 °C	0.62 °C	2.69 °C	5.96 °C
Jul	0.64 °C	2.24 °C	5.32 °C	0.50 °C	2.42 °C	5.68 °C	0.61 °C	2.47 °C	6.25 °C
Aug	0.65 °C	2.32 °C	5.59 °C	0.52 °C	2.78 °C	6.39 °C	0.67 °C	2.67 °C	6.58 °C
Sep	0.64 °C	2.48 °C	5.98 °C	0.64 °C	3.05 °C	6.88 °C	0.88 °C	2.44 °C	5.90 °C
Oct	0.80 °C	1.90 °C	4.76 °C	0.84 °C	2.88 °C	6.75 °C	1.02 °C	1.92 °C	4.64 °C
Nov	0.91 °C	1.60 °C	3.69 °C	0.76 °C	2.14 °C	5.31 °C	1.07 °C	1.38 °C	3.25 °C
Dec	0.84 °C	1.34 °C	2.75 °C	0.87 °C	2.05 °C	4.38 °C	1.05 °C	1.20 °C	2.25 °C
Tot	0.76 °C	1.89 °C	4.13 °C	0.66 °C	2.35 °C	5.10 °C	0.92 °C	2.02 °C	4.34 °C

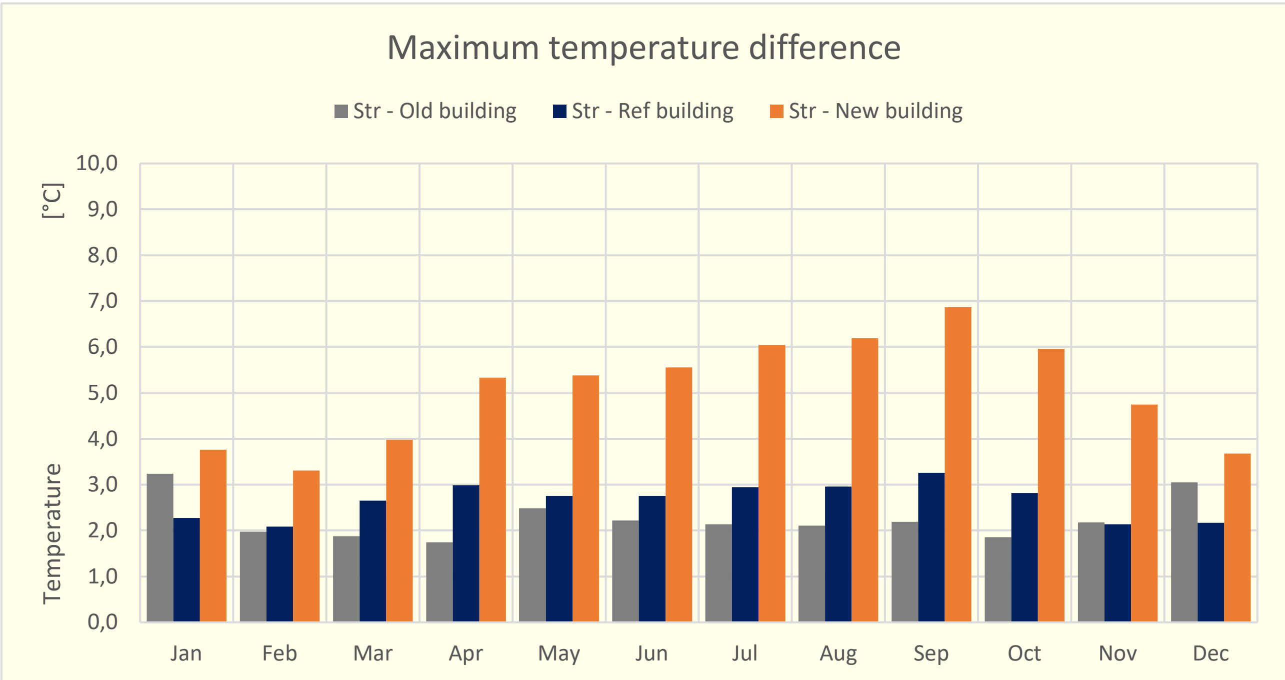


Figure 2.7 - Maximum temperature difference between Type 88 and Type 56 in free floating conditions

The first comparison is performed between the sole passive component of the building models, without any air-conditioning (free floating analysis).

It can observed that the difference between the two output temperatures goes up together with the increase of the technological performance of the building envelope. On the other hand, the discrepancy between average monthly values and its peaks is not very large, meaning that it is almost constant during the season and depends less on outdoor temperature variation. In SFH100 case, differences are very little and the peaks are concentrated at the start of the simulation, coming from the imposition of the boundary condition ($T_{initial}$=20 °C). For this reason, these irregularities are not significative data.

When I turn on the HVAC system, I assume it as ideal emitter, i.e. an air-conditioning system with infinite power that meets the user comfort during all the simulation time.

I obtain a temperature profile which is almost equal between the types, as desired. This means that I achieved a valid representation of the same building energetic configurations for the two different models. The achievement of this result will let me make a comparison of the energy performances.

Table 2.I, shown as example, was the one which gave the most irregular results I analysed, as observable in Figure 2.9.

Table 2.I - Temperature profiles in SFH 15 Athens

	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	Exterior	Type 88	Type 56	Exterior	Type 88	Type 56	Exterior	Type 88	Type 56
Jan	9.15	22.81	21.08	17.45	25.94	24.00	0.40	20.01	19.94
Feb	9.69	25.52	22.36	18.95	25.99	24.25	0.95	24.29	20.74
Mar	11.77	25.44	23.22	22.60	26.00	26.07	2.50	24.16	20.17
Apr	15.30	25.83	25.78	26.15	25.99	26.12	5.55	25.40	24.76
May	20.23	25.91	26.01	32.40	25.99	26.12	9.10	25.60	25.26
Jun	24.27	25.93	26.06	34.35	26.00	26.13	14.65	25.80	25.92
Jul	27.04	25.94	26.07	37.90	26.00	26.14	17.65	25.85	26.01
Aug	26.67	25.94	26.07	36.20	26.00	26.16	17.90	25.87	26.00
Sep	22.98	25.93	26.06	33.15	26.00	26.15	14.55	25.67	25.67
Oct	18.27	25.85	25.79	28.30	26.00	26.15	8.95	25.26	24.26
Nov	14.18	25.68	24.96	24.60	25.99	26.11	5.45	24.97	23.07
Dec	11.20	24.66	22.38	21.15	25.97	25.31	1.85	22.72	20.07
Total	17.56	25.45	24.66	37.90	26.00	26.16	0.40	20.01	19.94

Table 2.I is useful to demonstrate the substantial equivalence of the results: the annual average temperature difference between the two models is 0.79 °C, which becomes even smaller if analysed the maximum and minimum temperature difference, because they are direct consequence of the HVAC set-points.

For the same reason the biggest differences are confined into free-floating months, when nor heating or cooling is active. The maximum difference is 3.16°C between the types output in February, when less air-conditioning is necessary thanks to the heat capacity of the building.

This discrepancy is due to the fact that the dynamic energy balance written in Type 88 is:

$$\frac{dT}{dt} = \frac{U \cdot A}{C} \cdot (T_{int} - T_{ext}) + \frac{\dot{m}_{a,vent} \cdot c_{p,a}}{C} \cdot (T_{vent} - T_{ext}) + \frac{\dot{m}_{a,inf} \cdot c_{p,a}}{C} \cdot (T_{inf} - T_{ext}) + \sum \frac{Q_{gains}}{C} \quad [K/s]$$

As before, it refers to envelope transmission, air ventilation and infiltration and all thermal gains. The first derivative of temperature implies the thermal capacity involvement, which is lumped into a single parameter as the name of the type suggests.

Type 56 Multi-zone Building model provides a more efficient way to calculate the interaction between two or more zones by solving the coupled differential equations utilizing matrix inversion techniques. The effects of both short-wave and long-wave radiation exchange are accounted for with an area ratios method. The walls, ceilings, and floors are modelled according to the ASHRAE transfer function approach.[7]

[7] Solar Energy Laboratory, University of Madison-Wisconsin - TRNSYS 17 a TRaN sient S Ystem Simulation program - Volume 4, Mathematical Reference

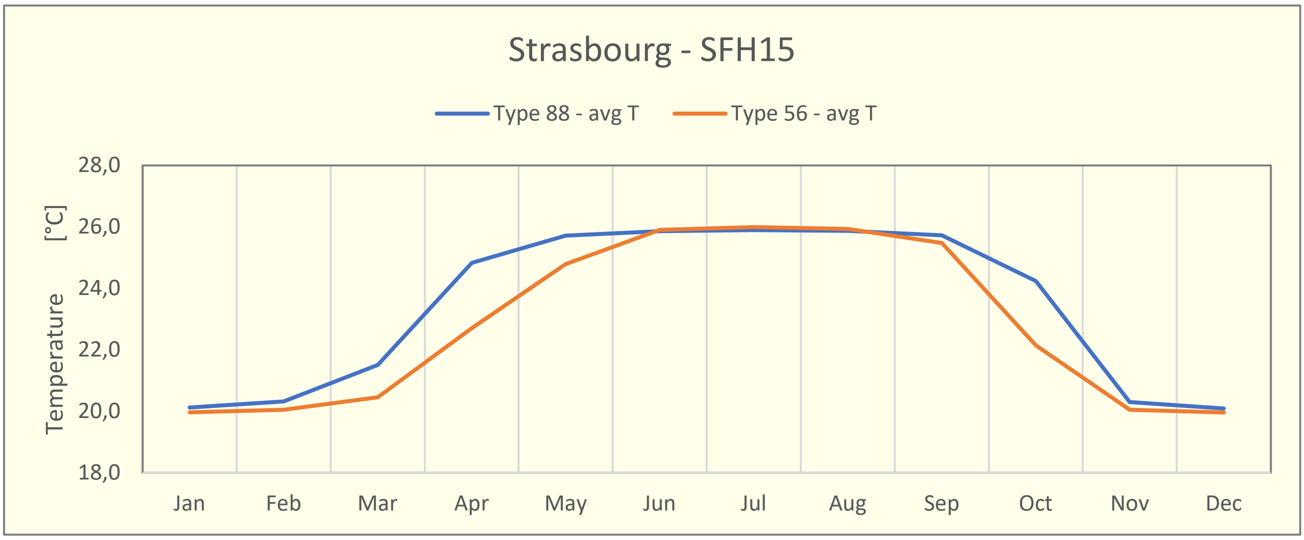


Figure 2.8- Monthly average of the internal temperature for SFH15 in Strasbourg

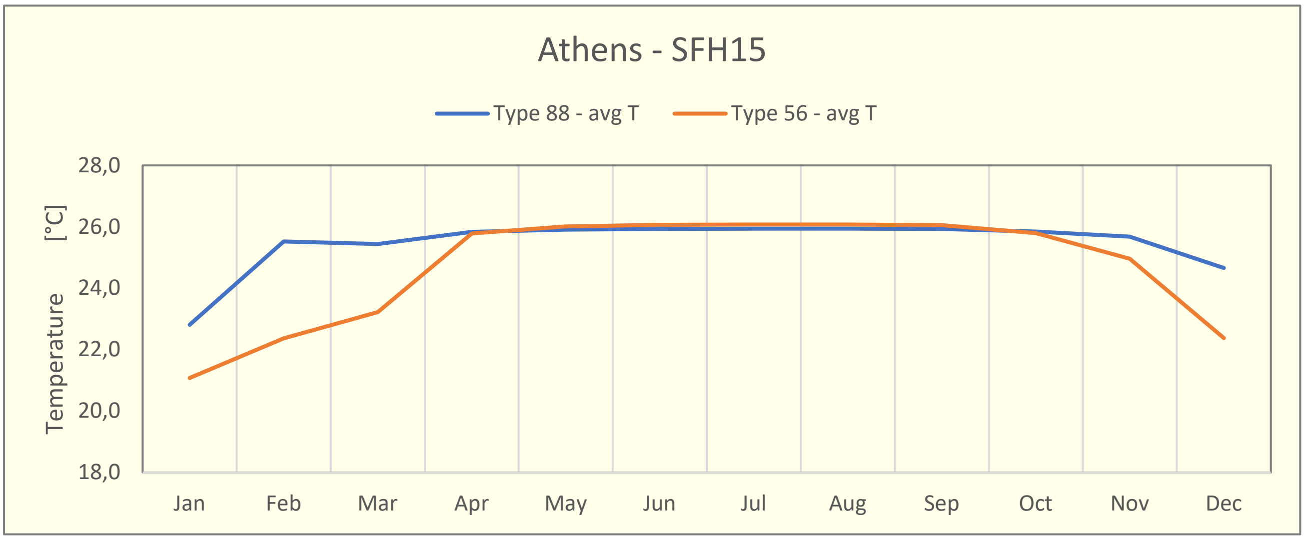


Figure 2.9- Monthly average of the internal temperature for SFH15 in Athens

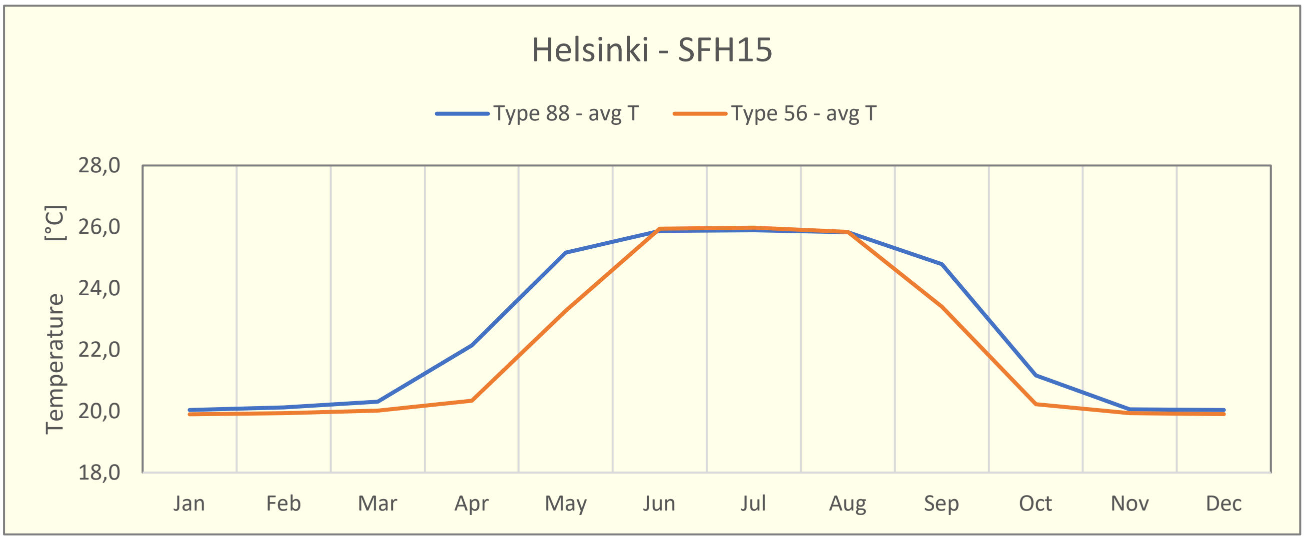


Figure 2.10- Monthly average of the internal temperature for SFH15 in Helsinki

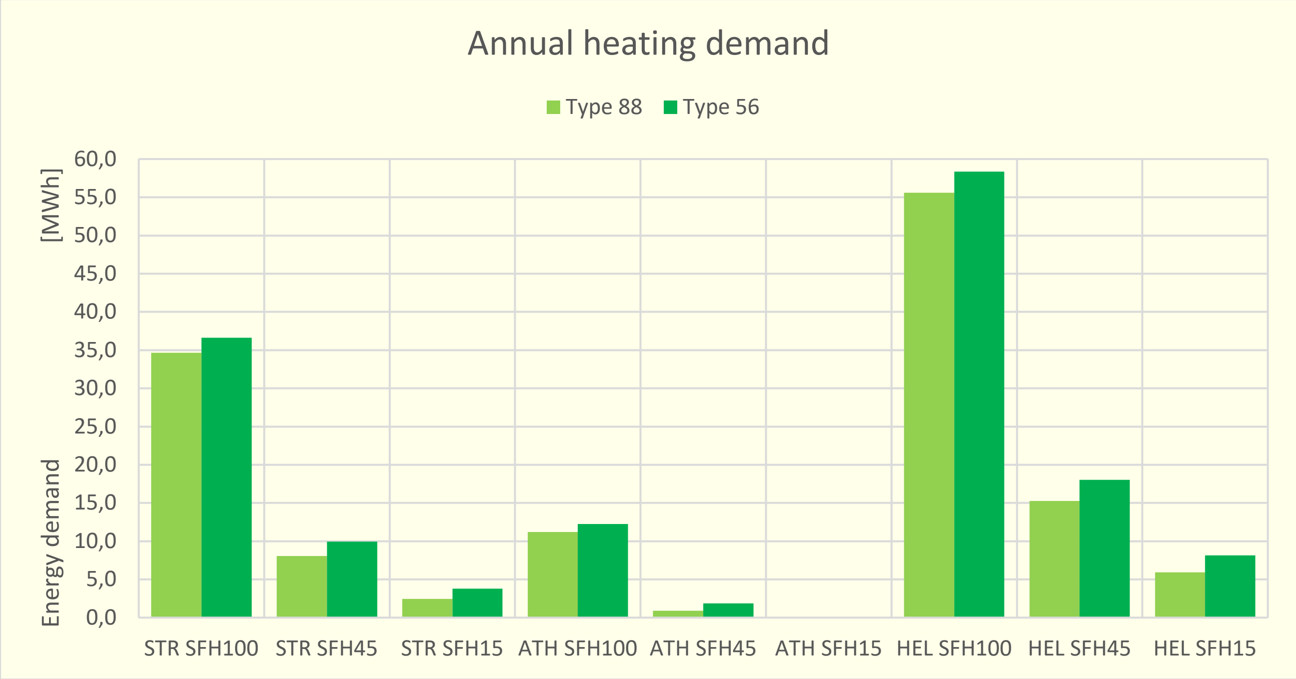


Figure 2.11 - Comparison of the annual heating demand

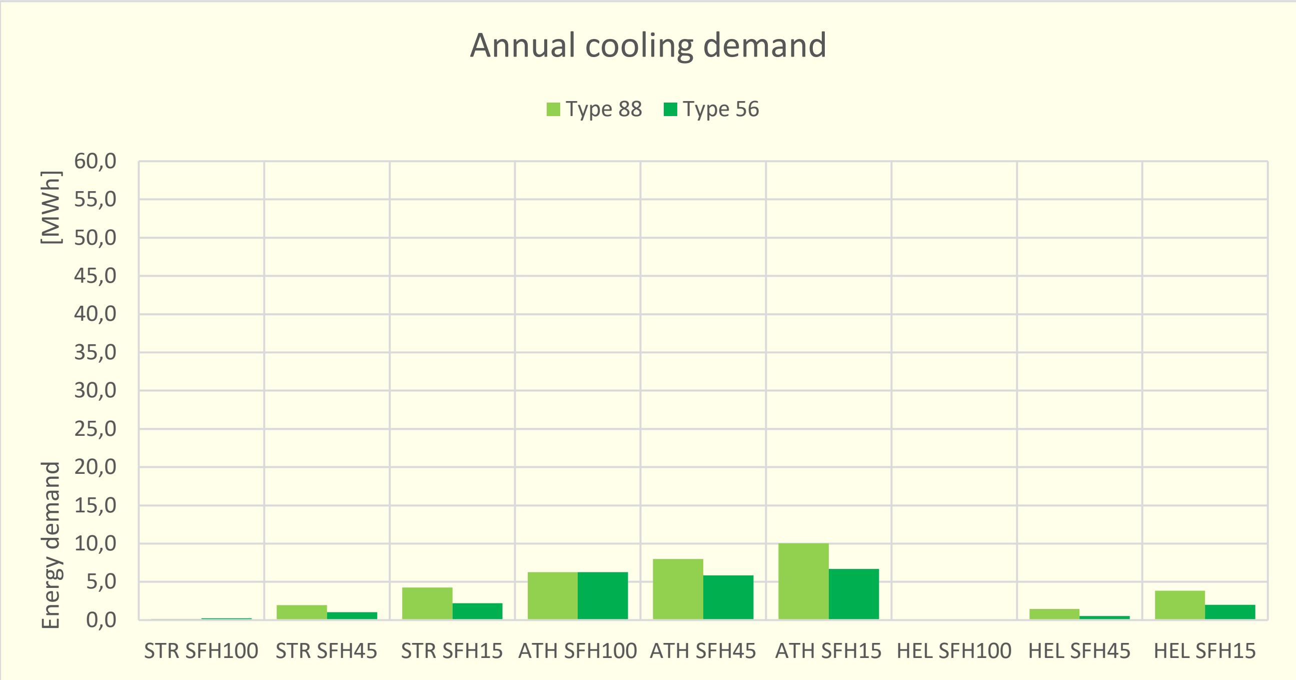


Figure 2.12 - Comparison of the annual cooling demand

Figure 2.11 and Figure 2.12 summarize the HVAC demand output from the different case studies.

The results are very similar in absolute values. The total demand in Table 2.J follows the expected trend, decreasing in more insulated buildings, but if divided into the seasonal demand, while the heating demand has a huge fall, the cooling demand increases. This phenomenon is repeated looking at lumped parameters model demand, because its internal temperature in free-floating is constantly higher than the output resulting from multi-nodal model of Type 56-B: therefore, its heating demand will be lower, but cooling demand higher.

If it is aimed to fix this discrepancy, a simple k-factor applied on building capacity C does not reach the bivalent effect aimed, because increasing/decreasing C it is obtained the same effect on both seasonal demands; the goal can be accomplished with a "seasonal" k-factor or through a corrective factor a posteriori on the heating/cooling demand.

Table 2.J - Comparison of the total energy demand

	Type 88	Type 56	Type 88 vs Type 56
STR SFH100	34.81 MWh	36.85 MWh	-5.52%
STR SFH45	10.04 MWh	11.00 MWh	-8.72%
STR SFH15	6.71 MWh	6.01 MWh	11.67%
ATH SFH100	17.46 MWh	18.52 MWh	-5.73%
ATH SFH45	8.88 MWh	7.72 MWh	15.10%
ATH SFH15	10.06 MWh	6.73 MWh	49.58%
HEL SFH100	55.59 MWh	58.35 MWh	-4.73%
HEL SFH45	16.75 MWh	18.58 MWh	-9.87%
HEL SFH15	9.79 MWh	10.12 MWh	-3.26%

Talking about the relative error, it results limited in two of the three climates (Strasbourg and Helsinki) but in Athens, especially for case SFH 15, the relative difference is almost half of the total amount of energy demand (about 4 MWh/year). Unfortunately, lumped capacity model loses precision in conditions with high cooling demand, where the effect of thermal inertia is more valuable. This is compensated in terms of simplicity, flexibility and, above all, computational speed of the program. From the moment that my algorithm aims to provide the sizing of a large number of solutions for the estimation of the energy demand, with the objective of isolate the best solutions for a further simulation of their performance with a Multi-Criteria Decision Making, it is a defect that I accepted to leave. Furthermore, in terms of impact on the sizing this error is quasi-irrelevant:

- in Chapter 4.5 I will show that the sizing parameters for the generators will be affected in the order of maximum 2 kW;
- for the final Primary Energy demand estimation, the significative output is the relative comparison between existing layout and retrofit layouts. The possible imprecisions of the model will not affect it from the moment that I use the same computational model for all the HVAC system layouts.

Moreover, making a global evaluation, the absolute difference between the outputs of the two energy models is acceptable for the purposes of the retrofitting tool, because the discrepancy is concentrated in the most modern building constructions which, in the same time, are not the main object of retrofit, while for older buildings the output equivalence is reliable, especially for heating period, where it is placed the largest part of energy demand and when the effect of internal heat capacity is less relevant on the thermal behaviour of the system.

3 The HVAC technologies contemplated by the algorithm

Heating, Ventilation and Air-Conditioning (HVAC) is managed with a large variety of systems, machineries and support elements. There is not an optimal solution conform to any type of building, because the performance depends on the dimensions of the heat flows involved and on the adaptation to different environments.

Chapter 3 introduces the state of the art of the retrofit solutions involved in the rehabilitation. It is present the most common HVAC equipment, together with some experimental machineries coming from the set for the project Heat4Cool.

3.1 The HVAC system types

Water-based system

The most ordinary HVAC system in residential buildings. Water is the heat carrier fluid that transfers heat from the generator to the emitters in the thermal zone.

In the past natural circulation systems were used, as for example the rain systems (top water distribution), and it was common the use of distribution with monotubes and heating bodies in series. Today, because of the evolution of pumps and plant technologies, the quasi-totality of water systems involves forced circulation plants, that is source plants (water distribution from below) with horizontal water distribution. The large majority of the hydraulic systems nowadays use also manifolds, each one supplying inlet water to its zone emitters.

Air-based system

These systems use as heat-transfer fluid for air conditioning the treated air in a centralized unit (called AHU, Air Handling Unit); air is distributed to the served rooms through a network of pipes. The air has the task of carrying out, at the same time, the control of the thermal load (sensible and latent) and the control of the quality of the ambient air. The origin of the air can be only external only, usually with heat recovery from the expelled air, or only internal, for delicate ambiences, or a mix of the two.

The major pros of these systems come out in applications on big buildings and large masses of air. Air emitters are frequent in northern countries, but they are generally adopted with a water-based system and in general in residential buildings it is infrequent to encounter such type of system, which on the other hand are much more frequent for the air-conditioning of public spaces and office buildings. At the same time, the layout of this plants is totally different from the others analysed, because it necessitates a detailed, specific design of the AHU.

For these reasons, I decided to not take in account this typology of HVAC system out of the cases where air is treated with a water HVAC system.

Electric system

Heat is provided though electric radiators which convert electric power into heating power for Joule effect. The efficiency of these systems, from an environmental point of view, is very low, because it consumes noble energy, such as electricity, for thermal purposes, without any intermediate process, wasting its potential. Because of the simplicity of installation, it was diffuse for the retrofit of very old buildings, before the growth of the eco-awareness, or in places with limited heating demand.

I decided to consider in the set of electric systems also the commonly called "air-conditioning" (A/C) for summer cooling in residential buildings, less commonly used also for heating in winter, which is in reality a system that uses a refrigerant fluid for a mono-split/multi-split fan-coils associated to an external chiller.

3.2 The emission subsystem

Heating elements are defined as "elements that yield the heat produced by a generator the environment; they are intended to yield heat in order to obtain, inside buildings, specific temperature conditions."[8]

They are classified into two main typologies:

- Natural convection heating body: heating body that does not include a ventilator or a similar device for activate or move the air on the heating element
- Forced convection heating body: heating body that requires the action of a fan or similar device.

Water radiators

The most frequent building heaters. They are heating bodies that emit heat by natural convection and irradiation. Radiators can be produced with different materials and forms (plate, column, tube).

The ideal functioning is with high water inlet temperature, because the yield decreases rapidly with lower water temperatures. They have mediocre speed of space heating and low uniformity of space heating. The regulation can be at zone control or at single element adjustment; they are silent elements and their average cost is very small.

Radiant floor

Radiant panels are heating bodies consisting in pipes placed behind the surfaces of the room to be heated. The heat is emitted in the environment partly by convection and, mainly, by radiation.

They can be:

- Radiant floor panels
- Wall-mounted radiant panels
- Radiant ceiling panels

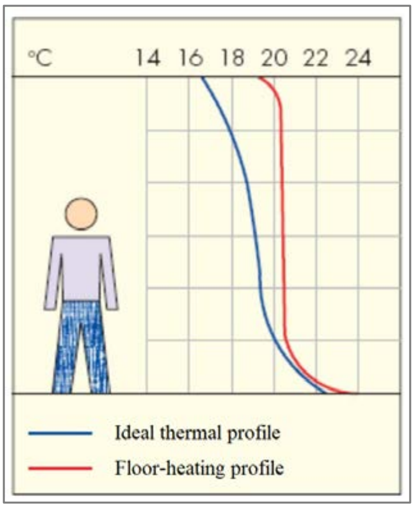


Figure 3.1 - Ideal temperature/height curve of the thermal comfort

Generally, in residential buildings they are placed underfloor, so I referred to the sole underfloor heating. Their main feature is the zone heating uniformity, with heat that is mainly yield by irradiation.

Figure 3.1, experimentally obtained, indicates that, in order to have ideal thermal conditions, it is necessary to maintain warm air near the floor and colder air on the ceiling. The radiant floor system allows to obtain a temperature curve close to the ideal one, thanks to the favourable position of the panels. It permits to keep the warm air near the floor and avoids the formation of hot air on the ceiling and cold on the floor, as happens on the contrary with traditional radiator or fan-coils systems.

The current trend prefers floor panels with surface temperature not lower than 19 °C and not higher than 28-29 ° C, to ensure comfort, respiratory and cardiovascular health. Compared to systems with

[8] EN 442-2:2014 - Radiators and convectors. Part 1: Technical specifications and requirements

traditional radiator heating elements, with underfloor heating it is possible to keep the ambient air at a lower temperature with the same thermal comfort conditions.

They are silent, but usually they are expensive. The working temperature of water is generally lower than the one for normal radiator, granting a possible source of energy saving.

Fan-coils

It is a heating body that emits heat though natural convection. A convector consists of, at least, the heating element and an outer casing that protects the ventilating unity. The ideal functioning of fan-coils is with low water inlet temperature, because it maximizes their yield. They have very good speed of space heating and high uniformity of space heating. As for radiators, the regulation can be a zone control or a single element adjustment. The noisiness is a sensible topic to be accurately designed; their average cost depends on the complexity of the unity but generally they can be not very expensive.

With water radiators and floor panels the cooling power obtained with cold water inlet is very poor and not-convenient. On the contrary, air emitting machineries can be coupled to mixed conditioning system for the emission of both heated or cooled air with equal efficacy, permitting the use of the same hydraulic system for the two purposes.

3.3 The generation subsystem

The heat generator is the component of the plant where the heat is produced, before it is transported to the terminals in the thermal zone. For summer cooling, the chillers produce the refrigerant power.

Heat generators

Traditional boiler

The traditional boiler is yet the most common heat generator in residential buildings.

In a boiler two parts are distinguished:

- the burner, inside a combustion chamber, where combustion takes place
- the actual boiler, where the transmission of heat from the flame and from the combustion products to the heat transfer fluid is completed.

There is a series of auxiliary elements:

- the mantle with thermos-acoustic insulation;
- control tools (thermometers, manometers, pyrometers) and safety devices (thermostats, pressure switches, safety valves, temperature regulators, expansion vessel);
- fuel supply tubes;
- fumes exhaust system.

Condensing boiler

The technological evolution of the traditional boiler. It achieves very remarkable heating performances.

In the traditional boiler they are summed various sources of heat dispersion in the different components of the water heating. The main innovation in condensing boiler is the possibility to manage condensation in exhaust fumes system, which gives the possibility to benefit of the the heat in exhaust fumes, lost in the combustion phase. This gives an extra-source of heat for the water pre-heating before it enters in the combustion chamber, producing a relevant increase in the efficiency of the boiler.

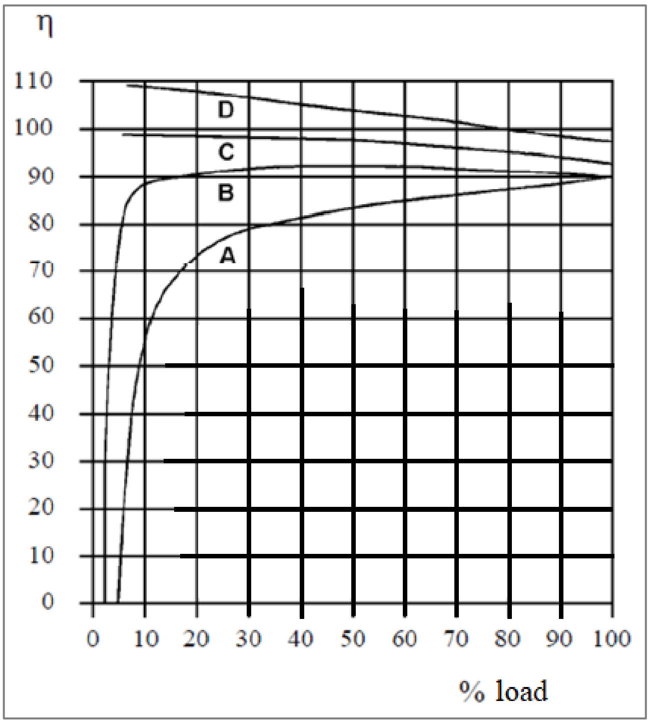


Figure 3.2 - Boiler efficiency in function of the load factor

Figure 3.2 refers to:

A: traditional boiler at constant temperature

B: modern boiler at constant temperature

C: Temperature compensation boilers

D: Condensing boiler

In most of the cases the boiler provides heated water for domestic use and building heating.; the exceptions are district heating or buildings without space heating.

Electric water heater

This electric device consumes electric energy to produce heated water. Heat is provided to water through an immersed electric resistance, which converts electric power into heating power, exploiting Joule effect. From the moment that it consumes noble energy, such as electricity, for a thermal utilization, it is a highly inefficient machine from an environmental point of view, but it is very simple to install and cheap. It can be used only for the production of domestic hot water.

Heat pump/chiller

With "Heat-pump/chillers" (HP) I group all the machines able to produce hot water up to the temperature of 50 °C and chilled water at 5 °C. Heat-pumps/chiller are thermal machines that work by transferring heat from a cold source to a hot one, able to do also the contrary (reversible cycle in Figure 3.3).

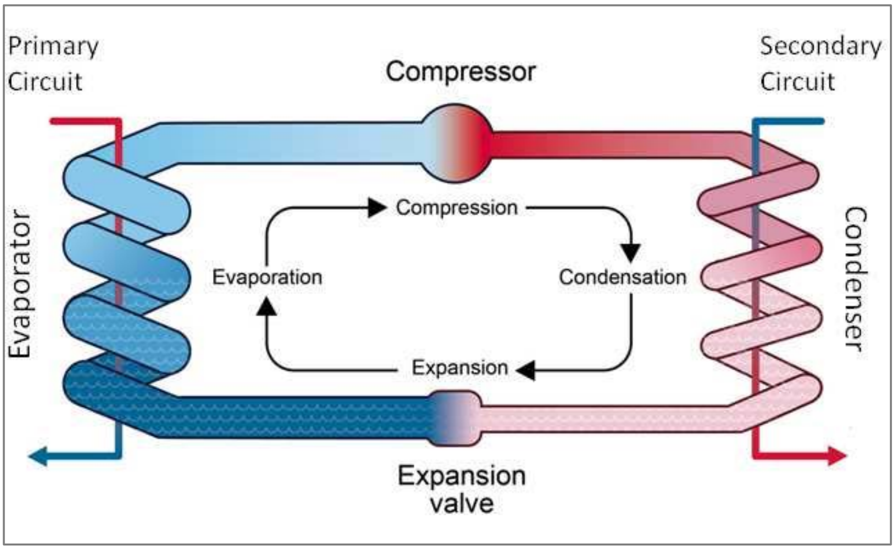


Figure 3.3 - Scheme of the heat-pump cycle

Out of the usual electric HP, in the algorithm I considered three other types of HP, coming from Heat4Cool set:

- DC powered heat pump: an electrical reversible HP powered with Direct-Current (without inverter), so that it can be directly connected to a photovoltaic alimentation;
- Adsorption heat pump: an advanced HP which exploits the thermal properties of some specific materials, with an adsorbing cooling vessel and a desorbing heating vessel.
- Absorption heat pump: a reversible thermally driven HP. This is not contemplated in Heat4Cool project, but I added it for an ampler analysis.

In presence of low external temperatures, heat pumps are affected by a severe decrease of their heating power, whereas the heating demand of the building is higher. For this reason, it is common to provide a back-up boiler as support for the critic conditions.

Heat generation source

I consider four different types of fuel for the boiler. Each one will be related to a different PEf in function of their environmental impact. The deriving types of boilers are:

- Coal-burning boiler;
- Oil-burning boiler;
- Gas-burning boiler;
- Biomass-burning boiler.

HPs are classified in function of the source used for the secondary circuit. This impacts on the COP (Coefficient of Performance) of the HP.

- Air source HP/Chiller;
- Water source HP/Chiller;
- Ground source HP/Chiller.

Renewable energy systems

They are added as possible additional source of energy, also two renewable generation systems.

Solar thermal collectors

Solar thermal plant means a system that uses Sun as an energy source making it available in the form of thermal energy. Solar energy exploited by the solar thermal collectors can serve:

- to integrate the domestic hot water production
- to integrate the heating system (combi-system)

Photovoltaic panels

Photovoltaic panels, called more properly photovoltaic modules, allow to transform solar energy into electricity. The photovoltaic process of transforming the energy of the sun into electricity takes place in photovoltaic cells, generally in silicon, assembled in an appropriate way to constitute one the photovoltaic module.

The yield of the plant depends on the type of silicon constituting the cell, the precision in the design of the best slope/orientation of the modules, the ability in the design of the wires for the electrical connections and the quality of the electrical storage.

3.4 Thermal energy storage

Hot water tank

Buildings can be provided of water tank, used for storing hot water for space heating or domestic use.

Indeed, water is a convenient and cheap heat storage medium because of its high specific heat capacity. An efficiently insulated tank can retain stored heat for days, reducing fuel costs for boilers, electric heaters or heat pumps. It is a necessaire element for the correct design of solar thermal plants, with high advantages especially in case it is used a stratified tank (Figure 3.4).

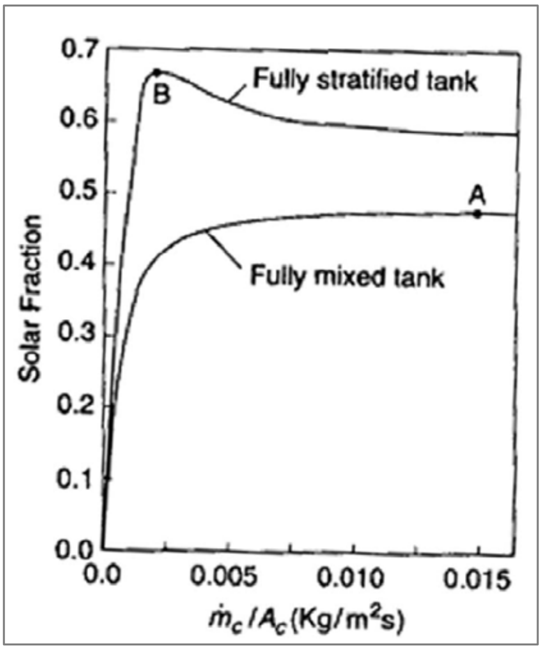


Figure 3.4 - Solar power available in function of the tank type

PCM tank

Currently, there are three major types of energy storage materials, including sensible, latent and thermochemical materials. Compared with sensible and thermo-chemical heat storage materials, phase change materials (PCM) have the advantage of high energy storage density and are able to maintain temperature (nearly) constant during the phase change process. Therefore, it has been widely used in many systems for storing thermal energy. [9]

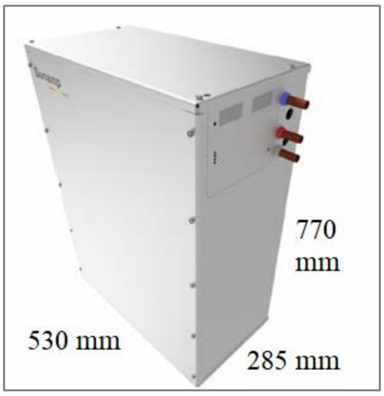


Figure 3.5 - Dimension of PCM tank module

RetroSim takes in account heat batteries made from a formulation based on Sodium Acetate Trihydrate (SAT), solving the problems of segregation and corrosion, obtaining in the same time very compact modular solutions (Figure 3.5).

[9] Y. Lia, G. Huanga, T. Xub, X. Liuc, H. Wub - Optimal design of PCM thermal storage tank and its application for winter

4 The filtering algorithm

The main object of the thesis is the formal definition of a general algorithm which can operate as filtering tool of the possible solutions for the retrofit of building systems.

The algorithm is developed into a MATLAB program which acquires the general input for the building system design, such as building dimensions, available areas and existing HVAC machineries, elaborating the set of solutions for its rehabilitation, taking in account multi-criteria constrains.

4.1 Description of the procedure

The filtering algorithm operates on more levels. The filter can act on three main fields:

- Technological constraints: the first level, the design limits coming from the technological aspects of the thermo-hydraulic requirements and performances of the building systems components, so that they are avoided impossible connections and configurations conceptually wrong;
- Building constraints: the second level of constraints derive from the application of a certain building system layout in the building site, whose performance is measured against a specific climate and its variability;
- Economic constraints: the final level of constraints is the economical availability of the desired system layout, depending on the costs of the components in comparison to the building user preferred budget.

Both retrofit solutions and its post-processing work on these first inputs.

The algorithm aims to be the more general possible, but some initial constraints must be set in order to have a starting point for the design:

- the repertoire of technologies collects the most common in European building stock, without having the claim of covering any possible existing HVAC layout. In fact it would be impossible to take in account also the existence of conceptually wrong layout, even if it could be legitimate. For this reason, my work pretends to examine the largest possible sample case, enlarging the set adopted in RetroSim (as shown in Chapter 3), but with some necessary constrains for its field of application;
- as for the retrofitting tool in Heat4Cool, my filtering algorithm is designed for residential buildings. Its precision is guaranteed for, at most, condominiums and little districts, then the design logic changes and it becomes no longer acceptable the assumption of neglecting distribution losses;
- differently from objectives in Heat4Cool, district heating or cooling is not part of the retrofit, from the moment that its design follows completely different criteria, because as before its main losses are concentrated in the distribution system and not in the generation/emission design;
- the retrofit operations concern just the building HVAC system: it is not considered any action on building frame or on its envelope, no constructive operation is contemplated;
- the sole exception is the construction of a water cooling system in cases where no cooling is present, otherwise great part of the retrofit potential would be lost and it would be a too large curtailment of its ambitions;

Schemes in Figure 4.1 and Figure 4.2 resume the different components involved in the building system design.

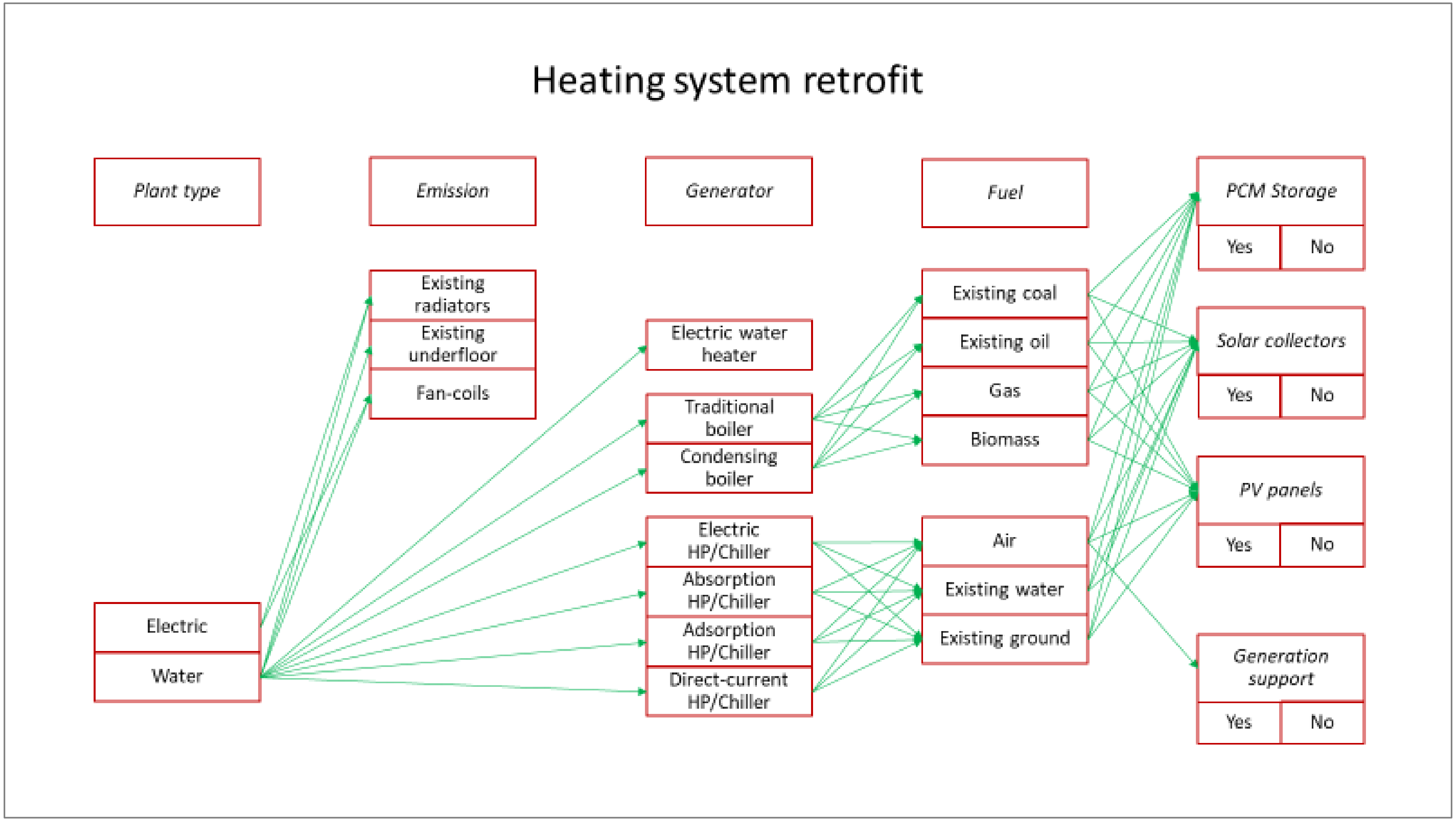


Figure 4.1 - Summary scheme of the heating system retrofit

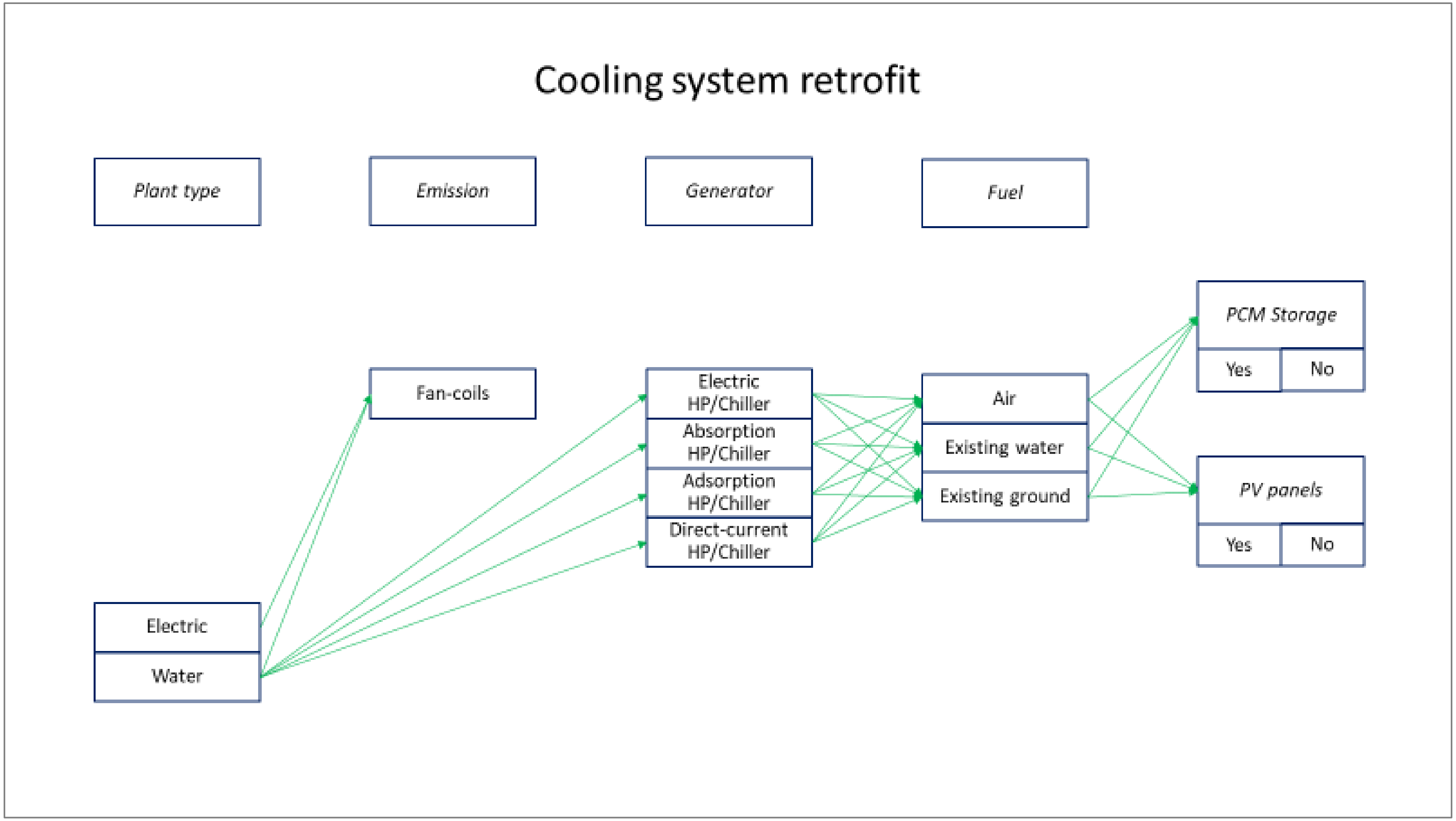


Figure 4.2 - Summary scheme of the cooling system retrofit

4.2 The climate data

The first step of building energy analysis is the acquirement of the climatic data of building site.

It is available an ample collection of climate data on EnergyPlus domain, in .epw format. These data gather various international and national sources (especially the second type), which means that the abundance of measurement depends on the nation of the site. Fortunately, for European nations there is a generous number of climate files, especially Spain (thanks to Grupo de Termotecnia of the Escuela Superior de Ingenieros in Seville), Poland (thanks to Instytutu Meteorologii i Gospodarki Wodnej -IMGW) and Italy (thanks to the collection "Gianni de Giorgio" created by prof. Livio Mazzarella, Politecnico di Milano).

For the employment of such format in the successive analysis, I wrote a MATLAB code (Annex IV) which scans the .epw file and produces the annual hourly average measurements.

- Dry Bulb Temperature [°C]
- Dew Point Temperature [°C]
- Relative Humidity [%]
- Atmospheric Station Pressure [Pa]
- Extraterrestrial Horizontal Radiation [W/m^2]
- Extraterrestrial Direct Normal Radiation [W/m^2]
- Horizontal Infrared Radiation from Sky [W/m^2]
- Global Horizontal Radiation [W/m^2]
- Direct Normal Radiation [W/m^2]
- Diffuse Horizontal Radiation [W/m^2]
- Global Horizontal Illuminance [lux]
- Direct Normal Illuminance [lux]
- Diffuse Horizontal Illuminance [lux]
- Zenith Illuminance [lux]
- Wind Direction [°]
- Wind Speed [m/s]
- Total Sky Cover
- Opaque Sky Cover
- Visibility [km]
- Ceiling Height [m]
- Present Weather Observation
- Present Weather Codes
- Precipitable Water [mm]
- Aerosol Optical Depth
- Snow Depth [cm]
- Days since last Snowfall

The main data of the site are recapitulated into the struct "Location", containing also maximum, minimum, and average annual temperature.

The radiation data are measured for the horizontal, but for both solar gains and solar plants they are needed vertical radiation oriented in 360°. For this reason, I implemented a program, named "tilted_radiation", which calculates the unitary radiation on a tilted surface following the isotropic diffuse sky model[10]. It is attached in Annex V.

[10] J. Duffie, W. Beckman - Solar Engineering of Thermal Processes

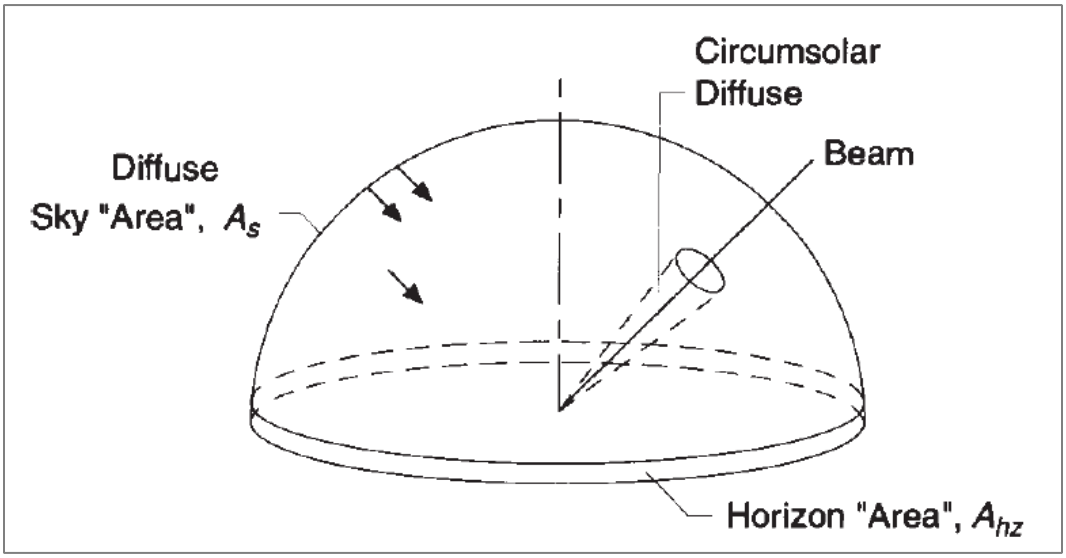


Figure 4.3 - Schematic of the distribution of diffuse radiation over the sky dome

"It can be assumed [as suggested by Hottel and Woertz (1942)] that the combination of diffuse and ground-reflected radiation is isotropic. With this assumption, the sum of the diffuse from the sky and the ground-reflected radiation on the tilted surface is the same regardless of orientation, and the total radiation on the tilted surface is the sum of the beam contribution calculated as I_bR_b and the diffuse on a horizontal surface, I_d. This represents an improvement over the assumption that all radiation can be treated as beam, but better methods are available.

An improvement on this model, the isotropic diffuse model, was derived by Liu and Jordan (1963). The radiation on the tilted surface was considered to include three components: beam, isotropic diffuse, and solar radiation diffusely reflected from the ground."

The total solar radiation on a tilted surface with slope β is the sum of the three different components:

$$I_{S,tilt} = I_{S,beam} \cdot R_b + I_{S,diff} \cdot \left(\frac{1+\cos\beta}{2}\right) + I_{S,hor} \cdot \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \qquad [\mathrm{W/m^2}]$$

Here the total solar radiation on the horizontal is divided between the diffuse radiation on the horizontal and the beam radiation, this one resulting from the subtraction of the diffuse radiation from the total solar radiation. Each component is multiplied with its view factor.

Figure 4.4 - Photo of a pyranometer

Both these two quantities are available in climate data. They are measured with the pyranometer (Figure 4.4), an instrument which is able to measure radiation and produces the shading necessary to divide the diffuse radiation from the direct solar radiation.

As albedo coefficient (ρ_G), i.e. the reflectance of the light of the ground, I assumed an average value of 0.5. This parameter depends on the type of ground radiated (0.2 for grass, 0.3 for dark buildings, 0.6 for white buildings).

The term R is defined as:

$$R = \frac{total\ radiation\ on\ the\ tilted\ surface}{total\ radiation\ on\ the\ horizontal\ surface} \qquad [-]$$

and R_b refers to beam radiation.

With δ I refer to the solar declination, that is the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive. Its value oscillates between $-23.45° \leq \delta \leq 23.45°$. It can be computed with equation of Cooper (1969):

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{n+284}{365}\right) \qquad [°]$$

where n is the number of the day in the year, from 1 to 365:

The hour angle is ω, that is the angular displacement of the sun to east or west of the local meridian due to rotation of the earth on its axis at 15° per hour (morning negative, afternoon positive).

$$\omega = 15 \cdot (h - 12) \qquad [°]$$

I can calculate now the average value in the space of R_b:

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{sin\delta \cdot (sin\varphi \cdot cos\beta - cos\varphi \cdot sin\beta \cdot cos\gamma) + cos\delta \cdot cos\omega \cdot (cos\varphi \cdot cos\beta + sin\varphi \cdot sin\beta \cdot cos\gamma) + cos\delta \cdot sin\beta \cdot sin\gamma \cdot sin\omega}{sin\delta \cdot sin\varphi + cos\delta \cdot cos\omega \cdot cos\varphi} \qquad [-]$$

The denominator $\cos\theta_z$ is the cosine of the angle of incidence for the beam radiation on the horizontal (so $\beta=0°$). This relation is always valid without integration if it is applied neglecting the hours of sunset and sunrise (an acceptable constrain because of the lack of radiation in those hours). It is necessary also the definition of a reasonable top limit, which I put at $R_b=10$.

This model works for surfaces of any orientation: it is easy to understand, it is conservative and simplifies calculation of radiation on tilted surfaces. Improved models have been developed, for example Hay and Davies anisotropic sky model, but for my application the previous model is totally trustworthy.

4.3 Acquisition of the inputs

Before the filtering operation is necessary to obtain several inputs from the users that describe the building passive and active existing state. This is done with the program "Inputs" (Annex VI).

With the dialogue with the front-end, I collect the necessary data for the next step. They are accrued inside a struct element, named "Building", following approximately the same procedure which has been chosen by Heat4Cool team, but also with some crucial differentiation because of my desire to unbind the filtering algorithm from their prearranged layouts.

Here is the list of them.

- Building.footprint	Building footprint [m^2]
- Building.envelope	Building external walls in contact with the environment [m^2]
- Building.floor	Building floor, equal to 0 if in contact with heated spaces [m^2]
- Building.roof	Building roof, equal to 0 if in contact with heated spaces [m^2]
- Building.height	Building total height [m]
- Building.floors	Number of floors
- Building.orientation	Building orientation, clockwise angle with the North [°]
- Building.window_N	Windows area exposed predominantly to N [m^2]
- Building.window_S	Windows area exposed predominantly to S [m^2]
- Building.window_W	Windows area exposed predominantly to W [m^2]
- Building.window_E	Windows area exposed predominantly to E [m^2]
- Building.solar_area	Total area available for solar plants [m^2]
- Building.solar_area_slope	Slope of the solar area (if available) [°]
- Building.solar_area_azimuth	Azimuth of the solar area (if available) [°]

From these quantities I can calculate:

- Building.area	Building useful area, i.e. the footprint times the floors number [m^3]
- Building.volume	Building volume obtained multiplying footprint and height [m^3]

I request also:

- Building.people — Building users. If unknown, I adopt the value of 0.04 pers/m^2 times the useful area[11].
- Building.age — Period of construction of the building. The list of option is:
  - Before 1945'
  - 'From 1945 to 1970'
  - 'In 1970s'
  - 'In 1980s'
  - 'In 1990s'
  - 'After 2000'
- Building.U_wall — Average external walls transmittance [W/m^2·K]
- Building.U_floor — Average floor transmittance [W/m^2·K], if in contact with exterior
- Building.U_roof — Average roof transmittance [W/m^2·K] , if in contact with exterior
- Building.U_window — Average window transmittance [W/m^2·K]
- Building.g_window — Average window solar factor

[11] Certificazione energetica degli edifici Procedura di calcolo, 3° supplemento straordinario al D.G.R. 5018/2007, Regione Lombardia 25/01/2008, from UNI 10339:1995

If these values are not known, I set the automatic consultation of the collection of average national data available for Heat4Cool project (Annex VII).

For the windows I found these values less reliable, so I decided to refine the investigation with the function "window". I ask to the user the window characteristics, in terms of glazing and frame, then I assume U-value and g-value of the window from the tables[12] in Figure 4.5.

Tipo di vetro	$g_{\perp}$	U_g [W/m²K]
Vetro singolo	0,82	5,9
Vetro singolo selettivo	0,66	3,2
Doppio vetro normale	0,70	3,3
Doppio vetro con rivestimento selettivo pirolitico	0,64	2
Doppio vetro con rivestimento selettivo catodico	0,62	2
Triplo vetro normale	0,60	1,8
Triplo vetro con rivestimento selettivo pirolitico	0,55	1,4
Triplo vetro con rivestimento selettivo catodico	0,53	1,4

Prospetto XIII – Valori della trasmittanza per energia solare totale, $g_{\perp}$, per alcune tipologie di vetri.

Tipo di telaio	U_t [W/m²K]
Legno	1,6
Metallo	5,9
PVC	1,7
Alluminio	5,5
Alluminio e Legno	3,5
Alluminio con taglio termico	3,1

Prospetto XIV – Valori della trasmittanza termica del telaio per alcune tipologie di materiale.

Figure 4.5 - Standard values for window properties

12 Certificazione energetica degli edifici Procedura di calcolo, 3° supplemento straordinario al D.G.R. 5018/2007, Regione Lombardia 25/01/2008, from UNI 10339:1995

The investigation finishes with the request of the existing HVAC system layout. They are 16 inputs, each one with one option to select between the ones shown.

- Existing_plant.Heating_system_type:
  - not present
  - Water system
  - Electric system
- Existing_plant.Heating_system_emitters:
  - not present
  - Radiators
  - Underfloor heating
  - Fan-coils
- Existing_plant.Heating_system_generator:
  - not present
  - Traditional boiler
  - Condensing boiler
  - Electric HP/Chiller
- Existing_plant.Heating_system_generator_fuel:
  - not present
  - Oil (for boiler)
  - Gas (for boiler)
  - Coal (for boiler)
  - Biomass (for boiler)
  - Air-source (for HP)
  - Water- source (for HP)
  - Ground- source (for HP)
- Existing_plant.Heating_system_DHW_generator:
  - not present
  - Traditional boiler
  - Condensing boiler
  - Electric water heater
- Existing_plant.Heating_system_DHW_generator_fuel:
  - not present
  - Oil (for boiler)
  - Gas (for boiler)
  - Coal (for boiler)
  - Biomass (for boiler)
- Existing_plant.Heating_system_support:
  - not present
  - Traditional boiler
  - Condensing boiler
- Existing_plant.Heating_system_support_fuel:
  - not present
  - Oil (for boiler)
  - Gas (for boiler)
  - Coal (for boiler)
  - Biomass (for boiler)

- Existing_plant.Heating_system_storage:
  - not present
  - Hot water tank
- Existing_plant.Cooling_system_type:
  - not present
  - Water system
  - Electric system
- Existing_plant.Cooling_system_emitters
  - not present
  - Fan-coils
- Existing_plant.Cooling_system_generator:
  - not present
  - Electric HP/Chiller
- Existing_plant.Cooling_system_generator_fuel:
  - not present
  - Air-source
  - Water- source
  - Ground- source
- Existing_plant.Cooling_system_storage
  - not present
  - Cold water tank
- Existing_plant.Renewable_support_ST
  - not present
  - Solar thermal collectors
- Existing_plant.Renewable_support_PV
  - not present
  - Photovoltaic panels

For the machineries I equipped the program with the possibility to let the user to insert the size of the component. I provided this option for:

- Existing_plant.Heating_system_generator
- Existing_plant.Heating_system_DHW_generator
- Existing_plant.Heating_system_support
- Existing_plant.Heating_system_storage
- Existing_plant.Cooling_system_generator
- Existing_plant.Cooling_system_storage
- Existing_plant.Renewable_support_ST
- Existing_plant.Renewable_support_PV

I stored the information into the vectors 'Power' and 'Volume', which will be the base of the following passages. If these data are not available for the user, they will be automatically calculated with the following parts of the program.

4.4 The building energy demand

Energy demand for space heating and cooling

A crucial instrument for the filtering and sizing is the energy demand of the building.

I adopt the theoretical energy model described in Chapter 2.1, with the modifications coming from the possibility to perform a succession of hourly energy balances[13].

$$\dot{Q}_H = \dot{Q}_T + \dot{Q}_V +\cdot \dot{Q}_S + \dot{Q}_i \qquad [W]$$

Heat flow for transmission

$$\dot{Q}_T = H_T \cdot \Delta T \qquad [W]$$

The expression of the heat transfer coefficient for transmission through the envelope (H_T) is:

$$H_T = \sum_i \frac{(A_i \cdot U_i)}{A_i} \qquad [W/K]$$

Heat flow for ventilation

With analogy with transmission, heat dispersion through ventilation is governed by the relation:

$$\dot{Q}_V = H_V \cdot \Delta T \qquad [W]$$

$$H_V = 0.334 \cdot \dot{V} \qquad [W/K]$$

The volume of ventilation is equal to the number of air changes per hour, which is function of the occupation of the building and, in residential building, it is fixed at 39.6 $m^3/(h \cdot pers)$, extracted from Figure 4.6.

Classificazione degli edifici per categoria	F_{oc}	$\dot{V}_{op}$
Edifici residenziali, collegi, luoghi di ricovero, case di pena, caserme, conventi	24	39,6
Alberghi, pensioni	8	39,6
Edifici per uffici e assimilabili	8	39,6
Ospedali, cliniche, case di cura e assimilabili	24	39,6
Edifici adibiti ad attività ricreative, associative e di culto	8	28,8
Attività industriali, Attività commerciali e assimilabili	8	36
Edifici adibiti ad attività sportive	8	36
Edifici adibiti ad attività scolastiche	8	21,6

Prospetto X – Periodo di occupazione giornaliero dei locali, F_{oc}, e portata d'aria esterna, $\dot{V}_{op}$, in edifici adibiti ad uso civile.

Figure 4.6 - Occupation and air change for class of building

Heat flow for solar radiation

$$Q_S = g \cdot A_W \cdot I_S \qquad [W]$$

Solar gains group the sum of all radiation entering from the windows, in all the orientation. For this purpose, I apply my program "tilted_radiation" to obtain the solar radiation in the four cardinal points, multiplying then the windows area for the corresponding direction of the radiation.

[13] Certificazione energetica degli edifici Procedura di calcolo, 3° supplemento straordinario al D.G.R. 5018/2007, Regione Lombardia 25/01/2008, from UNI 10339:1995

In the same time, I apply the program for the calculation of the incident solar radiation on the potential solar plant, because I already obtained the geometrical data necessary for its estimation, both for photovoltaic panels and/or solar thermal collectors.

Internal heat production

$$\dot{Q}_{o,s} = \alpha \cdot A_L \qquad [W]$$

For the global heat production for both occupants, electric equipment and lighting plant, I referred to Figure 4.7[14].

Destinazione d'uso	Apporti globali α	Unità di misura
Edifici residenziali* $A_L < 200$ m²	$6{,}25 - 0{,}02 \cdot A_L$	W/m²
Collegi, luoghi di ricovero, case di pena, caserme, conventi, alberghi e pensioni con area lorda riscaldata in pianta	6,25	W/m²
Edifici adibiti ad uffici e assimilabili, edifici adibiti ad attività ricreative, associative e di culto, edifici adibiti ad attività sportive e attività scolastiche	6	W/m²
Edifici adibiti ad attività commerciali, ospedali, cliniche, case di cura e assimilabili	8	W/m²

** Negli edifici residenziali, per le unità immobiliari con area lorda riscaldata in pianta superiore a 200 m² il valore degli apporti gratuiti, Q_L, si calcola moltiplicando 10,8 kWh/giorno per il numero dei giorni del mese e il numero delle unità immobiliari.*

Prospetto XII – Valori globali degli apporti interni.

Figure 4.7 - Internal gains for class of building

In case of useful areas smaller than 200 m² the global gain factor is equal to:

$$\alpha = 6.25 - 0.02 \cdot A_L \qquad [W/m^2]$$

otherwise it is equal to 10.8 kWh/day.

[14] Certificazione energetica degli edifici Procedura di calcolo, 3° supplemento straordinario al D.G.R. 5018/2007, Regione Lombardia 25/01/2008, from UNI 10339:1995

Domestic Hot Water demand estimation

Along with the energy demand, the heat generators generally supply hot water for domestic use (DHW demand). Figure 4.8 estimates the hot water demand of the dwelling.[15]

prospetto E.1 **Acqua calda: fabbisogno pro-capite**

Utenza	l/persona-giorno
Case di abitazioni*)	
- di tipo popolare	Da 40 a 50
- di tipo medio	Da 70 a 80
- di tipo di lusso	Da 150 a 200
Alberghi e pensioni	
- camere con servizi dotati di vasca	Da 180 a 200
- camere con servizi dotati di doccia	130
- camere con lavabo e bidet	60
Uffici	Da 15 a 200
Ospedali e cliniche	Da 130 a 150
Centri sportivi	Da 50 a 60
Spogliatoi di stabilimenti	Da 30 a 50

*) I valori indicati devono essere moltiplicati per i fattori correttivi riportati nei prospetti seguenti per tenere conto del numero degli alloggi, delle dimensioni di ogni alloggio e del tenore di vita dell'utente.

Figure 4.8 - Water demand per day for class of building

The table suggest a daily hot water demand per person in function of the standard of living:

- 40-50 l/day for public housing
- 70-80 l/day for average housing
- 150-200 l/day for wealthy housing

I assumed a global value of 75 l/person each day. Beside the average value, it is important to determine the peak demand. In dwellings the duration of the peak is established between 2 h and 3 h, with respect to the number of rooms. I assumed 2.5 hours. The maximum contemporary hot water consumption, in litres per hour, is expressed as:

$$v_{DHW} = \sum_i \frac{v_{n,i} \cdot n_i}{d_{p,i}} \cdot f_1 \cdot f_2 \cdot f_3 \qquad [l/h]$$

for *i* types of dwelling in the building complex (in our case i=1 and n_i=1). I assumed the nominal peak demand as two thirds of the daily hot water demand, the other factors are:

- f_1 is the decreasing factor in case of multiple dwellings. In our case it's a single dwelling so f_1=1;
- f_2 is the increasing factor in function of the number of rooms, assumed equal to 1 (3-4 rooms);
- f_3 is the factor with respect to the standard of living (good standard: f_3=1.1).

Known the volume need per unit of time, the power peak demand for DHW is easily calculated:

$$Q_{DHW} = q_m \cdot c_{p,w} \cdot \rho_w \cdot (T_h - T_C) \qquad [kW]$$

with density of water, assumed as constant along the range of temperature studied:

- T_h, the hot water temperature, generally in the range of 45÷55 °C (I assumed it at 50 °C);
- T_h, the cold water temperature, generally in the range of 7÷12 °C (I assumed it at 10 °C).

[15] UNI 9182:2014 - Hot and cold water supply and distribution installations. Design, installation and testing

4.5 The comparison with energy demand from TRNSYS models

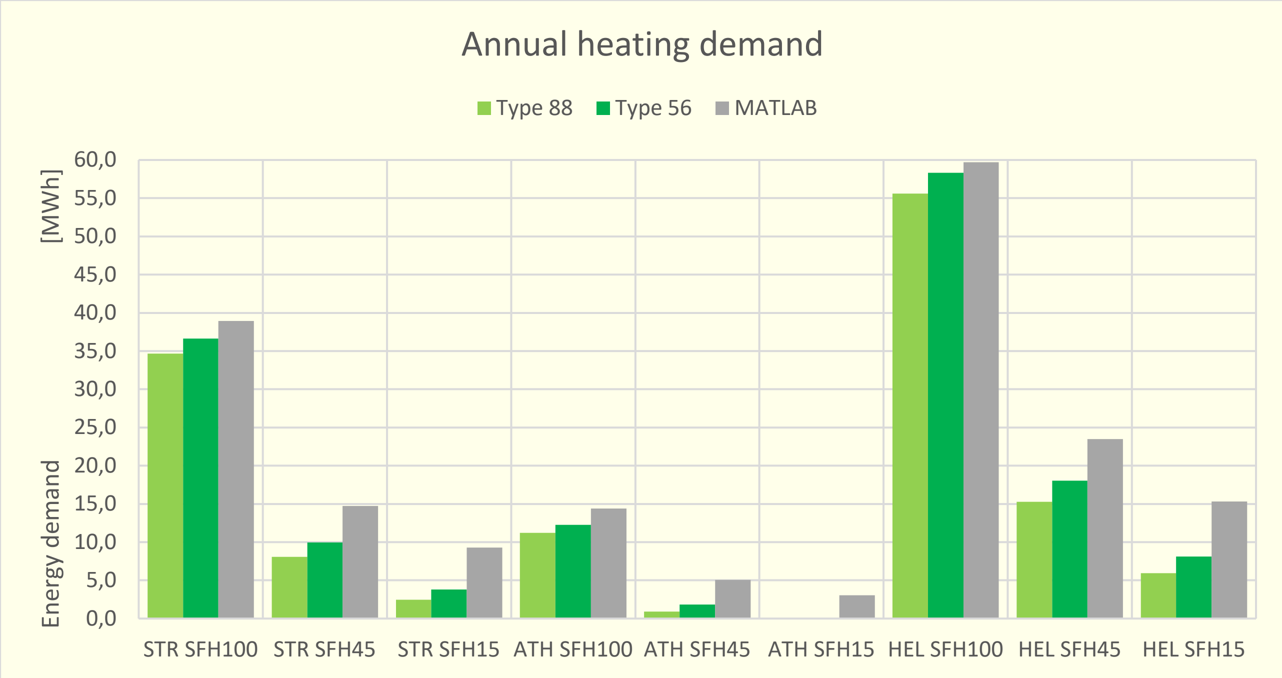


Figure 4.10 - Comparison of the annual heating demand

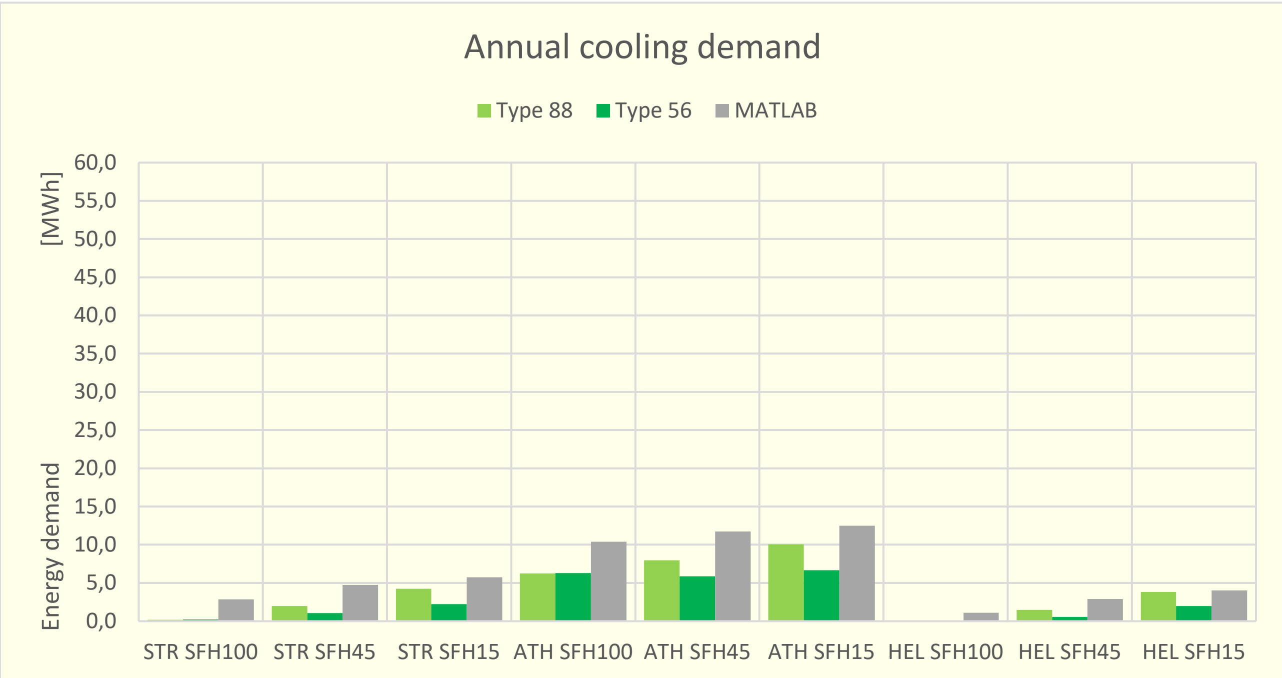


Figure 4.9 - Comparison of the annual heating demand

As explained in Chapter 2.4, the most evident difference between the two TRNSYS models for building study is the thermal capacity. In Type 88 the first derivative of temperature implies the thermal capacity involvement lumped into a single parameter as the name of the type suggests, while Type 56 calculates the interaction between two or more zones by solving the coupled differential equations.

The model I wrote in the program is a refinement of UNI 10339:1995, with an hourly static energy balance that neglects the effect of heat storage of the building masses. This simplification determines an oversizing of the estimation of the annual energy demand but with an acceptable error, inside the order of magnitude and its percentage influence decreases proportionally with the increase of total energy demand.

From the sizing perspective, more than the annual demand, it is important the peak value of the demand profile (Table 4.A and Table 4.B). The average oversizing error is 13% for heating and 26% for cooling; which is so on the safe side and determines, looking at absolute values, few cases where the final sizing power input differs and the error is limited to maximum 2 kW, an imprecision that is absolutely acceptable keeping in mind that the objective of my work is to isolate the best solutions for a further simulation of their performance with a Multi-Criteria Decision Making, not a definitive design.

The largest differences are placed on cooling side, where the effect of heat capacity is more important, but that is also the HVAC component which usually do not comprehend the largest absolute value and that, consequently, does not individuate the size of the generators.

Table 4.A - Peak of the heating power demand along the year

	TRNSYS average	MATLAB	TRNSYS vs MATLAB
STR SFH100	15,56 kW	15,19 kW	-2,37%
STR SFH45	5,78 kW	6,59 kW	13,95%
STR SFH15	3,53 kW	4,53 kW	28,33%
ATH SFH100	9,44 kW	9,05 kW	-4,16%
ATH SFH45	3,65 kW	3,82 kW	4,64%
ATH SFH15	1,75 kW	2,57 kW	47,28%
HEL SFH100	23,10 kW	21,61 kW	-6,45%
HEL SFH45	8,35 kW	9,48 kW	13,53%
HEL SFH15	5,21 kW	6,58 kW	26,30%

Table 4.B - Peak of the cooling power demand along the year

	TRNSYS average	MATLAB	TRNSYS vs MATLAB
STR SFH100	6,25 kW	8,96 kW	43,46%
STR SFH45	6,13 kW	7,51 kW	22,55%
STR SFH15	6,00 kW	7,21 kW	20,17%
ATH SFH100	10,18 kW	12,07 kW	18,59%
ATH SFH45	6,64 kW	8,81 kW	32,59%
ATH SFH15	6,18 kW	8,86 kW	43,37%
HEL SFH100	5,47 kW	7,37 kW	34,73%
HEL SFH45	5,77 kW	6,73 kW	16,70%
HEL SFH15	5,96 kW	6,58 kW	10,40%

The details of the program that implements the calculation of the building energy balance can be consulted in Annex VIII.

4.6 The filtering algorithm with MATLAB

The filtering algorithm is written in the MATLAB program I named "Filtering_tool.m".

It consists of 19 sections:

- Auxiliary parameters
- Filtering procedure of the retrofit layouts
- Cooling system type
- Cooling emission subsystem
- Space cooling generator
- Space cooling generator fuel
- Cold water storage
- Heating system type
- Heating emission subsystem
- Space heating generator
- Space heating generator fuel
- DHW generator
- DHW generator fuel
- Heat generation support
- Heat generation support fuel
- Hot water storage (SH+DHW)
- Renewable support - Solar thermal plant
- Renewable support - Photovoltaic plant
- Layout processing

The first section elaborates the inputs coming from the investigation of the existing building system. These constrains are used for the filtering of the components listed in the struct "Retrofit_alternatives", together with the general geometrical and constructive data coming from the building description, the site characteristics and the energy demand computed with the program "Energy_demand.m".

The algorithm core is a series of 16 for-cycles, each one nested into the other, so that it can be performed a multiple selection based on the inputs and the previous field. In fact, they are ordered in accordance to a hierarchy that puts on top the type of cooling system and then, in cascade, all the other features derive in sequence from the previous cycles. However, in some cases a cycle is independent from the other sections (for example the PV plant).

In the following pages it is reported the program. All sections are preceded by some comment lines that explain in detail the logic of the filter in the section.

```
%% Auxiliary parameters
% Conversion of Existing_plant struct in array

exs=struct2table(Existing_plant);
exs=table2array(exs)';
exs=exs([10:14 1:9 15 16]);

% Recap and storage of all the possible retrofitting technologies

Retrofit_alternatives.Cooling_system_type=[string('not_present');...
    string('Water system');string('Electric system')];

Retrofit_alternatives.Cooling_system_emitters=[string('not_present');...
    string('Fan-coils')];

Retrofit_alternatives.Cooling_system_generator=[string('not_present');...
    string('Electric HP/Chiller');string('Absorption HP/Chiller');...
    string('Adsorption HP/Chiller');string('DC HP/Chiller')];

Retrofit_alternatives.Cooling_system_generator_fuel=...
    [string('not_present');string('Air-source');string('Water-source');...
    string('Ground-source')];

Retrofit_alternatives.Cooling_system_storage=[string('not_present');...
    string('Hot water tank');string('PCM storage')];

Retrofit_alternatives.Heating_system_type=[string('not_present');...
    string('Water system');string('Electric system')];

Retrofit_alternatives.Heating_system_emitters=[string('not_present');...
    string('Radiators');string('Underfloor heating');string('Fan-coils')];

Retrofit_alternatives.Heating_system_generator=[string('not_present');...
    string('Traditional boiler');string('Condensing boiler'); ...
    string('Electric HP/Chiller');string('Absorption HP/Chiller');...
    string('Adsorption HP/Chiller');string('DC HP/Chiller')];

Retrofit_alternatives.Heating_system_generator_fuel=...
    [string('not_present');string('Coal');string('Oil');string('Gas');...
    string('Biomass');string('Air-source');string('Water-source');...
    string('Ground-source')];

Retrofit_alternatives.Heating_system_DHW_generator=[string('not_present');...
    string('Traditional boiler');string('Condensing boiler');...
    string('Electric water heater')];

Retrofit_alternatives.Heating_system_DHW_generator_fuel=...
    [string('not_present');string('Coal');string('Oil');string('Gas');...
    string('Biomass')];

Retrofit_alternatives.Heating_system_support=[string('not_present');...
    string('Traditional boiler');string('Condensing boiler')];

Retrofit_alternatives.Heating_system_support_fuel=...
    [string('not_present');string('Coal');string('Oil');string('Gas');...
    string('Biomass')];

Retrofit_alternatives.Heating_system_storage=[string('not_present');...
    string('Hot water tank');string('PCM storage')];
```

```
Retrofit_alternatives.Renewable_support_ST=[string('not_present');...
    string('Solar thermal collectors');string('Photovoltaic panels')];

Retrofit_alternatives.Renewable_support_PV=[string('not_present');...
    string('Solar thermal collectors');string('Photovoltaic panels')];

%% Filtering procedure of the retrofit layouts

counter=1;

%% Cooling system type
% The base of the retrofit layouts is the usage of water systems for
% cooling. It is contemplated the presence of electric solutions only if
% already adopted in the existing building system.

Retrofit.Cooling_system_type=string('Water system');
if Existing_plant.Cooling_system_type=='not_present'
    Retrofit.Cooling_system_type=Retrofit_alternatives.Cooling_system_type;
elseif Existing_plant.Cooling_system_type=='Electric system'
    Retrofit.Cooling_system_type=[Retrofit.Cooling_system_type;...
        Existing_plant.Cooling_system_type];
end

%% Cooling emission subsystem
% I define "Electric fan-coils system" the normal mono-split or
% multi-split air-conditioning with external unity. I neglect the usage of
% water radiators or underfloor system for cooling because it is very rare
% and largely inefficient.

    for idx_1=1:length(Retrofit.Cooling_system_type)
        aux(1,counter)=Retrofit.Cooling_system_type(idx_1);

if Retrofit.Cooling_system_type(idx_1)=='not_present'
    Retrofit.Cooling_system_emitters=string('not_present');
else
    Retrofit.Cooling_system_emitters=string('Fan-coils');
end

%% Space cooling generator
% In case of water cooling system, they can be adopted the four different
% types of chillers.

    for idx_2=1:length(Retrofit.Cooling_system_emitters)
        aux(2,counter)=Retrofit.Cooling_system_emitters(idx_2);

if Retrofit.Cooling_system_type(idx_1)~='Water system'
    Retrofit.Cooling_system_generator=string('not present');
else
    Retrofit.Cooling_system_generator=...
        Retrofit_alternatives.Cooling_system_generator([2;3;4;5]);
end

%% Space cooling generator fuel
% The solution for chiller thermal source contemplated is the air, because
% it is undoubtedly the most common solution for its ease of installation.
% Ground-source and water-source chiller have certainly great advantages
% and performances but necessitate particular site conditions and expensive
% setup, so it is contemplated only when already present in the existing
```

```
% building system.

    for idx_3=1:length(Retrofit.Cooling_system_generator)
        aux(3,counter)=Retrofit.Cooling_system_generator(idx_3);

if Retrofit.Cooling_system_generator(idx_3)==string('not present')
    Retrofit.Cooling_system_generator_fuel=string('not present');
else
    Retrofit.Cooling_system_generator_fuel=string('Air-source');
    if (Existing_plant.Cooling_system_generator=='Electric HP/Chiller' ...
            && Existing_plant.Cooling_system_generator_fuel~='Air-source')
        Retrofit.Cooling_system_generator_fuel=[...
            Retrofit.Cooling_system_generator_fuel;...
            Existing_plant.Cooling_system_generator_fuel];
    end
end

%% Cold water storage
% PCM storage increases the efficiency of the cooling system. It is
% contemplated the alternative of a normal cold water storage only when
% already present in the existing building system.

    for idx_4=1:length(Retrofit.Cooling_system_generator_fuel)
        aux(4,counter)=Retrofit.Cooling_system_generator_fuel(idx_4);

Retrofit.Cooling_system_storage=[string('not present');...
    string('PCM storage')];
if Existing_plant.Cooling_system_storage=='Cold water tank'
    Retrofit.Cooling_system_storage=[Retrofit.Cooling_system_storage;...
        Existing_plant.Cooling_system_storage];
end

%% Heating system type
% If used for cooling, the water system is automatically considered also
% for heating. It is contemplated the presence of electric solutions when
% already adopted in the existing building system.

    for idx_5=1:length(Retrofit.Cooling_system_storage)
        aux(5,counter)=Retrofit.Cooling_system_storage(idx_5);

Retrofit.Heating_system_type=string('Water system');
if Existing_plant.Heating_system_type=='not_present'
    Retrofit.Heating_system_type=Retrofit_alternatives.Heating_system_type;
elseif Existing_plant.Heating_system_type=='Electric system'
    Retrofit.Heating_system_type=[Retrofit.Heating_system_type;...
        Existing_plant.Heating_system_type];
end

%% Heating emission subsystem
% I define "Electric fan-coils system" the normal mono-split or
% multi-split air-conditioning with external unity; they are considered
% also the electrical radiators, where I consider all types of heaters and
% stoves. For water systems, the alternatives are radiators and underfloor
% heating (when already existing), and fan-coils.

    for idx_6=1:length(Retrofit.Heating_system_type)
        aux(6,counter)=Retrofit.Heating_system_type(idx_6);

if Retrofit.Heating_system_type(idx_6)=='not_present'
```

```
    Retrofit.Heating_system_emitters=string('not_present');
else
    Retrofit.Heating_system_emitters=string('Fan-coils');
    if Retrofit.Heating_system_type(idx_6)=='Electric system'
        Retrofit.Heating_system_emitters=[...
            Retrofit.Heating_system_emitters;string('Radiators')];
    elseif (any([string('Radiators') string('Underfloor heating')]==...
            Existing_plant.Heating_system_emitters) &&...
            Existing_plant.Heating_system_type~='Electric system')
        Retrofit.Heating_system_emitters=...
            [Retrofit.Heating_system_emitters;...
            Existing_plant.Heating_system_emitters];
    end
end

%% Space heating generator
% I contemplated the usage of HPs when they are already adopted as chiller
% for cooling, otherwise it would be scarsely efficient and too much
% expensive. The boiler alternatives consider a traditional boiler case
% only when it is present in the existing heating system.

    for idx_7=1:length(Retrofit.Heating_system_emitters)
        aux(7,counter)=Retrofit.Heating_system_emitters(idx_7);

if Retrofit.Heating_system_type(idx_6)~='Water system'
    Retrofit.Heating_system_generator=string('not_present');
elseif any(Retrofit_alternatives.Cooling_system_generator([2;3;4;5])==...
            Retrofit.Cooling_system_generator(idx_3))
        Retrofit.Heating_system_generator=...
            Retrofit.Cooling_system_generator(idx_3);
else
    Retrofit.Heating_system_generator=string('Condensing boiler');
    if Existing_plant.Heating_system_generator=='Traditional boiler'
        Retrofit.Heating_system_generator=[...
            Retrofit.Heating_system_generator;...
            Existing_plant.Heating_system_generator];
    end
end

%% Space heating generator fuel
% As explained for chillers, ground-source and water-source HPs are a
% reasonable alternative only when already present in the existing
% building system. On the other hand, I neglect the possibility to update
% the combustion of the traditional boiler because of the age of this
% solution, while for condensing boiler I consider the change only to gas
% and biomass fuel.

    for idx_8=1:length(Retrofit.Heating_system_generator)
        aux(8,counter)=Retrofit.Heating_system_generator(idx_8);

if Retrofit.Heating_system_generator(idx_8)==string('not present')
    Retrofit.Heating_system_generator_fuel=string('not present');
elseif Retrofit.Heating_system_generator(idx_8)=='Condensing boiler'
    Retrofit.Heating_system_generator_fuel=...
        Retrofit_alternatives.Heating_system_generator_fuel([4;5]);
    if any(Retrofit_alternatives.Heating_system_generator_fuel([2 3]')...
            ==Existing_plant.Heating_system_generator_fuel)
        Retrofit.Heating_system_generator_fuel=[...
            Retrofit.Heating_system_generator_fuel;...
```

```
            Existing_plant.Heating_system_generator_fuel];
    end
elseif Retrofit.Heating_system_generator(idx_8)=='Traditional boiler'
    Retrofit.Heating_system_generator_fuel=...
        Existing_plant.Heating_system_generator_fuel;
else
    Retrofit.Heating_system_generator_fuel=string('Air-source');
    if (any([Existing_plant.Heating_system_generator...
            Existing_plant.Cooling_system_generator]==...
            'Electric HP/Chiller') && ...
            Existing_plant.Cooling_system_generator_fuel~='Air-source')
        Retrofit.Heating_system_generator_fuel=[...
            Retrofit.Heating_system_generator_fuel;...
            Existing_plant.Heating_system_generator_fuel];
    end
end

%% DHW generator
% In old buildings in warm sites, there might be no heating system. The DHW
% is obtained with boilers or electrical water heaters. It is not
% contemplated HP case because, if present, it is necessarily coupled with
% fan-coils, at least for cooling, so it would be useless to not use it
% also for heating.

    for idx_9=1:length(Retrofit.Heating_system_generator_fuel)
        aux(9,counter)=Retrofit.Heating_system_generator_fuel(idx_9);

if (Existing_plant.Heating_system_DHW_generator==string('not present')||...
        Retrofit.Heating_system_generator(idx_8)~=string('not present'))
    Retrofit.Heating_system_DHW_generator=string('not present');
else
    Retrofit.Heating_system_DHW_generator=string('Condensing boiler');
    if Existing_plant.Heating_system_DHW_generator~='Condensing boiler'
        Retrofit.Heating_system_DHW_generator=[...
            Existing_plant.Heating_system_DHW_generator;...
            Retrofit.Heating_system_DHW_generator];
    end
end

%% DHW generator fuel
% It follows the same logic of Space heating generator fuel. These
% parameters are needed for Primary Energy assessments.

    for idx_10=1:length(Retrofit.Heating_system_DHW_generator)
        aux(10,counter)=Retrofit.Heating_system_DHW_generator(idx_10);

if Retrofit.Heating_system_DHW_generator(idx_10)=='Condensing boiler'
    Retrofit.Heating_system_DHW_generator_fuel=...
        Retrofit_alternatives.Heating_system_generator_fuel([4;5]);
    if any(Retrofit_alternatives.Heating_system_generator_fuel([2 3]')...
            ==Existing_plant.Heating_system_DHW_generator_fuel)
        Retrofit.Heating_system_DHW_generator_fuel=[...
            Retrofit.Heating_system_DHW_generator_fuel;...
            Existing_plant.Heating_system_DHW_generator_fuel];
    end
elseif Retrofit.Heating_system_DHW_generator(idx_10)=='Traditional boiler'
    Retrofit.Heating_system_DHW_generator_fuel=...
        Existing_plant.Heating_system_DHW_generator_fuel;
else
```

```
    Retrofit.Heating_system_DHW_generator_fuel=string('not present');
end

%% Heat generation support
% When an HP is used for heating generator, it is common to put an
% auxiliary heater.
% In particular, it is necessary for Absorption and Adsorption HPs and I
% considered it also for the other types of HPs when outside temperature is
% lower than 0°C, in fact for lower temperatures the COP of the process
% becomes not convenient and so it is common to cover the heating demand
% with the auxiliary boiler.

    for idx_11=1:length(Retrofit.Heating_system_DHW_generator_fuel)
        aux(11,counter)=Retrofit.Heating_system_DHW_generator_fuel(idx_11);

if any(Retrofit_alternatives.Heating_system_generator([5 6])'==...
        Retrofit.Heating_system_generator(idx_8))...
        || (any(Retrofit_alternatives.Heating_system_generator([4 7])'==...
        Retrofit.Heating_system_generator(idx_8)) && Location.T_min<0)
    Retrofit.Heating_system_support=string('Condensing boiler');
    if any([Existing_plant.Heating_system_generator...
            Existing_plant.Heating_system_DHW_generator...
            Existing_plant.Heating_system_support]=='Traditional boiler')
        Retrofit.Heating_system_support=...
            [string('Traditional boiler');...
            Retrofit.Heating_system_support];
    end
else
    Retrofit.Heating_system_support=string('not present');
end


%% Heat generation support fuel
% It follows the same logic of the two previous fuel paramters. The
% existing plant variable is scanned in many voices of the struct because
% the auxiliary heater is thinked to be, when available, the existing
% boiler, in order to economize.

    for idx_12=1:length(Retrofit.Heating_system_support)
        aux(12,counter)=Retrofit.Heating_system_support(idx_12);

if Retrofit.Heating_system_support(idx_12)=='not present'
    Retrofit.Heating_system_support_fuel=string('not present');
else
    if any([string('Traditional boiler') string('Condensing boiler')] ==...
            Existing_plant.Heating_system_generator)
        Retrofit.Heating_system_support_fuel=...
            Existing_plant.Heating_system_generator_fuel;
    elseif any([string('Traditional boiler') ...
            string('Condensing boiler')] == ...
            Existing_plant.Heating_system_DHW_generator)
        Retrofit.Heating_system_support_fuel=...
            Existing_plant.Heating_system_DHW_generator_fuel;
    elseif any([string('Traditional boiler') ...
            string('Condensing boiler')] == ...
            Existing_plant.Heating_system_support)
        Retrofit.Heating_system_support_fuel=...
            Existing_plant.Heating_system_support_fuel;
    end
```

```
    if Retrofit.Heating_system_support(idx_12)=='Condensing boiler'...
            && all(Retrofit.Heating_system_support_fuel~=...
            Retrofit_alternatives.Heating_system_generator_fuel([4;5]))
        Retrofit.Heating_system_support_fuel=[...
            Retrofit.Heating_system_support_fuel;...
            Retrofit_alternatives.Heating_system_generator_fuel([4;5])];
    end
end

%% Hot water storage (SH+DHW)
% PCM storage increases the efficiency of the heating system too. If
% already used for cooling, PCM storage is automatically contemplated for
% heat storage. The alternative of a normal hot water storage is used only
% when already present in the existing building system.

    for idx_13=1:length(Retrofit.Heating_system_support_fuel)
        aux(13,counter)=Retrofit.Heating_system_support_fuel(idx_13);

Retrofit.Heating_system_storage=string('PCM storage');
if Retrofit.Cooling_system_storage(idx_5)~='PCM storage'
    Retrofit.Heating_system_storage=[string('not present');...
        Retrofit.Heating_system_storage];
end
if Existing_plant.Heating_system_storage=='Hot water tank'
    Retrofit.Heating_system_storage=[Retrofit.Heating_system_storage;...
        Existing_plant.Heating_system_storage];
end

%% Renewable support - Solar thermal plant
% It is not considered the option to disuse a solar plant.

    for idx_14=1:length(Retrofit.Heating_system_storage)
        aux(14,counter)=Retrofit.Heating_system_storage(idx_14);

if Existing_plant.Renewable_support_ST=='not present' && ...
        Building.solar_area>0
    Retrofit.Renewable_support_ST=[string('not present');...
        string('Solar thermal collectors')];
else
    Retrofit.Renewable_support_ST=Existing_plant.Renewable_support_ST;
end

%% Renewable support - Photovoltaic plant
% It is not considered the option to disuse a solar plant.

    for idx_15=1:length(Retrofit.Renewable_support_ST)
        aux(15,counter)=Retrofit.Renewable_support_ST(idx_15);

if Existing_plant.Renewable_support_PV=='not present' && ...
        Building.solar_area>0
    Retrofit.Renewable_support_PV=[string('not present');...
        string('Photovoltaic panels')];
else
    Retrofit.Renewable_support_PV=Existing_plant.Renewable_support_PV;
end

%% Layout processing

    for idx_16=1:length(Retrofit.Renewable_support_PV)
```

```
        aux(16,counter)=Retrofit.Renewable_support_PV(idx_16);
        counter=counter+1;
        aux(1:16,counter)=aux(1:16,counter-1);

    end;end;end;end;end;end;end;end;end;end;end;end;end;end;end;end

aux=aux(:,1:end-1);
Configurations=array2table([exs aux],'RowNames',...
    {'Cooling_system_type' 'Cooling_system_emitters' ...
    'Cooling_system_generator' 'Cooling_system_generator_fuel' ...
    'Cooling_system_storage' 'Heating_system_type' ...
    'Heating_system_emitters' 'Heating_system_generator' ...
    'Heating_system_generator_fuel' 'Heating_system_DHW_generator' ...
    'Heating_system_DHW_generator_fuel' 'Heating_system_support' ...
    'Heating_system_support_fuel' 'Heating_system_storage' ...
    'Renewable_support_ST' 'Renewable_support_PV'});

clear idx_1 idx_2 idx_3 idx_4 idx_5 idx_6 idx_7 idx_8 idx_9 idx_10 ...
    idx_11 idx_12 idx_13 idx_14 idx_15 idx_16 counter aux exs Retrofit;
```

5 The sizing algorithm and the estimation of the energy demand

The definition of the possible retrofit layouts is the base of the successive steps.

Chapter 5 deals in the first part with the definition of the size of the components, though the description of a new MATLAB program. With this new information it is possible to estimate the expected Primary Energy consumption, that is the fundamental parameter for the evaluation of the quality of the results and the rating of the solutions obtained.

5.1 Procedure for the sizing

In the project Heat4Cool, before the study of the performance of the HVAC system through a dynamic simulation, it is necessary to consider reasonable dimensions of the components of the plant configuration. This is a pre-sizing step, which produces a rough estimation of the optimal size need to cut useless iterations that cost time, especially for our dynamic annual simulations. I followed this passage also in my algorithm because it was essential for the obtainment of an instrument for the evaluation and the visualization of the filtered solutions.

Technical books, standards and working experiences provide an important source for the research of simple, basic equations that let us assume a reasonable size of the machineries. We refer to them as "rules of thumb".

Rules of thumb pertain to building geometrical inputs, such as available areas or people occupancy, technological inputs concerning energetic and hydraulic aspects of the tools but, most of all, the energy demand of the building. This last is assessed, both in RetroSim process and in my algorithm, with the simulation of the building with "ideal plant", that covers perfectly the energy need of the building both in cooling and heating season to maintain the thermal zone temperature inside comfort boundaries.

Renewable energy systems

Solar thermal collectors sizing

They are extracted two simple rules of thumb, for the sizing respectively of the solar collectors area (in m^2) and the associated solar tank (in litres)[16]:

$$A_{STC} = k \cdot n_p \qquad [m^2]$$

$$V_{Sol} = (60 \div 75) \cdot A_{STC} \qquad [l]$$

The coefficient k depends on the solar radiation of the construction site. I wrote a simple criterion that determines the collectors area per person, making reference to the value of k=1.2 in Milan:

- if global annual radiation < 1.0 kWh/m^2: k=1.4
- if global annual radiation < 1.2 kWh/m^2: k=1.3
- if global annual radiation < 1.4 kWh/m^2: k=1.2
- if global annual radiation < 1.6 kWh/m^2: k=1.1
- if global annual radiation > 1.6 kWh/m^2: k=1.0

[16] J. Duffie, W. Beckman - Solar Engineering of Thermal Processes

The associated energy output (in kWh) is estimated with reference to a simplified method subscribed by International Energy Agency. It calculates the annual energy production of solar collectors from the global horizontal radiation of the site[17]:

- Un-glazed collectors: $E_{STC} = 0.29 \cdot I_{S,hor} \cdot A_{Sol}$
- Glazed collectors in DHW systems: $E_{STC} = 0.44 \cdot I_{S,hor} \cdot A_{Sol}$
- Glazed collectors in combi-systems: $E_{STC} = 0.33 \cdot I_{S,hor} \cdot A_{Sol}$

Photovoltaic panels sizing

I adopt a simplified method that computes the power delivered by the PV system as[18]:

$$W_{PV} = \frac{I_S \cdot W_{pk} \cdot f_{PV}}{I_{S,ref}} \qquad [\text{kW}]$$

with the solar radiation on the photovoltaic system (in kWh/m^2).

The peak power (W_{pk}) is the electrical power of a photovoltaic system with a given surface and for reference solar irradiance I_{ref} = 1 kWh/m^2 at 25 °C; f_{PV} is the system performance factor, which evaluates the inefficiencies coming from the conversion from direct current to alternating current (inverter element), from the operative temperature of the photovoltaic modules, from the building integration of the photovoltaic modules but above all from their ventilation. I assumed it equal to 0.75.

In absence of testing values, peak power results from the product of

$$W_{pk} = K_{pk} \cdot A_{PV} \qquad [\text{kW}]$$

The peak power coefficient, in function of the PV technology, is assumed equal to 0.10, as average of the values in Figure 5.1. A_{PV} is the net area of the photovoltaics modules, whose constraint come from geometrical limits (roof area available) and economical limits.

Type of photovoltaic module	K_{pk} kW/m²
Mono crystalline silicon [a]	0,12 to 0,18
Multi crystalline silicon [a]	0,10 to 0,16
Thin film amorphous silicon	0,04 to 0,08
Other thin film layers	0,035
Thin film Copper-Indium-Galium-diselenide	0,105
Thin film Cadmium-Telloride	0,095
[a] With a minimum package density of 80 %.	

Figure 5.1 - Standard values of the peak power coefficient of a photovoltaic module

Thermal energy storage

Hot water tank sizing

They are to identify the volume of the hot water tank and the thermal power stored.[19] These quantities have been introduced in Chapter 4.4; their final values are:

[17] International Energy Agency, Solar Heating and Cooling Programme - Converting installed solar collector Area & power capacity into Estimated Annual Solar collector energy output

[18] EN 15316-4:2008 - Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 4.6

[19] UNI 9182:2014 - Hot and cold water supply and distribution installations. Design, installation and testing

$$V_{HWT} = \frac{v_{DHW} \cdot d_p \cdot (T_m - T_c)}{d_p + P_p} \cdot \frac{P_p}{(T_h - T_c)} \qquad [l]$$

$$W_{HWT} = \frac{q_m \cdot d_p \cdot (T_m - T_c)}{d_p + P_p} \cdot 1.163 \qquad [W]$$

P_p, the pre-heating period, is assumed equal to 1 h. T_m is the stored water temperature, assumed equal to the hot water temperature T_m=T_h=50 °C; T_c is the cold water temperature T_c=10 °C.

Heat storage with phase-change materials

In the technical sheet of "Sunamp – Heat Batteries" it is expressed that the heat storage of a PCM module (25.45 litres) is equivalent to 60 litres of water, with constant power storage. The conversion factor is stored into the parameter "conversions.water2PCM" and it is equal to 0.441:

$$V_{PCM} = 0.441 \cdot V_{HWT} \qquad [l]$$

$$W_{PCM} = W_{HWT} \qquad [W]$$

Electric generators

Electric water heater sizing

The electric water heater is contemplated just for DHW supply. Its size is grossly derived from the water demand of the users, increasing of one step for each person living in the thermal zone (rule of thumb extracted from the website of the producer Ariston). The following vectors store the volume the electric heater and the associated power size.

- Electric water heater volume [l]: [30 50 80 100 120 150 200 300]
- Electric water heater power [kW]: [1.5 1.5 1.5 2.0 2.0 2.0 3.0 3.0]

I assume the index of each row of the matrix equal to the number of people, obtaining the size of the two variables.

Electric air conditioning

As explained in Chapter 5.1, with "Electric fan-coils system" I refer to normal mono-split or multi-split air-conditioning with external unity.

For the air-conditioning it is frequent to measure its heating/cooling power if BTU (British Thermal Unit), unit of measurement for power that is converted as: 1 kW= 3412 BTU/h.

The component dimension is determined with reference to the most common sizes on the market:

- Electric air-conditioning [BTU]:
  [4˙000 7˙000 10˙000 12˙000 18˙000 24˙000 30˙000 36˙000 42˙000 48˙000 60˙000]

I assume that the unities have equal heating and cooling power while in reality, they generally have a slightly higher heating power. If used just for cooling, the sizing relation becomes:

$$A/C\ nominal\ power \geq Space\ cooling\ demand\ peak$$

otherwise, if used also in heating mode:

$$A/C\ nominal\ power \geq max(Space\ cooling\ demand\ peak, Space\ heating\ demand\ peak)$$

Electric Heat-Pump/Chiller sizing

As for the air-conditioners, I assume that HPs have equal heating and cooling power. The HP covers heating demand up to external temperature of 0°C, otherwise the COP of the HP is no longer convenient and it is automatically contemplated an additional generator.

The size of the Heat-Pump/Chiller is rounded up to the unity (ceil- function on MATLAB).

$$Heat - Pump/Chiller\ nominal\ power \geq ceil(max(Space\ cooling\ demand\ peak, Total\ heating\ demand\ peak))$$

Boiler sizing

This section is the last one because boilers can have different roles in the retrofit layout. In fact, HPs precede boilers sizing in order to give them the right sizing demand, through the auxiliary parameter previously defined that changes if boilers are supposed to be main or auxiliary generators.

Traditional boiler sizing

It follows the same logic of the previous generators, taking in account the different type of demand the boiler may be devoted to cover.

$$Traditional\ boiler\ nominal\ power \geq ceil(\ Heating\ demand\ peak)$$

Condensing boiler sizing

While traditional boiler at constant temperature gets its maximum efficiency when it is loaded close to its maximum capacity, modern condensing boiler do the opposite, following a totally different design criterion. For this reason I decided to oversize the condensing boiler with the coefficient 1.1.

$$Condensing\ boiler\ nominal\ power \geq ceil(1.1 \cdot Heating\ demand\ peak)$$

5.2 The sizing algorithm with MATLAB

The sizing procedure is written in a program I named "Sizing_tool.m". As for the preceding program (Chapter 4.6), it follows a fixed path that allows to assign a dimension to all the components, in terms of power (storing the size in the table "Power") and volume (when significant, in the table "Volume").

The sections of the program are:

- For-cycle start
- Auxiliary parameters for sizing procedure
- Solar Thermal Collectors sizing
- Photovoltaics panels sizing
- Hot Water Tank sizing
- Electric Water Heater sizing
- Electric air-conditioning sizing
- Heat-Pumps sizing
- Traditional boiler sizing
- Condensing boiler sizing

The first two sections define the necessary auxiliary variables for the sizing path, for three main purposes:

- it creates a temporary variable that scales the energy demand for the different type of generators in accordance to their role, if primary or auxiliary generator;
- it sums to the space heating demand the DHW heating demand when needed;
- it cuts the available solar area for photovoltaics installation if already devoted (partly or totally) to solar thermal plant.

In the following pages it is reported the program. All sections are preceded by some comment lines that explain the source of the rule of thumb applied on the element.

```
%% For-cycle start

Power=[Power zeros(height(Configurations),width(Configurations)-1)];
Volume=[Volume zeros(height(Configurations),width(Configurations)-1)];

for INDEX=1:width(Configurations)
    %% Auxiliary parameters for sizing procedure

    if Configurations{[8],INDEX}=='not present'
        AUX.Heating_peak=HVAC.DHW.peak_power;
    else
        AUX.Heating_peak=HVAC.Heating.Heating_Plus_DHW_peak;% kW,
        % auxiliary parameter for sizing procedure
    end

    AUX.Solar_area=Building.solar_area(1);

    %% Solar Thermal Collectors sizing
    % procedure from IEA Solar Heating and Cooling Programme
    % and Solar Trade Associations

    if Configurations{15,INDEX}=='Solar thermal collectors'

        if sum(Radiation.Global/1000)<1000
            design_parameters.ST.K=1.40;% m2/pers
        elseif sum(Radiation.Global/1000)<1200
            design_parameters.ST.K=1.30;% m2/pers
        elseif sum(Radiation.Global/1000)<1400
            design_parameters.ST.K=1.20;% m2/pers
        elseif sum(Radiation.Global/1000)<1600
            design_parameters.ST.K=1.10;% m2/pers
        else
            design_parameters.ST.K=1.00;% m2/pers
        end
        % ST area per person

        if design_parameters.ST.area==0
            design_parameters.ST.area=min(...
                design_parameters.ST.K*Building.people,...
                AUX.Solar_area);
        end
        % m2

        AUX.Solar_area=Building.solar_area-...
            design_parameters.ST.area;% m2

        rule=60*design_parameters.ST.area/1000;% m3
        Volume=table_writing(...
            Volume,Configurations,INDEX,'Solar thermal collectors',rule);
        % m3

        design_parameters.ST.profile=0.44*design_parameters.ST.area*...
            Radiation.Global/1000;% kWh, annual profile

        rule=sum(design_parameters.ST.profile);% kWh, annual production
        Power=table_writing(...
            Power,Configurations,INDEX,'Solar thermal collectors',rule);
        % kWh
```

```
        AUX.Heating_peak=AUX.Heating_peak-Power(15,INDEX)/365;% kW

    end


    %% PhotoVoltaics panels sizing
    % EN15316:2007 procedure

    if Configurations{16,INDEX}=='Photovoltaic panels'

        design_parameters.PV.K=0.10; % peak power coefficient

        design_parameters.PV.f=0.75; % system performance factor

        design_parameters.PV.I_ref=1; % reference solar irradiance

        design_parameters.PV.profile=Radiation.Solar_plant/1000*...
            AUX.Solar_area*design_parameters.PV.K*...
            design_parameters.PV.f/design_parameters.PV.I_ref;% kWh, annual profile

        rule=round(max(design_parameters.PV.profile),1);% kW, peak production
        Power=table_writing(...
            Power,Configurations,INDEX,'Photovoltaic panels',rule);
        % kW peak power

    end

    %% Hot Water Tank sizing
    % from UNI 9182:2014 and 'Sunamp-Heat Batteries' technical sheet

    if Configurations{14,INDEX}~='not present'

        conversions.water2PCM=0.02645/0.060;
        % one PCM module is equivalent to 60 l of water tank

        rule=...
            round(HVAC.DHW.peak_volume*HVAC.DHW.peak_period*(50-10)/...
            (HVAC.DHW.peak_period+1)*(1/(50-10))+5,-1)/1000;
        % m3, assuming 1h of pre-heating period
        Volume=table_writing(...
            Volume,Configurations,INDEX,'Hot water tank',rule); % m3

        rule=conversions.water2PCM*rule;% m3
        Volume=table_writing(...
            Volume,Configurations,INDEX,'PCM storage',rule); % m3

        rule=...
            round((HVAC.DHW.peak_volume*HVAC.DHW.peak_period*(50-10)/...
            (HVAC.DHW.peak_period+1)*1.163+5)/1000,2);% kW
        Power=table_writing(...
            Power,Configurations,INDEX,'Hot water tank',rule); % kW
        Power=table_writing(...
            Power,Configurations,INDEX,'PCM storage',rule); % kW

        AUX.Heating_peak=...
            AUX.Heating_peak-0.5*HVAC.DHW.peak_power;% kW

    end
```

```
%% Electric Water Heater sizing
% Rule of thumbs extracted from ARISTON producer approach:

if Configurations{10,INDEX}=='Electric water heater'

    design_parameters.ElectricWaterHeater=[...
        30.0 50.0 80.0 100.0 120.0 150.0 200.0 300.0;
        1.50 1.50 1.50 2.000 2.000 2.000 3.000 3.000
        ];

    rule=design_parameters.ElectricWaterHeater(1,Building.people)/1000;
    % m3
    Volume=table_writing(...
        Volume,Configurations,INDEX,'Electric water heater',rule); % m3

    rule=design_parameters.ElectricWaterHeater(2,Building.people)/1000;
    % kW
    Power=table_writing(...
        Power,Configurations,INDEX,'Electric water heater',rule); % kW

end

%% Electric air-conditioning sizing

if (Configurations{2,INDEX}=='Fan-coils' && ...
        Configurations{3,INDEX}=='not present')

    design_parameters.AirConditioning=[4000 7000 10000 12000 18000...
        24000 30000 36000 42000 48000 60000];
    conversions.kW2BTU_h=3412.1411566;

    idx=1;
    while HVAC.Cooling.max*conversions.kW2BTU_h >...
            design_parameters.AirConditioning(idx)
        idx=idx+1;
    end

    if (Configurations{7,INDEX}=='Fan-coils' && ...
            Configurations{8,INDEX}=='not present')
        idx=1;
        while max(HVAC.Cooling.max,HVAC.Heating.max)*...
                conversions.kW2BTU_h>...
                design_parameters.AirConditioning(idx)
            idx=idx+1;
        end
    end

    rule=design_parameters.AirConditioning(idx);% British Thermal Unit
    Power=table_writing(...
        Power,Configurations,INDEX,'Fan-coils',rule); % kW

    if Configurations{8,INDEX}~='not present'
        Power(7,INDEX)=0;
    end

end

%% Heat-Pumps sizing
% I assume that the HPs have equal heating and cooling power
```

```
    % while in reality, they generally have a slightly higher heating
    % power. The HP covers heating demand up to external temperature of
    % 0°C, otherwise the COP of the HP is no longer convenient and it is
    % is automatically contemplated an additional generator.

    if any(Configurations{3,INDEX}==[string('Electric HP/Chiller') ...
            string('Absorption HP/Chiller') ...
            string('Adsorption HP/Chiller') string('DC HP/Chiller')])

        AUX.Heating_peak_HP=AUX.Heating_peak-...
            HVAC.Heating.Heating_Plus_DHW_peak+...
            max(Demand.Q_heating.*(Weather_data.Dry_Bulb_Temperature>=0));

        rule=ceil(max(HVAC.Cooling.max,AUX.Heating_peak_HP));% kW
        Power=table_writing(...
            Power,Configurations,INDEX,Configurations{3,INDEX},rule);% kW

    end

    %% Traditional boiler sizing
    % Rule of thumbs (best performances when load factor close to 100% )

    if any(Configurations{:,INDEX}=='Traditional boiler')

        rule=ceil(AUX.Heating_peak); % kW
        Power=table_writing(...
            Power,Configurations,INDEX,'Traditional boiler',rule); % kW

    end

    %% Condensing boiler sizing
    % Rule of thumbs (best performances when load factor far from 100% )

    if any(Configurations{:,INDEX}=='Condensing boiler')

        rule=ceil(AUX.Heating_peak*1.1); % kW
        Power=table_writing(...
            Power,Configurations,INDEX,'Condensing boiler',rule); % kW

    end

end

% Layout processing

Power=array2table(Power,'RowNames',...
    {'Cooling_system_type' 'Cooling_system_emitters' ...
    'Cooling_system_generator' 'Cooling_system_generator_fuel' ...
    'Cooling_system_storage' 'Heating_system_type' ...
    'Heating_system_emitters' 'Heating_system_generator' ...
    'Heating_system_generator_fuel' 'Heating_system_DHW_generator' ...
    'Heating_system_DHW_generator_fuel' 'Heating_system_support' ...
    'Heating_system_support_fuel' 'Heating_system_storage' ...
    'Renewable_support_ST' 'Renewable_support_PV'});

Volume=array2table(Volume,'RowNames',...
    {'Cooling_system_type' 'Cooling_system_emitters' ...
    'Cooling_system_generator' 'Cooling_system_generator_fuel' ...
    'Cooling_system_storage' 'Heating_system_type' ...
```

```
    'Heating_system_emitters' 'Heating_system_generator' ...
    'Heating_system_generator_fuel' 'Heating_system_DHW_generator' ...
    'Heating_system_DHW_generator_fuel' 'Heating_system_support' ...
    'Heating_system_support_fuel' 'Heating_system_storage' ...
    'Renewable_support_ST' 'Renewable_support_PV'});

clear INDEX exs conversions rule idx AUX

%% Function

function [table_output]=table_writing(table_output,table_input,index,...
    str,formula)

if table_output((table_input{:,index}==str),index)==0

    table_output((table_input{:,index}==str),index)=formula;

end

end
```

5.3 Estimation of the Primary Energy demand

Primary Energy is the "energy that has not been subjected to any conversion or transformation process"[20].

It is the common parameter for the evaluation of the energy performance in building sector. The comparison of energy consumptions of a different nature means comparing two values which are only similar in terms of size. Hence, the only way to determine which building consumes the least energy (methane and electricity for the first, only methane for the second) is to calculate the total consumption of Primary Energy.

For the analysis and the comment of the outputs coming from my algorithm, I decided to build a program that provides the total energy demand for each of the configurations of the filtering tool. I adopted the values of PEf coming from the Italian standards, while in a larger project as Heat4Cool is, it will be used a ampler collection of data because of the fact that PEf have national meaning, depending on the energy sources available in each country.

Table 5.A - Standard values of the Primary Energy factor

Energy vector	Primary Energy factor PEf[21]
Coal	1,20
Oil	1,10
Natural gas	1,10
Biomass	1,10
Solid urban waste	1,00
Renewable sources	1,00
National electricity mix	2,37

In the program "Primary_energy" I multiply the annual energy production of each generator, renewable and non-renewable, for the appropriate Primary Energy factor. For DHW estimation, I considered a heating demand profile constant during the daytime, from 6:00 to 22:00.

Renewable energy systems and thermal storage

Solar thermal collectors

For the solar thermal plant the Primary Energy factor is equal to 1.0. It is an energy producer, not consumer, so this energy has to be detracted from the Primary Energy balance of the building.

Photovoltaics

For the photovoltaic plant there are appropriate considerations which recall its lifecycle perspective. Instead of using the same PEf for electricity, which would have been too much effective, I decided to adopt a more reliable value, smaller than the previous, equal to PEf=1.87[22].

[20] EN 15316-1:2007 - Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 1: General
[21] prEN 15315 - Heating systems in buildings. Energy performance of buildings. Overall energy use, Primary Energy and CO2 emissions
[22] A. Esser, F. Sensfuss, C. Amann, P. Iñarra – Evaluation of Primary Energy factor calculation options for electricity

Impact of thermal energy tanks

All types of heat tank does not produce or consume energy but has impact on the efficiency of the building system. For this reason I decided to consider the presence of a tank (for heating or cooling) with the beneficial effect of increasing the efficiency of the generators with respect to the type of energy stored (heating or cooling energy), reducing in the same time the demand for domestic hot water heating.

Heating and cooling generators

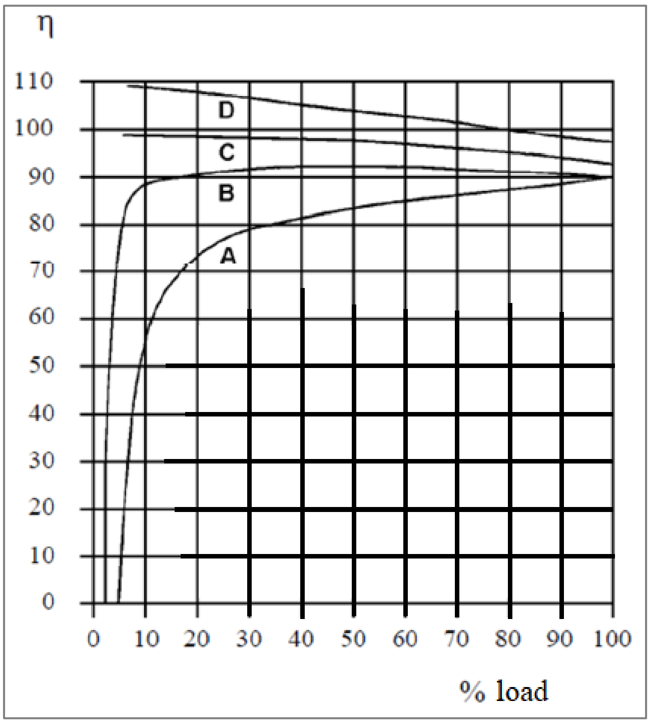
Electric generators

For the electric radiators/fan-coils/water heater, I considered the Primary Energy consumed equal to their heating emissions, multiplied by the PEf for electricity.

Traditional and condensing boiler

Thanks to the fact that I operated with hourly demand, I could estimate with good precision the hourly efficiency of boilers.

It depends especially on the load factor of the boiler, i.e. the ratio between the nominal power of the component and the load to which it is subjected. Thanks to performance maps, I could determine the efficiency for all the hours of activity.



A: Traditional boiler

D: Condensing boiler

Figure 5.2 - Boiler efficiency in function of the load factor

Adsorption Heat-Pump/Chiller

The operation of adsorption heat pumps and refrigerators is based on the ability of porous solids (the adsorbent) to adsorb vapour (the adsorbate or refrigerant) when subjected to low temperature, and to desorb it when heated. The adsorption cycle lets to achieve very high values of COP, but it pays this with a relevant demand of heat from the auxiliary heater. There are several applications of this technology, but nowadays it is limited mostly to little scale and experimentation; for these reasons I referred to data coming from Heat4Cool partners[23].

Electric Heat-Pump/Chiller

I related the COP of the Heat Pump to the external temperature, which can be approximated as the measurement of the temperature of all the source types.

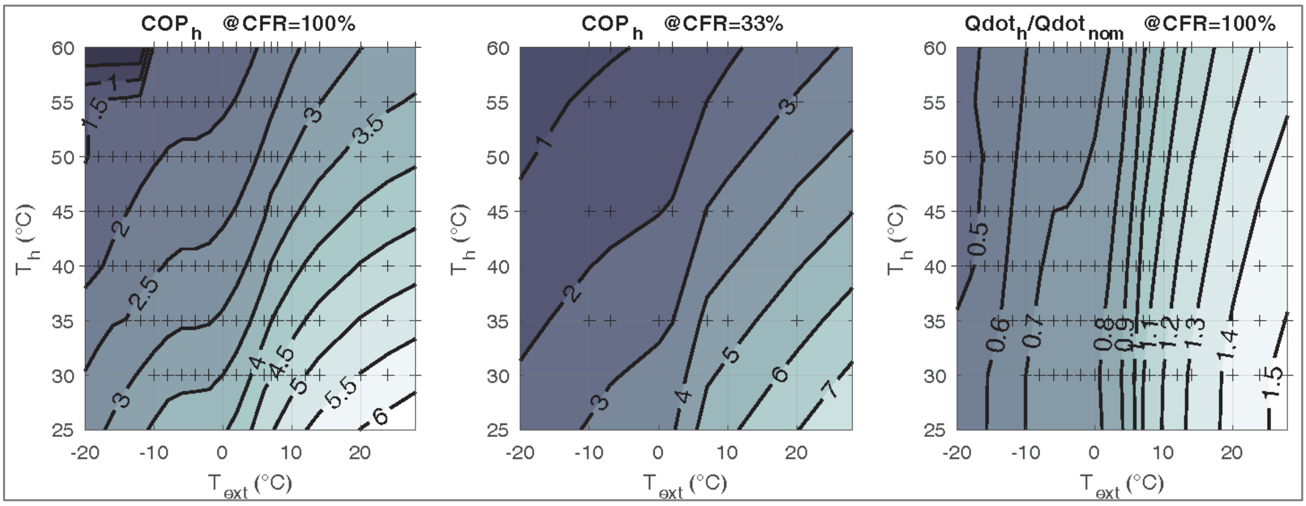


Figure 5.3 - COP of the heat pump in heating mode in function of the external temperature

I used COP_H performance maps[24] for common electric HP, converting it to COP_C (cooling mode) studying the relation between COP and thermal jump between working water temperature and external air temperature.

For Direct-Current HP, I considered the additional feature of the decrease of its PEf for electricity when coupled with photovoltaic plant, because its greatest characteristic is the possibility to bypass the inverter when fed by this type of plant.

For Absorption HP, the burner backup demand is measured by the Gas Utilization Efficiency (GUE).

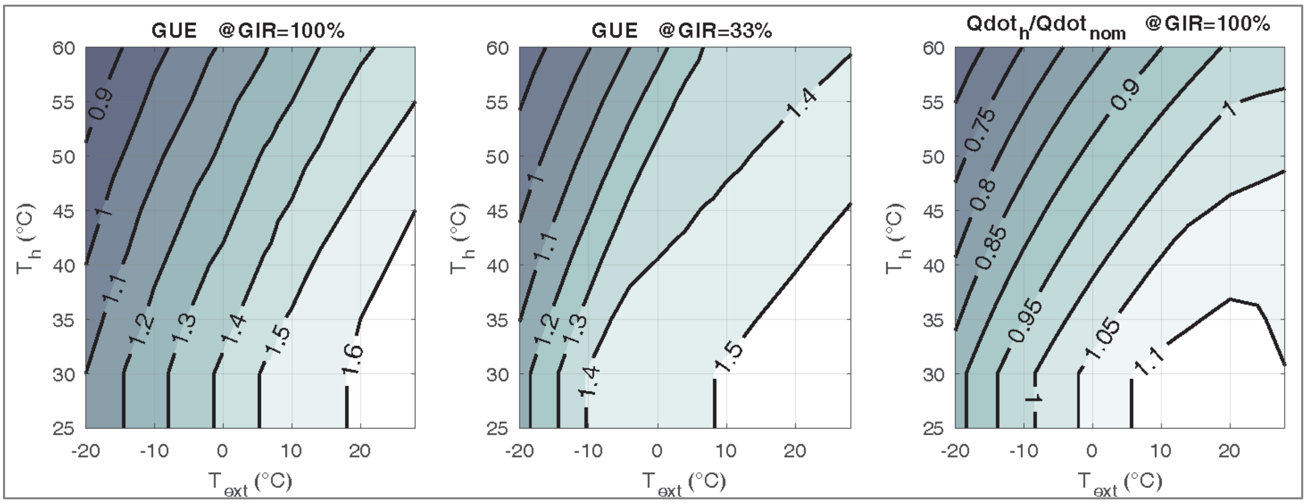


Figure 5.4 - GUE of the heat pump in function of the external temperature

[23] T. Núñez - Operating experience and development aspects of small adsorption chillers
[24] R. Scoccia, T. Toppi, M. Aprile, M. Motta - Absorption and compression heat pump systems for space heating and DHW in European buildings: energy, environmental and economic analysis

5.4 The estimation of the Primary Energy demand with MATLAB

The estimation of the annual Primary Energy balance for all the retrofit solutions filtered and sized by the previous program is assigned to an additional program I named "PE_demand.m".

It follows the same logic of the two previous programs (Chapter 4.6 and 5.2). It consists of 13 sections:

- Primary Energy consumption
- Auxiliary parameters for sizing procedure
- Solar Thermal Collectors
- PhotoVoltaics panels sizing
- Heating Tank case
- Electric Water Heater case
- Electric radiators case
- Electric air-conditioning case
- Electric HPs/Chillers case
- Adsorption HPs/Chillers case
- Traditional boiler case
- Condensing boiler case
- Post-processing

The first two sections design the auxiliary parameters for the computation, which is performed in the following sections, each one devoted to one element of the HVAC system. The last section collects the results and defines three additional output tables:

- "ranking", as the name tells, is the set of all the possible retrofit layouts sorted with respect to their annual Primary Energy demand;
- "top_7" is the table that groups the best seven retrofit solutions coming from the program;
- "generators_best_output" is the selection of the best results available for each generator.

In the following pages it is reported the program.

```
%% Primary energy consumption

PE=zeros(size(Configurations));

PEf=table(1.20,1.15,1.10,1.05,2.37,1.87,1.00,'VariableNames',{'Coal' ...
    'Oil' 'Gas' 'Biomass' 'Electricity' 'PhotoVoltaic' 'SolarThermal'});

for INDEX=1:size(PE,2)
    %% Auxiliary parameters for sizing procedure

    if Configurations{8,INDEX}=='not present'

        AUX.Q_heating_total=...
            (any(Weather_data.Hour==6:22,2)*HVAC.DHW.volume_day/(3600)...
            *4.186*(50-10)/17); % kWh

    else

        AUX.Q_heating_total=Demand.Q_heating+...
            (any(Weather_data.Hour==6:22,2)*HVAC.DHW.volume_day/(3600)...
            *4.186*(50-10)/17); % kWh

    end

    %% Solar Thermal Collectors

    if Configurations{15,INDEX}=='Solar thermal collectors'

        rule=-sum(design_parameters.ST.profile,'omitnan')*PEf{1,7};
        % kWh_PE
        PE(15,INDEX)=rule; % kWh, primary energy

    end

    %% PhotoVoltaics panels sizing

    if Configurations{16,INDEX}=='Photovoltaic panels'

        rule=-sum(design_parameters.PV.profile,'omitnan')*PEf{1,6};
        % kWh_PE
        PE(16,INDEX)=rule; % kWh, primary energy

    else

        PE(16,INDEX)=0;

    end

    %% Heating Tank case

    if Configurations{14,INDEX}~='not present'

        AUX.Q_heating_total=AUX.Q_heating_total -...
            (any(Weather_data.Hour==6:22,2)*HVAC.DHW.volume_day/(3600)...
            *4.186*(50-10)/17); % kWh

    end

    %% Electric Water Heater case
```

```
if Configurations{10,INDEX}=='Electric water heater'

    Q_h_gen=any(Weather_data.Hour==6:22,2)*Power(10,INDEX);
    % kWh, electric energy

    rule=sum(Q_h_gen,'omitnan')*PEf{1,5}; % kWh_PE
    PE(10,INDEX)=rule; % kWh_PE

end

%% Electric radiators case

if (Configurations{7,INDEX}=='Radiators' && ...
        Configurations{8,INDEX}=='not present')

    rule=sum(Demand.Q_heating,'omitnan')*PEf{1,5}; % kWh_PE
    PE(8,INDEX)=rule; % kWh_PE

end

%% Electric air-conditioning case

if (Configurations{2,INDEX}=='Fan-coils' && ...
        Configurations{3,INDEX}=='not present')

    Q_c_gen=(Demand.Q_cooling>0)*Power{2,INDEX}/10000;
    % kWh, electric energy

    rule=sum(Q_c_gen,'omitnan')*PEf{1,5}; % kWh_PE
    PE(2,INDEX)=rule; % kWh_PE

    if (Configurations{7,INDEX}=='Fan-coils' && ...
            Configurations{8,INDEX}=='not present')

        Q_h_gen=(Demand.Q_heating>0)*Power(7,INDEX)/10000;
        % kWh, electric energy

        rule=sum(Q_h_gen,'omitnan')*PEf{1,5}; % kWh_PE
        PE(2,INDEX)=rule; % kWh_PE

    end

end

%% Electric HPs/Chillers case

if any(Configurations{3,INDEX}==[string('Electric HP/Chiller') ...
        string('Absorption HP/Chiller') string('DC HP/Chiller')])

    AUX.Q_heating_HP=...
        AUX.Q_heating_total.*(Weather_data.Dry_Bulb_Temperature>=0);
    % kWh

    if Configurations{3,INDEX}=='DC HP/Chiller' && ...
            Configurations{16,INDEX}=='Photovoltaic panels'

        PEf_ele=PEf{1,6};
```

```
        else

            PEf_ele=PEf{1,5};

        end

        if Configurations{3,INDEX}==string('Absorption HP/Chiller')

            if (Configurations{7,INDEX}=='Radiators')

                GUE_vs_T=[...
                    0.00 5.00 10.0 15.0 20.0 25.0 30.0 Inf;...
                    1.21 1.30 1.37 1.42 1.47 1.52 1.53 Inf];

            else

                GUE_vs_T=[...
                    0.00 5.00 10.0 15.0 20.0 25.0 30.0 Inf;...
                    1.32 1.40 1.46 1.53 1.56 1.60 1.62 Inf];

            end

            GUE=zeros(size(AUX.Q_heating_HP));
            for idx_1=1:length(Weather_data.Dew_Point_Temperature)

                idx_2=1;
                while abs(Weather_data.Dew_Point_Temperature(idx_1) -...
                        GUE_vs_T(1,idx_2)) >...
                        abs(Weather_data.Dew_Point_Temperature(idx_1) -...
                        GUE_vs_T(1,idx_2+1))

                    idx_2=idx_2+1;

                end
                GUE(idx_1,1)=GUE_vs_T(2,idx_2);

            end

            AUX.Q_heating_HP=AUX.Q_heating_HP-AUX.Q_heating_HP./GUE;
            % kWh

        end

        % Cooling mode

        if Configurations{4,INDEX}=='Ground-source' || ...
                Configurations{4,INDEX}=='Water-source' || ...
                Configurations{5,INDEX}~='not present'

            COPc=4.80;

        else

            COPc_vs_T=[...
                20.0 25.0 30.0 35.0 Inf;...
                4.80 4.50 4.30 3.90 Inf];

            COPc=zeros(size(Demand.Q_cooling));
            for idx_1=1:length(Weather_data.Dew_Point_Temperature)
```

```
            idx_2=1;
            while abs(Weather_data.Dew_Point_Temperature(idx_1) -...
                    COPc_vs_T(1,idx_2)) >...
                    abs(Weather_data.Dew_Point_Temperature(idx_1) -...
                    COPc_vs_T(1,idx_2+1))

                idx_2=idx_2+1;

            end
            COPc(idx_1,1)=COPc_vs_T(2,idx_2);

        end

    end

    Q_c_gen=Demand.Q_cooling./COPc;% kWh electric energy

    rule=sum(Q_c_gen,'omitnan')*PEf_ele; % kWh_PE
    PE(3,INDEX)=rule; % kWh_PE


    % Heating mode

    if Configurations{9,INDEX}=='Ground-source' || ...
            Configurations{9,INDEX}=='Water-source' || ...
            Configurations{14,INDEX}~='not present'

        COPh=4.80;

    else

        if (Configurations{7,INDEX}=='Radiators')

            COPh_vs_T=[...
                0.00 5.00 10.0 15.0 20.0 25.0 30.0 Inf;...
                2.40 2.60 3.00 3.50 3.75 3.80 3.90 Inf];

        else

            COPh_vs_T=[...
                0.00 5.00 10.0 15.0 20.0 25.0 30.0 Inf;...
                2.80 3.50 3.90 4.30 4.50 4.70 4.80 Inf];

        end

        COPh=zeros(size(AUX.Q_heating_HP));
        for idx_1=1:length(Weather_data.Dew_Point_Temperature)

            idx_2=1;
            while abs(Weather_data.Dew_Point_Temperature(idx_1) -...
                    COPh_vs_T(1,idx_2)) >...
                    abs(Weather_data.Dew_Point_Temperature(idx_1) -...
                    COPh_vs_T(1,idx_2+1))

                idx_2=idx_2+1;

            end
            COPh(idx_1,1)=COPh_vs_T(2,idx_2);
```

```
            end

        end

        Q_h_gen=AUX.Q_heating_HP./COPh;% kWh electric energy

        rule=sum(Q_h_gen,'omitnan')*PEf_ele; % kWh_PE
        PE(8,INDEX)=rule; % kWh_PE

        if Configurations{3,INDEX}==string('Absorption HP/Chiller')

            AUX.Q_heating_total=AUX.Q_heating_total.*...
                (Weather_data.Dry_Bulb_Temperature<0)+...
                AUX.Q_heating_HP./GUE;% kWh

        else

            AUX.Q_heating_total=AUX.Q_heating_total.*...
                (Weather_data.Dry_Bulb_Temperature<0);% kWh

        end

    end


    %% Adsorption HPs/Chillers case

    if Configurations{3,INDEX}==string('Adsorption HP/Chiller')

        AUX.Q_heating_HP=...
            AUX.Q_heating_total.*(Weather_data.Dry_Bulb_Temperature>0);
        % kWh

        % Heating mode

        COPh=18.1;

        Q_h_gen=AUX.Q_heating_HP./COPh;% kWh electric energy

        rule=sum(Q_h_gen,'omitnan')*PEf{1,5}; % kWh_PE
        PE(8,INDEX)=rule; % kWh, primary energy

        GUE=1.43;

        AUX.Q_heating_total=AUX.Q_heating_total.*...
            (Weather_data.Dry_Bulb_Temperature<0)+AUX.Q_heating_HP/GUE;
        % kWh

        % Cooling mode

        COPc=9.8;

        Q_c_gen=Demand.Q_cooling./COPc;% kWh electric energy

        rule=sum(Q_c_gen,'omitnan')*PEf{1,5}; % kWh_PE
        PE(3,INDEX)=rule; % kWh_PE

        GUE=0.57;
```

```
        AUX.Q_heating_total=AUX.Q_heating_total+Demand.Q_cooling/GUE;% kWh

    end

    %% Traditional boiler case
    if any(Configurations{:,INDEX}=='Traditional boiler')

        gen_size=table2array(...
            Power((Configurations{:,INDEX}=='Traditional boiler'),INDEX));
        % kW

        LF=AUX.Q_heating_total/gen_size;

        eta_vs_LF=[...
            0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 Inf;...
            0.10 0.57 0.63 0.67 0.71 0.73 0.75 0.77 0.79 0.81 0.83 Inf...
            ];

        eta=zeros(size(LF));
        for idx_1=1:length(LF)

            idx_2=1;
            while abs(LF(idx_1)-eta_vs_LF(1,idx_2))>abs(LF(idx_1)-...
                    eta_vs_LF(1,idx_2+1))

                idx_2=idx_2+1;

            end
            eta(idx_1,1)=eta_vs_LF(2,idx_2);

        end

        Q_h_gen=AUX.Q_heating_total./eta;% kWh

        if any(Configurations{:,INDEX}=='Coal')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,1}; % kWh
        elseif any(Configurations{:,INDEX}=='Oil')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,2}; % kWh
        elseif any(Configurations{:,INDEX}=='Gas')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,3}; % kWh
        elseif any(Configurations{:,INDEX}=='Biomass')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,4}; % kWh
        end
        % kWh

        PE=table_writing(PE,Configurations,INDEX,'Traditional boiler',...
            rule); % kWh_PE

    end

    %% Condensing boiler case
    if any(Configurations{:,INDEX}=='Condensing boiler')

        gen_size=table2array(...
            Power((Configurations{:,INDEX}=='Condensing boiler'),INDEX));
        % kW

        LF=AUX.Q_heating_total/gen_size;
```

```
        eta_vs_LF=[...
            0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 Inf;...
            0.99 0.99 0.99 0.99 0.97 0.95 0.94 0.92 0.91 0.90 0.89 Inf;...
            ];

        eta=zeros(size(LF));
        for idx_1=1:length(LF)

            idx_2=1;
            while abs(LF(idx_1)-eta_vs_LF(1,idx_2))>abs(LF(idx_1)-...
                    eta_vs_LF(1,idx_2+1))

                idx_2=idx_2+1;

            end
            eta(idx_1,1)=eta_vs_LF(2,idx_2);

        end

        Q_h_gen=AUX.Q_heating_total./eta;% kWh

        if any(Configurations{:,INDEX}=='Coal')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,1}; % kWh
        elseif any(Configurations{:,INDEX}=='Oil')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,2}; % kWh
        elseif any(Configurations{:,INDEX}=='Gas')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,3}; % kWh
        elseif any(Configurations{:,INDEX}=='Biomass')
            rule=sum(Q_h_gen,'omitnan')*PEf{1,4}; % kWh
        end

        PE=table_writing(PE,Configurations,INDEX,'Condensing boiler',...
            rule); % kWh_PE
    end


end

% Layout processing

PE=array2table(PE,'RowNames',...
    {'Cooling_system_type' 'Cooling_system_emitters' ...
    'Cooling_system_generator' 'Cooling_system_generator_fuel' ...
    'Cooling_system_storage' 'Heating_system_type' ...
    'Heating_system_emitters' 'Heating_system_generator' ...
    'Heating_system_generator_fuel' 'Heating_system_DHW_generator' ...
    'Heating_system_DHW_generator_fuel' 'Heating_system_support' ...
    'Heating_system_support_fuel' 'Heating_system_storage' ...
    'Renewable_support_ST' 'Renewable_support_PV'});

clear AUX COPc COPc_vs_T COPh COPh_vs_T eta eta_vs_LF eta_vs_LF gen_size...
    GUE GUE_vs_T idx_1 idx_2 INDEX LF PEf_ele Q_c_gen Q_h_gen rule;

%% Post-processing

ranking=table2cell(Configurations);
PE_profile=sum(table2array(PE))/Building.area;
Existing_plant.PE_demand=PE_profile(1);
```

```
for idx_1=1:length(PE_profile)
    ranking(17,idx_1)={PE_profile(idx_1)};
end

ranking=sortrows(ranking',17)';
ranking=cell2table(ranking,'RowNames',...
    {'Cooling_system_type' 'Cooling_system_emitters' ...
    'Cooling_system_generator' 'Cooling_system_generator_fuel' ...
    'Cooling_system_storage' 'Heating_system_type' ...
    'Heating_system_emitters' 'Heating_system_generator' ...
    'Heating_system_generator_fuel' 'Heating_system_DHW_generator' ...
    'Heating_system_DHW_generator_fuel' 'Heating_system_support' ...
    'Heating_system_support_fuel' 'Heating_system_storage' ...
    'Renewable_support_ST' 'Renewable_support_PV' 'PE_demand_kWh/m2'});

PE_profile=sort(PE_profile);
top7=ranking(:,1:7);

generators_best_output=ranking(:,1);
aux=string(ranking{8,1});
for idx=2:width(ranking)

    if any(aux==ranking{8,idx})==0

        generators_best_output=[generators_best_output ranking(:,idx)];
        aux=[aux; string(ranking{8,idx})];

    end
end

clear idx_1 idx aux

%% Function

function [table_output]=table_writing(table_output,table_input,index,...
    str,formula)

if table_output((table_input{:,index}==str),index)==0

    table_output((table_input{:,index}==str),index)=formula;

end

end
```

6 Results and comments

Chapter 6 shows some reference results obtained running the algorithm, adopting typical configurations of the building system. First, they are reported the outputs that result directly from the run of the program, then I extracted and resumed in some graphs the most important information, especially for SFH 100 case, always followed by some comments.

6.1 Description of the program

I report the application of the whole program on the building simulated in chapter 2, in three climates (warm in Athens, cold in Helsinki and Strasbourg as average). It consists of the run in sequence of the programs introduced in Chapter 4 and Chapter 5:

- Inputs.m
- Energy_demand.m
- Filtering_tool.m
- Sizing_tool.m
- PE_demand.m

I report entirely the outputs for SFH 100, while, for brevity, the simulations for SFH 45 and SFH 15 are reported respectively in Annex IX and Annex X. They can be examined different outputs:

- with the stamp of the Workspace I want to give a global view of the outputs of the program;
- the variable "Building" collects all the inputs asked through the front-end to the user, both spatial and constructive, adding the resuming parameters which are calculated automatically by the program.
- the variable "Location" resumes the constrains coming from the building site with respect to its coordinates and climate. The weather data are stored with hourly interval in the tables "Weather_data" and "Radiation".
- the variable "Existing_plant" resumes all the parameters for the description of the existing building system layout. It is the base for the filtering algorithm.
- the variable "HVAC" resumes the main parameters for the sizing algorithm, which are the peak values during the year coming from the program "Energy_demand.m". The program stores also the hourly values of each component of the energy balance of the building, in the appropriate table "Demand".
- all possible HVAC layouts are reported in the table "Configurations", filtered from the struct "Retrofit_alternatives". These are sized in the table "Power" and "Volume", respectively for energy and space. The auxiliary parameters regarding the HVAC components are stored into the struct "design_parameters". The number of layouts is equal to the second dimension of the table, while the first one is fix and indicates all the sixteen variables analysed by the program.

The remaining objects are outputs from the program "PE_demand":

- "ranking", as the name tells, is the set of all the possible retrofit layouts sorted with respect to their annual Primary Energy demand;
- "top_15" is the table that groups the best fifteen retrofit solutions coming from the program;
- "generators_best_output" is the selection of the best results available for each generator.

MATLAB Workspace
SFH 100_STR

Value	Name
1x1 struct	Building
16x481 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x6 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x481 table	PE
1x481 double	PE_profile
1x7 table	PEf
16x481 table	Power
8760x9 table	Radiation
17x481 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x481 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 100_STR

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Radiators"
Heating_system_generator	"Traditional boiler"
Heating_system_generator_fuel	"Coal"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	659.0638

MATLAB Variable: Building
SFH 100_STR

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"From1945to1970"
U_wall	1.2920
U_floor	1.1240
U_roof	0.9080
U_window	2.8300
g_window	0.7550
H_T	450.3948
H_V	79.3584

MATLAB Variable: Location
SFH 100_STR

Field	Value
Country	"FRA"
City	"STRASBOURG"
latitude	48.5500
longitude	7.6300
T_mean	10.2973
T_max	31
T_min	-9.6000

MATLAB Variable: HVAC.Heating
SFH 100_STR

Field	Value
total	3.8944e+04
max	15.1977
avg	8.5041
Heating_Plus_DHW_peak	22.1744

MATLAB Variable: HVAC.Cooling
SFH 100_STR

Field	Value
total	2.8520e+03
max	8.9642
avg	0

MATLAB Variable: HVAC.DHW
SFH 100_STR

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 100_STR

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Radiators"	"Radiators"	"Radiators"	"Radiators"	"Fan-coils"	"Fan-coils"	"Radiators"
8 Heating_system_generator	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...
13 Heating_system_support_fuel	"Biomass"	"Biomass"	"Gas"	"Gas"	"Biomass"	"Biomass"	"Coal"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"68.4785"	"68.4795"	"73.7533"	"73.7544"	"81.8988"	"81.8998"	"84.303"

MATLAB Variable: generators_best_output
SFH 100_STR

	1 ranking1	2 ranking11	3 ranking44	4 ranking228	5 ranking305	6 ranking426
1 Cooling_system_type	"Water syst...	"Water syste...	"Water syste...	"Water system"	"Electric syste...	"Electric syste...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"DC HP/Chill...	"Electric HP/...	"Adsorption ...	"not present"	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"	"not present"
5 Cooling_system_storage	"PCM stora...	"PCM storage"	"PCM storage"	"not present"	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syste...	"Water syste...	"Water system"	"Water system"	"Water system"
7 Heating_system_emitters	"Radiators"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"Absorptio...	"DC HP/Chill...	"Electric HP/...	"Adsorption ...	"Condensing ...	"Traditional b...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"	"Coal"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensing...	"Condensing...	"Condensing ...	"not present"	"not present"
13 Heating_system_support_fuel	"Biomass"	"Biomass"	"Biomass"	"Biomass"	"not present"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM storage"	"PCM storage"	"PCM storage"	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar therm...	"Solar therm...	"Solar thermal...	"Solar thermal...	"Solar thermal...
16 Renewable_support_PV	"Photovolta...	"Photovoltai...	"Photovoltai...	"Photovoltaic ...	"Photovoltaic ...	"Photovoltaic ...
17 PE_demand_kWh/m2	"68.4785"	"89.3605"	"114.063"	"229.9158"	"302.1205"	"417.3529"

MATLAB Workspace
SFH 100_ATH

Value	Name
1x1 struct	Building
16x337 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x6 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x337 table	PE
1x337 double	PE_profile
1x7 table	PEf
16x337 table	Power
8760x9 table	Radiation
17x337 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x337 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 100_ATH

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Radiators"
Heating_system_generator	"Traditional boiler"
Heating_system_generator_fuel	"Coal"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	495.2592

MATLAB Variable: Building
SFH 100_ATH

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"From1945to1970"
U_wall	1.2920
U_floor	1.1240
U_roof	0.9080
U_window	2.8300
g_window	0.7550
H_T	450.3948
H_V	79.3584

MATLAB Variable: Location
SFH 100_ATH

Field	Value
Country	"GRC"
City	"ATHENS"
latitude	37.9000
longitude	23.7300
T_mean	17.9025
T_max	37.2000
T_min	2

MATLAB Variable: HVAC.Heating
SFH 100_ATH

Field	Value
total	1.4408e+04
max	9.0526
avg	3.7035
Heating_Plus_DHW_peak	16.0292

MATLAB Variable: HVAC.Cooling
SFH 100_ATH

Field	Value
total	1.0411e+04
max	12.0704
avg	0.0522

MATLAB Variable: HVAC.DHW
SFH 100_ATH

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 100_ATH

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"DC HP/Chi...	"DC HP/Chi...	"DC HP/Chi...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"PCM stora...	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Radiators"	"Radiators"	"Radiators"	"Radiators"	"Fan-coils"	"Radiators"	"Fan-coils"
8 Heating_system_generator	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"DC HP/Chi...	"DC HP/Chi...	"DC HP/Chi...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"not present"	"not present"	"not present"
13 Heating_system_support_fuel	"Biomass"	"Biomass"	"Gas"	"Gas"	"not present"	"not present"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"-42.2998"	"-42.2954"	"-41.3444"	"-41.34"	"-41.262"	"-41.262"	"-41.2585"

MATLAB Variable: generators_best_output
SFH 100_ATH

	1 ranking1	2 ranking5	3 ranking21	4 ranking139	5 ranking164	6 ranking197
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syste...	"Water system"	"Electric syste...	"Electric syste...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"DC HP/Chi...	"Electric HP/...	"Adsorption ...	"not present"	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"	"not present"
5 Cooling_system_storage	"PCM stora...	"PCM stora...	"PCM storage"	"not present"	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syste...	"Water system"	"Water system"	"Water system"
7 Heating_system_emitters	"Radiators"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"Absorptio...	"DC HP/Chi...	"Electric HP/...	"Adsorption ...	"Condensing ...	"Traditional b...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"	"Coal"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"not present"	"not present"	"Condensing ...	"not present"	"not present"
13 Heating_system_support_fuel	"Biomass"	"not present"	"not present"	"Biomass"	"not present"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar therm...	"Solar thermal...	"Solar thermal...	"Solar thermal...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltaic ...	"Photovoltaic ...	"Photovoltaic ...
17 PE_demand_kWh/m2	"-42.2998"	"-41.262"	"-22.7953"	"159.7477"	"206.5837"	"234.6859"

MATLAB Workspace
SFH 100_HEL

Value	Name
1x1 struct	Building
16x481 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x6 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x481 table	PE
1x481 double	PE_profile
1x7 table	PEf
16x481 table	Power
8760x9 table	Radiation
17x481 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x481 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 100_HEL

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Radiators"
Heating_system_generator	"Traditional boiler"
Heating_system_generator_fuel	"Coal"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	985.0280

MATLAB Variable: Building
SFH 100_HEL

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"From1945to1970"
U_wall	1.2920
U_floor	1.1240
U_roof	0.9080
U_window	2.8300
g_window	0.7550
H_T	450.3948
H_V	79.3584

MATLAB Variable: Location
SFH 100_HEL

Field	Value
Country	"FIN"
City	"HELSINKI"
latitude	60.3200
longitude	24.9700
T_mean	5.1811
T_max	28.7000
T_min	-21.7000

MATLAB Variable: HVAC.Heating
SFH 100_HEL

Field	Value
total	5.9707e+04
max	21.6077
avg	12.0048
Heating_Plus_DHW_peak	28.5844

MATLAB Variable: HVAC.Cooling
SFH 100_HEL

Field	Value
total	1.1097e+03
max	7.3725
avg	0

MATLAB Variable: HVAC.DHW
SFH 100_HEL

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 100_HEL

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Radiators"	"Radiators"	"Fan-coils"	"Fan-coils"	"Radiators"	"Radiators"	"Radiators"
8 Heating_system_generator	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...	"Absorptio...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...
13 Heating_system_support_fuel	"Biomass"	"Biomass"	"Biomass"	"Biomass"	"Gas"	"Gas"	"Biomass"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"not present"
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"258.145"	"258.145"	"270.6838"	"270.6838"	"272.4845"	"272.4845"	"273.0223"

MATLAB Variable: generators_best_output
SFH 100_HEL

	1 ranking1	2 ranking9	3 ranking31	4 ranking163	5 ranking226	6 ranking435
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syste...	"Water system"	"Electric syste...	"Electric syste...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"DC HP/Chi...	"Electric HP/...	"Adsorption ...	"not present"	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"	"not present"
5 Cooling_system_storage	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syste...	"Water system"	"Water system"	"Water system"
7 Heating_system_emitters	"Radiators"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"Absorptio...	"DC HP/Chi...	"Electric HP/...	"Adsorption ...	"Condensing ...	"Traditional b...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"	"Coal"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensing...	"Condensing ...	"not present"	"not present"
13 Heating_system_support_fuel	"Biomass"	"Biomass"	"Biomass"	"Biomass"	"not present"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar therm...	"Solar thermal...	"Solar thermal...	"Solar thermal...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltaic ...	"Photovoltaic ...	"Photovoltaic ...
17 PE_demand_kWh/m2	"258.145"	"279.9004"	"300.5531"	"384.0062"	"434.2047"	"651.222"

6.2 SFH 100: comments

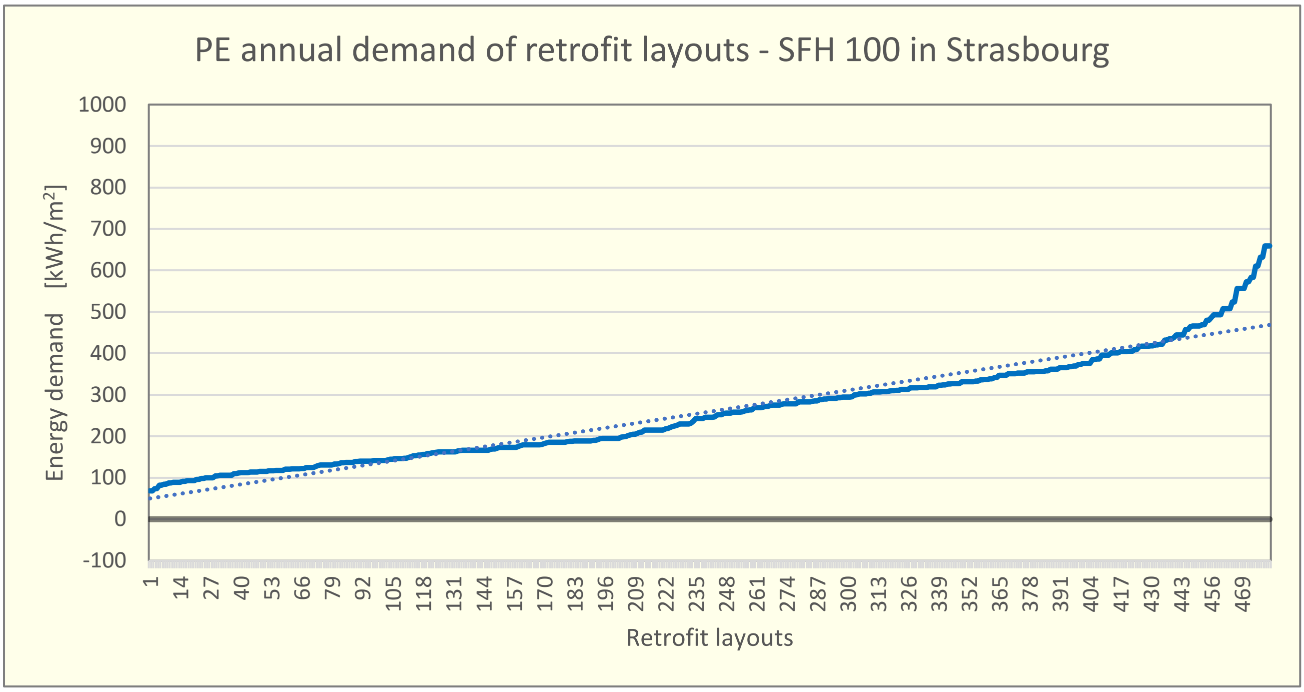


Figure 6.1 - Annual Primary Energy demand of the retrofit solutions for SFH 100 in Strasbourg

Table 6.A - Main values of the total amount of Primary Energy demand for SFH 100 in Strasbourg

Existing system demand	Maximum demand	Minimum demand	Average saving
659 kWh/m^2	659 kWh/m^2	68 kWh/m^2	400 kWh/m^2

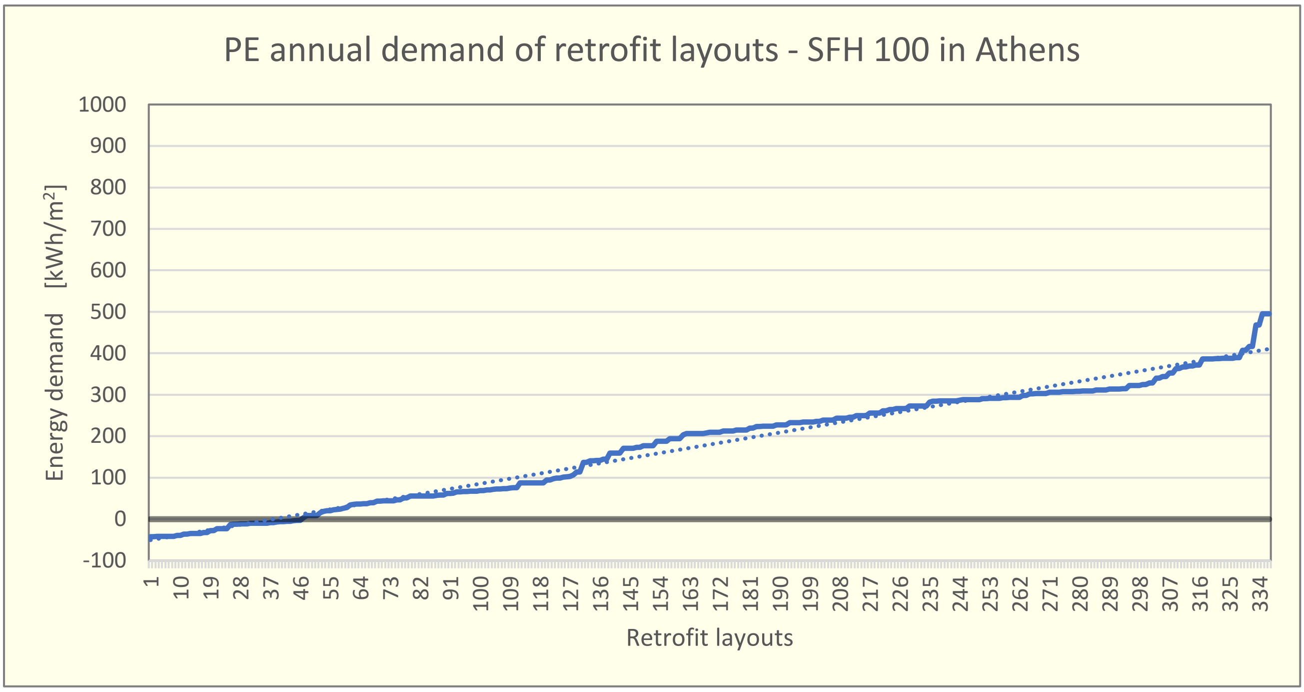


Figure 6.2 - Annual Primary Energy demand of the retrofit solutions for SFH 100 in Athens

Table 6.B - Main values of the total amount of Primary Energy demand for SFH 100 in Athens

Existing system demand	Maximum demand	Minimum demand	Average saving
495 kWh/m^2	495 kWh/m^2	-42 kWh/m^2	315 kWh/m^2

Table 6.C - Main values of the total amount of Primary Energy demand for SFH 100 in Helsinki

Existing system demand	Maximum demand	Minimum demand	Average saving
985 kWh/m²	985 kWh/m²	258 kWh/m²	526 kWh/m²

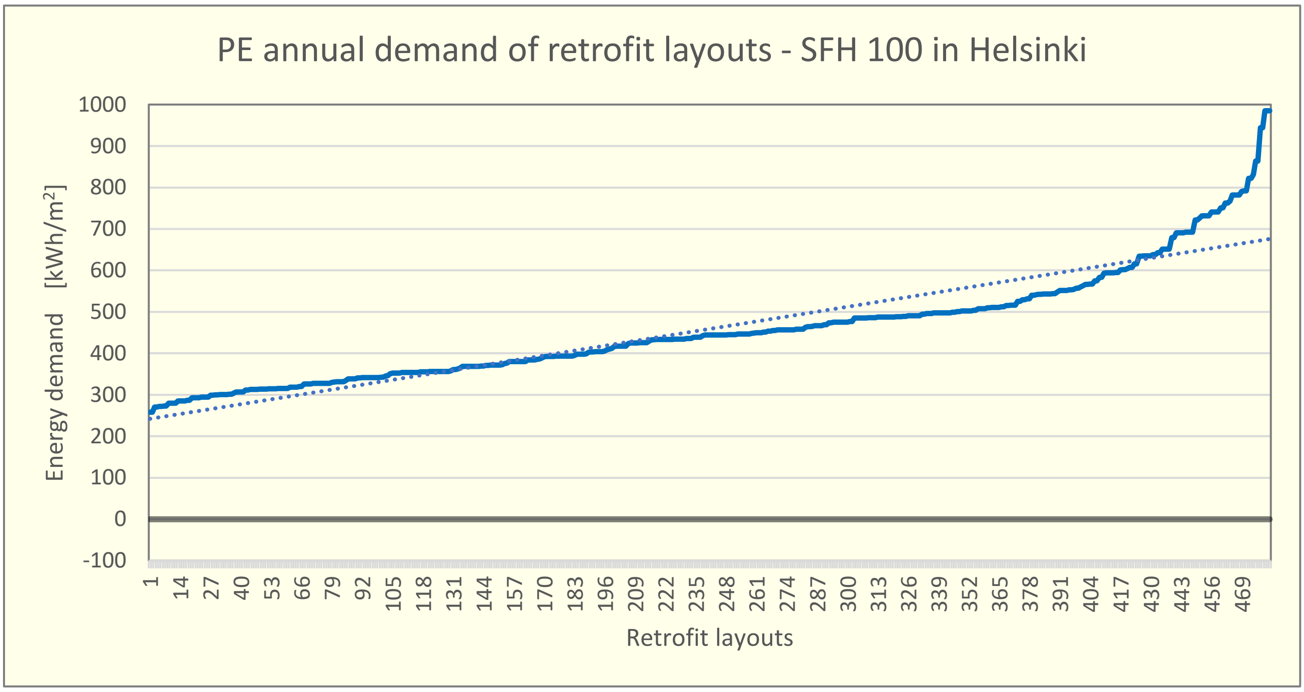


Figure 6.3 - Annual Primary Energy demand of the retrofit solutions for SFH 100 in Helsinki

For SFH 100 I tested the program with an old but yet very common building system layout, with a traditional boiler as heat generator alimenting radiators and, for summer period, electrical air-conditioning.

From the moment that the existing HVAC system is made of outdated machineries, the set of retrofit solutions is larger than the one that results in Chapter 6.3 and Chapter 6.4. In SFH 100 the number of solutions is different between Athens and the other two because of the climate constraints I established for HP in winter; in fact, Athens beneficiates of winter temperatures that do not reach the situations where the COP of the heat-pump is no longer convenient. While the retrofit layouts resulting for colder climates is 481 combinations, for Athens they are 338 (x-axis respectively in Figure 6.1, Figure 6.3 and Figure 6.2).

These graphs represent a first exponential decrease of the energy demand: this is due to the fact that the starting point is an inefficient generator, in fact the constant temperature boiler works better at full load than at partial load but the large majority of time a generator is charged with much less than its nominal power. Out from the exponential first phase, the relation has a linear trend, as consequence of the large number of building variables involved in the retrofit. The worst performance coincides always with the initial HVAC configuration existing in the building, in fact the program is designed to propose always improvements of the equipment, ignoring the possible detrimental solutions; with layouts that involve a full retrofit of the building system adopting all the best machineries I took in account in the program, theoretically becomes possible to reach NZEB status in two of the three climates.

The best performance is achieved in the warmest climate (Athens), where the best solution reaches negative energy demand (-42 kWh/m2) meaning that the amount of energy produced with renewables overpasses the annual demand for HVAC. Athens is also the place where the initial demand is the lowest (495 kWh/m^2) and, at the same time, it is important also to keep in mind that I hypothesised the installation of a 50 m^2 PV plant, which is something out of the ordinary because its area uses to be more limited for cost issues.

In Strasbourg and Helsinki, the starting point is a much more inefficient situation (respectively 659 and 985 kWh/m^2) and the NZEB status remains far from both but the average energy saving in both sites is larger than in Athens. In order to explain why it is useful to look at Figure 6.4 and Figure 6.5.

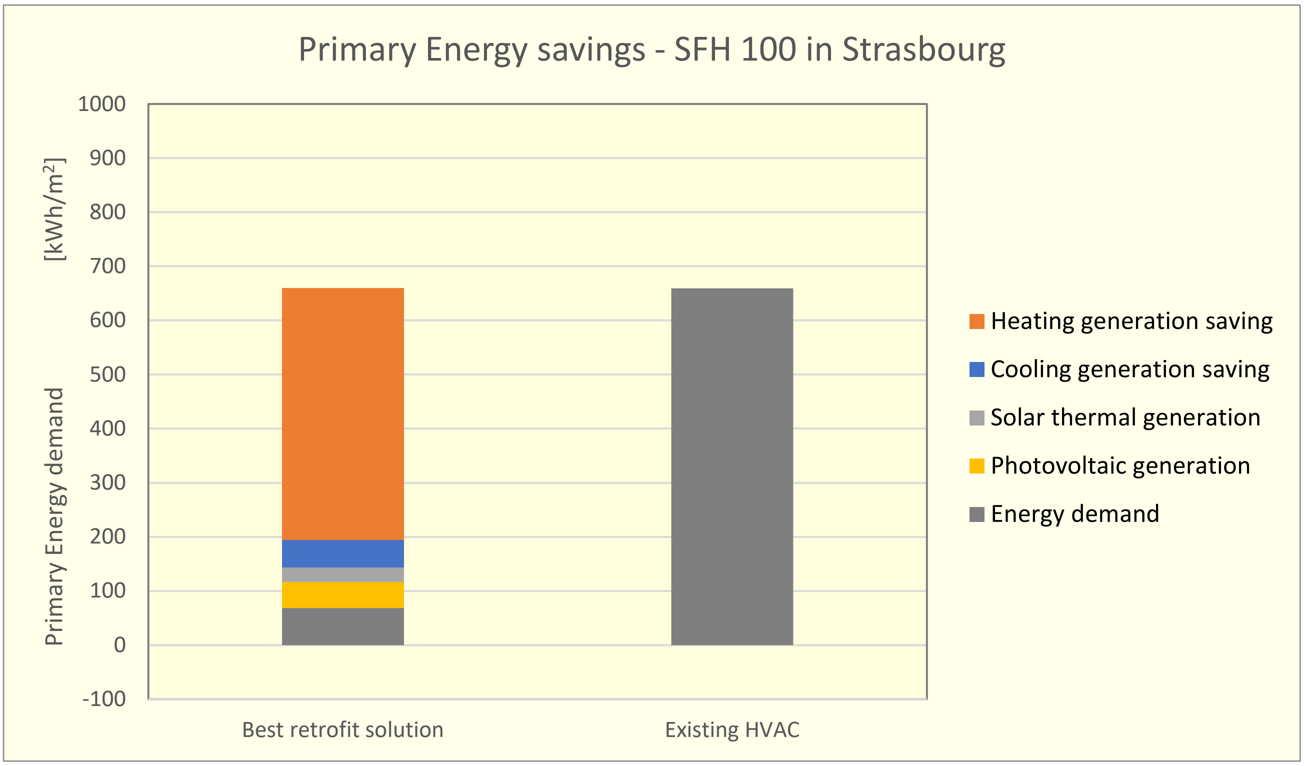


Figure 6.4 - PE demand comparison between the best retrofit solution and the existing HVAC system for SFH 100 in Strasbourg

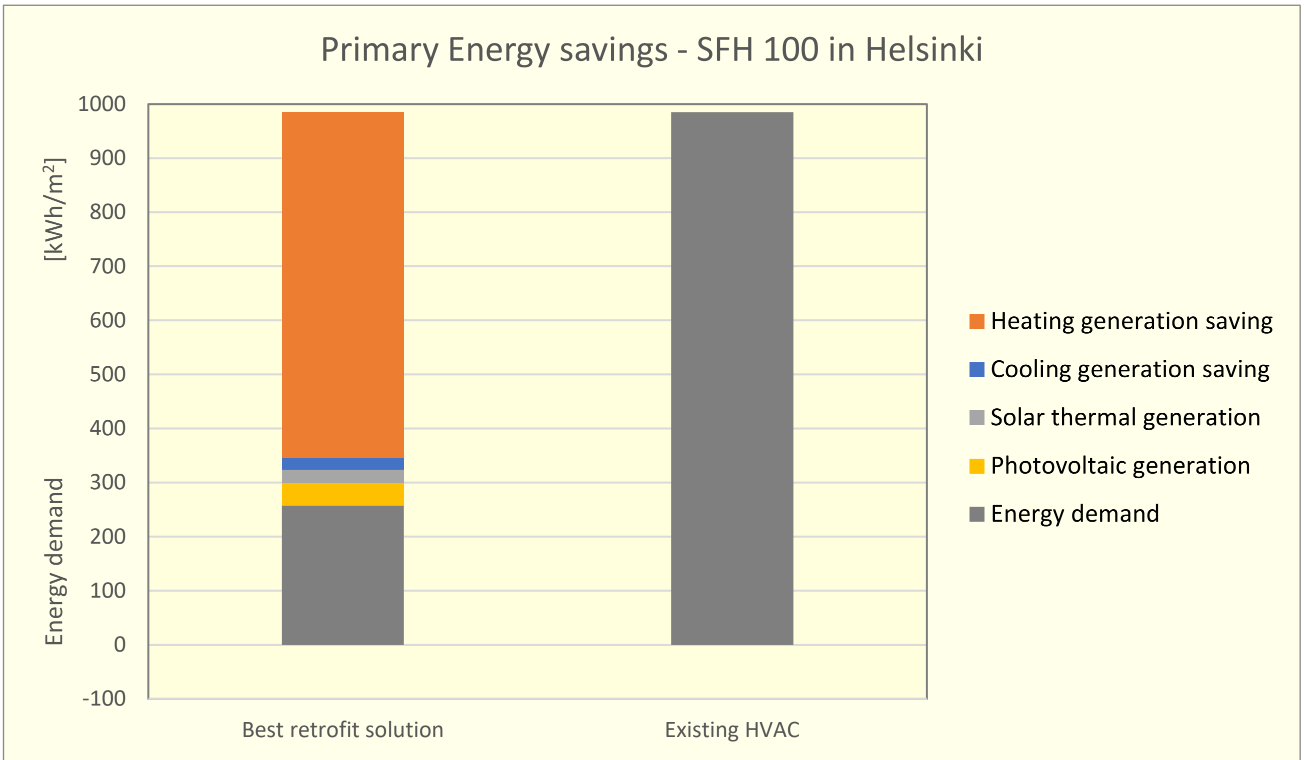


Figure 6.5 - PE demand comparison between the best retrofit solution and the existing HVAC system for SFH 100 in Helsinki

Table 6.D - Components of the best retrofit solution for SFH 100 in Strasbourg

Cooling system type	Water system
Cooling system emitters	Fan-coils
Cooling system generator	Absorption HP/Chiller
Cooling system generator fuel	Air-source
Cooling system storage	PCM storage
Heating system type	Water system
Heating system emitters	Fan-coils
Heating system generator	Absorption HP/Chiller
Heating system generator fuel	Air-source
Heating system DHW generator	not present
Heating system DHW generator fuel	not present
Heating system support	Condensing boiler
Heating system support fuel	Biomass
Heating system storage	PCM storage
Renewable support ST	Solar thermal collectors
Renewable support PV	Photovoltaic panels
PE demand	68,5 kWh/m2

Table 6.E – Focus on the Primary Energy savings for SFH 100 in Strasbourg

	Best retrofit solution	Existing HVAC	Energy saving
Annual PE demand for cooling	1408 MWh	8489 MWh	-83%
Annual PE demand for heating	18730 MWh	83779 MWh	-78%

Table 6.F - Components of the best retrofit solution for SFH 100 in Helsinki

Cooling system type	Water system
Cooling system emitters	Fan-coils
Cooling system generator	Absorption HP/Chiller
Cooling system generator fuel	Air-source
Cooling system storage	not present
Heating system type	Water system
Heating system emitters	Fan-coils
Heating system generator	Absorption HP/Chiller
Heating system generator fuel	Air-source
Heating system DHW generator	not present
Heating system DHW generator fuel	not present
Heating system support	Condensing boiler
Heating system support fuel	Biomass
Heating system storage	PCM storage
Renewable support ST	Solar thermal collectors
Renewable support PV	Photovoltaic panels
PE demand	68,5 kWh/m2

Table 6.G - Focus on the Primary Energy savings for SFH 100 in Strasbourg

	Best retrofit solution	Existing HVAC	Energy saving
Annual PE demand for cooling	548 MWh	3491 MWh	-84%
Annual PE demand for heating	44837 MWh	134413 MWh	-67%

These figures give evidence of the fact that the potential saving of the energy consumed for heating is very remarkable, one of the most influent results for the whole program. For SFH 100 in Strasbourg the 79% of energy saving comes from the consumption for heat generation and this amount goes up to 88% in Helsinki: as consequence, all the other components become much less relevant for the retrofit and this is something to absolutely keep in mind in the perspective of a MCDM (Multi-Criteria Decision Making).

For example, the installation of renewable plants is often expensive and not easy to design, especially if I remind that the retrofit is considering an available solar area of 50 m^2; for this reason it is important to observe that the percentage of PE saving coming from ST and PV is in the order of 13% in Strasbourg and 9% in Helsinki, which means that, in presence of technical or economical constrains, it would be preferable to act on the sole heat generation, thanks to the considerable PE saving deriving from the installation of just a HP.

It can be observed also that the only difference between the best retrofit solutions coming out in the two climates is the absence of the PCM storage for cooling in Helsinki (Table 6.D and Table 6.F). The substantial equivalence is maintained also for Athens (Table 6.H in next page), as expected from the fact that these case are all inside the "heating-prevalence" cases; in SFH 45 and SFH 15, with the severe curtailment of the heating needs thanks to the implementation of more sophisticated envelopes, it becomes more important the decrease of cooling demand. In those examples the best generator will be no longer the Absorption HP, but the DC HP: while the first is the one having the highest performances with heating prevalence, the second one is the best solution in cooling-predominant demands.

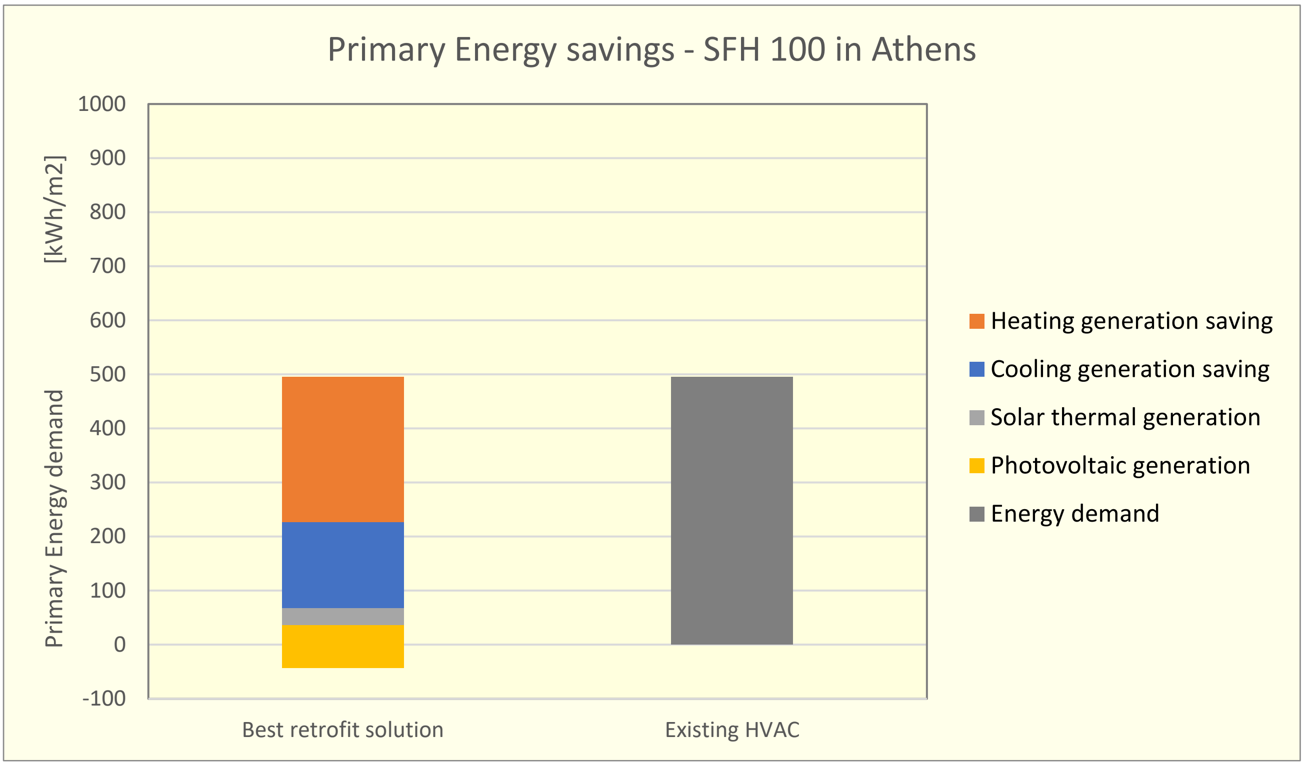


Figure 6.6 - PE demand comparison between the best retrofit solution and the existing HVAC system for SFH 100 in Athens

Table 6.H - Components of the best retrofit solution for SFH 100 in Athens

Cooling system type	Water system
Cooling system emitters	Fan-coils
Cooling system generator	Absorption HP/Chiller
Cooling system generator fuel	Air-source
Cooling system storage	PCM storage
Heating system type	Water system
Heating system emitters	Fan-coils
Heating system generator	Absorption HP/Chiller
Heating system generator fuel	Air-source
Heating system DHW generator	not present
Heating system DHW generator fuel	not present
Heating system support	Condensing boiler
Heating system support fuel	Biomass
Heating system storage	PCM storage
Renewable support ST	Solar thermal collectors
Renewable support PV	Photovoltaic panels
PE demand	68,5 kWh/m2

Table 6.I - Focus on the Primary Energy savings for SFH 100 in Athens

	Best retrofit solution	Existing HVAC	Energy saving
Annual PE demand for cooling	5140 MWh	27383 MWh	-81%
Annual PE demand for heating	4383 MWh	41953 MWh	-90%

In Athens case, as I previously mentioned, it is possible to reach the NZEB status, thanks to the fact that the available amount of energy from renewables is much more important than in the previous climates (21% of the PE saving). This logic is repeated for SFH 45 and SFH 15. The energy demand goes below zero, meaning that theoretically the sum of PE consumed and produced gives a positive amount of energy, with a renewable production that overpasses the HVAC demand. Once again, this outstanding result is effect of the use of very complex and expensive retrofit layout: for this reason it is suitable to use this output as starting point for a MCDM.

Looking at the energy demand net of the renewable production, it can be seen that both cooling and heating demand are subjected to a severe decrease, in the order of 80% and 90% respectively, a percentage even higher than the one obtained in the two previous climates. The reason why is the oscillation of the external temperature, which is more restricted in Athens: It can be seen in the Annex III, Figure III.1. This boundary condition permits a more efficient use of HPs, but remembering that also for the cold climates the use of HP achieved great results (energy saving in the range of 67%-83%).

6.3 SFH 45: comments

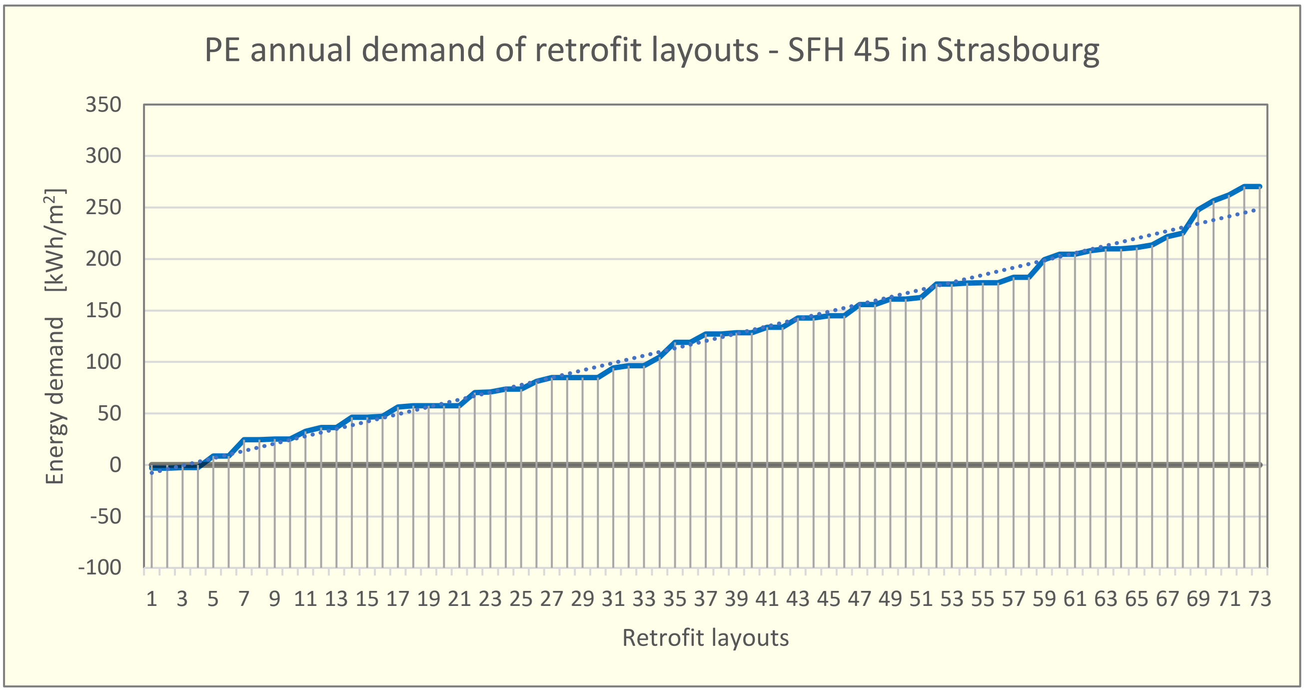


Figure 6.7 - Annual Primary Energy demand of the retrofit solutions for SFH 45 in Strasbourg

Table 6.J - Main values of the total amount of Primary Enegry demand for SFH 45 in Strasbourg

Existing system demand	Maximum demand	Minimum demand	Average saving
270 kWh/m^2	270 kWh/m^2	-3 kWh/m^2	150 kWh/m^2

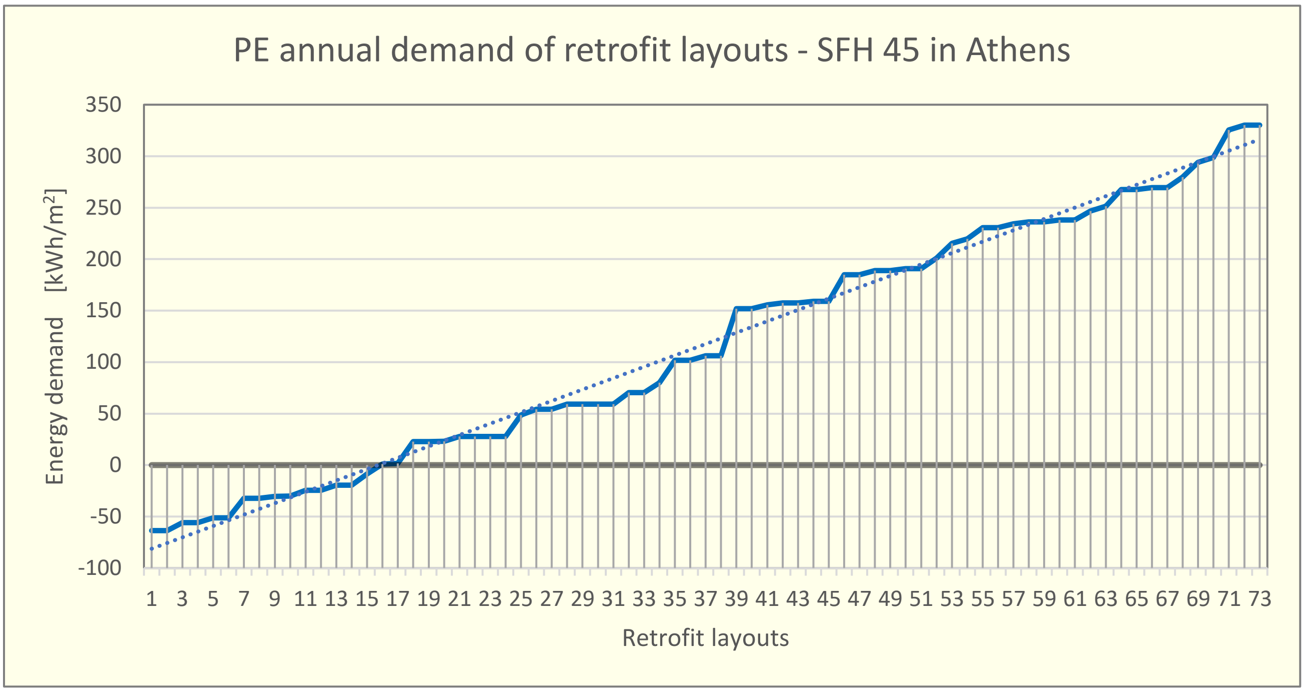


Figure 6.8 - Annual Primary Energy demand of the retrofit solutions for SFH 45 in Athens

Table 6.K - Main values of the total amount of Primary Enegry demand for SFH 45 in Athens

Existing system demand	Maximum demand	Minimum demand	Average saving
330 kWh/m^2	330 kWh/m^2	-64 kWh/m^2	213 kWh/m^2

Table 6.L - Main values of the total amount of Primary Energy demand for SFH 45 in Helsinki

Existing system demand	Maximum demand	Minimum demand	Average saving
303 kWh/m²	303 kWh/m²	89 kWh/m²	119 kWh/m²

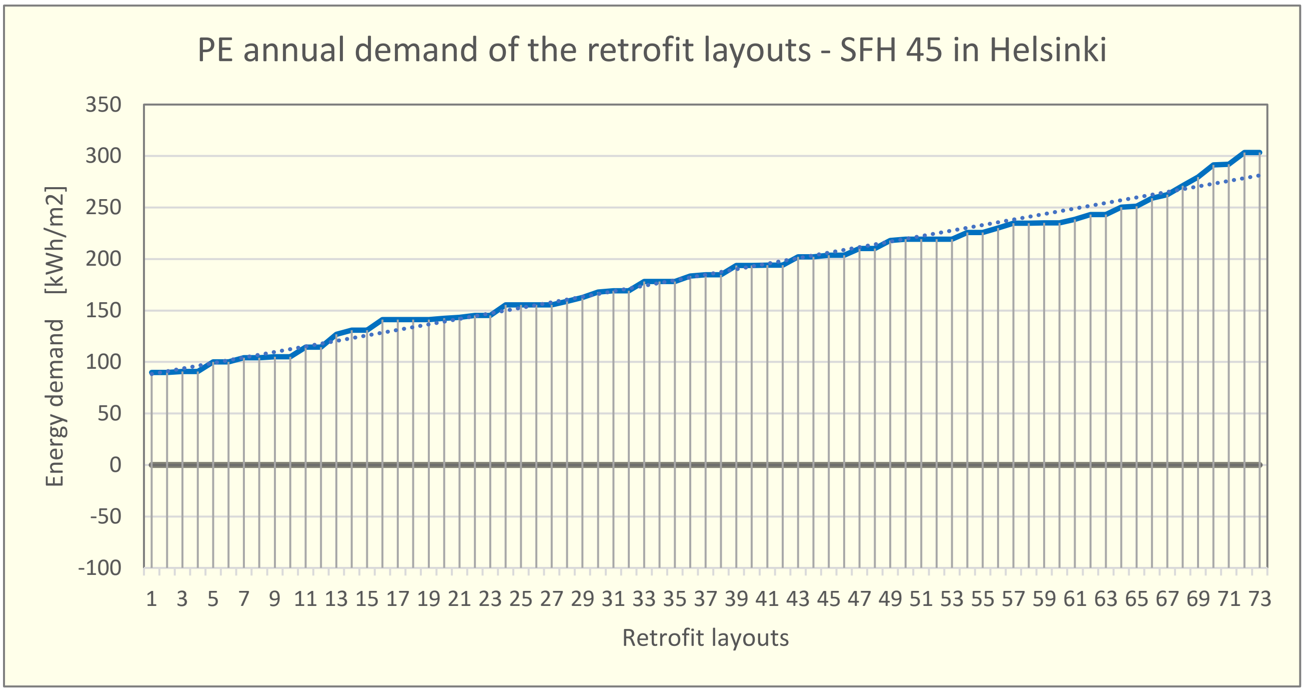


Figure 6.9 - Annual Primary Energy demand of the retrofit solutions for SFH 45 in Helsinki

Figure 6.7, Figure 6.8 and Figure 6.9 represent a clear linear trend, more regular than the ones in Chapter 6.2. The worst performance coincides, as always, with the initial HVAC configuration existing in the building, as effect of the design philosophy of the algorithm. With the layouts that involve a strong retrofit of the building system, adopting all the best machineries I took in account in the program, theoretically becomes possible to reach NZEB status in two of the three climates.

In Strasbourg, which represents an average European continental climate, the improvement trend is very linear and can obtain very important Primary Energy savings if the retrofit takes in account a DC HP/chiller, renewables and heat storage. We are in fact in the "cooling-predominant" case, where the DC HP reaches better results than thermally-driven HPs.

In Athens the curtailment of the energy demand is once again the strongest thanks to the fact that, in warm and sunny climate as the it is the capital of Greece, it can be exploited a relevant amount of energy coming from solar radiation. In the same time the warm temperatures of air all along the year improve the performances of HP/Chiller. Indeed, the saving profile is more irregular. NZEB is achievable with less effort than in Strasbourg but, anyway, it is important to remember also that the installation of these machineries all together would imply a significant economical investment.

In Helsinki, in the end, green strategies are much more difficult, in fact in so cold climates the first measure for the energy saving is to work on the envelope insulation. Anyway, the decrement of the demand can be very important, in fact the average saving is in the order of magnitude of almost half of the initial Primary Energy demand. Differently from the two other climates, in Helsinki the NZEB remains a far goal and the best solutions are obtained with the use of an Absorption HP as generator for heating and cooling.

6.4 SFH 15: comments

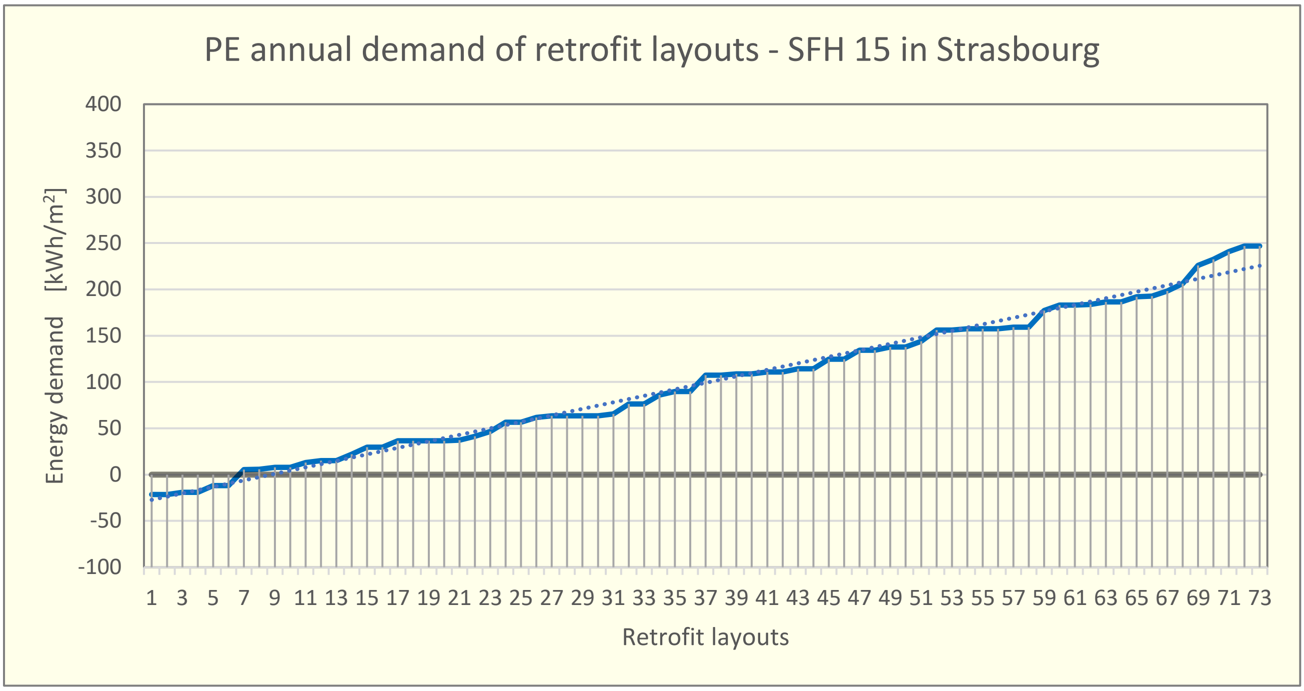


Figure 6.10 - Annual Primary Energy demand of the retrofit solutions for SFH 15 in Strasbourg

Table 6.M - Main values of the total amount of Primary Energy demand for SFH 15 in Strasbourg

Existing system demand	Maximum demand	Minimum demand	Average saving
247 kWh/m^2	247 kWh/m^2	-21 kWh/m^2	148 kWh/m^2

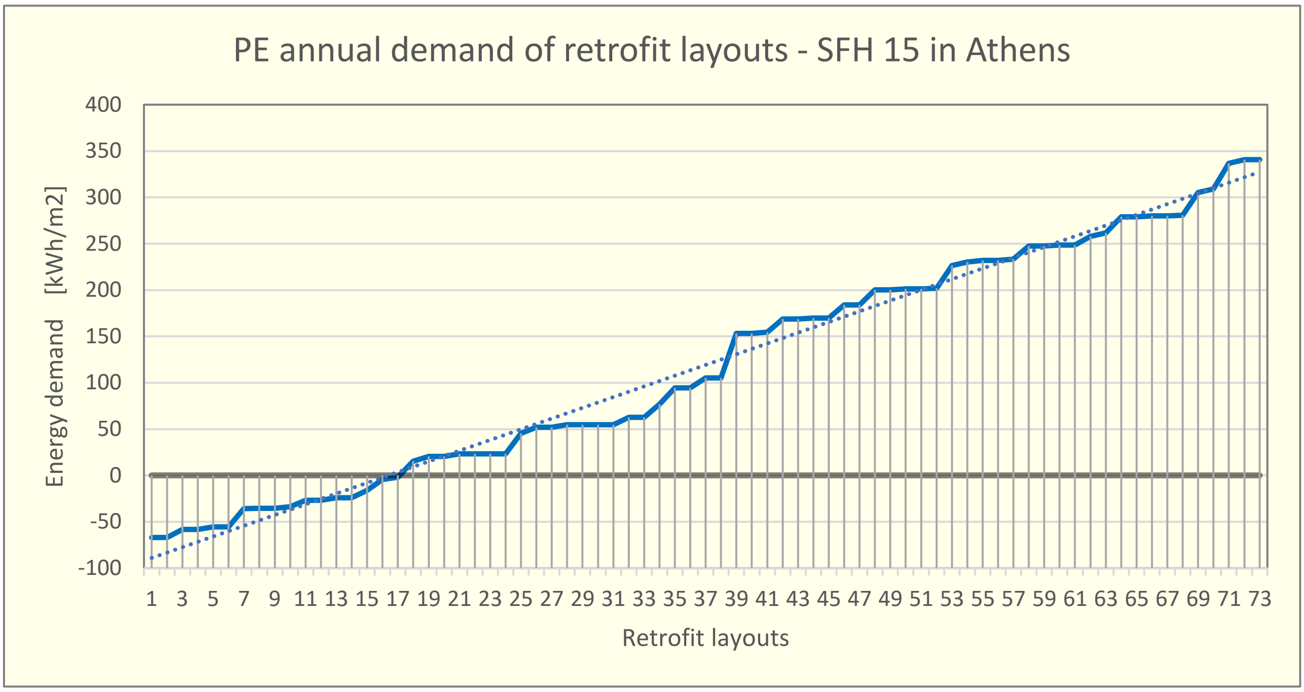


Figure 6.11 - Annual Primary Energy demand of the retrofit solutions for SFH 15 in Athens

Table 6.N - Main values of the total amount of Primary Energy demand for SFH 15 in Athens

Existing system demand	Maximum demand	Minimum demand	Average saving
341 kWh/m^2	341 kWh/m^2	-67 kWh/m^2	222 kWh/m^2

Table 6.O - Main values of the total amount of Primary Energy demand for SFH 15 in Helsinki

Existing system demand	Maximum demand	Minimum demand	Average saving
256 kWh/m^2	256 kWh/m^2	44 kWh/m^2	118 kWh/m^2

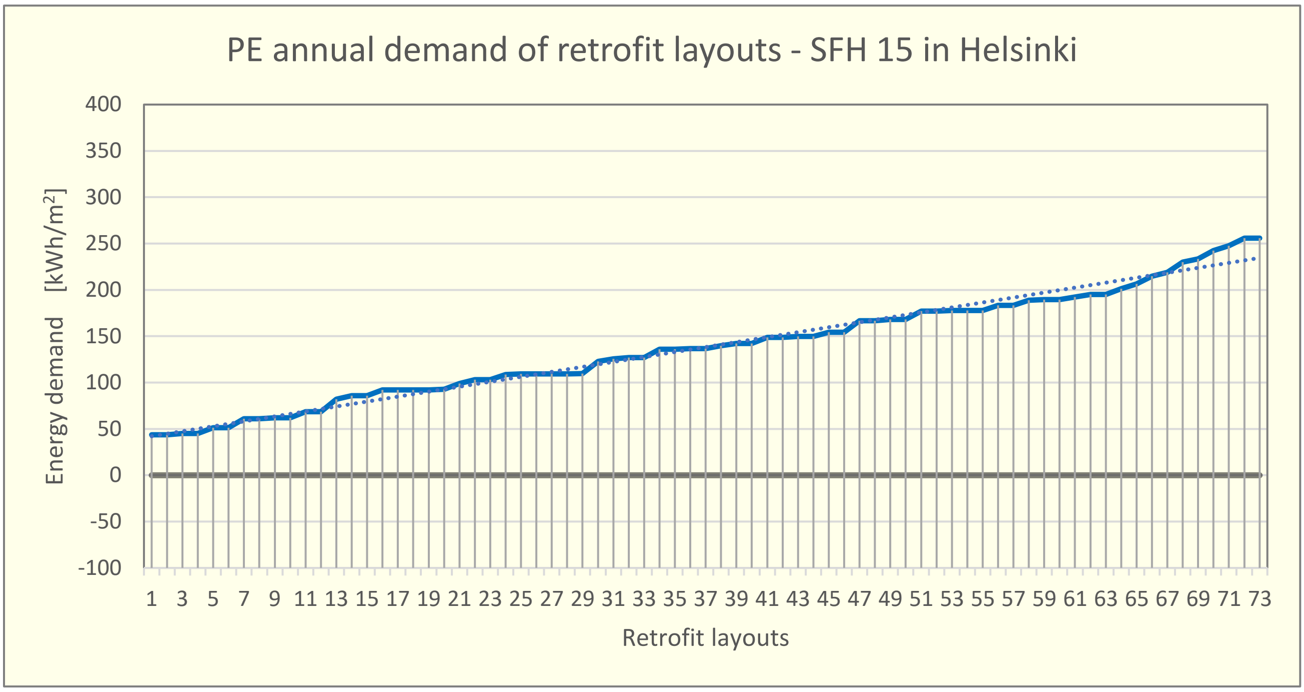


Figure 6.12 - Annual Primary Energy demand of the retrofit solutions for SFH 15 in Helsinki

For SFH 15 I adopted a HVAC system very similar to the one in SFH 45, with heat generation with condensing boiler but with fan-coil, that means an increase of the energy performance of the starting condition. For the summer cooling is assumed the installation of the electrical fan-coils which, in the program, refer to the common air conditioning made of a mono-split or multi-split system with fan-coils connected to an external unity where ah air-source chiller exchanges heat for the cooling of its refrigerant fluid.

The number of retrofit solutions coming out from the filtering algorithm is the same for all cases (73 configurations).

With an envelope exploiting very good insulating characteristics, it is interesting to observe that in all climates and especially the ones reaching the lowest values of Primary Energy consumption, the linear trend of the decrease becomes more something like a "stair decrease", meaning that it is needed more effort to obtain a cut of the demand when it gets closer to zero or less. This is true especially in Athens, where there was an almost null heating demand and the total amount of energy need was almost entirely covered by summer cooling. The steps of the stair are relative to a big variation of the HVAC layout, for example the contemplation of different type of generator or the installation of a renewable plant.

In Helsinki the NZEB remains a far goal. The construction part is known to be, in these regions, the fundamental way to achieve a quasi-zero energy consumption, exploiting especially the heat capacity of the building which, on the other hand, was necessarily neglected in the static model assumed by the design program. The possible green strategies for a very cold climate can lean on heat-pumps integration just partially, because its performance is very poor in the hardest months and the use of solar plants cannot give a strong help.

Conclusion

The results obtained in Chapter 6 satisfy all the theoretical previsions. They are performed analysis on a large number of HVAC configurations, from the 73 layouts in modern HVAC up to 481 in the case of rehabilitation of outdated traditional boilers in poorly insulated buildings. The average PE saving between all the studied cases is a little more than 50%, with cases that reach also 100%, that is Net-Zero Energy Building. These remarkable values confirm the great potential of HVAC retrofit and suggest an interesting pay-back period and return of investment time, also in cases with strong intervention.

Thanks to its optimal weather conditions, the save of energy in Athens is the highest and the most stable, around 65%, because of the fact that renewables have more impact (up to 45% of the saving in the best envelope performance case). NZEB status is available not only in Greece but also in Strasbourg, with more effort (it is reached only with strong retrofits on SFH45 and SFH 15). Diametrically opposite are results in Helsinki, where an average of 85% of the saved PE that comes with the sole intervention on heating generation: in very cold climates, more than solar plants, results fundamental the use of thermally-driven HPs with appropriate heat source and implementation of heat storage, because of the outside temperatures that often are not suitable for air-source HPs.

In the end, the algorithm works as expected in all the different climates and on the different frameworks tested, with continuity solution. It follows the predicted trend of achieving the best results in warm climates, where there is the possibility to take advantage of better external conditions both for the heat generation and the solar plants. It is respected also the decrease of the energy demand with respect to the envelope performance, with the result of having an ambivalent effect on heating and cooling demand if it is modified the "transpiration" of the building. The use of the same PEfs let us make transnational comparisons, otherwise the particular economic conditions of the countries would have affected the results. The main imprecisions deal with the involvement of the heat capacity and its effect of thermal inertia during the cooling season, which is lost with the use of static energy balances instead of dynamic simulations based on differential models (as used for example in TRNSYS and in RetroSim simulation backend, Figure 1.1). However, the use of this simplified model has been done and justified regarding the fact that it increases drastically the flexibility and the speed of the algorithm; in the same time, the imprecision is not affecting the filtering nor the sizing. This irregularity may have repercussions on the absolute values of the outputs from the final program "PE_demand", limited to most modern buildings case. However, this tool is studied for the comparison of the final outputs of the previous passages and for this reason it is not relevant an error, even if limited, on absolute values because the algorithm aims to study the relative performances of the various HVAC systems.

It can be affirmed that the algorithm reaches the goal to be an instrument for the pre-design of the HVAC retrofit. Its greatest potential would come out together with a dynamic simulation of the outputs and multi-criteria decision analysis.

On this final aspect especially, it may be concentrated the logical next step of this work, in fact the program "PE_Demand" is just one of the possible translation of the set of solution obtained for the HVAC rehabilitation. Following the same logic described in the path of this program, they can be written additional auxiliary programs that rate the building system retrofit in function of its spatial dimensions or its CO2 emissions or its cost. The topic is one of the most important aspect conceived by Heat4Cool team for RetroSim, in order to procure a tool that meets the requirements of the users as a multi-variable problem. This, indeed, is imagined to be the right way to obtain a diffusion at large scale of the HVAC system retrofit.

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An energy efficiency driven algorithm for filtering and sizing HVAC system layouts for building retrofit

ANNEX I

Computation of the thermal characteristics of the reference framework for system simulations “Single Family House – SFH”

SFH 100				
HX surface	394.300	m2		
H_T	**450.395**	**W/K**		
C	**116362.736**	**kJ/K**		
Air change rate	0.400	V/h		

INTERNAL WALL

			A	*400.000*	*m2*
			U	*0.964*	*W/(m2*K)*
			C	*47840.000*	*kJ/K*
	t	*Specific heat*	*Density*	*Heat capacity*	
Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1 Clincker	0.200	0.920	650.000	47840.000	
Total	0.200			47840.000	

ROOF CIELING

			A	*81.000*	*m2*
			U	*0.908*	*W/(m2*K)*
			C	*3725.093*	*kJ/K*
	t	*Specific heat*	*Density*	*Heat capacity*	
Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1 Gypsum	0.025	1.000	900.000	1822.500	
2 Plywood	0.015	2.500	300.000	911.250	
3 Rockwool	0.016	1.030	60.000	80.093	
4 Plywood	0.015	2.500	300.000	911.250	
Total	0.071			3725.093	

EXTERNAL WALL

			A	*180.400*	*m2*
			U	*1.292*	*W/(m2*K)*
			C	*25379.803*	*kJ/K*
	t	*Specific heat*	*Density*	*Heat capacity*	
Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1 Plaster	0.015	1.000	1200.000	1458.000	
2 Brick	0.210	1.000	1380.000	23473.800	
3 EPS	0.011	0.700	17.000	10.603	
4 Plaster_out	0.003	1.000	1800.000	437.400	
Total	0.239			25379.803	

GROUND FLOOR

			A	*70.000*	*m2*
			U	*1.124*	*W/(m2*K)*
			C	*39417.840*	*kJ/K*
	t	*Specific heat*	*Density*	*Heat capacity*	
Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1 Plaster_floor	0.080	1.000	2000.000	12960.000	
2 Ins_sound	0.022	1.500	80.000	213.840	
3 Concr	0.150	1.080	2000.000	26244.000	
Total	0.252			39417.840	

WINDOW

			g	*0.755*	*m2*
			U	*2.830*	*W/(m2*K)*
			Frame ratio	*0.150*	
Orientation	*Area*				
North	3.000	m2			
South	12.000	m2			
West	4.000	m2			
East	4.000	m2			
Total	23.000	m2			

SFH 45		
HX surface	409.800	m2
H_T	**159.573**	**W/K**
C	**99153.063**	**kJ/K**
Air change rate	0.200	V/h

INTERNAL WALL

A	*400.000*	*m2*
U	*0.964*	*W/(m2*K)*
C	*47840.000*	*kJ/K*

	Layer	*t [m]*	*Specific heat kJ/(kg*K)*	*Density kg/m3*	*Heat capacity kJ/K*
1	Clincker	0.200	0.920	650.000	47840.000
	<u>Total</u>	0.200			47840.000

ROOF CIELING

A	*81.000*	*m2*
U	*0.510*	*W/(m2*K)*
C	*3880.273*	*kJ/K*

	Layer	*t [m]*	*Specific heat kJ/(kg*K)*	*Density kg/m3*	*Heat capacity kJ/K*
1	Gypsum	0.025	1.000	900.000	1822.500
2	Plywood	0.015	2.500	300.000	911.250
3	Rockwool	0.047	1.030	60.000	235.273
4	Plywood	0.015	2.500	300.000	911.250
	<u>Total</u>	0.102			3880.273

EXTERNAL WALL

A	*180.400*	*m2*
U	*0.333*	*W/(m2*K)*
C	*25465.590*	*kJ/K*

	Layer	*t [m]*	*Specific heat kJ/(kg*K)*	*Density kg/m3*	*Heat capacity kJ/K*
1	Plaster	0.015	1.000	1200.000	1458.000
2	Brick	0.210	1.000	1380.000	23473.800
3	EPS	0.100	0.700	17.000	96.390
4	Plaster_out	0.003	1.000	1800.000	437.400
	<u>Total</u>	0.328			25465.590

GROUND FLOOR

A	*70.000*	*m2*
U	*0.414*	*W/(m2*K)*
C	*21967.200*	*kJ/K*

	Layer	*t [m]*	*Specific heat kJ/(kg*K)*	*Density kg/m3*	*Heat capacity kJ/K*
1	Plaster_floor	0.015	1.000	2000.000	2430.000
2	Ins_sound	0.210	1.500	80.000	2041.200
3	Concr	0.100	1.080	2000.000	17496.000
	<u>Total</u>	0.325			21967.200

WINDOW

g	*0.624*	*m2*
U	*1.270*	*W/(m2*K)*

Orientation	*Area*	
North	3.000	m2
South	12.000	m2
West	4.000	m2
East	4.000	m2
<u>Total</u>	23.000	m2

				SFH 15		
				HX surface	420.800	m2
				H_T	**90.030**	**W/K**
				C	**118915.929**	**kJ/K**
				Air change rate	0.100	V/h

INTERNAL WALL

				A	*400.000*	*m2*
				U	*0.964*	*W/(m2*K)*
				C	*47840.000*	*kJ/K*
		t	*Specific heat*	*Density*	*Heat capacity*	
	Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1	Clincker	0.200	0.920	650.000	47840.000	
	Total	0.200			47840.000	

ROOF CEILING

				A	*81.000*	*m2*
				U	*0.180*	*W/(m2*K)*
				C	*4531.027*	*kJ/K*
		t	*Specific heat*	*Density*	*Heat capacity*	
	Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1	Gypsum	0.025	1.000	900.000	1822.500	
2	Plywood	0.015	2.500	300.000	911.250	
3	Rockwool	0.177	1.030	60.000	886.027	
4	Plywood	0.015	2.500	300.000	911.250	
	Total	0.232			4531.027	

EXTERNAL WALL

				A	*180.400*	*m2*
				U	*0.200*	*W/(m2*K)*
				C	*25542.702*	*kJ/K*
		t	*Specific heat*	*Density*	*Heat capacity*	
	Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1	Plaster	0.015	1.000	1200.000	1458.000	
2	Brick	0.210	1.000	1380.000	23473.800	
3	EPS	0.180	0.700	17.000	173.502	
4	Plaster_out	0.003	1.000	1800.000	437.400	
	Total	0.408			25542.702	

GROUND FLOOR

				A	*70.000*	*m2*
				U	*0.201*	*W/(m2*K)*
				C	*41002.200*	*kJ/K*
		t	*Specific heat*	*Density*	*Heat capacity*	
	Layer	*[m]*	*kJ/(kg*K)*	*kg/m3*	*kJ/K*	
1	Plaster_floor	0.080	1.000	2000.000	12960.000	
2	Ins_sound	0.185	1.500	80.000	1798.200	
3	Concr	0.150	1.080	2000.000	26244.000	
	Total	0.415			41002.200	

WINDOW

				g	*0.609*	*m2*
				U	*1.100*	*W/(m2*K)*

Orientation	*Area*	
North	3.000	m2
South	12.000	m2
West	4.000	m2
East	4.000	m2
Total	23.000	m2

An energy efficiency driven algorithm for filtering and sizing HVAC system layouts for building retrofit

ANNEX II

TRNSYS deck file for the case “SFH 45” in Strasbourg

```
VERSION 17
*******************************************************************************
*******************************************************************************
*** Units
*******************************************************************************

*******************************************************************************
*** Control cards
*******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760
STEP=0.016666666666
SIMULATION   START   STOP    STEP   ! Start time    End time    Time step
TOLERANCES 0.001 0.001          ! Integration    Convergence
LIMITS 100000 100000 100000             ! Max iterations    Max warnings    Trace limit
DFQ 1                   ! TRNSYS numerical integration solver method
WIDTH 80                ! TRNSYS output file width, number of characters
LIST                    ! NOLIST statement
                    ! MAP statement
SOLVER 0 1 1                ! Solver statement  Minimum relaxation factor   Maximum relaxation factor
NAN_CHECK 0             ! Nan DEBUG statement
OVERWRITE_CHECK 0           ! Overwrite DEBUG statement
TIME_REPORT 0           ! disable time report
EQSOLVER 0              ! EQUATION SOLVER statement
* User defined CONSTANTS


* Model "T88" (Type 88)
*

UNIT 3 TYPE 88   T88
*$UNIT_NAME T88
*$MODEL .\Loads and Structures\Single Zone Models\Lumped Capacitance Building (Type 88)\Type88.tmf
*$POSITION 630 224
*$LAYER Main #
PARAMETERS 10
bui_loss_coefficient        ! 1 Building loss coefficient
bui_capacitance     ! 2 Building capacitance
1.007       ! 3 Specific heat  of building air
1.2     ! 4 Density of building air
bui_area        ! 5 Building surface area
bui_volume      ! 6 Building volume
1       ! 7 Humidity ratio multiplier
20      ! 8 Initial temperature
0.005       ! 9 Initial humidity ratio
2501        ! 10 Latent heat of vaporization
INPUTS 10
0,0     ! [unconnected] Temperature of ventilation air
0,0     ! [unconnected] Humidity ratio of ventilation air
0,0     ! [unconnected] Ventilation mass flow rate
10,1        ! CLIMATE:Dry bulb temperature ->Ambient temperature
10,6        ! CLIMATE:Humidity ratio ->Ambient humidity ratio
bui_mv      ! [equation] Mass flow rate of infiltration air
bui_Qlight      ! [equation] Rate of energy gain from lights
T88_QEquip      ! T88_Equipment:T88_QEquip ->Rate of energy from equipment
bui_Qp_sens     ! [equation] Rate of sensible energy gain from people
bui_mw_p_lat        ! [equation] Rate of humidity gain
*** INITIAL INPUT VALUES
40.0 0.008 0.0 10.0 0.006 bui_mv bui_Qlight 0.0 bui_Qp_sens bui_mw_p_lat

*------------------------------------------------------------------------------

* EQUATIONS "INPUTS"
*
EQUATIONS 15
bui_area = 409.8 !envelope area, in m2
```

```
bui_volume = 389.45 !building volume in m3
bui_window_N = 3 !window area with north exposure in m2
bui_window_S = 12 !window area with south exposure in m2
bui_window_W = 4 !window area with west exposure in m2
bui_window_E = 4 !window area with east exposure in m2
bui_frame_ratio = 0.15 !window frame percentage, adimensional
bui_window_g = 0.755 !window g-value (solar factor), adimensional
bui_Ht = 159.573 !building envelope thermal losses coefficient for transmittance, in W/K
bui_env_capacitance = 99153.063 !building envelope heat capacity, in kJ/K
bui_vent_rate = 0.2 !number of air changes per hour
bui_q_ppl = 60 !sensible heat gain from occupants, in W/pers
bui_mw_ppl = 0.059 !humidity gain from occupants, in kg/(h*pers)
sim_sum = 1 !1 for power summary step in hours, -1 in months
out_type = 1 !0 for "equal Q" simulation, 1 for "equal T"
*$UNIT_NAME INPUTS
*$LAYER Main
*$POSITION 966 51

*------------------------------------------------------------------------------


* EQUATIONS "Calcs"
*
EQUATIONS 11
bui_loss_coefficient = bui_Ht*3.6/bui_area !kJ/hm2K
bui_capacitance = bui_env_capacitance+bui_volume*0.34*3.6 !kJ/K
bui_Qs_N = [10,26]*bui_window_N*(1-bui_frame_ratio)*bui_window_g !kJ/h
bui_Qs_S = [10,24]*bui_window_S*(1-bui_frame_ratio)*bui_window_g !kJ/h
bui_Qs_W = [10,25]*bui_window_W*(1-bui_frame_ratio)*bui_window_g !kJ/h
bui_Qs_E = [10,27]*bui_window_E*(1-bui_frame_ratio)*bui_window_g !kJ/h
bui_Qs = bui_Qs_N+bui_Qs_S+bui_Qs_W+bui_Qs_E !kJ/h
bui_mv = bui_vent_rate*1.2*bui_volume !kg/h
bui_Qp_sens = bui_q_ppl*[8,2]*3.6 !kJ/h
bui_mw_p_lat = bui_mw_ppl*[8,2] !kg/h
bui_Qlight = bui_Qs+[7,2] !kJ/h
*$UNIT_NAME Calcs
*$LAYER Main
*$POSITION 852 146

*------------------------------------------------------------------------------


* Model "Occupancy" (Type 14)
*

UNIT 8 TYPE 14   Occupancy
*$UNIT_NAME Occupancy
*$MODEL .\Utility\Forcing Functions\Occupancy\Type14a.tmf
*$POSITION 748 146
*$LAYER Main #
PARAMETERS 60
0       ! 1 Initial value of time
4       ! 2 Initial number of people
6       ! 3 Time at point
4       ! 4 Value at point
6       ! 5 Time at point
2       ! 6 Value at point
7       ! 7 Time at point
2       ! 8 Value at point
7       ! 9 Time at point
3       ! 10 Value at point
8       ! 11 Time at point
3       ! 12 Value at point
8       ! 13 Time at point
2       ! 14 Value at point
9       ! 15 Time at point
2       ! 16 Value at point
9       ! 17 Time at point
0       ! 18 Value at point
11      ! 19 Time at point
```

```
0       ! 20 Value at point
11      ! 21 Time at point
1       ! 22 Value at point
12      ! 23 Time at point
1       ! 24 Value at point
12      ! 25 Time at point
3       ! 26 Value at point
13      ! 27 Time at point
3       ! 28 Value at point
13      ! 29 Time at point
2       ! 30 Value at point
14      ! 31 Time at point
2       ! 32 Value at point
14      ! 33 Time at point
1       ! 34 Value at point
15      ! 35 Time at point
1       ! 36 Value at point
15      ! 37 Time at point
0       ! 38 Value at point
17      ! 39 Time at point
0       ! 40 Value at point
17      ! 41 Time at point
1       ! 42 Value at point
18      ! 43 Time at point
1       ! 44 Value at point
18      ! 45 Time at point
2       ! 46 Value at point
20      ! 47 Time at point
2       ! 48 Value at point
20      ! 49 Time at point
4       ! 50 Value at point
21      ! 51 Time at point
4       ! 52 Value at point
21      ! 53 Time at point
3       ! 54 Value at point
22      ! 55 Time at point
3       ! 56 Value at point
22      ! 57 Time at point
4       ! 58 Value at point
24      ! 59 Time at point
4       ! 60 Value at point
*------------------------------------------------------------------------------

* Model "Electricity" (Type 14)
*

UNIT 7 TYPE 14   Electricity
*$UNIT_NAME Electricity
*$MODEL .\Utility\Forcing Functions\Lighting\Type14d.tmf
*$POSITION 624 93
*$LAYER Main #
PARAMETERS 56
0       ! 1 Initial value of time
378     ! 2 Initial value of lighting
1       ! 3 Time at point
378     ! 4 Value at point
1       ! 5 Time at point
198     ! 6 Value at point
6       ! 7 Time at point
198     ! 8 Value at point
6       ! 9 Time at point
1413        ! 10 Value at point
7       ! 11 Time at point
1413        ! 12 Value at point
7       ! 13 Time at point
1647        ! 14 Value at point
8       ! 15 Time at point
1647        ! 16 Value at point
8       ! 17 Time at point
1512        ! 18 Value at point
9       ! 19 Time at point
```

```
1512		! 20 Value at point
9	! 21 Time at point
198	! 22 Value at point
11	! 23 Time at point
198	! 24 Value at point
11	! 25 Time at point
900	! 26 Value at point
12	! 27 Time at point
900	! 28 Value at point
12	! 29 Time at point
198	! 30 Value at point
13	! 31 Time at point
198	! 32 Value at point
13	! 33 Time at point
432	! 34 Value at point
17	! 35 Time at point
432	! 36 Value at point
17	! 37 Time at point
612	! 38 Value at point
19	! 39 Time at point
612	! 40 Value at point
19	! 41 Time at point
2214		! 42 Value at point
20	! 43 Time at point
2214		! 44 Value at point
20	! 45 Time at point
1512		! 46 Value at point
22	! 47 Time at point
1512		! 48 Value at point
22	! 49 Time at point
1593		! 50 Value at point
23	! 51 Time at point
1593		! 52 Value at point
23	! 53 Time at point
1278		! 54 Value at point
24	! 55 Time at point
1278		! 56 Value at point
*------------------------------------------------------------------------------

* Model "T56" (Type 56)
*

UNIT 9 TYPE 56	 T56
*$UNIT_NAME T56
*$MODEL .\Loads and Structures\Multi-Zone Building\Type56.tmf
*$POSITION 434 459
*$LAYER Main #
*$#
PARAMETERS 3
44	! 1 Logical unit for building description file (*.b17, *.bui)
0	! 2 Star network calculation switch
0.50		! 3 Weighting factor for operative temperature
INPUTS 29
10,1		! CLIMATE:Dry bulb temperature -> 1- TAMB
10,7		! CLIMATE:Percent relative humidity -> 2- RELHUMAMB
10,4		! CLIMATE:Effective sky temperature -> 3- TSKY
10,1		! CLIMATE:Dry bulb temperature -> 4- TSGRD
10,16		! CLIMATE:Solar zenith angle -> 5- AZEN
AAZM_TYPE56		! Turn:AAZM_TYPE56 -> 6- AAZM
10,26		! CLIMATE:Total tilted surface radiation for surface-3 -> 7- IT_NORTH
10,24		! CLIMATE:Total tilted surface radiation for surface-1 -> 8- IT_SOUTH
10,27		! CLIMATE:Total tilted surface radiation for surface-4 -> 9- IT_EAST
10,25		! CLIMATE:Total tilted surface radiation for surface-2 -> 10- IT_WEST
10,18		! CLIMATE:Total horizontal radiation -> 11- IT_HORIZONTAL
10,31		! CLIMATE:Beam radiation for surface-3 -> 12- IB_NORTH
10,29		! CLIMATE:Beam radiation for surface-1 -> 13- IB_SOUTH
10,32		! CLIMATE:Beam radiation for surface-4 -> 14- IB_EAST
10,30		! CLIMATE:Beam radiation for surface-2 -> 15- IB_WEST
10,19		! CLIMATE:Horizontal beam radiation -> 16- IB_HORIZONTAL
10,51		! CLIMATE:Angle of incidence for surface-3 -> 17- AI_NORTH
10,49		! CLIMATE:Angle of incidence for surface-1 -> 18- AI_SOUTH
```

```
10,52        ! CLIMATE:Angle of incidence for surface-4 -> 19- AI_EAST
10,50        ! CLIMATE:Angle of incidence for surface-2 -> 20- AI_WEST
10,23        ! CLIMATE:Angle of incidence for horizontal -> 21- AI_HORIZONTAL
10,91        ! CLIMATE:Ground reflectance -> 22- GRDREF
10,1         ! CLIMATE:Dry bulb temperature -> 23- T_GROUND
8,2          ! Occupancy:Instantaneous number of occupants -> 24- OCCUPANCY
7,2          ! Electricity:Instantaneous lighting -> 25- ELECTRICITY
T56_OnOffHeat       ! Mode-2:T56_OnOffHeat -> 26- INPUT_HEAT
T56_OnOffCool       ! Mode-2:T56_OnOffCool -> 27- INPUT_COOL
11,1         ! Heating Setpoint:Average temperature -> 28- SETPOINT_HEAT
20,1         ! Cooling Setpoint:Average temperature -> 29- SETPOINT_COOL
*** INITIAL INPUT VALUES
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*** External files
ASSIGN "Bui_ref.bui" 44
*|? Building description file (*.b17, *.bui) |1000
*------------------------------------------------------------------------------------------

* Model "CLIMATE" (Type 15)
*

UNIT 10 TYPE 15  CLIMATE
*$UNIT_NAME CLIMATE
*$MODEL .\Weather Data Reading and Processing\Standard Format\TMY2\Type15-2.tmf
*$POSITION 650 350
*$LAYER Main #
PARAMETERS 21
2       ! 1 File Type
45      ! 2 Logical unit
3       ! 3 Tilted Surface Radiation Mode
0.2     ! 4 Ground reflectance - no snow
0.7     ! 5 Ground reflectance - snow cover
5       ! 6 Number of surfaces
1       ! 7 Tracking mode-1
90      ! 8 Slope of surface-1
0       ! 9 Azimuth of surface-1
1       ! 10 Tracking mode-2
90      ! 11 Slope of surface-2
90      ! 12 Azimuth of surface-2
1       ! 13 Tracking mode-3
90      ! 14 Slope of surface-3
180     ! 15 Azimuth of surface-3
1       ! 16 Tracking mode-4
90      ! 17 Slope of surface-4
270     ! 18 Azimuth of surface-4
1       ! 19 Tracking mode-5
30      ! 20 Slope of surface-5
0       ! 21 Azimuth of surface-5
*** External files
ASSIGN "FR-Strasbourg-71900.tm2" 45
*|? Which file contains the TMY-2 weather data? |1000
*------------------------------------------------------------------------------------------

* Model "Temperatures" (Type 46)
*

UNIT 12 TYPE 46  Temperatures
*$UNIT_NAME Temperatures
*$MODEL .\Output\Printegrator\Unformatted\Type46.tmf
*$POSITION 912 437
*$LAYER Main #
*$# PRINTEGRATOR
PARAMETERS 5
52      ! 1 Logical unit
-1      ! 2 Logical unit for monthly summaries
0       ! 3 Relative or absolute start time
1       ! 4 Printing & integrating interval
0       ! 5 Number of inputs to avoid integration
INPUTS 6
10,88        ! CLIMATE:Hour of the day ->Input to be integrated & printed-1
10,89        ! CLIMATE:Day of the year ->Input to be integrated & printed-2
```

```
10,86        ! CLIMATE:Month ->Input to be integrated & printed-3
10,1         ! CLIMATE:Dry bulb temperature ->Input to be integrated & printed-4
3,1          ! T88:Zone temperature ->Input to be integrated & printed-5
9,1          ! T56: 1- TAIR_Z1 ->Input to be integrated & printed-6
*** INITIAL INPUT VALUES
Year_hour Year_day Year_month T_ext T_T88 T_T56
LABELS 6
- - - °C °C °C
*** External files
ASSIGN "Temperatures.out" 52
*|? Output file for integrated results? |1000
*-------------------------------------------------------------------------------

* EQUATIONS "Turn"
*
EQUATIONS 13
TURN = 0
HEMISPHERE = 1 ! northern hemisphere: 1  - southern hemisphere: -1
AA_H_0_0 = 0  ! azimuth angle of orientation
AA_S_0_90 = (0  +TURN)*GT(HEMISPHERE,0)+ (180-0 -TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_W_45_90 = (45 +TURN)*GT(HEMISPHERE,0)+ (180-45-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_W_90_90 = (90 +TURN)*GT(HEMISPHERE,0)+ (180-90-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_N_135_90 = (135+TURN)*GT(HEMISPHERE,0)+ (180-135-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_N_180_90 = (180+TURN)*GT(HEMISPHERE,0)+ (180-180-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_E_225_90 = (225+TURN)*GT(HEMISPHERE,0)+ (180-225-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_E_270_90 = (270+TURN)*GT(HEMISPHERE,0)+ (180-270-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AA_S_315_90 = (315+TURN)*GT(HEMISPHERE,0)+ (180-315-TURN)*NOT(GT(HEMISPHERE,0)) ! azimuth angle of orientation
AAZM_CORR_HEM = [10,17]*GT(HEMISPHERE,0) + NOT(GT(HEMISPHERE,0))*((180-[10,17])*GT([10,17],0)*LE([10,17],180) + (-180-[10,17])*NOT(GT([10,17],0)*LE([10,17],180))) !solar azimuth corrected for southern hemisphere such that north=180, south=0, west =90, east=-90
AAZM_TYPE56 = (AAZM_CORR_HEM - TURN) ! solar azimuth corrected by building rotation - Input for Type 56 sun position for SHM and ISM
*$UNIT_NAME Turn
*$LAYER Main
*$POSITION 436 327

*-------------------------------------------------------------------------------


* Model "Heating Setpoint" (Type 14)
*

UNIT 11 TYPE 14  Heating Setpoint
*$UNIT_NAME Heating Setpoint
*$MODEL .\Utility\Forcing Functions\Temperature\Type14e.tmf
*$POSITION 125 111
*$LAYER Main #
PARAMETERS 4
0       ! 1 Initial value of time
20      ! 2 Initial temperature
24      ! 3 Time at point
20      ! 4 Value at point
*-------------------------------------------------------------------------------

* EQUATIONS "Mode"
*
EQUATIONS 2
T88_OnOffHeat = LT([17,2],20)
T88_OnOffCool = GT([17,2],26)
*$UNIT_NAME Mode
*$LAYER Main
*$POSITION 191 243
```

```
*------------------------------------------------------------------------------


* Model "Cooling controller" (Type 22)
* 

UNIT 16 TYPE 22  Cooling controller
*$UNIT_NAME Cooling controller
*$MODEL .\Controllers\Iterative Feedback Controller\Type22.tmf
*$POSITION 213 378
*$LAYER Main # 
PARAMETERS 2
0       ! 1 mode
0       ! 2 Maximum number of oscillations
INPUTS 7
20,1        ! Cooling Setpoint:Average temperature ->Setpoint
3,1         ! T88:Zone temperature ->Controlled variable
T88_OnOffCool       ! Mode:T88_OnOffCool ->On / Off signal
0,0     ! [unconnected] Minimum control signal
0,0     ! [unconnected] Maximum control signal
0,0     ! [unconnected] Threshold for non-zero output
0,0     ! [unconnected] Tolerance on tracking error
*** INITIAL INPUT VALUES
0 0 0 -1000000 0 0 0 
*------------------------------------------------------------------------------

* Model "Type93" (Type 93)
* 

UNIT 17 TYPE 93  Type93
*$UNIT_NAME Type93
*$MODEL .\Utility\Input Value Recall\Type93.tmf
*$POSITION 343 320
*$LAYER Main # 
PARAMETERS 2
1       ! 1 Number of inputs to be stored
2       ! 2 Number of timesteps to be stored (including the curent step)
INPUTS 1
3,1         ! T88:Zone temperature ->Input value
*** INITIAL INPUT VALUES
0 
*------------------------------------------------------------------------------

* Model "Heating controller" (Type 22)
* 

UNIT 18 TYPE 22  Heating controller
*$UNIT_NAME Heating controller
*$MODEL .\Controllers\Iterative Feedback Controller\Type22.tmf
*$POSITION 464 191
*$LAYER Main # 
PARAMETERS 2
0       ! 1 mode
0       ! 2 Maximum number of oscillations
INPUTS 7
11,1        ! Heating Setpoint:Average temperature ->Setpoint
3,1         ! T88:Zone temperature ->Controlled variable
T88_OnOffHeat       ! Mode:T88_OnOffHeat ->On / Off signal
0,0     ! [unconnected] Minimum control signal
0,0     ! [unconnected] Maximum control signal
0,0     ! [unconnected] Threshold for non-zero output
0,0     ! [unconnected] Tolerance on tracking error
*** INITIAL INPUT VALUES
0 0 1 0 1000000 0 0 
*------------------------------------------------------------------------------

* EQUATIONS "T88_Equipment"
* 
EQUATIONS 1
T88_QEquip = ([18,1]+[16,1])*out_type+[9,2]*(-1+out_type) !kJ/h
```

```
*$UNIT_NAME T88_Equipment
*$LAYER Main
*$POSITION 456 57

*------------------------------------------------------------------------------


* Model "Cooling Setpoint" (Type 14)
*

UNIT 20 TYPE 14  Cooling Setpoint
*$UNIT_NAME Cooling Setpoint
*$MODEL .\Utility\Forcing Functions\Temperature\Type14e.tmf
*$POSITION 193 484
*$LAYER Main #
PARAMETERS 4
0       ! 1 Initial value of time
26      ! 2 Initial temperature
24      ! 3 Time at point
26      ! 4 Value at point
*------------------------------------------------------------------------------

* EQUATIONS "Mode-2"
*
EQUATIONS 2
T56_OnOffHeat = LT([22,2],20)
T56_OnOffCool = GT([22,2],26)
*$UNIT_NAME Mode-2
*$LAYER Main
*$POSITION 189 683

*------------------------------------------------------------------------------


* Model "Type93-2" (Type 93)
*

UNIT 22 TYPE 93  Type93-2
*$UNIT_NAME Type93-2
*$MODEL .\Utility\Input Value Recall\Type93.tmf
*$POSITION 383 680
*$LAYER Main #
PARAMETERS 2
1       ! 1 Number of inputs to be stored
2       ! 2 Number of timesteps to be stored (including the curent step)
INPUTS 1
9,1         ! T56: 1- TAIR_Z1 ->Input value
*** INITIAL INPUT VALUES
0
*------------------------------------------------------------------------------

* Model "Heat_flows" (Type 46)
*

UNIT 23 TYPE 46  Heat_flows
*$UNIT_NAME Heat_flows
*$MODEL .\Output\Printegrator\Unformatted\Type46.tmf
*$POSITION 786 596
*$LAYER Main #
*$# PRINTEGRATOR
PARAMETERS 5
53      ! 1 Logical unit
-1      ! 2 Logical unit for monthly summaries
0       ! 3 Relative or absolute start time
sim_sum     ! 4 Printing & integrating interval
0       ! 5 Number of inputs to avoid integration
INPUTS 4
26,1        ! Type57:Output-1 ->Input to be integrated & printed-1
26,2        ! Type57:Output-2 ->Input to be integrated & printed-2
26,3        ! Type57:Output-3 ->Input to be integrated & printed-3
26,4        ! Type57:Output-4 ->Input to be integrated & printed-4
```

```
*** INITIAL INPUT VALUES
T88_QHEAT T88_QCOOL T56_QHEAT T56_QCOOL
LABELS 4
kWh kWh kWh kWh
*** External files
ASSIGN "***.out" 53
*|? Output file for integrated results? |1000
*------------------------------------------------------------------------------

* Model "Control_function" (Type 65)
*

UNIT 24 TYPE 65  Control_function
*$UNIT_NAME Control_function
*$MODEL .\Output\Online Plotter\Online Plotter Without File\Type65d.tmf
*$POSITION 87 514
*$LAYER Main #
PARAMETERS 12
4       ! 1 Nb. of left-axis variables
0       ! 2 Nb. of right-axis variables
-1.5        ! 3 Left axis minimum
1.5     ! 4 Left axis maximum
-1.5        ! 5 Right axis minimum
1.5     ! 6 Right axis maximum
1       ! 7 Number of plots per simulation
12      ! 8 X-axis gridpoints
0       ! 9 Shut off Online w/o removing
-1      ! 10 Logical unit for output file
0       ! 11 Output file units
0       ! 12 Output file delimiter
INPUTS 4
T88_OnOffHeat       ! Mode:T88_OnOffHeat ->Left axis variable-1
T88_OnOffCool       ! Mode:T88_OnOffCool ->Left axis variable-2
T56_OnOffHeat       ! Mode-2:T56_OnOffHeat ->Left axis variable-3
T56_OnOffCool       ! Mode-2:T56_OnOffCool ->Left axis variable-4
*** INITIAL INPUT VALUES
Type88_HCF Type88_CCF Type56_HCF Type56_CCF
LABELS  3
"Control function"
""
"Control function"
*------------------------------------------------------------------------------

* Model "Type57" (Type 57)
*

UNIT 26 TYPE 57  Type57
*$UNIT_NAME Type57
*$MODEL .\Utility\Unit Conversion Routine\Type57.tmf
*$POSITION 592 608
*$LAYER Main #
PARAMETERS 12
12      ! 1 Table Nb. for input-1
1       ! 2 ID number from table for input -1
3       ! 3 ID number from table for output-1
12      ! 4 Table Nb. for input-2
1       ! 5 ID number from table for input -2
3       ! 6 ID number from table for output-2
12      ! 7 Table Nb. for input-3
1       ! 8 ID number from table for input -3
3       ! 9 ID number from table for output-3
12      ! 10 Table Nb. for input-4
1       ! 11 ID number from table for input -4
3       ! 12 ID number from table for output-4
INPUTS 4
18,1        ! Heating controller:Control signal ->Input-1
16,1        ! Cooling controller:Control signal ->Input-2
9,3         ! T56: 3- QHEAT_Z1 ->Input-3
9,4         ! T56: 4- QCOOL_Z1 ->Input-4
*** INITIAL INPUT VALUES
0.0 0.0 0.0 0.0
```

```
*------------------------------------------------------------------------------

* Model "Type65d" (Type 65)
*

UNIT 25 TYPE 65  Type65d
*$UNIT_NAME Type65d
*$MODEL .\Output\Online Plotter\Online Plotter Without File\Type65d.tmf
*$POSITION 953 530
*$LAYER Main #
PARAMETERS 12
3       ! 1 Nb. of left-axis variables
4       ! 2 Nb. of right-axis variables
-10     ! 3 Left axis minimum
40      ! 4 Left axis maximum
-100        ! 5 Right axis minimum
100     ! 6 Right axis maximum
1       ! 7 Number of plots per simulation
12      ! 8 X-axis gridpoints
0       ! 9 Shut off Online w/o removing
-1      ! 10 Logical unit for output file
0       ! 11 Output file units
0       ! 12 Output file delimiter
INPUTS 7
10,1        ! CLIMATE:Dry bulb temperature ->Left axis variable-1
3,1         ! T88:Zone temperature ->Left axis variable-2
9,1         ! T56: 1- TAIR_Z1 ->Left axis variable-3
26,1        ! Type57:Output-1 ->Right axis variable-1
26,2        ! Type57:Output-2 ->Right axis variable-2
26,3        ! Type57:Output-3 ->Right axis variable-3
26,4        ! Type57:Output-4 ->Right axis variable-4
*** INITIAL INPUT VALUES
T_ext T_T88 T_T56 T88_QHEAT T88_QCOOL T56_QHEAT T56_QCOOL
LABELS  3
"Temperatures"
""
"Temperatures"
*------------------------------------------------------------------------------

END
```

An energy efficiency driven algorithm for filtering and sizing HVAC system layouts for building retrofit

ANNEX III

Results of the comparative analysis between
"Lumped capacitance building" and "Multi-Zone Building"
on TRNSYS

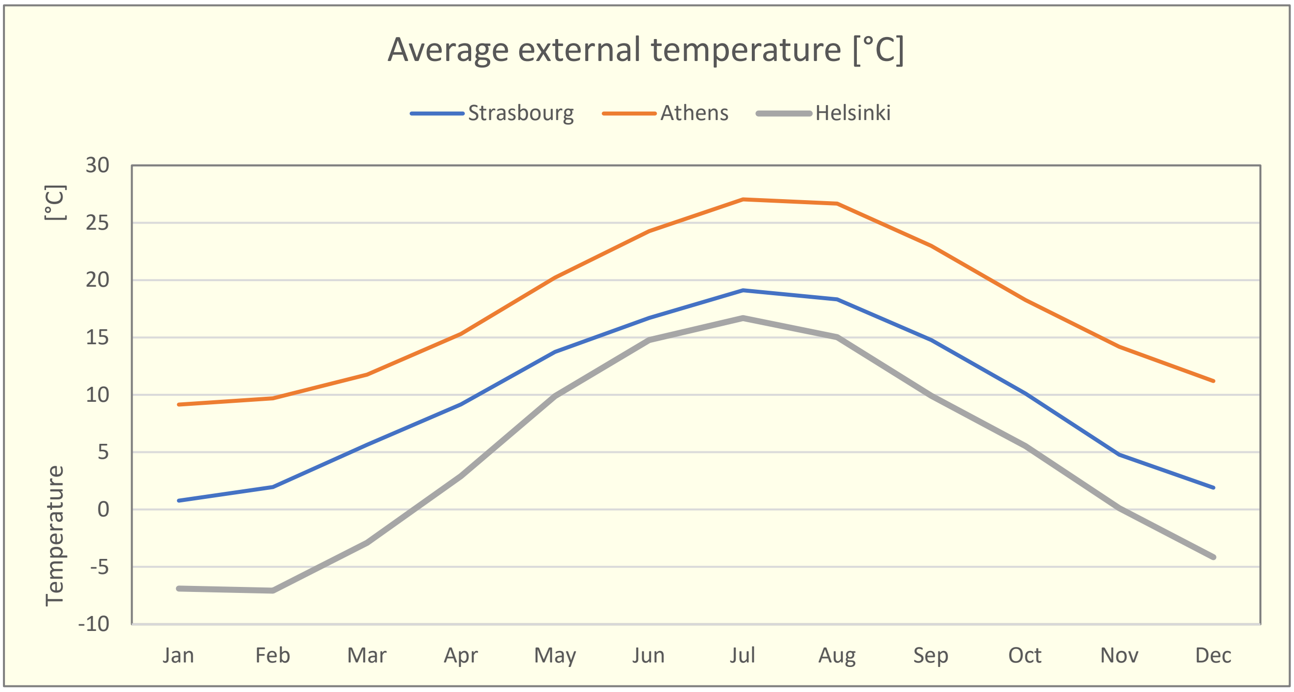

Figure 1 - Monthly average external temperature in the reference climates

Table A - Monthly values of external temperatures in the reference climates

	Strasbourg			Athens			Helsinki		
	Avg T [°C]	Max T [°C]	Min T [°C]	Avg T [°C]	Max T [°C]	Min T [°C]	Avg T [°C]	Max T [°C]	Min T [°C]
Jan	0.78	11.85	-11.40	9.15	17.45	0.40	-6.90	1.55	-25.00
Feb	1.97	14.80	-8.75	9.69	18.95	0.95	-7.07	4.65	-25.15
Mar	5.64	18.75	-4.40	11.77	22.60	2.50	-2.91	9.80	-15.90
Apr	9.17	21.00	-2.65	15.30	26.15	5.55	2.92	15.70	-8.10
May	13.74	27.00	2.45	20.23	32.40	9.10	9.90	23.45	-2.15
Jun	16.69	29.75	5.60	24.27	34.35	14.65	14.78	26.05	4.00
Jul	19.11	31.95	8.20	27.04	37.90	17.65	16.69	27.45	6.75
Aug	18.31	30.80	6.15	26.67	36.20	17.90	15.02	25.25	4.80
Sep	14.78	26.75	4.40	22.98	33.15	14.55	9.92	21.00	-0.35
Oct	10.12	21.90	-0.85	18.27	28.30	8.95	5.54	14.65	-5.00
Nov	4.79	14.45	-4.25	14.18	24.60	5.45	0.13	9.00	-9.40
Dec	1.91	13.65	-9.35	11.20	21.15	1.85	-4.14	4.55	-19.90
Total	9.80	31.95	-11.40	17.61	37.90	0.40	4.56	27.45	-25.15

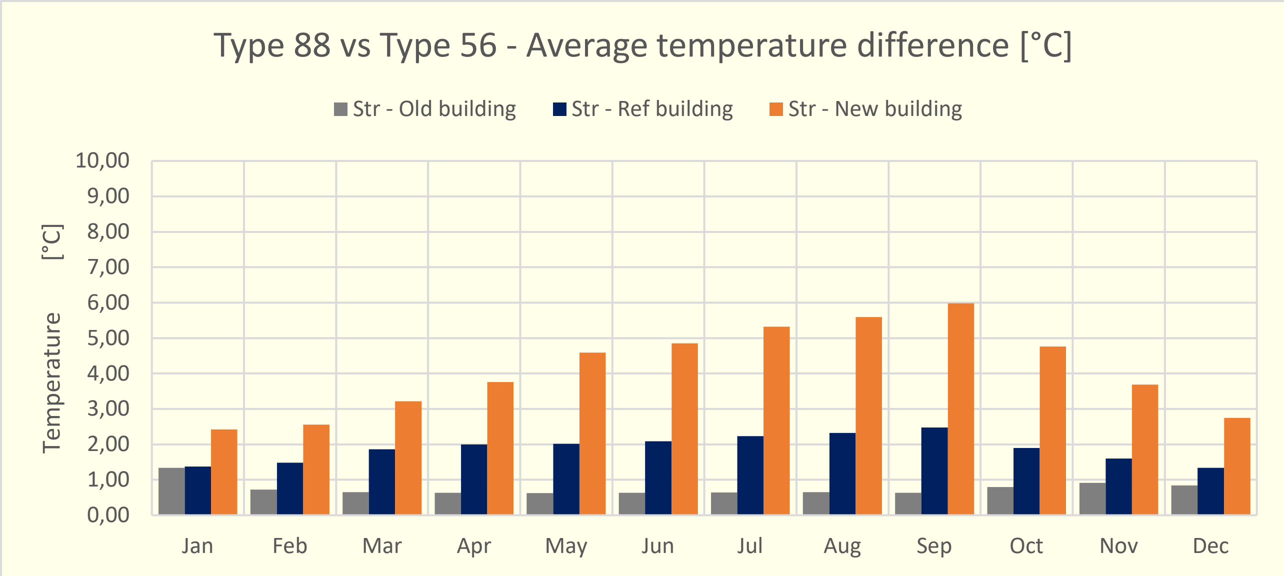

Figure 4 - Monthly average temperature difference between between Type 88 and Type 56 in Strasbourg in free floating conditions

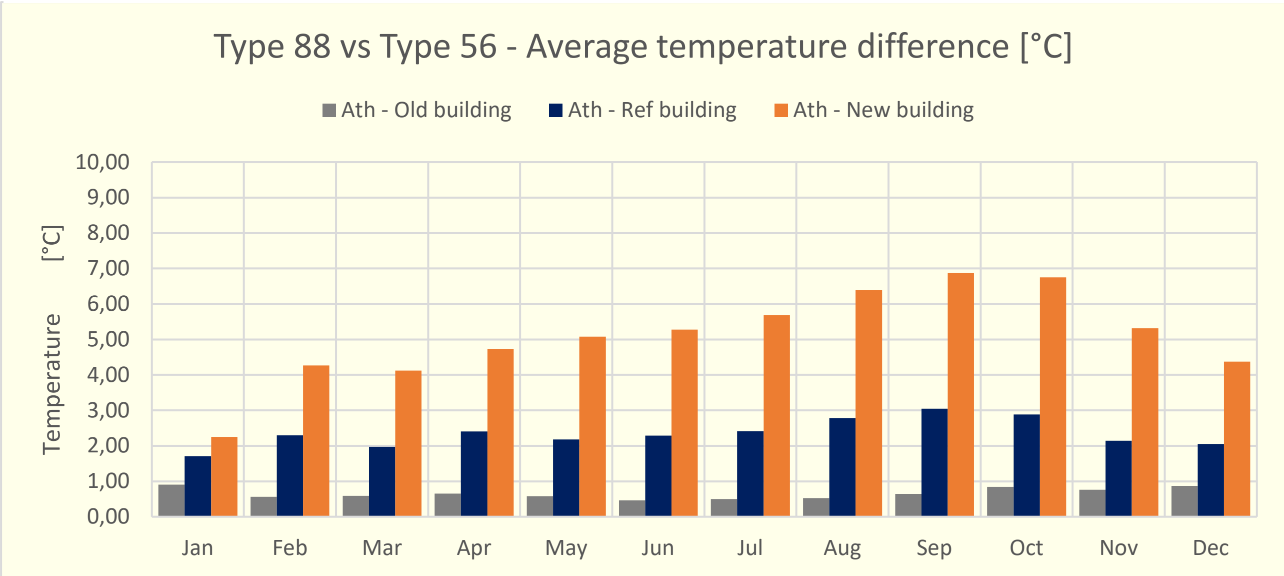

Figure 3 - Monthly average temperature difference between Type 88 and Type 56 in Athens in free floating conditions

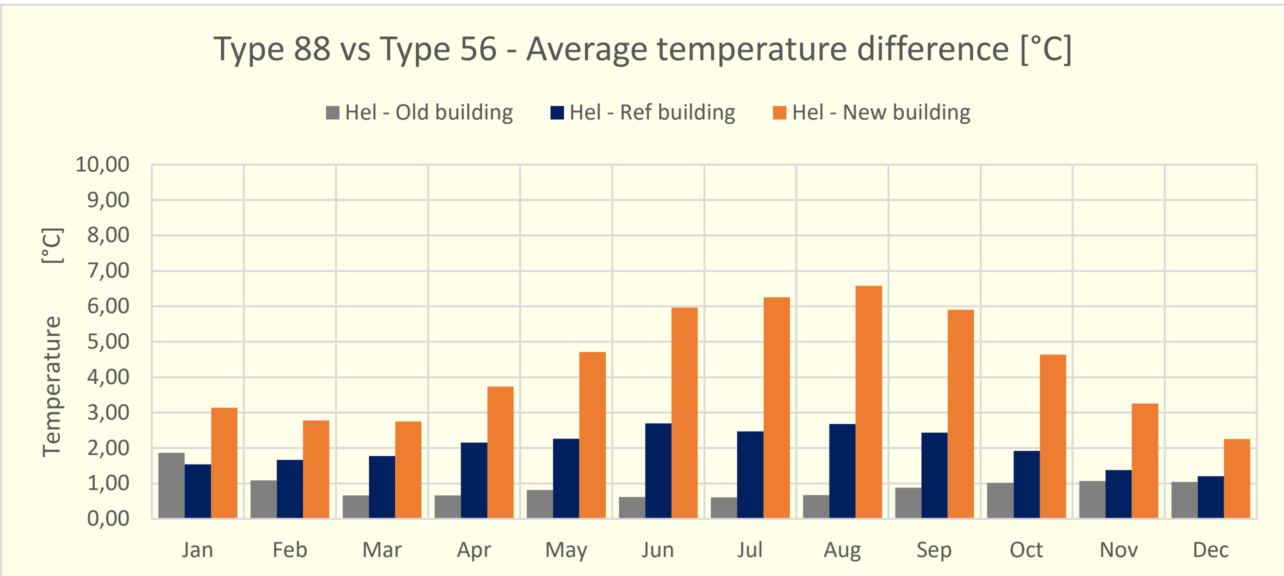

Figure 2 - Monthly average temperature difference between Type 88 and Type 56 in Helsinki in free floating conditions

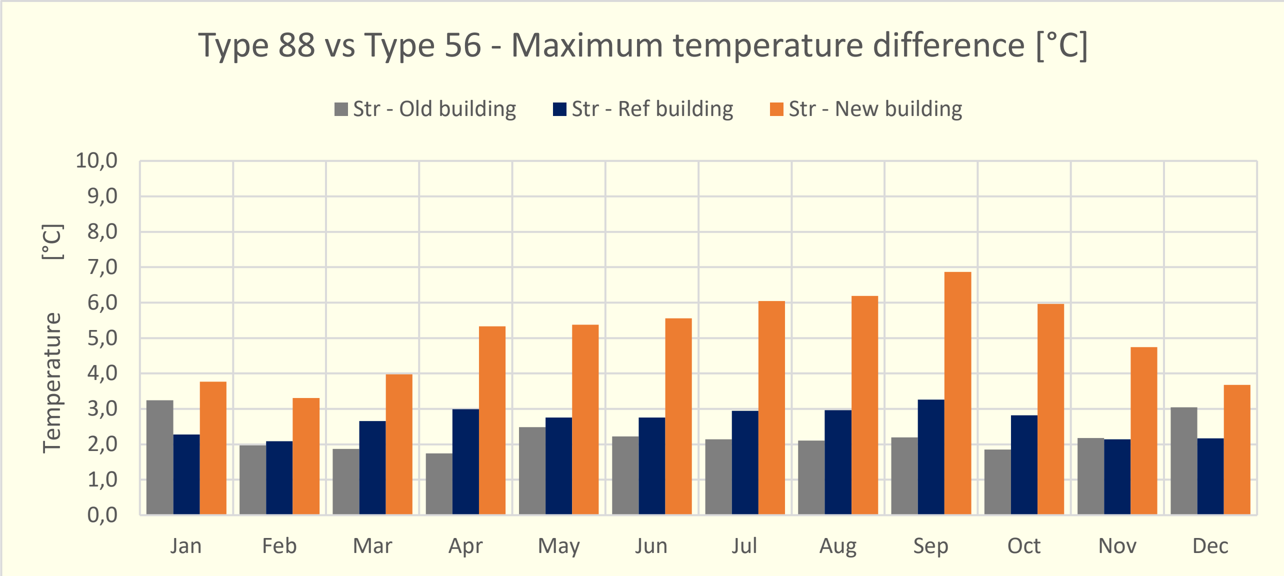

Figure 5 - Monthly maximum temperature difference between Type 88 and Type 56 in Strasbourg in free floating conditions

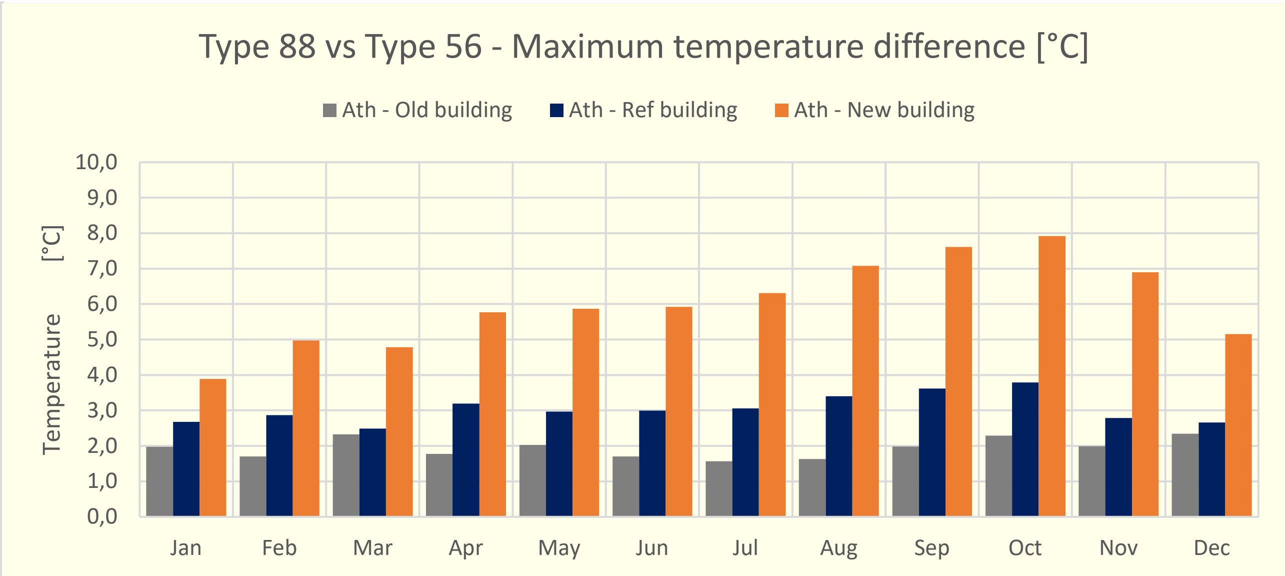

Figure 7- Monthly maximum temperature difference between Type 88 and Type 56 in Athens in free floating conditions

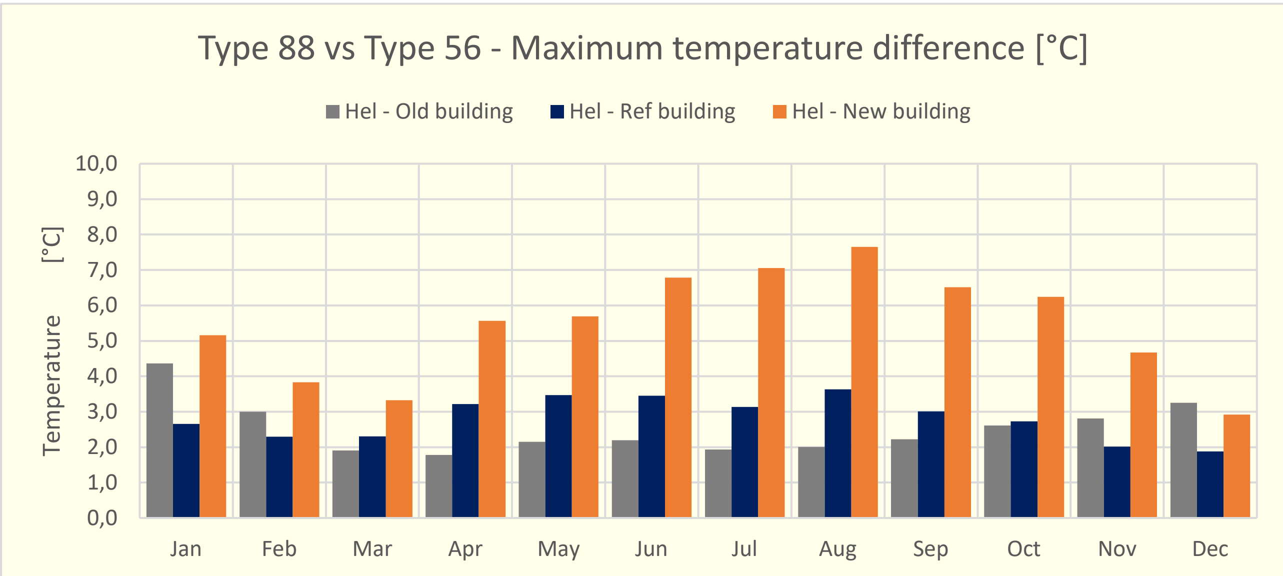

Figure 6- Monthly maximum temperature difference between Type 88 and Type 56 in Helsinki in free floating conditions

Table B - Output temperatures in Strasbourg

STR SFH100	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	0.78	20.02	19.63	11.85	20.23	19.95	-11.40	20.01	19.42
Feb	1.97	20.03	19.67	14.80	20.45	19.93	-8.75	20.01	19.45
Mar	5.64	20.06	19.76	18.75	20.87	20.17	-4.40	20.01	19.59
Apr	9.17	20.13	19.88	21.00	21.03	20.92	-2.65	20.01	19.67
May	13.74	20.68	20.61	27.00	23.04	24.22	2.45	20.01	19.71
Jun	16.69	21.92	21.90	29.75	25.95	26.10	5.60	20.01	19.81
Jul	19.11	23.10	23.24	31.95	25.95	26.17	8.20	20.02	19.87
Aug	18.31	22.73	22.68	30.80	25.98	26.16	6.15	20.02	19.83
Sep	14.78	21.05	20.83	26.75	24.67	25.38	4.40	20.01	19.81
Oct	10.12	20.08	19.85	21.90	20.89	20.91	-0.85	20.00	19.68
Nov	4.79	20.03	19.72	14.45	20.47	19.97	-4.25	20.01	19.54
Dec	1.91	20.02	19.65	13.65	20.22	19.92	-9.35	20.01	19.43
Total	9.75	20.83	20.63	31.95	25.98	26.17	-11.40	20.00	19.42
STR SFH45	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	0.78	20.06	20.00	11.85	21.00	20.69	-11.40	20.00	20.00
Feb	1.97	20.13	20.02	14.80	21.24	20.94	-8.75	20.01	20.00
Mar	5.64	20.32	20.11	18.75	21.47	21.33	-4.40	20.01	20.00
Apr	9.17	21.22	20.49	21.00	23.51	22.55	-2.65	20.00	20.00
May	13.74	23.34	22.24	27.00	26.00	26.07	2.45	20.01	20.00
Jun	16.69	25.31	24.51	29.75	26.00	26.12	5.60	23.57	21.64
Jul	19.11	25.66	25.60	31.95	25.99	26.15	8.20	24.24	23.57
Aug	18.31	25.47	25.18	30.80	25.99	26.16	6.15	23.22	22.17
Sep	14.78	24.00	22.82	26.75	25.98	26.12	4.40	20.99	20.00
Oct	10.12	20.58	20.18	21.90	22.87	21.95	-0.85	20.00	20.00
Nov	4.79	20.11	20.03	14.45	21.06	21.07	-4.25	20.01	20.00
Dec	1.91	20.06	20.00	13.65	20.60	20.57	-9.35	20.01	20.00
Total	9.75	22.20	21.78	31.95	26.00	26.16	-11.40	20.00	20.00
STR SFH15	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	0.78	20.12	19.97	11.85	21.19	21.18	-11.40	20.01	19.88
Feb	1.97	20.33	20.05	14.80	21.31	21.40	-8.75	20.01	19.89
Mar	5.64	21.51	20.46	18.75	23.67	22.38	-4.40	20.00	19.92
Apr	9.17	24.84	22.71	21.00	25.99	25.48	-2.65	21.72	19.95
May	13.74	25.72	24.79	27.00	25.99	26.11	2.45	24.19	20.55
Jun	16.69	25.86	25.90	29.75	26.00	26.12	5.60	25.13	24.54
Jul	19.11	25.90	25.99	31.95	26.00	26.13	8.20	25.56	25.19
Aug	18.31	25.87	25.94	30.80	26.00	26.15	6.15	25.22	24.63
Sep	14.78	25.73	25.48	26.75	26.00	26.13	4.40	24.70	23.37
Oct	10.12	24.23	22.15	21.90	25.98	25.85	-0.85	20.27	19.94
Nov	4.79	20.30	20.05	14.45	21.60	21.73	-4.25	20.01	19.91
Dec	1.91	20.09	19.96	13.65	20.77	20.81	-9.35	20.01	19.89
Total	9.75	23.39	22.80	31.95	26.00	26.15	-11.40	20.00	19.88

Table C - Output temperatures in Athens

ATH SFH100	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	9.15	20.09	19.84	17.45	20.85	20.42	0.40	20.00	19.66
Feb	9.69	20.08	19.85	18.95	20.70	20.33	0.95	20.01	19.69
Mar	11.77	20.23	20.03	22.60	22.05	22.56	2.50	20.01	19.71
Apr	15.30	21.05	20.91	26.15	24.30	25.10	5.55	20.01	19.81
May	20.23	23.58	23.67	32.40	25.98	26.19	9.10	20.03	19.87
Jun	24.27	25.73	25.87	34.35	26.00	26.24	14.65	24.56	23.99
Jul	27.04	25.89	26.10	37.90	25.99	26.29	17.65	25.23	25.25
Aug	26.67	25.88	26.08	36.20	26.00	26.31	17.90	25.28	25.01
Sep	22.98	25.56	25.56	33.15	26.00	26.25	14.55	23.21	21.69
Oct	18.27	23.08	22.68	28.30	25.99	26.13	8.95	20.01	19.85
Nov	14.18	20.39	20.21	24.60	22.53	23.39	5.45	20.01	19.75
Dec	11.20	20.14	19.92	21.15	21.32	21.66	1.85	20.00	19.68
Total	17.56	22.66	22.58	37.90	26.00	26.31	0.40	20.00	19.66
ATH SFH45	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	9.15	20.51	20.21	17.45	21.93	21.79	0.40	20.01	20.00
Feb	9.69	20.60	20.22	18.95	21.65	21.59	0.95	20.01	20.00
Mar	11.77	21.74	20.86	22.60	24.63	23.91	2.50	20.01	20.00
Apr	15.30	24.89	23.64	26.15	25.99	26.09	5.55	22.60	20.15
May	20.23	25.74	25.65	32.40	26.00	26.14	9.10	23.91	21.89
Jun	24.27	25.89	26.04	34.35	26.00	26.16	14.65	25.53	25.55
Jul	27.04	25.92	26.08	37.90	26.00	26.18	17.65	25.70	25.87
Aug	26.67	25.92	26.08	36.20	26.00	26.20	17.90	25.70	25.81
Sep	22.98	25.87	26.01	33.15	26.00	26.18	14.55	25.29	24.97
Oct	18.27	25.30	25.07	28.30	26.00	26.15	8.95	22.47	21.14
Nov	14.18	23.12	21.63	24.60	25.63	24.73	5.45	20.42	20.00
Dec	11.20	20.90	20.40	21.15	24.20	23.68	1.85	20.01	20.00
Total	17.56	23.88	23.51	37.90	26.00	26.20	0.40	20.01	20.00
ATH SFH15	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	9.15	22.81	21.08	17.45	25.94	24.00	0.40	20.01	19.94
Feb	9.69	25.52	22.36	18.95	25.99	24.25	0.95	24.29	20.74
Mar	11.77	25.44	23.22	22.60	26.00	26.07	2.50	24.16	20.17
Apr	15.30	25.83	25.78	26.15	25.99	26.12	5.55	25.40	24.76
May	20.23	25.91	26.01	32.40	25.99	26.12	9.10	25.60	25.26
Jun	24.27	25.93	26.06	34.35	26.00	26.13	14.65	25.80	25.92
Jul	27.04	25.94	26.07	37.90	26.00	26.14	17.65	25.85	26.01
Aug	26.67	25.94	26.07	36.20	26.00	26.16	17.90	25.87	26.00
Sep	22.98	25.93	26.06	33.15	26.00	26.15	14.55	25.67	25.67
Oct	18.27	25.85	25.79	28.30	26.00	26.15	8.95	25.26	24.26
Nov	14.18	25.68	24.96	24.60	25.99	26.11	5.45	24.97	23.07
Dec	11.20	24.66	22.38	21.15	25.97	25.31	1.85	22.72	20.07
Total	17.56	25.45	24.66	37.90	26.00	26.16	0.40	20.01	19.94

Table D - Output temperatures in Helsinki

HEL SFH100	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	-6.90	20.02	19.46	1.55	20.03	19.93	-25.00	20.01	19.12
Feb	-7.07	20.02	19.48	4.65	20.04	19.77	-25.15	20.01	19.13
Mar	-2.91	20.02	19.59	9.80	20.05	19.83	-15.90	20.01	19.32
Apr	2.92	20.03	19.73	15.70	20.42	19.94	-8.10	20.00	19.51
May	9.90	20.26	20.10	23.45	22.00	22.78	-2.15	20.00	19.58
Jun	14.78	21.37	21.43	26.05	24.99	26.04	4.00	20.01	19.81
Jul	16.69	21.89	22.08	27.45	24.97	26.03	6.75	20.00	19.86
Aug	15.02	20.99	20.94	25.25	24.29	25.64	4.80	20.00	19.81
Sep	9.92	20.21	19.98	21.00	21.81	22.44	-0.35	20.01	19.68
Oct	5.54	20.04	19.74	14.65	20.41	19.98	-5.00	20.01	19.53
Nov	0.13	20.02	19.61	9.00	20.04	19.77	-9.40	20.01	19.39
Dec	-4.14	20.02	19.51	4.55	20.03	19.69	-19.90	20.01	19.24
Total	4.49	20.41	20.14	27.45	24.99	26.04	-25.15	20.00	19.12
HEL SFH45	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	-6.90	20.03	20.00	1.55	20.22	20.00	-25.00	20.01	20.00
Feb	-7.07	20.06	20.00	4.65	20.63	20.08	-25.15	20.01	20.00
Mar	-2.91	20.11	20.01	9.80	20.89	20.34	-15.90	20.01	20.00
Apr	2.92	20.26	20.06	15.70	21.49	21.22	-8.10	20.00	20.00
May	9.90	22.27	21.56	23.45	25.98	26.05	-2.15	20.01	20.00
Jun	14.78	25.39	24.65	26.05	25.98	26.13	4.00	23.49	21.86
Jul	16.69	25.59	25.40	27.45	26.00	26.13	6.75	23.86	22.84
Aug	15.02	25.23	24.38	25.25	26.00	26.13	4.80	23.61	22.05
Sep	9.92	21.99	21.27	21.00	25.96	25.94	-0.35	20.00	20.00
Oct	5.54	20.19	20.05	14.65	21.24	21.07	-5.00	20.01	20.00
Nov	0.13	20.04	20.00	9.00	20.56	20.10	-9.40	20.01	20.00
Dec	-4.14	20.03	20.00	4.55	20.30	20.00	-19.90	20.01	20.00
Total	4.49	21.78	21.46	27.45	26.00	26.13	-25.15	20.00	20.00
HEL SFH15	Avg temperature [°C]			Max temperature [°C]			Min temperature [°C]		
	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56	T_ext	T_T88	T_T56
Jan	-6.90	20.04	19.90	1.55	20.39	20.11	-25.00	20.01	19.81
Feb	-7.07	20.13	19.93	4.65	20.86	20.73	-25.15	20.00	19.81
Mar	-2.91	20.31	20.01	9.80	21.45	21.03	-15.90	20.01	19.86
Apr	2.92	22.14	20.34	15.70	24.51	22.17	-8.10	20.01	19.91
May	9.90	25.16	23.26	23.45	25.99	26.12	-2.15	22.43	19.93
Jun	14.78	25.87	25.94	26.05	25.99	26.13	4.00	25.59	25.05
Jul	16.69	25.89	25.98	27.45	26.00	26.14	6.75	25.60	25.23
Aug	15.02	25.83	25.84	25.25	25.99	26.14	4.80	25.47	24.88
Sep	9.92	24.79	23.40	21.00	26.00	26.13	-0.35	22.34	19.97
Oct	5.54	21.17	20.23	14.65	22.89	21.64	-5.00	20.01	19.90
Nov	0.13	20.06	19.94	9.00	20.74	20.69	-9.40	20.01	19.87
Dec	-4.14	20.04	19.91	4.55	20.47	20.18	-19.90	20.01	19.83
Total	4.49	22.62	22.06	27.45	26.00	26.14	-25.15	20.00	19.81

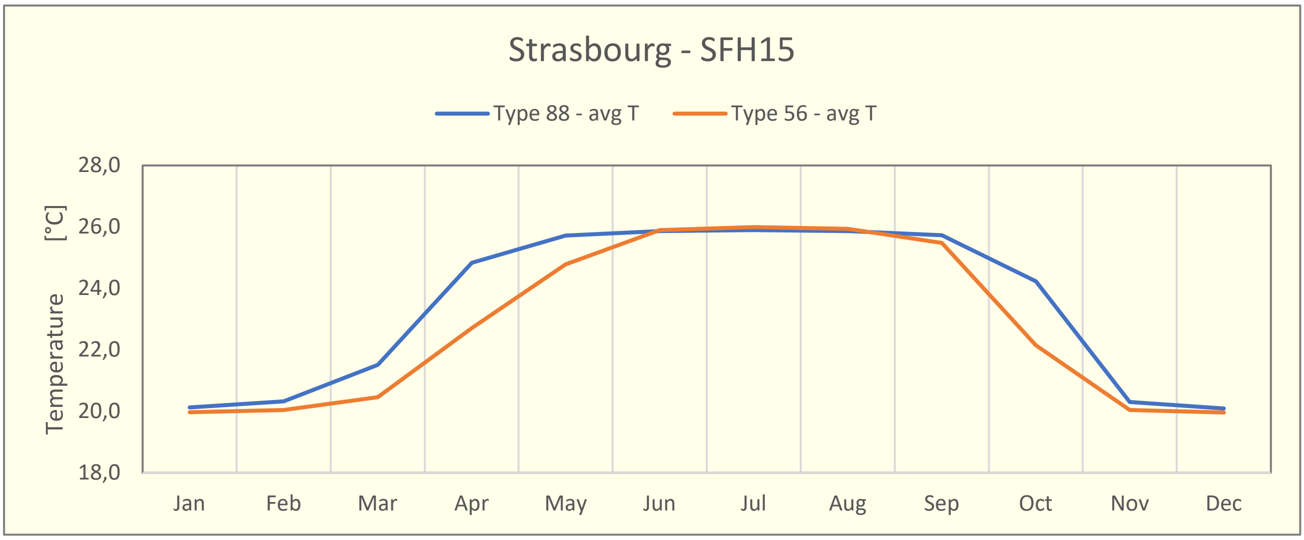

Figure 8 - Monthly average of the internal temperature for SFH15 in Strasbourg

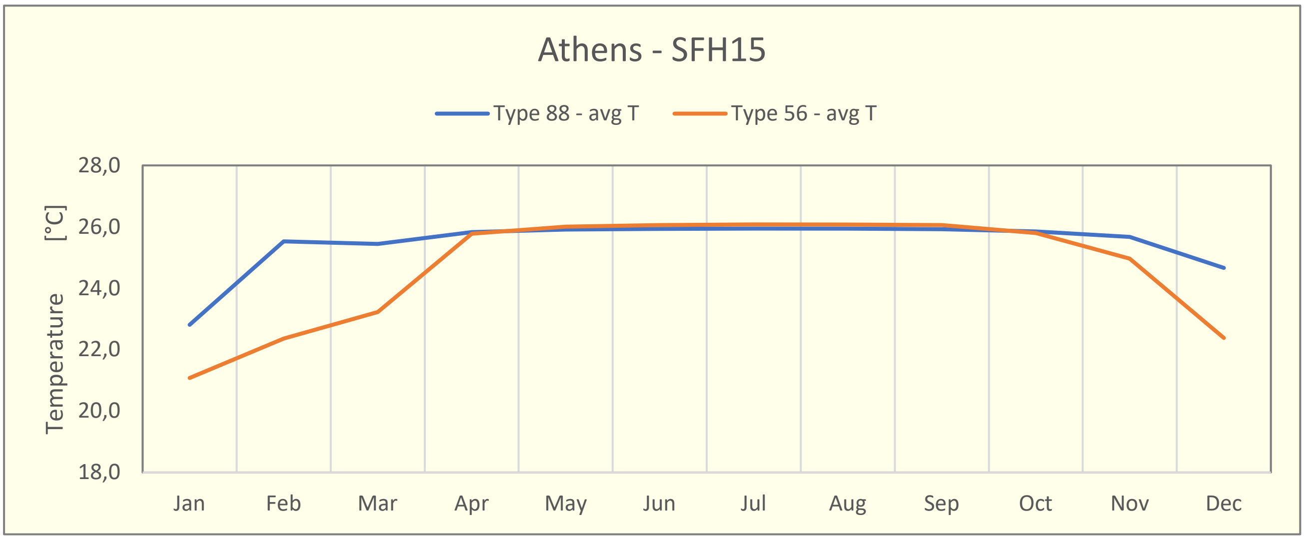

Figure 9 - Monthly average of the internal temperature for SFH15 in Athens

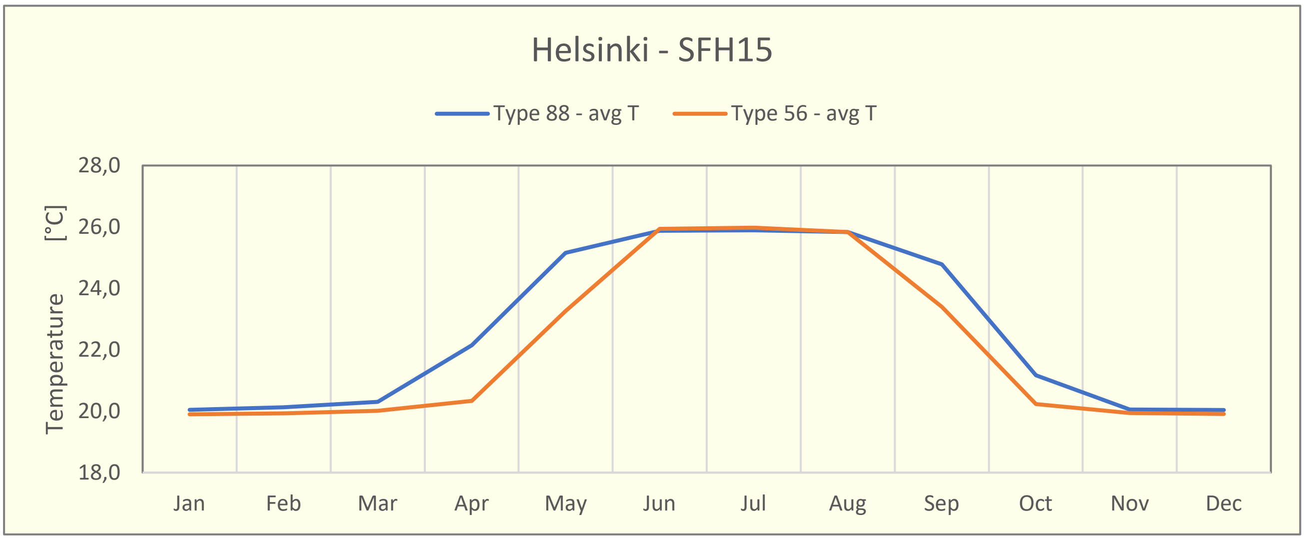

Figure 10 - Monthly average of the internal temperature for SFH15 in Helsinki

Table E - Output energy demand for space heating and cooling in Strasbourg

STR SFH100	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	6.55	6.87	0.00	0.00
Feb	5.20	5.50	0.00	0.00
Mar	4.17	4.42	0.00	0.00
Apr	2.59	2.64	0.00	0.00
May	1.07	1.14	0.00	0.00
Jun	0.39	0.37	0.01	0.06
Jul	0.01	0.05	0.06	0.09
Aug	0.17	0.18	0.08	0.08
Sep	0.84	0.91	0.00	0.00
Oct	2.77	2.94	0.00	0.00
Nov	4.76	5.05	0.00	0.00
Dec	6.15	6.54	0.00	0.00
Total	34.65	36.62	0.16	0.23
STR SFH45	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	2.01	2.28	0.00	0.00
Feb	1.39	1.67	0.00	0.00
Mar	0.81	1.12	0.00	0.00
Apr	0.21	0.43	0.00	0.00
May	0.04	0.09	0.11	0.02
Jun	0.00	0.00	0.39	0.21
Jul	0.00	0.00	0.72	0.40
Aug	0.00	0.00	0.58	0.31
Sep	0.00	0.02	0.18	0.10
Oct	0.44	0.65	0.00	0.00
Nov	1.29	1.54	0.00	0.00
Dec	1.89	2.17	0.00	0.00
Total	8.07	9.96	1.97	1.04
STR SFH15	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	0.83	1.08	0.00	0.00
Feb	0.41	0.67	0.00	0.00
Mar	0.05	0.28	0.00	0.00
Apr	0.00	0.01	0.15	0.00
May	0.00	0.00	0.59	0.19
Jun	0.00	0.00	0.86	0.48
Jul	0.00	0.00	1.12	0.71
Aug	0.00	0.00	0.99	0.61
Sep	0.00	0.00	0.50	0.23
Oct	0.00	0.11	0.05	0.00
Nov	0.39	0.61	0.00	0.00
Dec	0.78	1.02	0.00	0.00
Total	2.45	3.78	4.25	2.23

Table F - Output energy demand for space heating and cooling in Athens

ATH SFH100	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	2.83	3.05	0.00	0.00
Feb	2.33	2.52	0.00	0.00
Mar	1.86	2.00	0.00	0.00
Apr	0.58	0.62	0.00	0.00
May	0.03	0.03	0.20	0.24
Jun	0.00	0.00	1.06	1.07
Jul	0.00	0.00	2.09	2.11
Aug	0.00	0.00	2.03	2.01
Sep	0.00	0.00	0.82	0.78
Oct	0.23	0.28	0.06	0.06
Nov	1.09	1.23	0.00	0.00
Dec	2.25	2.52	0.00	0.00
Total	11.20	12.24	6.26	6.28
ATH SFH45	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	0.36	0.60	0.00	0.00
Feb	0.16	0.42	0.00	0.00
Mar	0.15	0.29	0.00	0.00
Apr	0.00	0.00	0.21	0.05
May	0.00	0.00	0.81	0.46
Jun	0.00	0.00	1.38	1.07
Jul	0.00	0.00	1.82	1.50
Aug	0.00	0.00	1.84	1.49
Sep	0.00	0.00	1.32	0.97
Oct	0.00	0.00	0.61	0.34
Nov	0.00	0.07	0.00	0.00
Dec	0.23	0.47	0.00	0.00
Total	0.90	1.85	7.98	5.87
ATH SFH15	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	0.00	0.06	0.03	0.00
Feb	0.00	0.00	0.09	0.00
Mar	0.00	0.00	0.25	0.02
Apr	0.00	0.00	0.72	0.33
May	0.00	0.00	1.17	0.76
Jun	0.00	0.00	1.47	1.08
Jul	0.00	0.00	1.75	1.35
Aug	0.00	0.00	1.80	1.38
Sep	0.00	0.00	1.48	1.08
Oct	0.00	0.00	0.92	0.60
Nov	0.00	0.00	0.32	0.09
Dec	0.00	0.00	0.07	0.00
Total	0.00	0.06	10.06	6.67

Table G - Output energy demand for space heating and cooling in Helsinki

HEL SFH100	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	9.57	9.98	0.00	0.00
Feb	8.35	8.78	0.00	0.00
Mar	7.35	7.70	0.00	0.00
Apr	4.72	4.87	0.00	0.00
May	2.03	2.14	0.00	0.00
Jun	0.52	0.50	0.00	0.01
Jul	0.22	0.21	0.00	0.00
Aug	0.52	0.58	0.00	0.00
Sep	2.39	2.52	0.00	0.00
Oct	4.57	4.86	0.00	0.00
Nov	6.72	7.08	0.00	0.00
Dec	8.62	9.12	0.00	0.00
Total	55.59	58.34	0.00	0.01
HEL SFH45	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	3.23	3.57	0.00	0.00
Feb	2.58	3.00	0.00	0.00
Mar	1.95	2.39	0.00	0.00
Apr	0.84	1.20	0.00	0.00
May	0.15	0.32	0.14	0.01
Jun	0.00	0.00	0.44	0.20
Jul	0.00	0.00	0.61	0.27
Aug	0.00	0.00	0.23	0.06
Sep	0.25	0.44	0.06	0.00
Oct	1.17	1.42	0.00	0.00
Nov	2.18	2.43	0.00	0.00
Dec	2.93	3.26	0.00	0.00
Total	15.27	18.04	1.48	0.54
HEL SFH15	Heating demand [MWh]		Cooling demand [MWh]	
	T88	T56	T88	T56
Jan	1.57	1.90	0.00	0.00
Feb	1.08	1.48	0.00	0.00
Mar	0.57	1.00	0.00	0.00
Apr	0.02	0.24	0.00	0.00
May	0.00	0.02	0.58	0.21
Jun	0.00	0.00	1.03	0.58
Jul	0.00	0.00	1.14	0.69
Aug	0.00	0.00	0.80	0.41
Sep	0.00	0.00	0.28	0.09
Oct	0.26	0.52	0.00	0.00
Nov	1.00	1.22	0.00	0.00
Dec	1.44	1.74	0.00	0.00
Total	5.95	8.13	3.84	1.99

Table H- Comparison of the energy demand for space heating

	Heating demand [MWh]		
	Type 88	Type 56	Type 88 vs Type 56
STR SFH100	34.65	36.62	-5.36%
STR SFH45	8.07	9.96	-18.98%
STR SFH15	2.45	3.78	-35.13%
ATH SFH100	11.20	12.24	-8.57%
ATH SFH45	0.90	1.85	-51.05%
ATH SFH15	0.00	0.06	-92.45%
HEL SFH100	55.59	58.34	-4.72%
HEL SFH45	15.27	18.04	-15.34%
HEL SFH15	5.95	8.13	-26.87%

Table I- Comparison of the energy demand for space cooling

	Cooling demand [MWh]		
	Type 88	Type 56	Type 88 vs Type 56
STR SFH100	0.16	0.23	-31.16%
STR SFH45	1.97	1.04	89.61%
STR SFH15	4.25	2.23	91.17%
ATH SFH100	6.26	6.28	-0.21%
ATH SFH45	7.98	5.87	35.92%
ATH SFH15	10.06	6.67	50.75%
HEL SFH100	0.00	0.01	-100.00%
HEL SFH45	1.48	0.54	173.22%
HEL SFH15	3.84	1.99	93.36%

Table J- Comparison of the total energy demand

	Total demand [MWh]		
	Type 88	Type 56	Type 88 vs Type 56
STR SFH100	34.81	36.85	-5.52%
STR SFH45	10.04	11.00	-8.72%
STR SFH15	6.71	6.01	11.67%
ATH SFH100	17.46	18.52	-5.73%
ATH SFH45	8.88	7.72	15.10%
ATH SFH15	10.06	6.73	49.58%
HEL SFH100	55.59	58.35	-4.73%
HEL SFH45	16.75	18.58	-9.87%
HEL SFH15	9.79	10.12	-3.26%

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ANNEX IV

MATLAB program 'ReadEPW.m'

```
function [Location, Weather_data, Radiation]=ReadEPW(epw_file)
%EPW file reader

fid = fopen(epw_file);
loc = fgetl(fid);
loc = textscan(loc, '%*s %s %s %s %s %f %f %f %f %f', 'delimiter',',');
Location.Country=string(loc{3});
Location.City=string(loc{1});
Location.latitude=loc{6};
Location.longitude=loc{7};
for i = 1:7
    fgetl(fid);
end

%% Read weather data

r = 1;
while 1
    readin = fgetl(fid);
    if readin == -1 break;
    end
    data(r,:) = textscan(readin,'%f %f %f %f %f %s %f %f %f %f %f %f %f %f %f %f %f %f %f %↙
%f %f %f %f %f %f %f %f %f %f %f %f %*[^\n]', 'delimiter',',','MultipleDelimsAsOne',1);
    r = r+1;
end

data(:,6)= [];
Weather_data=cell2table(data);
Weather_data.Properties.VariableNames = {'Year', 'Month', 'Day', 'Hour',...
    'Minute', 'Dry_Bulb_Temperature', 'Dew_Point_Temperature', ...
    'Relative_Humidity', 'Atmospheric_Station_Pressure', ...
    'Extraterrestrial_Horizontal_Radiation', ...
    'Extraterrestrial_Direct_Normal_Radiation', ...
    'Horizontal_Infrared_Radiation_from_Sky', ...
    'Global_Horizontal_Radiation', 'Direct_Normal_Radiation', ...
    'Diffuse_Horizontal_Radiation', 'Global_Horizontal_Illuminance', ...
    'Direct_Normal_Illuminance', 'Diffuse_Horizontal_Illuminance', ...
    'Zenith_Illuminance', 'Wind_Direction', 'Wind_Speed', ...
    'Total_Sky_Cover', 'Opaque_Sky_Cover', 'Visibility', ...
    'Ceiling_Height', 'Present_Weather_Observation', ...
    'Present_Weather_Codes', 'Precipitable_Water', ...
    'Aerosol_Optical_Depth', 'Snow_Depth', 'Days_Since_Last_Snowfall'};
Weather_data.Properties.VariableUnits = {'-', '-', '-', '-', '-', '°C', ...
    '°C', '%', 'Pa', 'Wh/m2', 'Wh/m2', 'Wh/m2', 'Wh/m2', 'Wh/m2', ...
    'Wh/m2', 'lux', 'lux', 'lux', 'lux', 'deg', 'm/s', '-', '-', 'km', ...
    'm', '-', '-', 'mm', 'thousandths', 'cm', '-'};

Location.T_mean=mean(Weather_data.Dry_Bulb_Temperature);% °C
Location.T_max=max(Weather_data.Dry_Bulb_Temperature);% °C
Location.T_min=min(Weather_data.Dry_Bulb_Temperature);% °C
Radiation.Global=Weather_data.Global_Horizontal_Radiation;% Wh/m2
Radiation.Diffuse=Weather_data.Diffuse_Horizontal_Radiation;% Wh/m2
Radiation.Direct=Radiation.Global-Radiation.Diffuse;% Wh/m2
Radiation.GroundReflected=Radiation.Global*0.5;% Wh/m2
Radiation=struct2table(Radiation);

fclose('all');
clear fid loc i r readin data idx ans
```

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ANNEX V

MATLAB function ‘tilted_radtion.m’

```
function [radiation_n]=...
    tilted_radiation(direct_radiation,diffuse_radiation,...
    ground_reflected_radiation,slope,latitude,azimuth,hour_of_day,...
    day_of_year)

% Isotropic sky model from Duffie J, Beckman W - Solar Engineering of
% Thermal Processes

if diffuse_radiation==0

    radiation_n=0;

else

    delta=23.45*sind(360*(day_of_year+284)/365);
    omega=15*(hour_of_day-12);

    cosd_theta=sind(delta)*sind(latitude)*cosd(slope)-sind(delta)*...
        cosd(latitude)*sind(slope)*cosd(azimuth)+cosd(delta)*cosd(omega)...
        *(cosd(latitude)*cosd(slope)+sind(latitude)*sind(slope)*...
        cosd(azimuth))+cosd(delta)*sind(slope)*sind(azimuth)*sind(omega);
    cosd_theta_z=cosd(delta)*cosd(omega)*cosd(latitude)+sind(delta)*...
        sind(latitude);

    R_b=cosd_theta/cosd_theta_z;

    if R_b<0
        R_b=0;
    elseif R_b>10
        R_b=10;
    end

    radiation_n=R_b*direct_radiation+((1+cosd(slope))/2)*...
        diffuse_radiation+((1-cosd(slope))/2)*ground_reflected_radiation;

end

end
```

An energy efficiency driven algorithm for filtering and sizing HVAC system layouts for building retrofit

ANNEX VI

MATLAB program 'Inputs.m'

```
%% Building input data

[Location, Weather_data, Radiation]=...
    ReadEPW('Weather_files\FRA_Strasbourg.071900_IWEC.epw');

Building.footprint=get_input('Building floor area (footprint): [m2] ',...
    10,Inf);
% Building footprint in m2

Building.envelope=get_input...
    ('Total surface of walls in contact with exterior: [m2] ',10,Inf);
% Building envelope in m2

answer=input('Is ground floor in contact with heated space? y/n: ','s');
if answer=='N' || answer=='n'
    Building.floor=Building.footprint;
else
    Building.floor=0;
end
% Building floor in m2

answer=input('Is roof in contact with heated space? y/n: ','s');
if answer=='N' || answer=='n'
    Building.roof=input...
        ('Building roof area (insert 0 if unknown): [m2] ',...
        0,Inf);
    if Building.roof==0
        % I calculate a coefficient that contemplates the average roof
        % angle in function of the external temperature.
        % I assume flat roof if T_mean>20, 30° angle if T_mean<20 and 45°
        % if T_mean<10
        if Location.T_mean<20 && Location.T_mean>10
            K=1/cosd(30);
            Building.roof=K*Building.footprint;
        elseif Location.T_mean<10
            K=1/cosd(45);
            Building.roof=Building.envelope+K*Building.footprint;
        else
            Building.roof=Building.envelope+Building.footprint;
        end
    end
else
    Building.roof=0;
end
%% Building roof in m2

Building.height=get_input('Building total height: ',2,Inf);
% Building height in m

Building.volume=Building.footprint*Building.height;
% Building volume in m3

Building.floors=get_input('Building floors: ',1,Building.height/2);
% Building floors

Building.area=Building.floors*Building.footprint;
% Building floors area in m2

Building.orientation=get_input(...
```

```
    'Building orientation (clockwise angle with the North, range [0,90]): [°] ',0,90);
% Building orientation in °

Building.window_N=get_input(...
    'Total area of windows exposed predominantly to N: [m2] ',0,...
    Building.envelope);
Building.window_S=get_input(...
    'Total area of windows exposed predominantly to S: [m2] ',0,...
    Building.envelope-Building.window_N);
Building.window_W=get_input(...
    'Total area of windows exposed predominantly to W: [m2] ',0,...
    Building.envelope-Building.window_N-Building.window_S);
Building.window_E=get_input(...
    'Total area of windows exposed predominantly to E: [m2] ',0,...
    Building.envelope-Building.window_N-Building.window_S...
    -Building.window_W);
% Building windows area in m2

Building.solar_area=get_input(...
    'Total area available for solar plants installation: [m2] ',0, Inf);
if Building.solar_area>0
    Building.solar_area_slope=get_input...
        ('Slope of the solar area: [°] ',0,90);
    Building.solar_area_azimuth=get_input...
        ('Orientation of the solar area (clockwise angle from South, range [-180,+180]): [°]
',-180,180);
end
% Building solar area in m2. If present, acquires the average slope and its
% orientation in [°]

Building.people=get_input('Building users (insert 0 if unknown): ',...
    0,Building.area*0.1);
if Building.people==0
    Building.people=ceil(Building.area*0.04);% in Certificazione
    % energetica degli edifici Procedura di calcolo, 3° supplemento
    % straordinario al D.G.R. 5018/2007, Regione Lombardia 25/01/2008, from
    % UNI 10339:1995
end
% Building users. If unknown, it calculates it with a standard procedure

Building.age=[string('Before1945');string('From1945to1970');...
    string('In1970s');string('In1980s');...
    string('In1990s');string('After2000')];
disp('Building age:');
display_options(Building.age);
idx=input('Selection: ');
Building.age=Building.age(idx);
% Building age

% Available countries for U-values: Bulgaria, France, Germany,
% Greece, Hungary, Italy, Poland, Spain, Switzerland, United Kingdom

Building.U_wall=get_input(...
    'Average external walls transmittance (insert 0 if unknown): ', 0, 3);
if Building.U_wall==0
    Building.U_wall=get_U(Location.Country, Building.age, 1);
end

if Building.floor~=0
```

```
    Building.U_floor=get_input(...
        'Average floor transmittance (insert 0 if unknown): ', 0, 4);
    if Building.U_floor==0
        Building.U_floor=get_U(Location.Country, Building.age, 2);
    end
else
    Building.U_floor=0;
end

if Building.roof~=0
    Building.U_roof=get_input(...
        'Average roof transmittance (insert 0 if unknown): ', 0, 4);
    if Building.U_roof==0
        Building.U_roof=get_U(Location.Country, Building.age, 3);
    end
else
    Building.U_roof=0;
end

Building.U_window=get_input(...
    'Average window transmittance (insert 0 if unknown): ', 0, 7);
Building.g_window=get_input(...
    'Average solar factor (insert 0 if unknown): ', 0, 7);
if Building.U_window==0 && Building.g_window==0
    [Building.U_window,Building.g_window]=window;
elseif Building.U_window==0
    Building.U_window=window;
elseif Building.g_window==0
    [~,Building.g_window]=window;
end
% Building U-values in W/m2K nad window g-value

Limit.technical_area=get_input...
    ('Area available for technical equipments: [m2] ',0, Inf);

Limit.budget=get_input('Available budget: [€] ',0, Inf);

%% Selection of the components - Heating System

% Heating system type

Existing_plant.Heating_system_type=[string('not present');...
    string('Water system');string('Electric system')];
disp('Heating system type');
display_options(Existing_plant.Heating_system_type);
idx=input('Selection: ');
Existing_plant.Heating_system_type=Existing_plant.Heating_system_type(idx);


% Heating emission subsystem

if Existing_plant.Heating_system_type=='not present'
    Existing_plant.Heating_system_emitters=string('not present');
else
    Existing_plant.Heating_system_emitters=[string('Radiators');...
        string('Underfloor heating');string('Fan-coils')];
    if Existing_plant.Heating_system_type=='Electric system'
        Existing_plant.Heating_system_emitters=...
            Existing_plant.Heating_system_emitters([1;3]);
```

```
    end
    disp('Heat emitters');
    display_options(Existing_plant.Heating_system_emitters);
    idx=input('Selection: ');
    Existing_plant.Heating_system_emitters=...
        Existing_plant.Heating_system_emitters(idx);
end


% Space heating generator

if Existing_plant.Heating_system_type=='Water system'
    Existing_plant.Heating_system_generator=...
        [string('Traditional boiler');string('Condensing boiler');...
        string('Electric HP/Chiller')];
    disp('Space heating generator');
    display_options(Existing_plant.Heating_system_generator);
    idx=input('Selection: ');
    Existing_plant.Heating_system_generator=...
        Existing_plant.Heating_system_generator(idx);
else
    Existing_plant.Heating_system_generator=string('not present');
end

if Existing_plant.Heating_system_generator~=string('not present')
    Power(8,1)=input('Heating generator size (0 if unknown): [kW] ');
else
    Power(8,1)=0;
end


% Space heating generator fuel

if Existing_plant.Heating_system_generator~='not present'
    Existing_plant.Heating_system_generator_fuel=[string('Coal');...
        string('Oil');string('Gas');string('Biomass');...
        string('Air-source');string('Water-source');...
        string('Ground-source')];
    if Existing_plant.Heating_system_generator=='Electric HP/Chiller'
        Existing_plant.Heating_system_generator_fuel=...
            Existing_plant.Heating_system_generator_fuel([5;6;7]);
    else
        Existing_plant.Heating_system_generator_fuel=...
            Existing_plant.Heating_system_generator_fuel([1;2;3;4]);
    end
    disp('Space heating generator fuel');
    display_options(Existing_plant.Heating_system_generator_fuel);
    idx=input('Selection: ');
    Existing_plant.Heating_system_generator_fuel=...
        Existing_plant.Heating_system_generator_fuel(idx);
else
    Existing_plant.Heating_system_generator_fuel=string('not present');
end


% DHW generator

if Existing_plant.Heating_system_type~='Water system'
    Existing_plant.Heating_system_DHW_generator=...
```

```
        [string('Traditional boiler');string('Condensing boiler'); ...
        string('Electric water heater')];
    disp('Domestic hot water generator');
    display_options(Existing_plant.Heating_system_DHW_generator);
    idx=input('Selection: ');
    Existing_plant.Heating_system_DHW_generator=...
        Existing_plant.Heating_system_DHW_generator(idx);
else
    Existing_plant.Heating_system_DHW_generator=string('not present');
end

if Existing_plant.Heating_system_DHW_generator~=string('not present')
    Power(10,1)=input('DHW generator size (0 if unknown): [kW] ');
else
    Power(10,1)=0;
end


% DHW generator fuel

if any([string('Traditional boiler') string('Condensing boiler')]==...
        Existing_plant.Heating_system_DHW_generator)
    Existing_plant.Heating_system_DHW_generator_fuel=[string('Coal');...
        string('Oil');string('Gas');string('Biomass')];
    disp('Domestic hot water generator fuel');
    display_options(Existing_plant.Heating_system_DHW_generator_fuel);
    idx=input('Selection: ');
    Existing_plant.Heating_system_DHW_generator_fuel=...
        Existing_plant.Heating_system_DHW_generator_fuel(idx);
else
    Existing_plant.Heating_system_DHW_generator_fuel=string('not present');
end


% Heat generation support

if Existing_plant.Heating_system_generator=='Electric HP/Chiller'
    Existing_plant.Heating_system_support=[string('not present');...
        string('Traditional boiler');string('Condensing boiler')];
    disp('Heat generation support');
    display_options(Existing_plant.Heating_system_support);
    idx=input('Selection: ');
    Existing_plant.Heating_system_support=...
        Existing_plant.Heating_system_support(idx);
else
    Existing_plant.Heating_system_support=string('not present');
end

if Existing_plant.Heating_system_support~=string('not present')
    Power(12,1)=input('Support generator size (0 if unknown): [kW] ');
else
    Power(12,1)=0;
end


% Heat generation support fuel

if any([string('Traditional boiler') string('Condensing boiler')]==...
        Existing_plant.Heating_system_support)
```

```
    Existing_plant.Heating_system_support_fuel=[string('Coal');...
        string('Oil');string('Gas');string('Biomass')];
    disp('Generation support fuel');
    display_options(Existing_plant.Heating_system_support_fuel);
    idx=input('Selection: ');
    Existing_plant.Heating_system_support_fuel=...
        Existing_plant.Heating_system_support_fuel(idx);
else
    Existing_plant.Heating_system_support_fuel=string('not present');
end


% Hot water storage (SH+DHW)

Existing_plant.Heating_system_storage=[string('not present');...
    string('Hot water tank')];
disp('Heat storage');
display_options(Existing_plant.Heating_system_storage);
idx=input('Selection: ');
Existing_plant.Heating_system_storage=...
    Existing_plant.Heating_system_storage(idx);

if Existing_plant.Heating_system_storage~=string('not present')
    Volume(14,1)=input('Storage size (0 if unknown): [m3] ');
else
    Volume(14,1)=0;
end


%% Selection of the components - Cooling System

% Cooling system type

if Existing_plant.Heating_system_generator=='Electric HP/Chiller'
    Existing_plant.Cooling_system_type=string('Water system');
else
    Existing_plant.Cooling_system_type=[string('not present');...
        string('Water system');string('Electric system')];
    disp('Cooling system type');
    display_options(Existing_plant.Cooling_system_type);
    idx=input('Selection: ');
    Existing_plant.Cooling_system_type=...
        Existing_plant.Cooling_system_type(idx);
end


% Cooling emission subsystem

if Existing_plant.Cooling_system_type=='not present'
    Existing_plant.Cooling_system_emitters=string('not present');
else
    Existing_plant.Cooling_system_emitters=string('Fan-coils');
end


% Space cooling generator
if Existing_plant.Cooling_system_type=='Water system'
    Existing_plant.Cooling_system_generator=string('Electric HP/Chiller');
else
```

```
    Existing_plant.Cooling_system_generator=string('not present');
end

if Existing_plant.Cooling_system_generator~=string('not present')
    Power(3,1)=input('Cooling generator size (0 if unknown): [kW] ');
else
    Power(3,1)=0;
end


% Space cooling generator fuel

if Existing_plant.Heating_system_generator==string('Electric HP/Chiller')
    Existing_plant.Cooling_system_generator_fuel=...
        Existing_plant.Heating_system_generator_fuel;
elseif Existing_plant.Cooling_system_generator ==...
        string('Electric HP/Chiller')
    Existing_plant.Cooling_system_generator_fuel=[string('Air-source');...
        string('Water-source');string('Ground-source')];
    disp('Space cooling generator fuel');
    display_options(Existing_plant.Cooling_system_generator_fuel);
    idx=input('Selection: ');
    Existing_plant.Cooling_system_generator_fuel=...
        Existing_plant.Cooling_system_generator_fuel(idx);
else
    Existing_plant.Cooling_system_generator_fuel=string('not present');
end


% Cold water storage

Existing_plant.Cooling_system_storage=[string('not present');...
    string('Cold water tank')];
disp('Cold storage');
display_options(Existing_plant.Cooling_system_storage);
idx=input('Selection: ');
Existing_plant.Cooling_system_storage=...
    Existing_plant.Cooling_system_storage(idx);

if Existing_plant.Cooling_system_storage~=string('not present')
    Volume(5,1)=input('Storage size (0 if unknown): [m3] ');
else
    Volume(5,1)=0;
end


% Renewable support - Solar thermal plant

answer=input('Is it present a solar thermal plant? y/n: ','s');
if answer=='N' || answer=='n'
    Existing_plant.Renewable_support_ST=string('not present');
    design_parameters.ST.area=0;
else
    Existing_plant.Renewable_support_ST=string('Solar thermal collectors');
    design_parameters.ST.area=input('Plant size (0 if unknown): [m2] ');
end


% Renewable support - Photovoltaic plant
```

```
answer=input('Is it present a photo-voltaic plant? y/n: ','s');
if answer=='N' || answer=='n'
    Existing_plant.Renewable_support_PV=string('not present');
    Power(16,1)=0;
else
    Existing_plant.Renewable_support_PV=string('Photovoltaic panels');
    Power(16,1)=input('Plant size (0 if unknown): [kW] ');
end

Volume(16,1)=0;

clear answer idx K
%% Functions

function [Q]=get_input(string, min_value, max_value)
Q=input(string);
while Q<min_value || Q>max_value
    disp('Invalid value');
    Q=input(string);
end
end

function display_options(X)
for idx=1:length(X)
    fprintf('Option % d: % s\n',idx, X(idx))
end
end

function [U]=get_U(country,age,element)
% element: 1 for walls, 2 for windows, 3 for floor, 4 for roof

% Import of U-values
countries={'BGR','FRA','DEU','GRC','HUN','ITA','POL','ESP','CHE','GBR'};
periods={'Before1945','From1945to1970','In1970s','In1980s','In1990s',...
    'After2000'};
U=array2table(xlsread...
    ('H4C_Data\DATA_Heat4Cool_countries_U-Values.xlsx',element,...
    'B3:G12'),'VariableNames',periods,'RowNames',countries);

U=U{{country{:}},{age{:}}};

end

function [U,g]=window

window_type=...
    [string('ClearSingleGlazing');string('SelectiveSingleGlazing');...
    string('ClearDoubleGlazing');string('SelectiveDoubleGlazing');...
    string('ClearTripleGlazing');string('SelectiveTripleGlazing')];
disp('Window type');
display_options(window_type);
U=[5.9;3.2;3.3;2;1.8;1.4];
g=[0.82;0.66;0.7;0.63;0.60;0.54];
window_values=table(U,g,'RowNames',{window_type{:}});
idx=input('Selection: ');
window_type=window_type(idx);
window_frame=...
    [string('WoodenFrame');string('OldMetallicFrame');...
    string('NewMetallicFrame')];
```

```
disp('Window frame');
display_options(window_frame);
idx=input('Selection: ');
window_frame=[1.5;5;3];
window_frame=window_frame(idx);
U=window_values{{window_type{:}},1}*0.87+window_frame*0.13;
g=window_values{{window_type{:}},2};

% values from in Certificazione energetica degli edifici Procedura di
% calcolo, 3° supplemento straordinario al D.G.R. 5018/2007,
% Regione Lombardia 25/01/2008, from UNI 10339:1995

end
```

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ANNEX VII

U-values for the countries in Heat4Cool project

Wall U-value by age (unit: W/m²K)

	Before 1945	From 1945 to 1970	In the 1970s	In the 1980s	In the 1990s	After 2000
BGR	1.6	1.6	1.5	1.2	1.0	0.5
FRA	2.4	2.4	1.0	0.7	0.5	0.4
DEU	1.7	1.3	0.8	0.6	0.4	0.4
GRC	1.6	1.6	1.6	0.9	0.9	0.7
HUN	1.6	1.6	1.5	0.8	0.8	0.5
ITA	1.8	1.6	1.6	1.0	0.9	0.9
POL	1.7	1.4	0.9	0.9	0.6	0.4
ESP	2.5	2.1	2.1	1.6	1.6	0.8
CHE	0.9	0.9	0.9	0.7	0.3	0.3
GBR	1.8	1.8	1.3	0.6	0.4	0.4

Floor U-value by age (unit: W/m²K)

	Before 1945	From 1945 to 1970	In the 1970s	In the 1980s	In the 1990s	After 2000
BGR	1.6	1.6	1.2	0.8	0.6	0.5
FRA	1.9	1.9	0.8	0.7	0.5	0.4
DEU	1.4	1.4	1.0	0.6	0.4	0.3
GRC	2.4	2.4	2.4	2.4	2.3	0.7
HUN	1.6	1.6	1.2	0.8	0.6	0.5
ITA	1.9	1.8	1.6	1.4	1.4	1.3
POL	1.9	1.4	1.2	1.1	0.9	0.6
ESP	2.5	2.5	2.5	0.8	0.8	0.7
CHE	0.7	0.7	0.7	0.7	0.4	0.3
GBR	2.0	1.7	1.4	1.1	0.5	0.3

Roof U-value by age (unit: W/m²K)

	Before 1945	From 1945 to 1970	In the 1970s	In the 1980s	In the 1990s	After 2000
BGR	1.6	1.6	0.7	0.5	0.4	0.3
FRA	2.5	2.4	1.1	0.7	0.6	0.2
DEU	1.5	1.5	0.6	0.4	0.3	0.2
GRC	2.5	2.5	2.5	1.1	1.1	0.5
HUN	1.6	1.6	0.7	0.5	0.4	0.3
ITA	2.2	2.0	1.7	1.2	1.0	0.9
POL	0.8	0.7	0.6	0.6	0.6	0.3
ESP	1.8	1.4	1.4	1.0	1.0	0.5
CHE	0.8	0.7	0.6	0.6	0.3	0.2
GBR	2.4	2.0	0.9	0.5	0.3	0.2

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ANNEX VIII

MATLAB program ‘Energy_demand.m’

```
%% Calculation of the energy demand

% from Certificazione energetica degli edifici Procedura di calcolo,
% 3° supplemento straordinario al D.G.R. 5018/2007, Regione Lombardia
% 25/01/2008, from UNI 10339:1995

%% Loading the hourly profile of the annual energy demand from TRNSYS
% Only if available, in .txt format, first column for heating demand
% and second column for cooling demand

answer=input('Is it available the energy demand from TRNSYS? y/n: ','s');
if answer=='Y' || answer=='y'

    % Data load from TRNSYS

    aux=dlmread('heat_flows.txt',' ',[2 5 8761 10]);
    aux=array2table([aux(1:9,[4 6]);...
        aux(10:99,[3 5]);aux(100:999,[2 4]);...
        aux(1000:end,[1 3])]);
    aux.Properties.VariableUnits = {'kW' 'kW'};
    Demand.Q_heating=abs(aux(:,1));
    Demand.Q_cooling=abs(aux(:,2));
    clear aux

end

%% Conversion of Existing_plant struct in array

exs=struct2table(Existing_plant);
exs=table2array(exs)';
exs=exs([10:14 1:9 15 16]);

%% Heat transmission through the envelope

Building.H_T=(Building.U_wall*Building.envelope+Building.U_window*...
    (Building.window_N+Building.window_S+Building.window_W+...
    Building.window_E)+...
    Building.U_floor*Building.floor+Building.U_roof*Building.roof);% W/K

Demand.q_t_h=Building.H_T*(20-Weather_data.Dry_Bulb_Temperature)/1000;% kW
Demand.q_t_c=Building.H_T*(Weather_data.Dry_Bulb_Temperature-26)/1000;% kW

%% Heat dispersion for ventilation

Building.H_V=0.334*(39.6*Building.people);% W/K

Demand.q_v_h=Building.H_V*(20-Weather_data.Dry_Bulb_Temperature)/1000;% kW
Demand.q_v_c=Building.H_V*(Weather_data.Dry_Bulb_Temperature-26)/1000;% kW

%% Internal heat production

if Building.area<200
    Demand.q_i(1)=(6.25-0.02*Building.area)*Building.area/1000;% kW
else
    Demand.q_i(1)=10.8/24; % kW
end
Demand.q_i(1:8760,1)=Demand.q_i(1);

%% Solar gains
```

```
Radiation.Direct_N([1 height(Radiation)],1)=0;
Radiation.Direct_S([1 height(Radiation)],1)=0;
Radiation.Direct_W([1 height(Radiation)],1)=0;
Radiation.Direct_E([1 height(Radiation)],1)=0;

for idx=2:(height(Radiation)-1)
    if Radiation.Diffuse(idx-1)==0
        Radiation.Direct_N(idx)=0;
        Radiation.Direct_S(idx)=0;
        Radiation.Direct_W(idx)=0;
        Radiation.Direct_E(idx)=0;
    elseif Radiation.Diffuse(idx+1)==0
        Radiation.Direct_N(idx)=0;
        Radiation.Direct_S(idx)=0;
        Radiation.Direct_W(idx)=0;
        Radiation.Direct_E(idx)=0;
    else
        Radiation.Direct_N(idx,1)=tilted_radiation(...
            Radiation.Direct(idx),Radiation.Diffuse(idx),...
            Radiation.GroundReflected(idx),90,Location.latitude,...
            -180+Building.orientation,Weather_data.Hour(idx),ceil(idx/24));
        % Wh/m2
        Radiation.Direct_S(idx,1)=tilted_radiation(...
            Radiation.Direct(idx),Radiation.Diffuse(idx),...
            Radiation.GroundReflected(idx),90,Location.latitude,...
            Building.orientation,Weather_data.Hour(idx),ceil(idx/24));
        % Wh/m2
        Radiation.Direct_W(idx,1)=tilted_radiation(...
            Radiation.Direct(idx),Radiation.Diffuse(idx),...
            Radiation.GroundReflected(idx),90,Location.latitude,...
            90+Building.orientation,Weather_data.Hour(idx),ceil(idx/24));
        % Wh/m2
        Radiation.Direct_E(idx,1)=tilted_radiation(...
            Radiation.Direct(idx),Radiation.Diffuse(idx),...
            Radiation.GroundReflected(idx),90,Location.latitude,...
            -90+Building.orientation,Weather_data.Hour(idx),ceil(idx/24));
        % Wh/m2
    end
end


Demand.q_s=(Radiation.Direct_N*Building.window_N*...
    0.87*Building.g_window*0.85*0.85+...
    Radiation.Direct_S*Building.window_S*...
    0.87*Building.g_window*0.85*0.85+...
    Radiation.Direct_W*Building.window_W*...
    0.87*Building.g_window*0.85*0.85+...
    Radiation.Direct_E*Building.window_E*...
    0.87*Building.g_window*0.85*0.85)/1000;% kW

%% Total energy demand

Demand.Q_heating=Demand.q_t_h+Demand.q_v_h-Demand.q_i-Demand.q_s;% kW
Demand.Q_heating(Demand.Q_heating<0)=0;% kW


Demand.Q_cooling=Demand.q_t_c+Demand.q_v_c+Demand.q_i+Demand.q_s;% kW
Demand.Q_cooling(Demand.Q_cooling<0)=0;% kW
```

```
if isstruct(Demand)
Demand=struct2table(Demand);
end

HVAC.Heating.total=sum(Demand.Q_heating,'omitnan'); % kWh
HVAC.Cooling.total=sum(Demand.Q_cooling,'omitnan'); % kWh

HVAC.Heating.max=max(Demand.Q_heating);
HVAC.Cooling.max=max(Demand.Q_cooling);

HVAC.Heating.avg=mean(Demand.Q_heating...
    (Weather_data.Month==(1|2|11|12)));% for the heating season, KW
HVAC.Cooling.avg=mean(Demand.Q_cooling...
    (Weather_data.Month==(5|6|7|8)));% for the cooling season, KW

%% Hot Water demand
% from UNI 9182:2014

HVAC.DHW.volume_day=75*Building.people;% liters of water per day

HVAC.DHW.peak_period=2.5;
% 2-3 hours from standard, related to the number of rooms
HVAC.DHW.peak_volume=round...
    (2/3*HVAC.DHW.volume_day/HVAC.DHW.peak_period*1.15*1*1.1,-1);
% liters of water/h, assuming peak demand=2/3 of the total daily demand
HVAC.DHW.peak_power=HVAC.DHW.peak_volume/(3600)*4.186*(50-10);
% kW

HVAC.Heating.Heating_Plus_DHW_peak=...
    HVAC.Heating.max+HVAC.DHW.peak_power;% kW

clear idx answer

%% Radiation on solar plant

if (any(exs([15 16])~='not present') || Building.solar_area>0)

    Radiation.Solar_plant([1 height(Radiation)],1)=0;
    for idx=2:(height(Radiation)-1)
        if Radiation.Diffuse(idx-1)==0
            Radiation.Solar_plant(idx)=0;
        elseif Radiation.Diffuse(idx+1)==0
            Radiation.Solar_plant(idx)=0;
        else
            Radiation.Solar_plant(idx)=...
                tilted_radiation(Radiation.Direct(idx),...
                Radiation.Diffuse(idx),Radiation.GroundReflected(idx),...
                Building.solar_area_slope,Location.latitude,...
                Building.solar_area_azimuth,Weather_data.Hour(idx),...
                ceil(idx/24)); % Wh/m2
        end
    end

end

clear idx

% Plot of the energy demand
```

```
figure
plot(1:height(Demand),Demand.Q_heating,':r')
hold on
plot(1:height(Demand),Demand.Q_cooling,':b')
title 'HVAC demand'
legend({'Heating demand' 'Cooling demand'},'Location','north');
xlabel('Year')
ylabel('Energy demand   kWh')
axis([0 8760 0 20] )
hold off
```

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ANNEX IX

Results for Single Family House SFH 45

MATLAB Workspace
SFH 45_STR

Value	Name
1x1 struct	Building
16x73 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x5 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x73 table	PE
1x73 double	PE_profile
1x7 table	PEf
16x73 table	Power
8760x9 table	Radiation
17x73 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x73 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 45_STR

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Underfloor panels"
Heating_system_generator	"Condensing boiler"
Heating_system_generator_fuel	"Gas"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	270.3706

MATLAB Variable: Building
SFH 45_STR

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"In1990s"
U_wall	0.3330
U_floor	0.4140
U_roof	0.5100
U_window	1.2700
g_window	0.7550
H_T	159.5732
H_V	79.3584

MATLAB Variable: Location
SFH 45_STR

Field	Value
Country	"FRA"
City	"STRASBOURG"
latitude	48.5500
longitude	7.6300
T_mean	10.2973
T_max	31
T_min	-9.6000

MATLAB Variable: HVAC.Heating
SFH 45_STR

Field	Value
total	1.4716e+04
max	6.5894
avg	3.3847
Heating_Plus_DHW_peak	13.5660

MATLAB Variable: HVAC.Cooling
SFH 45_STR

Field	Value
total	4.7344e+03
max	7.5101
avg	0.0110

MATLAB Variable: HVAC.DHW
SFH 45_STR

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 45_STR

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"not present"
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"-3.0536"	"-3.0527"	"-2.4103"	"-2.4092"	"8.7925"	"8.7936"	"24.3641"

MATLAB Variable: generators_best_output
SFH 45_STR

	1 ranking1	2 ranking3	3 ranking5	4 ranking32	5 ranking39
1 Cooling_system_type	"Water syst…	"Water syst…	"Water syst…	"Water syste…	"Electric syst…
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi…	"Absorptio…	"Electric HP…	"Adsorption …	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"
5 Cooling_system_storage	"PCM stora…	"PCM stora…	"PCM stora…	"not present"	"not present"
6 Heating_system_type	"Water syst…	"Water syst…	"Water syst…	"Water syste…	"Water syste…
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi…	"Absorptio…	"Electric HP…	"Adsorption …	"Condensing…
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin…	"Condensin…	"Condensin…	"Condensing…	"not present"
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"not present"
14 Heating_system_storage	"PCM stora…	"PCM stora…	"PCM stora…	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther…	"Solar ther…	"Solar ther…	"Solar therm…	"Solar therm…
16 Renewable_support_PV	"Photovolta…	"Photovolta…	"Photovolta…	"Photovoltai…	"Photovoltai…
17 PE_demand_kWh/m2	"-3.0536"	"-2.4103"	"8.7925"	"96.4203"	"128.3945"

MATLAB Workspace
SFH 45_ATH

Value	Name
1x1 struct	Building
16x73 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x5 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x73 table	PE
1x73 double	PE_profile
1x7 table	PEf
16x73 table	Power
8760x9 table	Radiation
17x73 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x73 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 45_ATH

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Underfloor panels"
Heating_system_generator	"Condensing boiler"
Heating_system_generator_fuel	"Gas"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	330.1514

MATLAB Variable: Building
SFH 45_ATH

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"In1990s"
U_wall	0.3330
U_floor	0.4140
U_roof	0.5100
U_window	1.2700
g_window	0.7550
H_T	159.5732
H_V	79.3584

MATLAB Variable: Location
SFH 45_ATH

Field	Value
Country	"GRC"
City	"ATHENS"
latitude	37.9000
longitude	23.7300
T_mean	17.9025
T_max	37.2000
T_min	2

MATLAB Variable: HVAC.Heating
SFH 45_ATH

Field	Value
total	5.0521e+03
max	3.8178
avg	1.3365
Heating_Plus_DHW_peak	10.7944

MATLAB Variable: HVAC.Cooling
SFH 45_ATH

Field	Value
total	1.1734e+04
max	8.8132
avg	0.3811

MATLAB Variable: HVAC.DHW
SFH 45_ATH

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 45_ATH

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"not present"	"not present"	"Condensin...	"Condensin...	"not present"	"not present"	"not present"
13 Heating_system_support_fuel	"not present"	"not present"	"Gas"	"Gas"	"not present"	"not present"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"not present"
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"-63.6156"	"-63.6127"	"-56.0189"	"-56.0153"	"-51.1258"	"-51.1222"	"-32.1316"

MATLAB Variable: generators_best_output
SFH 45_ATH

	1 ranking1	2 ranking3	3 ranking5	4 ranking37	5 ranking42
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Electric syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"
5 Cooling_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Water syste...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"Condensing...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"not present"	"Condensin...	"not present"	"Condensing...	"not present"
13 Heating_system_support_fuel	"not present"	"Gas"	"not present"	"Gas"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar therm...	"Solar therm...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltai...
17 PE_demand_kWh/m2	"-63.6156"	"-56.0189"	"-51.1258"	"106.0893"	"157.3352"

MATLAB Workspace
SFH 45_HEL

Value	Name
1x1 struct	Building
16x73 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x5 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x73 table	PE
1x73 double	PE_profile
1x7 table	PEf
16x73 table	Power
8760x9 table	Radiation
17x73 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x73 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 45_HEL

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Underfloor panels"
Heating_system_generator	"Condensing boiler"
Heating_system_generator_fuel	"Gas"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	303.4407

MATLAB Variable: Building
SFH 45_HEL

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"In1990s"
U_wall	0.3330
U_floor	0.4140
U_roof	0.5100
U_window	1.2700
g_window	0.7550
H_T	159.5732
H_V	79.3584

MATLAB Variable: Location
SFH 45_HEL

Field	Value
Country	"FIN"
City	"HELSINKI"
latitude	60.3200
longitude	24.9700
T_mean	5.1811
T_max	28.7000
T_min	-21.7000

MATLAB Variable: HVAC.Heating
SFH 45_HEL

Field	Value
total	2.3504e+04
max	9.4804
avg	5.0654
Heating_Plus_DHW_peak	16.4571

MATLAB Variable: HVAC.Cooling
SFH 45_HEL

Field	Value
total	2.8969e+03
max	6.7327
avg	0

MATLAB Variable: HVAC.DHW
SFH 45_HEL

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 45_HEL

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"Absorptio...	"DC HP/Chi...	"DC HP/Chi...	"Electric HP...	"Electric HP...	"Absorptio...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"Absorptio...	"Absorptio...	"DC HP/Chi...	"DC HP/Chi...	"Electric HP...	"Electric HP...	"Absorptio...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"not present"
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"89.8219"	"89.8219"	"90.7385"	"90.7385"	"100.116"	"100.116"	"104.1408"

MATLAB Variable: generators_best_output
SFH 45_HEL

	1 ranking1	2 ranking3	3 ranking5	4 ranking31	5 ranking37
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Electric syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"Absorptio...	"DC HP/Chi...	"Electric HP...	"Adsorption ...	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"
5 Cooling_system_storage	"not present"	"not present"	"not present"	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Water syste...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"Absorptio...	"DC HP/Chi...	"Electric HP...	"Adsorption ...	"Condensing...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensing...	"not present"
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar therm...	"Solar therm...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltai...
17 PE_demand_kWh/m2	"89.8219"	"90.7385"	"100.116"	"169.228"	"184.6079"

An energy efficiency driven algorithm for filtering and sizing HVAC system layouts for building retrofit

ANNEX X

Results for Single Family House SFH 15

MATLAB Workspace
SFH 15_STR

Value	Name
1x1 struct	Building
16x73 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x5 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x73 table	PE
1x73 double	PE_profile
1x7 table	PEf
16x73 table	Power
8760x9 table	Radiation
17x73 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x73 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 15_STR

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Fan-coils"
Heating_system_generator	"Condensing boiler"
Heating_system_generator_fuel	"Gas"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	246.8555

MATLAB Variable: Building
SFH 15_STR

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"After2000"
U_wall	0.2000
U_floor	0.2010
U_roof	0.1800
U_window	1.1000
g_window	0.7550
H_T	90.0300
H_V	79.3584

MATLAB Variable: Location
SFH 15_STR

Field	Value
Country	"FRA"
City	"STRASBOURG"
latitude	48.5500
longitude	7.6300
T_mean	10.2973
T_max	31
T_min	-9.6000

MATLAB Variable: HVAC.Heating
SFH 15_STR

Field	Value
total	9.2951e+03
max	4.5309
avg	2.2064
Heating_Plus_DHW_peak	11.5076

MATLAB Variable: HVAC.Cooling
SFH 15_STR

Field	Value
total	5.7347e+03
max	7.2124
avg	0.0484

MATLAB Variable: HVAC.DHW
SFH 15_STR

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 15_STR

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"not present"
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"-21.4179"	"-21.417"	"-19.0091"	"-19.008"	"-11.9856"	"-11.9844"	"5.6315"

MATLAB Variable: generators_best_output
SFH 15_STR

	1 ranking1	2 ranking3	3 ranking5	4 ranking32	5 ranking37
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Electric syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"
5 Cooling_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Water syste...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"Condensing...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensing...	"not present"
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar therm...	"Solar therm...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltai...
17 PE_demand_kWh/m2	"-21.4179"	"-19.0091"	"-11.9856"	"76.1775"	"107.3879"

MATLAB Workspace
SFH 15_ATH

Value	Name
1x1 struct	Building
16x73 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x5 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x73 table	PE
1x73 double	PE_profile
1x7 table	PEf
16x73 table	Power
8760x9 table	Radiation
17x73 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x73 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 15_ATH

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Fan-coils"
Heating_system_generator	"Condensing boiler"
Heating_system_generator_fuel	"Gas"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	340.6959

MATLAB Variable: Building
SFH 15_ATH

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"After2000"
U_wall	0.2000
U_floor	0.2010
U_roof	0.1800
U_window	1.1000
g_window	0.7550
H_T	90.0300
H_V	79.3584

MATLAB Variable: Location
SFH 15_ATH

Field	Value
Country	"GRC"
City	"ATHENS"
latitude	37.9000
longitude	23.7300
T_mean	17.9025
T_max	37.2000
T_min	2

MATLAB Variable: HVAC.Heating
SFH 15_ATH

Field	Value
total	3.0385e+03
max	2.5660
avg	0.8185
Heating_Plus_DHW_peak	9.5427

MATLAB Variable: HVAC.Cooling
SFH 15_ATH

Field	Value
total	1.2507e+04
max	8.8594
avg	0.5401

MATLAB Variable: HVAC.DHW
SFH 15_ATH

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 15_ATH

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"not present"	"not present"	"Condensin...	"Condensin...	"not present"	"not present"	"not present"
13 Heating_system_support_fuel	"not present"	"not present"	"Gas"	"Gas"	"not present"	"not present"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"not present"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"-67.0696"	"-67.0669"	"-58.4789"	"-58.4755"	"-55.5034"	"-55.5"	"-35.9502"

MATLAB Variable: generators_best_output
SFH 15_ATH

	1 ranking1	2 ranking3	3 ranking5	4 ranking37	5 ranking42
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Electric syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"
5 Cooling_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Water syste...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"Condensing...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"not present"	"Condensin...	"not present"	"Condensing...	"not present"
13 Heating_system_support_fuel	"not present"	"Gas"	"not present"	"Gas"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar therm...	"Solar therm...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltai...
17 PE_demand_kWh/m2	"-67.0696"	"-58.4789"	"-55.5034"	"105.1188"	"168.6517"

MATLAB Workspace
SFH 15_HEL

Value	Name
1x1 struct	Building
16x73 table	Configurations
8760x8 table	Demand
1x1 struct	design_parameters
1x1 struct	Existing_plant
17x5 table	generators_best_o...
1x1 struct	HVAC
1x1 struct	Location
16x73 table	PE
1x73 double	PE_profile
1x7 table	PEf
16x73 table	Power
8760x9 table	Radiation
17x73 table	ranking
1x1 struct	Retrofit_alternatives
17x7 table	top7
16x73 table	Volume
8760x31 table	Weather_data

MATLAB Variable: Existing_plant
SFH 15_HEL

Field	Value
Heating_system_type	"Water system"
Heating_system_emitters	"Fan-coils"
Heating_system_generator	"Condensing boiler"
Heating_system_generator_fuel	"Gas"
Heating_system_DHW_generator	"not present"
Heating_system_DHW_generator_fuel	"not present"
Heating_system_support	"not present"
Heating_system_support_fuel	"not present"
Heating_system_storage	"not present"
Cooling_system_type	"Electric system"
Cooling_system_emitters	"Fan-coils"
Cooling_system_generator	"not present"
Cooling_system_generator_fuel	"not present"
Cooling_system_storage	"not present"
Renewable_support_ST	"not present"
Renewable_support_PV	"not present"
PE_demand	255.8416

MATLAB Variable: Building
SFH 15_HEL

Field	Value
footprint	79.4000
envelope	180.4000
floor	70
roof	81
height	8.2300
volume	389.4500
floors	2
area	140
orientation	0
window_N	3
window_S	12
window_W	4
window_E	4
solar_area	50
solar_area_slope	20
solar_area_azimuth	90
people	6
age	"After2000"
U_wall	0.2000
U_floor	0.2010
U_roof	0.1800
U_window	1.1000
g_window	0.7550
H_T	90.0300
H_V	79.3584

MATLAB Variable: Location
SFH 15_HEL

Field	Value
Country	"FIN"
City	"HELSINKI"
latitude	60.3200
longitude	24.9700
T_mean	5.1811
T_max	28.7000
T_min	-21.7000

MATLAB Variable: HVAC.Heating
SFH 15_HEL

Field	Value
total	1.5305e+04
max	6.5805
avg	3.4076
Heating_Plus_DHW_peak	13.5572

MATLAB Variable: HVAC.Cooling
SFH 15_HEL

Field	Value
total	4.0335e+03
max	6.5797
avg	0

MATLAB Variable: HVAC.DHW
SFH 15_HEL

Field	Value
volume_day	450
peak_period	2.5000
peak_volume	150
peak_power	6.9767

MATLAB Variable: top7
SFH 15_HEL

	1 ranking1	2 ranking2	3 ranking3	4 ranking4	5 ranking5	6 ranking6	7 ranking7
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
5 Cooling_system_storage	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"	"PCM stora...	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...	"Water syst...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"DC HP/Chi...	"Absorptio...	"Absorptio...	"Electric HP...	"Electric HP...	"DC HP/Chi...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Air-source"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...	"Condensin...
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"	"Gas"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...	"PCM stora...
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"Solar ther...	"not present"
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...	"Photovolta...
17 PE_demand_kWh/m2	"43.6762"	"43.6762"	"44.9205"	"44.9205"	"51.1858"	"51.1858"	"60.9117"

MATLAB Variable: generators_best_output
SFH 15_HEL

	1 ranking1	2 ranking3	3 ranking5	4 ranking32	5 ranking34
1 Cooling_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Electric syst...
2 Cooling_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
3 Cooling_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"not present"
4 Cooling_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"not present"
5 Cooling_system_storage	"not present"	"not present"	"not present"	"not present"	"not present"
6 Heating_system_type	"Water syst...	"Water syst...	"Water syst...	"Water syste...	"Water syste...
7 Heating_system_emitters	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"	"Fan-coils"
8 Heating_system_generator	"DC HP/Chi...	"Absorptio...	"Electric HP...	"Adsorption ...	"Condensing...
9 Heating_system_generator_fuel	"Air-source"	"Air-source"	"Air-source"	"Air-source"	"Biomass"
10 Heating_system_DHW_generator	"not present"	"not present"	"not present"	"not present"	"not present"
11 Heating_system_DHW_generator_fuel	"not present"	"not present"	"not present"	"not present"	"not present"
12 Heating_system_support	"Condensin...	"Condensin...	"Condensin...	"Condensing...	"not present"
13 Heating_system_support_fuel	"Gas"	"Gas"	"Gas"	"Gas"	"not present"
14 Heating_system_storage	"PCM stora...	"PCM stora...	"PCM stora...	"PCM storage"	"PCM storage"
15 Renewable_support_ST	"Solar ther...	"Solar ther...	"Solar ther...	"Solar therm...	"Solar therm...
16 Renewable_support_PV	"Photovolta...	"Photovolta...	"Photovolta...	"Photovoltai...	"Photovoltai...
17 PE_demand_kWh/m2	"43.6762"	"44.9205"	"51.1858"	"126.9864"	"136.0422"