Computational analysis of energy and cost efficient retrofitting measures for the French house

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Abstract

Energy-efficient housing has become a mandatory aim to address climate change. This paper presents a computational analysis taking a French single family house as a case study, and aims to investigate both energy and cost-efficiency of market available retrofit measures using dynamic thermal modelling. A parametric analysis tool was developed to run automated batch-simulations using EnergyPlus simulation engine and to calculate the cost associated with retrofit measures, at each simulation run. The automated simulations are carried out, using an exhaustive search technique, for all permutations of measures. These included different building fabrics, ventilation strategies, levels of air-tightness and 5 different heating systems for 4 main climatic regions of France (7680 variants for each of the 4 climatic region). In this analysis, an optimization problem is set to minimise the delivered energy and retrofitting investment cost subject to an energy-saving minimum limit, payback criterion, and summer overheating-risk. The results showed optimum solutions with different fabric and system retrofit combinations that varied in numbers for the different climatic zones. The upper bound of optimum investment cost varied from 80 and 290 €/m^2 for Nice and Paris, respectively.

Keywords: French house; Housing retrofit; Energy efficiency; Cost efficiency; Optimization; Dynamic thermal modelling; Domestic heating

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Highlights (max 85 Characters including spaces)

- Retrofitting of pre-1974 French houses can serve the EU 2050 energy-saving target
- Retrofitting measures are evaluated for energy/cost efficiency& overheating risk
- Wall insulation& energy-efficient systems had the greatest impact on energy-saving
- Energy/cost efficient candidate solutions varied in numbers for each city climate
- Candidate solutions did not include wall insulation variants with major system investment

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Nomenclature

E	is the annual system energy calculated using DTM (kWh)
UA	is the overall conductance value (W/K)
ΔT	is the indoor-outdoor temperature difference as 'indicator of weather' (K)
η_s	is the heating system efficiency
C	is the total retrofit cost over the chosen cycle/loan length (€)
IC	is the material initial cost including tax (€)
Lab	is the labour installation cost (€)
$Cashback$	is assumed incentive paid by the government based on investment rate (€)
MC	is the operating maintenance cost (€)
APR	is the annual percentage interest rate used with mortgage calculations

E_{saved}	is the heating annual saved energy (kWh)
E_{base}	is the base heating annual energy (kWh)
X	is the minimum limit of energy saving as a fraction
p	is the average price of kWh energy over loan period for base or variant fuel(€)
x	is a variant of retrofit
y	is a year in the assumed payback period
T_O	is the room operative temperature of Living room and Bedroom (°C)
h	is an hour in the total occupied hours
H	is the total number of occupied hours.
z	is the permissible fraction of overheating hours
Ym	is the loan period (years)
MD	is the mean deviation in energy units (kWh)
N	is the total number of variants

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1. Introduction

The Energy Performance of Buildings Directive (EPBD) recast in 2010 [1] and amendment in 2018 [2] demands that new buildings should be nearly zero-energy (NZEB) buildings by the end of 2020. The EPBD recast [1] and [2] also calls for the application of cost-efficient measures for both building envelope and technical systems (including heating systems). The NZEB definition was explained in that document as a very low amount of energy that should be covered to a very significant extent by energy from renewable sources. Example studies [3]–[7] discussed these terms at time it was introduced, investigated methods and presented computational analyses. For most if not all member states of the EU, the ambitious energy-efficiency target cannot be met through only measures for new buildings. The EPBD recast–

Article 2a [2] demands member states to establish long-term renovation strategy and stimulate cost-effective deep renovation to support the renovation of the national stock of buildings into a highly efficient and decarbonised building stock by 2050. The concept of 'deep renovation' was defined earlier as a percentage of reduction in current energy consumption by 60 to 90% [8] or precisely as 75% [9]. Member states started from the beginning to pass regulations in mandatory local standards (e.g. [10]–[12]), whilst other states further reinforced the Directive through additional schemes (e.g. [13]), policies and incentives (e.g. [14]) and most recently by issuing laws to commit to 2050 net-zero emissions [15]. In practice, such ambitious energy-efficiency and emissions reduction plans are nationally in the hands of main key stakeholders with different interests in the building sector. These include governmental organisations, financing entities, construction firms, systems and materials manufacturers, utility providers, and end-consumers or householders for domestic buildings. Pombo et al. [16] investigated energy and cost efficiency of domestic buildings renovation for 3 different scenarios over a case study of a Spanish multi-family block of flats. The scenarios included 3 simulation variants of typical Spanish renovations applied for existing building, Spanish regulations for new buildings, and the Passive house standard [17]. Similarly, Ekström et al. [18] investigated same 3 scenarios for reference Swedish houses to show cost-effective measures. Multi-objective optimization tools were introduced to find optimum renovation measures (energy and cost optimal) accounting for future weather [19], and dealing with historic buildings [20].

In France, the building sector consumes 43% of the country's whole sectorial energy consumption. The housing stock, consists of 36.3 million houses, and is responsible for 67% of the consumption of the building sector [21]. The French building stock increases annually by less than 1% [22], which makes the need for retrofitting existing buildings even more critical if this energy-efficiency target is to be achieved.

A few studies on the thermal performance of the French housing have been conducted to address the EPBD targets for building energy-efficiency, or performance of retrofit measures in general, [23]–[26]; and account for cost optimality [27]–[30] . For example, Romani et. al [29] searched for optimal solutions using economic and environmental databases. Brangeon et al. [30] developed automated method using statistical and manufacturer databases to search for refurbishment solution of a collective housing building. However, market available retrofit solutions for single-family-houses were not investigated. Further, there is no investigation against financing options for householders to support the initial investment. This would have been useful to investigate possible energy and cost-efficiency solutions to help decision-making by householders.

This study aims to support decision-making for an archetype of a French single-family house, by conducting optimization focusing on applying: 1) popular marketed building fabric/system retrofit measures and 2) realistic mortgage financial calculations. The study assumes a financing scenario that householders are offered a loan to fully pay for recommended retrofit measures specific for their house. The basis for recommended retrofit measures is that the loan need to be paid off through energy bills' savings brought by these measures. These were the basis of the so-called Green Deal UK retrofit scheme [13], that sounded attractive when was introduced to the UK public. For this work, a parametric simulation tool has been developed to run the dynamic thermal modelling (DTM) software 'EnergyPlus 7.20' based on a 2D matrix of retrofit parameters. These simulations included 1536 variants of retrofits with 5 post-processing to account for the heating system's efficiency for each of the 4 climatic regions (a total of 30,720 variants). The post-processing of results, carried out within the simulation routine at each run, included calculations of the associated retrofit costs.

2. Methods

2.1. Simulation-based optimization

Simulation-based optimization is a technique used to assist decision-making in many different fields, by setting clearly the optimization problem; addressing the objectives and constraints; and then carrying out simulations to search for optimum solutions. In this study, an exhaustive-search with constraint-based filtering technique was used to find out the optimum combinations of retrofit measures from a set that is introduced for the French market by local and international trades. These measures include: wall, ground slab and loft insulation; window type; ventilation strategies; air-tightness levels; and 5 heating systems, for main 4 climatic regions of France.

The optimization problem may be formulated as the minimization of the annual delivered energy (which householders are charged against) and retrofit costs, subject to an energy-saving minimum limit, payback and comfort (selected summer overheating risk) criteria:

$$\text{Min}\begin{cases} E_x = f(UA_x, \Delta T, \eta_s) \\ C_x = IC_x + Lab_x - Cashback \end{cases} \tag{1}$$

Subject to: (2)

$$E_{x-saved} \geq X * E_{base}$$

$$\left[\sum_{y=1}^{Ym} C_x^y + MC - (E_{base} * P_{base} - E_x * P_x)\right] \leq 0$$

$$\sum_{h=1}^{H} (T_{O-Bedroom} > 26) \;\&\; \left(T_{O-Living} > 28\right) < z * H$$

The retrofit financing was assumed to be fully through a bank loan. At first, a possible loan option that is introduced in France, for home improvement, [31] was used for these calculations. This available loan (760€-75,000€) is offered for a maximum of 9 years amortization with a compound annual interest rate, APR, of 5.9%. Then, an additional assumption was investigated for the case of the loan period would be extended to 15 years at the same annual interest rate, and with an assumed moderate governmental support (e.g. [13]) in the shape of cashback (incentive that is based on the investment rate). This assumption was to improve the viability of the different variants and to obtain scalable figures of the retrofit finance. The cashback was assumed based on the investment rate as: 300€ for investment from 3000 to 9000€; 1200€ for investment from 9000 to 15000€; and 2500€ for investment higher than 15000€. The mortgage annuity is calculated as:

$$C_x^{year=y} = C_x * (APR + APR/((1+APR)^{Ym} - 1)) \qquad (3)$$

The energy prices were assumed to escalate by 2% annual increase for the loan period, following the example calculation given in the European Standard EN15459 [32].

The minimum limit of energy saving (X) is taken as 20% reduction of the energy consumption by the baseline (E_{base}) condition, for the different cities. The baseline condition is assumed to have the original building envelope, natural ventilation strategy and an oil boiler heating system (i.e. used by 35% of the building type in scope). The annual energy consumption baseline for space heating was estimated (using the base model) as: 286 kWh//m^2.a for Paris; 276 kWh/m^2.a for Lyon; 249 kWh/m^2.a for Brest; and 181 kWh/m^2.a for Nice.

2.2. French house model

2.2.1. House typology

A typological investigation of the French building stock was carried out during the EU Intelligence Energy Europe (IEE) project TABULA [33]. A French study [34] with more in-depth analysis has followed that typological investigation. The typology of the French housing stock, in [34] was divided into two main categories: a) individual houses and b) blocks of flats. According to that study, the individual houses represent 55% of the French housing stock, of which 63% were built before the year 1974. As the first French thermal regulations did not come into action until 1974, these houses were mainly built with non-insulated constructions. Consequently, retrofitting these houses would most likely enhance the energy efficiency of the French housing stock. Sub-categories of individual houses are introduced in [34] based on age band and sub-types. These included 23% explicitly stated as detached houses (built before 1974). Other sub-types (built before 1948) may also be related to the detached houses are: country house; suburban house; and eclectic house, where these represent 25% of the individual houses. The rest are 15% of town and bourgeois houses (built before 1948) and 47% of detached houses built after the year 1974. A description of fabrics and typical characteristics of pre-1974 French house (mostly solid wall construction) is given in [34] that was used as the base model (described in Table 1) for these parametric simulations. Two layouts of the French individual house were given in [35], which represent: a single-storey detached house called 'Mozart' house and a two storey detached house called 'Puccini' house. The breakdown between these two layouts was not identified, yet it was mentioned implicitly that the majority of individual houses in France are two-storey buildings. In this work, a Puccini layout that represents a two-storey detached house (pre-1974) (Fig. 1) was used to construct the model of the French house.

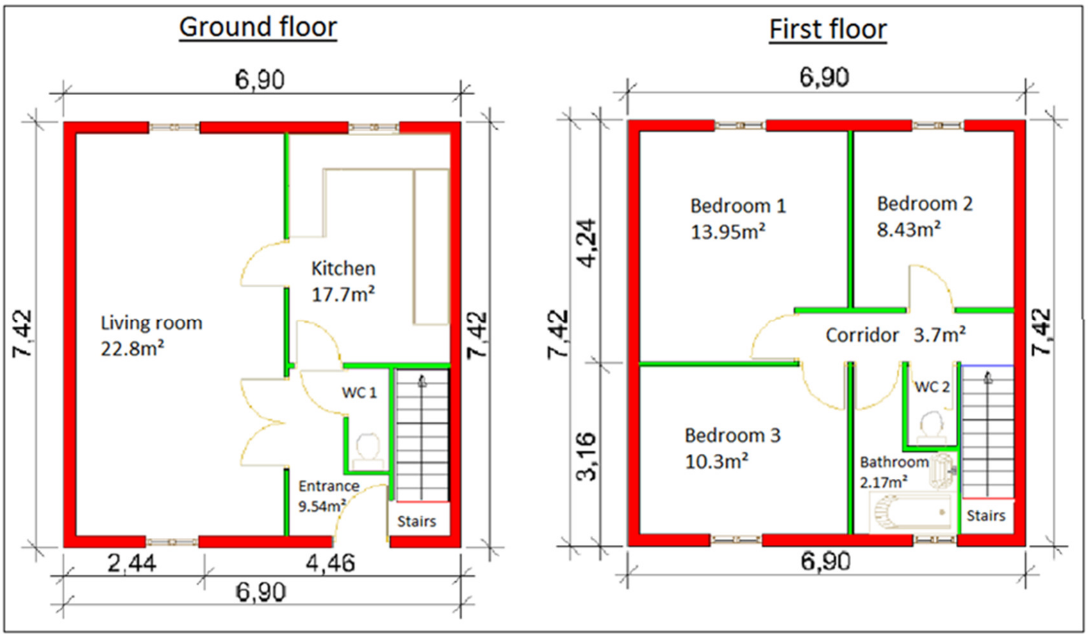

Fig. 1 The French house layout (Modified with English labels from [35])

2.2.2. DTM software

Dynamic thermal modelling (DTM) is a powerful tool that allows evaluation of building thermal performance based on a 3D model of a building and subject to: design, building materials, systems and controls. EnergyPlus software [36], developed by the U.S. Department of Energy (DOE), is a widely used and trusted freeware to study dynamic energy performance of buildings. Mainly it is best described as a simulation engine that features simple input/output files structures. Several tools were developed to run Energyplus simulations with a Graphical User Interface (GUI) for standard modelling work such as DesignBuilder and Simergy software. In this work, the DesignBuilder 3.2 software was used to create the house base model (Table 1) and that was converted into an EnergyPlus 7.20 input file (IDF). The IDF-file was then modified to add search tags (needed for the parametric simulations) and to develop a second version that uses a mechanical ventilation system with heat recovery (MVHR). Hence, the IDF-file is used as a parameter in this case (two IDF-files were used, one for each ventilation strategy).

2.2.3. DTM implementations and input

The constructed house model was based on the given characteristics in [34] and the layout from [35] (as mentioned in section 2.2.1). This represented a single-family detached house, constructed mainly of solid brick external walls, unoccupied (un-heated) pitched roof space, single glazing, wooden intermediate floor, light construction partition walls and a solid concrete ground slab with parquet finish-floor. The number of occupants based on the house layout was estimated according to [37] as 4 persons, while the occupancy schedule and related activities for the main occupied zones (Living, bedrooms, kitchen and bathroom) were according to the time-use survey conducted in [38]. The occupancy of other zones such as toilets and the circulation areas were taken from the DesignBuilder 3.2 library of suggested domestic schedules. Typical domestic appliances (mainly domestic kitchen appliance, audio/visual appliance and personal computers) were assumed for each zone based on the modern technology available in market, and usage was associated with the activities and occupancy schedules based on the data from [37] and [38].

Lighting was also according to domestic use schedules and powers provided in the DesignBuilder 3.2 objects library. The ventilation standard rate of 0.5 air change per hour (ACH), due to intentional window opening or operation of mechanical ventilation, was applied as a constant input for the relevance of this comparison. The house air permeability, due to leakage and cracks, of the base model was taken as 1.0 ACH. The heating system in the base model was an electrical system with the efficiency of 1.0, whereas standard systems' efficiencies were accounted for within the post-processing of results.

Four climate zones of France were chosen for this study. Typical EnergyPlus (EPW) reference-year weather files were obtained from [39] for 4 main cities that represents 4 main climatic types (i.e. excluding high mountain, and degraded types): 1) semi-oceanic climate of Paris; 2) continental climate of Lyon; 3) oceanic climate of Brest; and 4) mediterranean climate of Nice. The weather files of the 4 climatic regions of France were saved under the 'Weather Data' folder in the EnergyPlus main folder, and called as a parameter during simulations.

Table 1 House base model and input parameters

Input	Description
IDF-templates	Two templates comprise two ventilation strategies i.e. Natural ventilation and mechanical ventilation with heat recovery (MVHR).
Weather	Four main climatic regions of France represented in Paris, Lyon, Brest and Nice.
House layout	A 'Puccini' layout of a detached single-family house was used.
Construction	Typical detached house before 1974 with non-insulated solid wall, non-insulated wooden loft, non-insulated concrete /parquet ground flooring.
Window type	Single glazed with painted wooden frame.
Infiltration	Pre-1974 very-poor condition, correspond to 1.0 air change per hour (ACH)
Ventilation	Scheduled ventilation of 0.5 ACH with always-on schedule
Internal gains	Modern appliance rate assumed and applied according to the occupancy profiles from [37] and [38]
Occupancy	A typical French family profile for 4 persons was estimated according to [37] and the time-use survey in [38]
Heating Season	From January-April & October-December
Heating schedule	System is on with a set-point of 21°C from 7:00-9:00& 16:00-22:00 and with night setback of 18°C from 22:00-7:00
Heating system	Electric radiators in zones with the efficiency of 1.0

2.3. Parametric simulation tool

Several tools were developed to assist running EnergyPlus batch-simulations, parametric analysis and simulation-based optimization e.g. GenOpt [40] , JePlus [41], and ROBESim [42]. In this work, a parametric version of the FE+ tool [43] was developed, in order to freely customize the pre and post processing of the simulations input and output, respectively. The FE+ tool is constructed using the G programming language on the LabVIEW platform. The main routine consists of three subroutines that: 1) modify IDF-template with retrofit variables; 2) run EnergyPlus; 3) carry out post-processing of results (Fig. 2) and calculate the associated cost of retrofit measures based on the input prices.

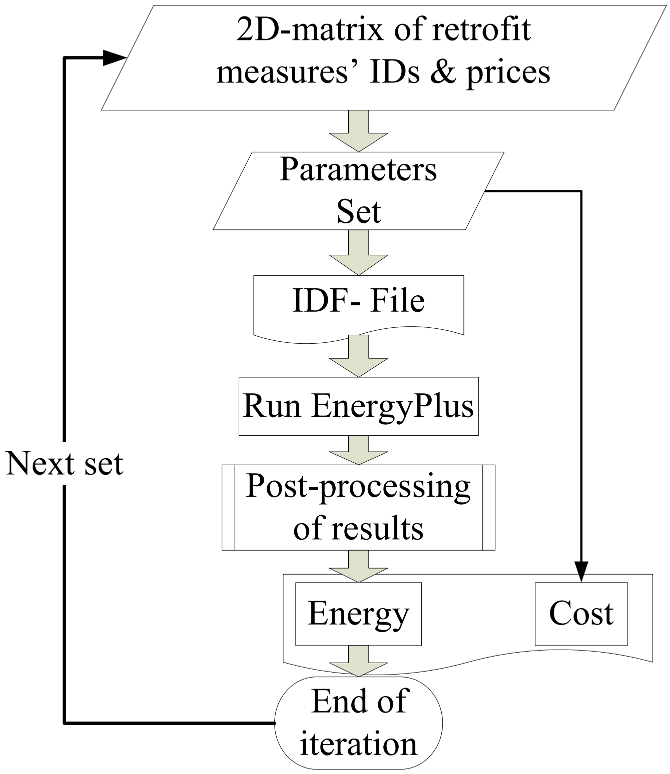

Fig. 2 Flow chart of the FE+ code for parametric analysis

The input parameters to the FE+ are from a 2D matrix that comprises DTM input in one dimension (e.g. wall construction) and different variants of that input in the other dimension. The GUI of FE+ allows users to assign the list of parameters and corresponding costs, location of IDF-templates, and path to save the simulation output and a summary output report. The user interface shows progress of the EnergyPlus simulation and a chart/indicator of the chosen post-processed results at each simulation. The FE+ tool can run on any computer, not necessarily with a LabVIEW licence, using the free-download of the runtime engine.

2.4. Retrofit measures

Ventilation strategy

Indoor air quality is important for wellbeing and health of habitants, therefore houses have to be ventilated with minimum rates (based on applications) given in standards and guidelines. The natural ventilation (NV) strategy, variant V1, relies on habitants opening windows to ventilate the room, which may not comply with that standard minimum rate. While there is no air-driving energy consumed with this system, usually this ventilation strategy comes at the expense of heating energy, when it brings unconditioned outdoor air into the space. The rate of fresh air can be controlled using mechanical ventilation system with heat recovery (MVHR), variant V2, to adhere with the minimum standard rates. Further, the fresh air can exchange heat with the exhaust air through the heat recovery system before being supplied. The viability of using this system may vary based on climate or the building insulation level and tightness. In this work, both NV and MVHR strategies were investigated based on the same ACH to ensure the relevance of comparison. An average cost of the MVHR system was used based on market prices of material and installation (See Table 2 for the used cost and the Appendix section for references). Two EnergyPlus input files (IDF- templates) were created, and called as a parameter, that differs only in the ventilation strategy, identified as V1 for NV and V2 for MVHR.

Glazing

In this work, only normal clear glass-type windows were investigated on the basis of single (variant F1: clear 6mm), double (variant F2: Low emissivity clear 3mm /13mm Argon spacer/ clear 6mm) and triple (variant F3: Low emissivity clear 3mm /clear 3mm with Air spacers) glazing typical window types available in France. The glazed area according to the Puccini layout [35] is only 10 m² which is less than 5% of the total facade area. Constructions of these glazing measures were included in the IDF-templates. U-values and prices are listed in Table 2. Examples of pricing references are included in the Appendix section.

External wall insulation

In this work, three insulated solid wall constructions (variants W2, W3, and W4) were investigated against the base condition of non-insulated walls. These constructions vary either in thickness or material of insulation (i.e. glass fibre or expanded polystyrene). A two centimetre of cement render as most outer layer is common for these 3 constructions and a plaster-board as most inner layer for the 4 constructions (including base wall). The wall constructions and corresponding materials were included in the IDF-templates. Fig.3 shows the construction layers of the wall variants. The selected wall's retrofit constructions were externally insulated which is considered as a less thermal bridging option with no impact on internal floor area (i.e. assumed as favourable option for the householder).

Loft insulation

The roof insulation applied at the ceiling level had 3 different variants that vary in the thickness or material of insulation, similar to the wall insulation measures (Fig. 3). These included a 90mm and 140mm glass fibre insulation; and 120mm expanded polystyrene insulation.

Ground slab construction

The base model's ground slab consisted of 200mm cast concrete as the outer most layer and 2 cm of timber flooring as the floor finish. The ground slab retrofit variants included 3 constructions offered in the market (Fig. 3). These included: adding a 50mm compressed glass fibre batt at top of the base concrete slab, 100mm of 1% reinforced concrete with the timber flooring and concrete base as inner and outer layers, respectively (i.e. variant G2); adding 100mm of wood fir pine with an air-spacing layer above the base concrete topped with the timber flooring (i.e. variant G3); or additionally adding a fibre glass batt instead of the air-spacing in variant G3 (i.e. variant G4). The ground constructions and corresponding materials were included in the IDF-templates

Improvement to air-tightness

In this work, arbitrary ACH values (0.2-1.0) due to infiltration were adopted to study this intervention and to assume and account for draught- proofing of building's openings or treatment of visible cracks. These values are listed in Table 2 with assumed materials and 'Do-It-Yourself' (DIY) cost. Variants with infiltration ACH rate of 0.2 were only enabled with external wall retrofit, while variants with ACH of 0.4 were enabled generally with window retrofit (assumed not possible through only draught proofing).

Heating system

Heating systems' efficiency has a great impact on energy consumption. This work, therefore, investigated five systems (i.e. oil boiler, gas boiler, electrical radiators, air-source heat pump, and ground-source heat pump) that can be used for domestic applications. This was carried out using the system corresponding efficiency values, emissions and carrier factors from the French standard [12]. Table 3 lists these values with the system cost and energy prices of 2014 (See appendix section for data source).

Wall variants (W1-W4) layers:
1- Plaster board 13mm
2- Solid brick 300mm
3- Glass fibre quilt in frame 100mm
3'- Glass fibre quilt in frame 150mm
3''- Expanded polystyrene 120mm
4- Cement render 20mm

Roof variants (R1-R4) layers:
1- Plaster board 20mm
2- Roof wooden floor 200mm
3- Glass fibre quilt 90mm
3'- Glass fibre quilt 140mm
3''- Expanded polystyrene 120mm
4- Roof space
5- Rooftop construction

Ground variants (G1-G4) layers:
1- Soil and levelling layers
2- Cast concrete 200mm
3- Glass fibre batt 50mm
3'- Woods- fir pine 100mm
4- Concrete 1% reinforced 100mm
4'- Air gap 100mm
4''- Glass fibre batt 50mm
5- Timber flooring 20mm

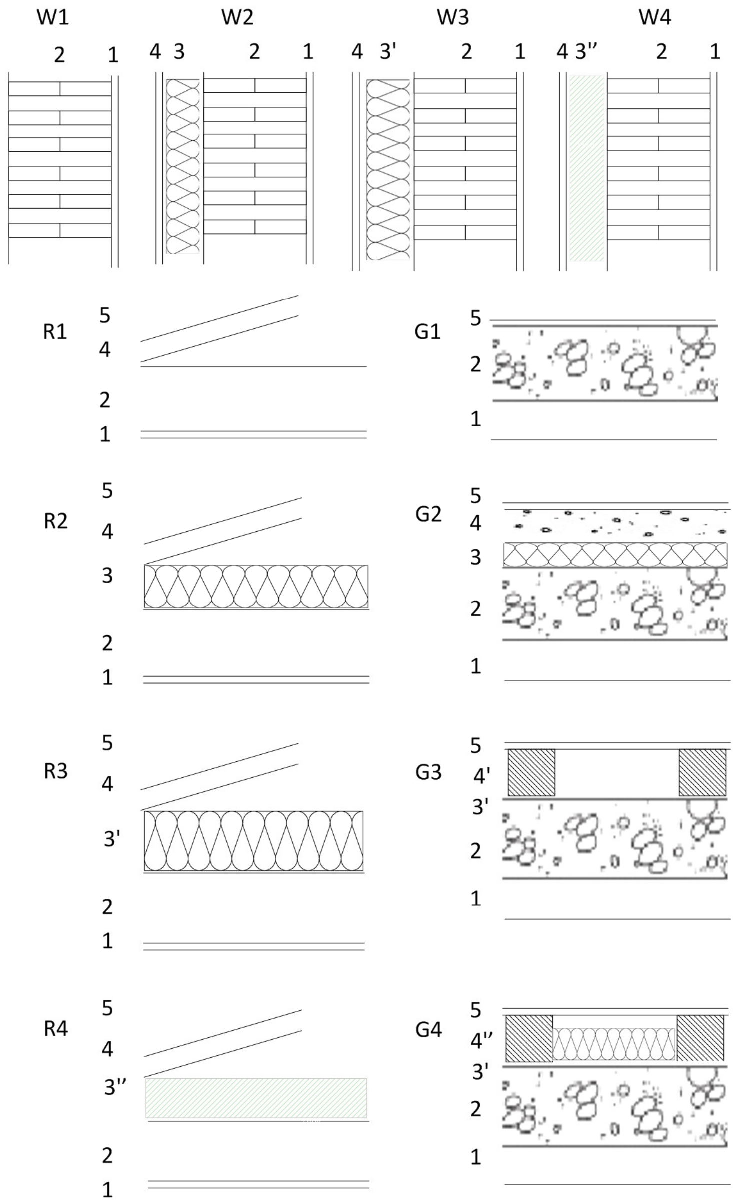

Fig. 3 Construction layers of wall, roof and floor retrofit measures

Table 2 Description of retrofit variables and prices [1]

Retrofit measure	2D Matrix of retrofit Variables			
Ventilation				
Identifier	V1	V2		
Description	Natural	MVHR		
Price (€)	NA	3500		
Window type				
Identifier	F1	F2	F3	
Description	Single	Double	Triple glazing	
U-value (W/m²K)	5.77	1.3	0.9	
Price (€)	NA	4142	5407	
External Wall				
Identifier	W1	W2	W3	W4
Description	Original	+10cm glass fibre	+15cm glass fibre	+12cm Ext-polyst.
U-value (W/m²K)	1.5	0.36	0.25	0.23
Price (€)	NA	11534	11850	12640
Roof-Loft				
Identifier	R1	R2	R3	R4
Description	Original	+9cm glass fibre	+14cm glass fibre	+12cm Ext-polystyrene
U-value (W/m²K)	0.58	0.18	0.13	0.11
Price (€)	NA	1321	1506	1966
Ground slab				
Identifier	G1	G2	G3	G4
Description	Original	+5cm glass fibre	+Wooden structure	G3+5cm glass fibre
U-value (W/m²K)	1.9	0.65	0.58	0.43
Price (€)	NA	4300	3000	3800
Infiltration				
Identifier	I1	I2	I3	I4
Description	Very bad	Bad	Good	Very good
ACH	1	0.8	0.4	0.2
Price (€)	NA	60	140	500

[1] Prices of construction elements are average market prices from French trades that includes installation and tax.

Table 3 Heating systems and corresponding parameters

Heat System	Efficiency/ COP [a]	Emission factor (kg CO2/kWh) [a]	Energy carrier factor [a]	System cost (€) [b]	Current energy price (€/kWh) [b]	Future 15-yrs average energy price (€/kWh) [d]
Oil boiler	0.8	0.3	1	3700	0.0979	0.1151
Gas Boiler	0.9	0.234	1	3600	0.0728	0.0856
Electric radiators	1	0.18	2.58	2100	0.144	0.1729
Air source heat pump	2.5	0.18	2.58	10500 [c]	0.144	0.1729
Ground source heat pump	4	0.18	2.58	19000 [c]	0.144	0.1729

[a] French typical standard values.
[b] French typical market prices collected in 2019.
[c] Prices of the heat pump systems include replacement of radiators to suit a low temperature heating system.
[d] Future energy prices are based on 2% annual escalation rate.

2.5. Thermal comfort analysis

Thermal comfort is analysed in this work from the perspective of possible summer overheating due to construction insulation. This was carried out as a second-stage analysis (as a constraint) over the candidate solutions that fulfilled the energy and payback constraint. Shading and ventilation strategies (with no extra retrofit measures) were incorporated with a schedule for summer operation in the IDF files. These are simply assuming, for summertime schedule, optimal use of the French typical external shading (wooden shutters) to minimise solar gain during daytime; and a full benefit of the lowered outdoor temperatures to apply the ventilation. The operative temperature was investigated in the house's living room and bedrooms during summertime for the different climates. A threshold of 1% for the number of overheating hours (above 28°C for living room and 26°C for bedrooms) [44] was adopted as the criterion for acceptable thermal comfort level during summertime. Additionally, the fulfilment of the adaptive comfort criteria [45] was also investigated to demonstrate differences between these criteria.

3. Results

3.1 Parametric analysis

The parametric simulations (6,140 simulations with 5 post-processing for the heating system's efficiency) were completed over 6 days on a personal laptop computer. Part of the simulations was repeated to analyse the results' sensitivity to the building orientation. This was done separately as the orientation was not considered as a retrofit measure. The FE+ output report was then used to analyse the results. Fig. 4-6 show example parametric analysis of the results, while Table 4 lists numeric values of the chosen parametric indicator from the analysis, with retrofits' identifiers.

Fig. 4 shows the simulations' output sorted in ascending order to manifest the outlines of the results and general observations of the estimated delivered heating energy and associated retrofit costs. As can be seen, the figure illustrates 3 main different sets of the retrofit solutions. A clear deflection point in heating energy and retrofit cost is shown on the figure, splitting a set of variants that do not include external wall retrofit (insulation). The other two sets of retrofit solutions are dominated by NV or MV variants. The heat pump variants (ASHP and GSHP) were, in general, in a narrower band for the 4 cities.

In order to quantify the energy-saving brought by these retrofit measures, a proper indicator is needed. Statistical indicators that are based on percentage can sometimes be misleading and hard to follow especially when used to analyse the impact of measures under different permutations of variants. The mean deviation (*MD*) indicator, in energy units, was selected to inform on the impact of the different measures. This is calculated as the mean deviation of normalized heating energy between the retrofit measure and its base condition for all permutations and under the different climates, where:

$$MD_x = \frac{\sum_{x=1}^{N}(E_{x\_base} - E_x)}{N} \tag{4}$$

A higher MD_x (in kWh/m^2.a) indicates better energy efficiency of that variant *x* and can also be interpreted into savings on energy bills. Figs. 5 and Fig. 6 (a zoom-in figure of the highlighted area on Fig. 5) illustrate examples of the analysed figures for the different retrofit measures, while Table 4 provides the numeric values of the *MD* values and estimates of energy savings due to these measures. As can be seen, the impact of wall insulation on energy consumption is the highest among other measures with a significant energy saving (~100 kWh/m^2.a) . The difference between the insulated wall variants (W2-W4) was up to 10 kWh/m^2.a. MVHR's energy saving was in a range from 16 to 25 kWh/m^2.a for Nice and Paris climates, respectively. The glazing area of the chosen architectural type was only 10 m^2.The energy saving due to glazing type was thus only from 9 to 18 kWh/m^2.a for Nice and Paris climates, respectively. Improvement of air-tightness to reduce ACH by 0.2 could save around 12 kWh/m^2.a. The loft insulation contribution to energy saving was quantified by 5 to 11 kWh/m^2.a. Savings due to ground slab construction was 30 kWh/m^2.a. This considerably high saving is perhaps due to the used ground temperatures i.e. outdoor monthly average temperatures (also assumed constant for the 4 cities). Furthermore, the sensitivity analysis of results to variations in building orientation revealed a percentage difference in a range of +0.5% to -4% for Paris, Lyon and Brest, while for Nice this was +1% to -10%.

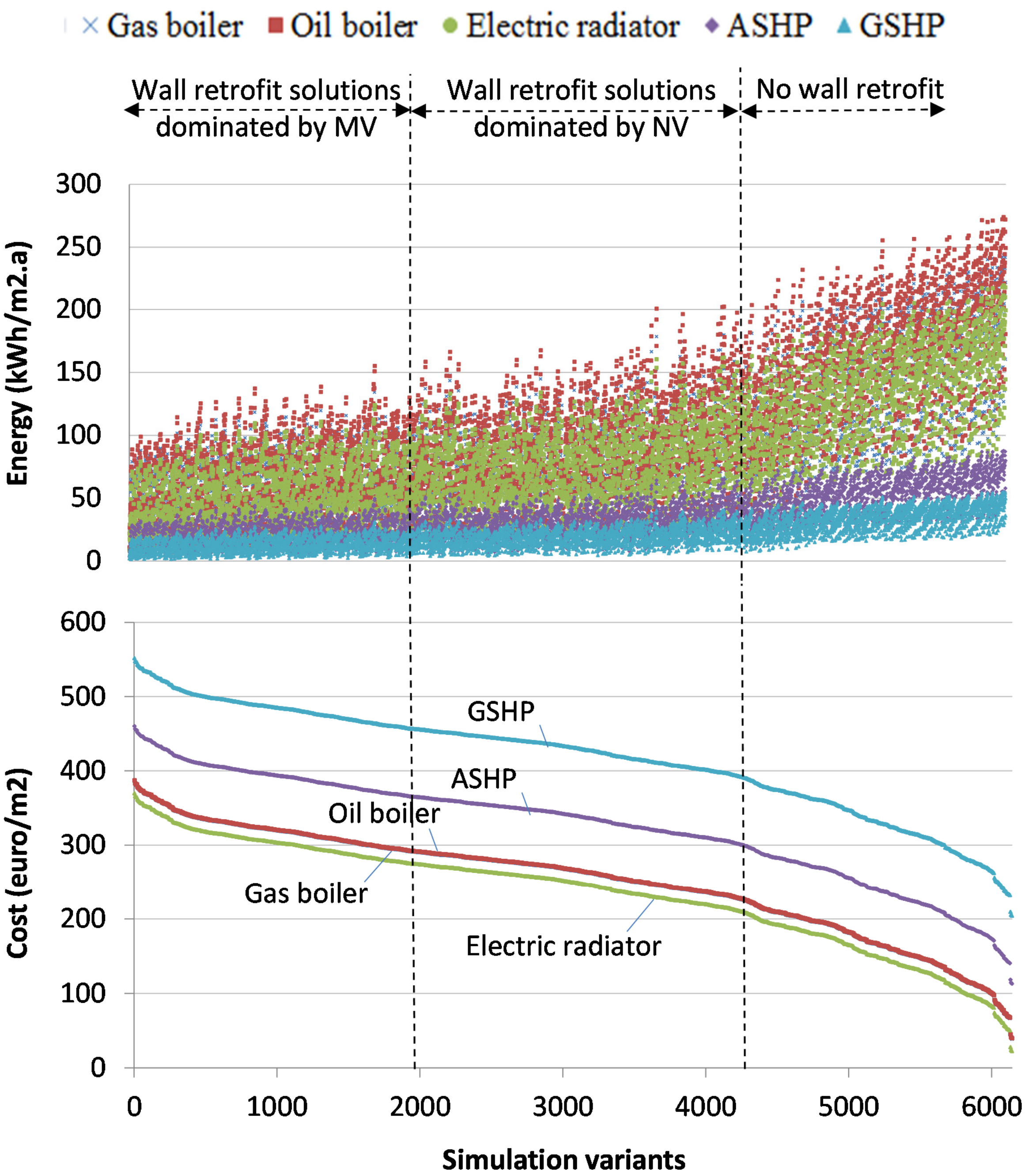

Fig. 4 Sorted simulations' output (as an overview) of normalised heating energies and cost of the different permutations of retrofit measures (total number of outputs 30,720)

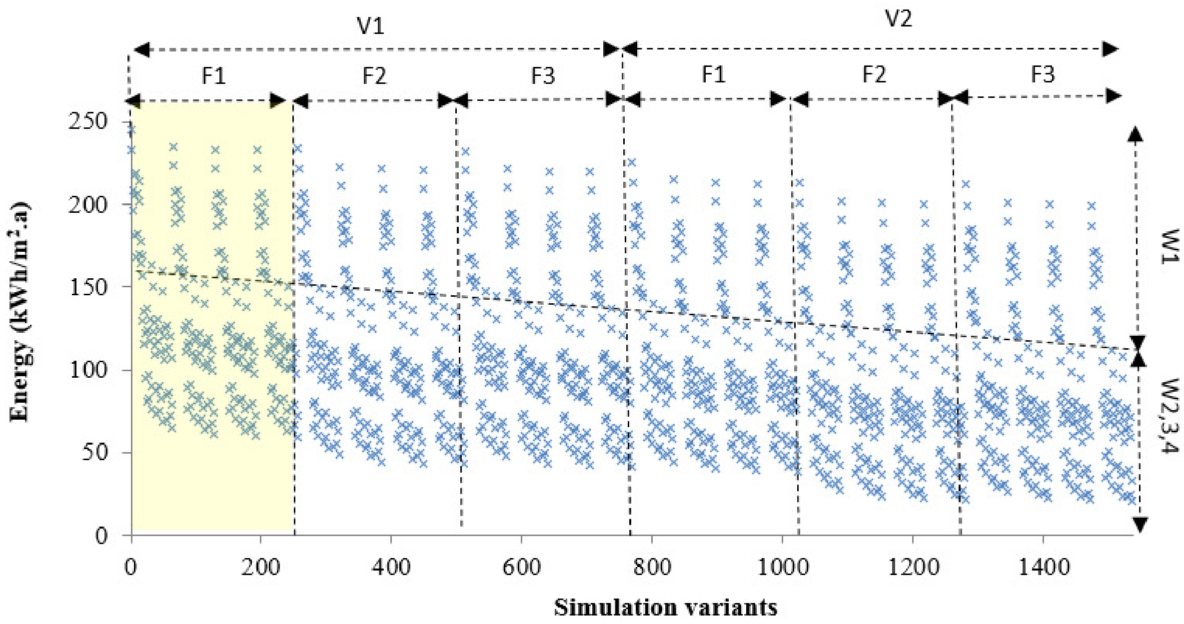

Fig. 5 Example parametric analysis figure: impact of glazing (F1-F3), wall insulation (W1-W4), and ventilation strategy (V1 and V2) for Lyon

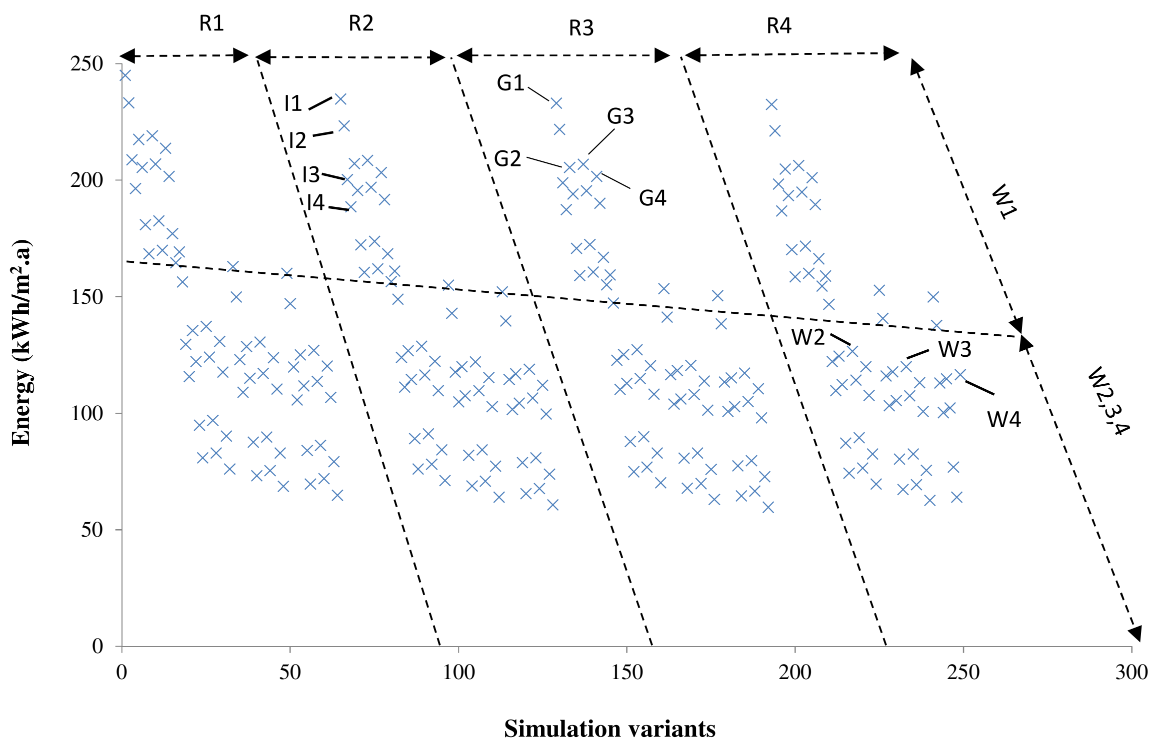

Fig. 6 Example parametric analysis figure “Magnification of the highlighted area on Fig 5”: impact of roof insulation (R1-R4), ground construction (G1-G4), wall insulation (W1-W4), and air tightness (I1-I4) for Lyon

Table 4 Annual heating energy's *MD* values of retrofit measures and expected annual energy bill's saving (values in brackets represent the standard deviation)

Baseline- E_{base} (kWh/m^2.a)	**Paris** 286	**Lyon** 276	**Brest** 249	**Nice** 181
Ventilation				
MVHR, V2: energy-saving (kWh/m^2.a)	23 (2)	22 (2)	20 (2)	16 (2)
annual bills saving (€)	214 (19)	205 (19)	195 (19)	144 (19)
Window glazing type				
Double, F2: energy-saving (kWh/m^2.a)	17 (2)	16 (2)	16 (2)	9 (1)
annual bills saving (€)	158 (19)	150 (19)	150 (19)	84 (9)
Triple, F3: energy (kWh/m^2.a)	18 (2)	16 (2)	16 (2)	10 (1)
annual bills saving (€)	186 (19)	167 (19)	158 (19)	102 (9)
Wall insulation				
W2: energy-saving (kWh/m^2.a)	88 (4)	84 (4)	76 (4)	51 (3)
annual bills saving (€)	818 (37)	781 (37)	707 (37)	474 (28)
W3: energy (kWh/m^2.a)	95 (4)	91 (4)	82 (4)	55 (3)
annual bills saving (€)	884 (37)	846 (37)	763 (37)	512 (28)
W4: energy-saving (kWh/m^2.a)	99 (6)	95 (6)	86 (5)	57 (3)
annual bills saving (€)	921 (56)	884 (56)	799 (47)	531 (28)
Loft insulation				
R2 energy-saving (kWh/m^2.a)	8 (2)	8 (2)	7 (2)	5 (1)
annual bills saving (€)	74 (19)	74 (19)	63 (19)	46 (9)
R3: energy-saving (kWh/m^2.a)	10 (2)	10 (2)	9 (2)	6 (1)
annual bills saving (€)	93 (19)	93 (19)	92 (19)	52 (9)
R4: energy-saving (kWh/m^2.a)	11 (5)	11 (4)	9 (4)	6 (2)
annual bills saving (€)	103 (47)	103 (37)	92 (37)	52 (19)
Ground slab				
G2: energy-saving (kWh/m^2.a)	33 (3)	33(3)	33 (3)	33 (3)
annual bills saving-saving (€)	305 (28)	305 (28)	305 (28)	305 (28)
G3: energy-saving (kWh/m^2.a)	31 (3)	31 (3)	31 (3)	31 (3)
annual bills saving (€)	286 (28)	286 (28)	286 (28)	286 (28)
G4: energy-saving (kWh/m^2.a)	37 (5)	37 (5)	37 (5)	37 (3)
annual bills saving (€)	344 (47)	344 (47)	344 (47)	344 (28)
Infiltration				
0.8 ACH, I2: energy-saving (kWh/m^2.a)	13 (3)	13 (3)	11 (3)	9 (2)
annual bills saving (€)	121 (28)	121 (28)	102 (28)	83 (19)
0.4 ACH, I3: energy-saving (kWh/m^2.a)	39 (3)	38 (3)	33 (2)	26 (2)
annual bills saving (€)	363 (28)	354 (28)	307 (19)	242 (19)
0.2 ACH, I4: energy-saving (kWh/m^2.a)	52 (3)	51 (3)	45 (3)	34 (2)
annual bills saving (€)	484 (28)	475 (28)	419 (28)	316 (19)

3.2. Optimum solutions

This study aims to support decision-making within the French house retrofit process. The above analysis showed the impact of the different retrofit measures, whilst in this section the optimum solutions are investigated. This is carried out by analyzing the fulfillment of the chosen optimization criteria (Eq.1 and 2). The analysis was first carried out based on the French avilable home improvement loan, offered with amortization over a 9 years period. Few variants of gas boiler system that could fulfill the criteria with that 9 years loan period are listed in Table 5. As can be seen, these did not include any wall retrofit measure or even solutions for Nice. The maximum optimum cost was in a range of 50-60 €/m^2 for Paris and Lyon while it was 35 €/m^2 for Brest. The candidate solutions included a single mechanical ventilation solution for Paris accompanied with draught-proofing. The 9 years amortization seems to be insufficient for most of the retrofit measures to fulfil the criteria.

Table 5 Identifiers of candidate solutions based on the 9-years bank loan[1]

Paris	Lyon	Brest
V1-F1-R1-W1-G3-I2	V1-F1-R1-W1-G3-I2	V1-F1-R1-W1-G3-I2
V1-F1-R1-W1-G4-I2	V1-F1-R1-W1-G4-I2	
V1-F2-R1-W1-G1-I3	V1-F2-R1-W1-G1-I3	
V1-F3-R1-W1-G1-I3		
V2-F1-R1-W1-G1-I2		

[1] The definition of the measures' identifiers is given in Table 2

The following shows the analysis with a 15 years loan period and assumed cashback implementation. Fig. 7 shows plots of the normalized delivered energy on the x-axis versus normalized cost on the y-axis for the 4 cities. The plots on the right side show the exhaustive-search (all solutions) full results while the plots on the left show only candidate solutions that fulfilled the constraints. As can be seen from the figure, the system efficiencies clearly separated the systems' variants into different groups (shown with marker colors). In addition, a clear split due to the wall insulation divides each system's variants into two groups, which is visible on the plots (every system variants got two clusters of solutions). The size of candidate solutions varied with the different climates where it included only a few solutions for Nice. The upper bound of the optimum investement cost was up to 80 and 290 €/m^2 for Nice and Paris, respectively. The delivered energy used in these plots is the energy quantity that householders are charged against in their energy bills. Fig. 8 shows plots of normalized primary energy (i.e. energy produced at plant) and its associated carbon emmissions. The primary energy and emmissions are calculated using the energy carrier and emissions factors (Table 3) used specifcally in France. As can be seen, the primary energy and emissions plots (left side) brought on the frontier the candidate solutions of gas and oil boiler systems (e.g. for Paris and Lyon). Fig. 9 shows the Pareto frontier solutions (where the Parteo frontier is defined as the set of efficient solutions that consists of alternatives not dominated by any other alternative and lies on the solutions' frontier) based on the delivered energy and cost criteria. Candidate solutions on the Pareto frontier did not include any oil boiler solutions. Few solutions on the frontier which included wall insulation retrofit, was accompanied with electric heating system for Brest and with electric heating and ASHP for Paris and Lyon. The frontier solutions also included a few GSHP system variants with no or very minor fabric retrofit measures for Paris, Lyon and Brest. The solutions of Nice included only gas boiler system with a very minor fabric change. Mechanical ventilation was especially with high cost variants accompanied with with wall insulation and electric heating. Table 6 lists the Pareto frontier solutions for the different cities using variants' identifiers (described in Table2). The thermal comfort (summer overheating) constraint was fulfilled by the vast majority of candidate solutions.Based on the used overheating criterion [44], the overheating thresholds are only exceeded for Nice with most insulated cosntruction and the use of passive cooling measures. These variants were anyway filtered out due to the payback constarint. Fig. 10 shows plots of summer operative temperatures at living and bedroom zones for the most insulated construction during the month of August to illustrate this criterion using an extreme case under the different climates. The figure also shows the adaptive comfort temperature [45] as another criterion for this assessment. As can be seen, with insulated construction, the operative temperature exceeded the threshold of overheating for Nice, whilst for other cities only natural/passive cooling measures with the insulated construction could encounter summer overheating risk. The adaptive comfort temperatures (claculated according to [45]) even allows higher threshold for this assessment of overheating risk and indicate no risk even for the case of Nice. It should be noted that this analysis was carried out using the 'Internationl Weather for Energy Calculation (IWEC) weather files of the French cities [39].

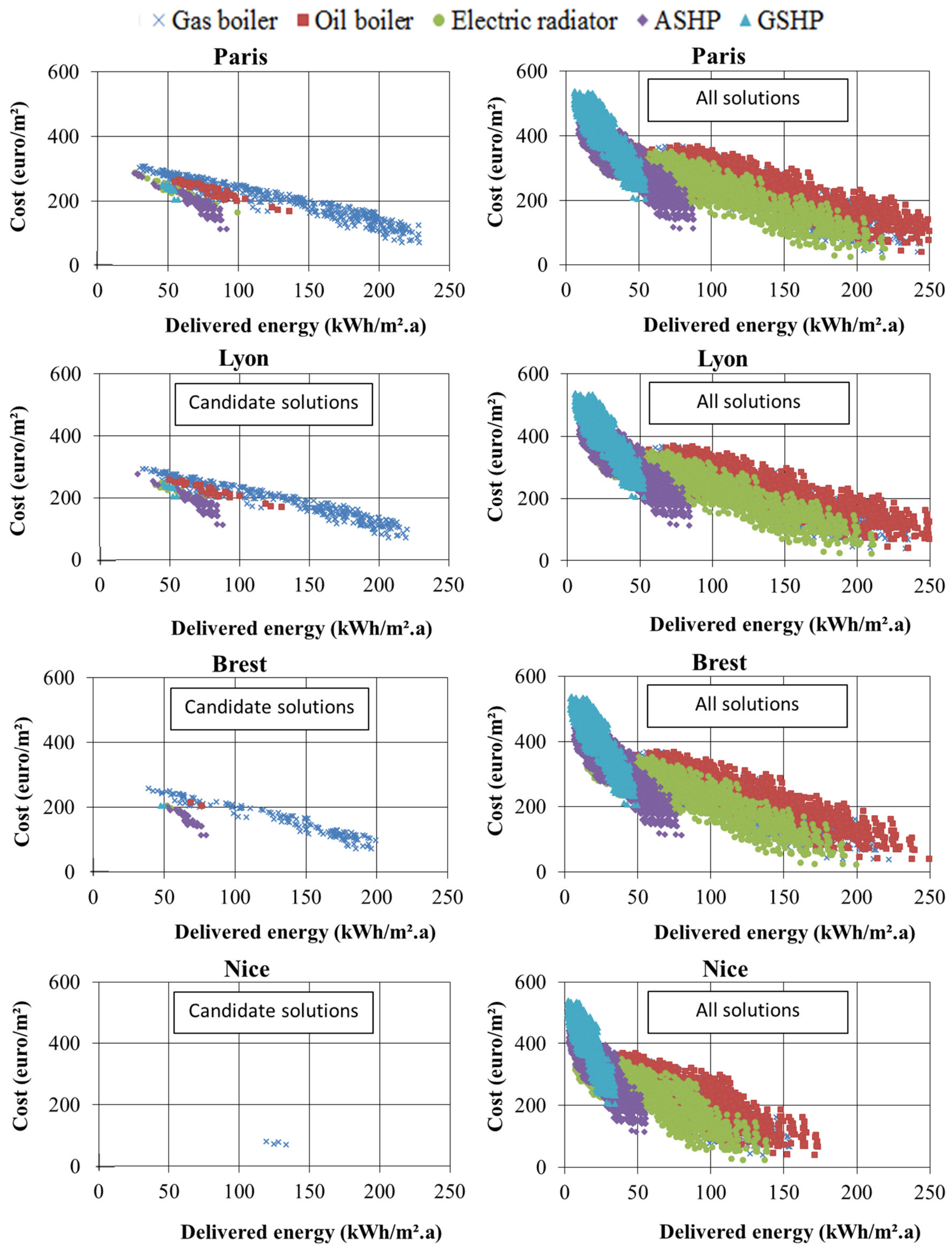

Fig. 7 Normalised delivered heating energy against normalised costs for all solutions (right side) and candidate solutions (left side) for the 4 climatic regions

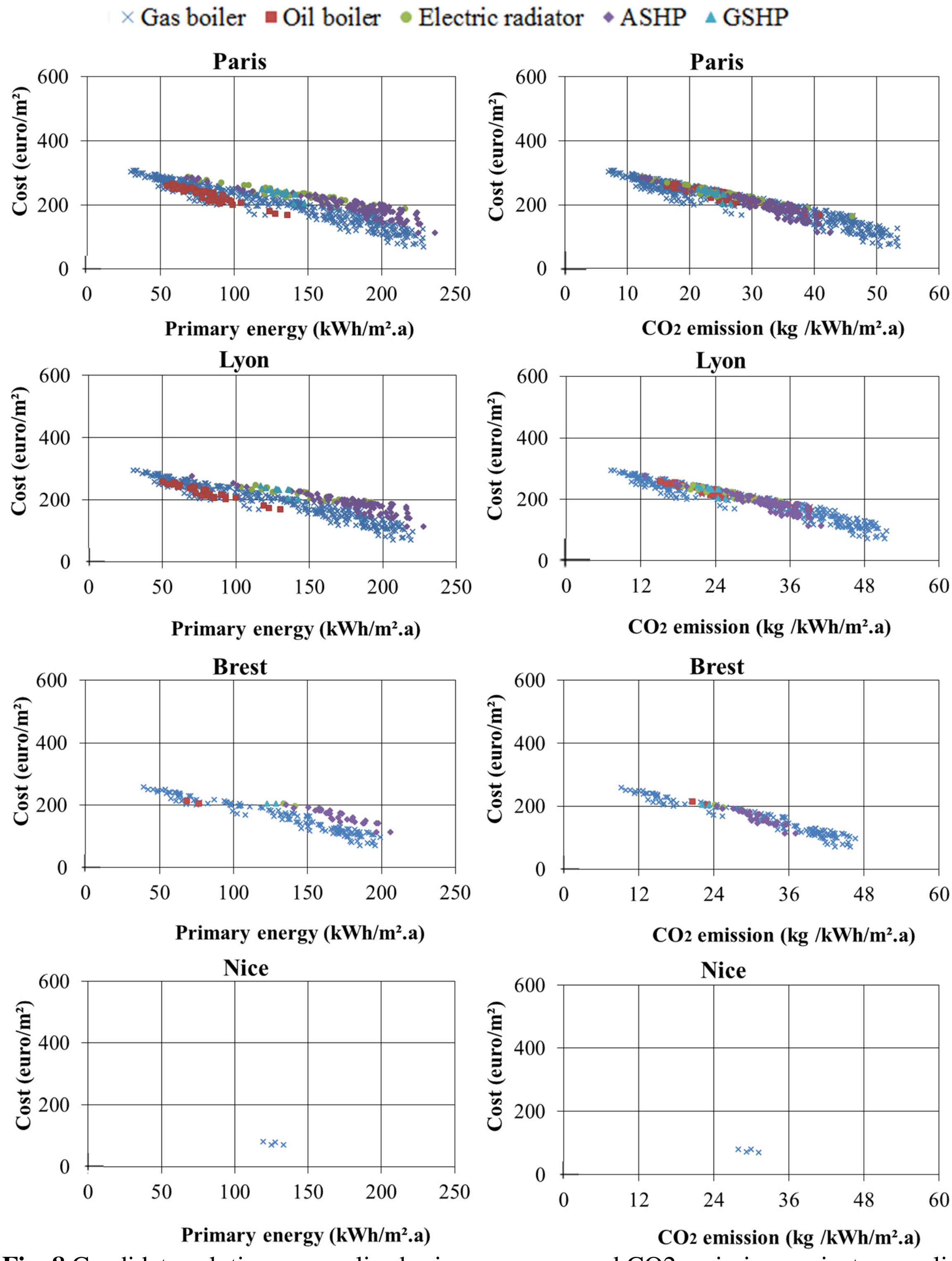

Fig. 8 Candidate solutions normalised primary energy and CO2 emission against normalised cost for the 4 climatic regions

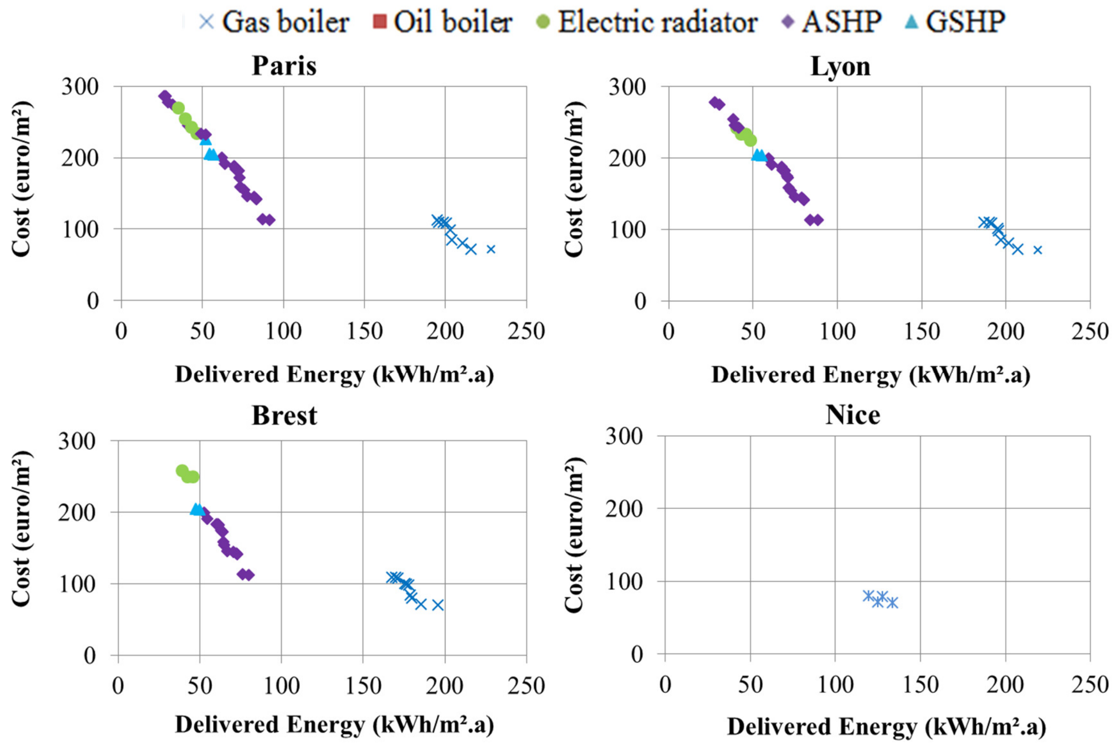

Fig. 9 Normalised delivered energy and cost Pareto frontier solutions for the 4 climatic regions

Table 6 Identifiers of the Pareto front solutions for Paris, Lyon and Brest[1]

Paris	Energy kWh/m²	Cost €/m²	Lyon	Energy kWh/m²	Cost €/m²	Brest	Energy kWh/m²	Cost €/m²
V1-F1-R1-W1-G3-I1	228	71	V1-F1-R1-W1-G3-I1	219	71	V1-F1-R1-W1-G3-I1	196	71
V1-F1-R1-W1-G3-I2	216	72	V1-F1-R1-W1-G3-I2	207	72	V1-F1-R1-W1-G3-I2	185	72
V1-F1-R1-W1-G4-I2	211	80	V1-F1-R1-W1-G4-I2	202	80	V1-F1-R1-W1-G4-I2	180	80
V1-F2-R1-W1-G1-I3	204	85	V1-F2-R1-W1-G1-I3	197	85	V1-F2-R1-W1-G1-I3	179	85
V1-F3-R1-W1-G1-I3	203	98	V1-F3-R1-W1-G1-I3	196	98	V1-F3-R1-W1-G1-I3	178	98
V1-F1-R2-W1-G4-I2	201	108	V1-F1-R3-W1-G3-I2	195	101	V1-F1-R2-W1-G3-I2	177	99
V1-F1-R3-W1-G4-I2	199	109	V1-F1-R2-W1-G4-I2	192	108	V1-F1-R3-W1-G3-I2	175	101
V2-F1-R1-W1-G3-I2	196	109	V1-F1-R3-W1-G4-I2	190	109	V1-F1-R2-W1-G4-I2	171	108
V1-F2-R2-W1-G1-I3	195	113	V2-F1-R1-W1-G3-I2	187	109	V1-F1-R3-W1-G4-I2	170	109
V1-F1-R1-W1-G1-I1	91	113	V1-F1-R1-W1-G1-I1	88	113	V2-F1-R1-W1-G3-I2	167	109
V1-F1-R1-W1-G1-I2	87	114	V1-F1-R1-W1-G1-I2	84	114	V1-F1-R1-W1-G1-I1	80	113
V1-F1-R2-W1-G1-I2	84	141	V1-F1-R2-W1-G1-I2	80	141	V1-F1-R1-W1-G1-I2	76	114
V1-F1-R3-W1-G1-I2	83	143	V1-F1-R3-W1-G1-I2	80	143	V1-F1-R2-W1-G1-I2	73	141
V1-F1-R1-W1-G3-I1	82	145	V1-F1-R1-W1-G3-I1	79	145	V1-F1-R3-W1-G1-I2	73	143
V1-F1-R1-W1-G3-I2	78	146	V1-F1-R1-W1-G3-I2	74	146	V1-F1-R1-W1-G3-I1	70	145
V1-F1-R1-W1-G4-I2	76	154	V1-F1-R1-W1-G4-I2	73	154	V1-F1-R1-W1-G3-I2	67	146
V1-F2-R1-W1-G1-I3	73	159	V1-F2-R1-W1-G1-I3	71	159	V1-F1-R1-W1-G4-I2	65	154
V1-F3-R1-W1-G1-I3	73	173	V1-F3-R1-W1-G1-I3	70	173	V1-F2-R1-W1-G1-I3	64	159
V1-F1-R2-W1-G4-I2	72	182	V1-F1-R3-W1-G3-I2	70	175	V1-F3-R1-W1-G1-I3	64	173
V1-F1-R3-W1-G4-I2	72	183	V1-F1-R2-W1-G4-I2	69	182	V1-F1-R2-W1-G3-I2	64	174
V2-F1-R1-W1-G3-I2	70	183	V1-F1-R3-W1-G4-I2	68	183	V1-F1-R3-W1-G3-I2	63	175
V1-F2-R2-W1-G1-I3	70	187	V2-F1-R1-W1-G3-I2	67	183	V1-F1-R2-W1-G4-I2	62	182
V1-F2-R3-W1-G1-I3	70	188	V1-F2-R3-W1-G1-I3	67	188	V1-F1-R3-W1-G4-I2	61	183
V1-F2-R1-W1-G3-I3	64	191	V1-F2-R1-W1-G3-I3	61	191	V2-F1-R1-W1-G3-I2	60	183
V1-F2-R1-W1-G4-I3	62	200	V1-F2-R1-W1-G4-I3	59	200	V1-F2-R1-W1-G3-I3	55	191
V1-F1-R1-W1-G1-I1	57	204	V1-F1-R1-W1-G1-I1	55	204	V1-F2-R1-W1-G4-I3	53	200
V1-F1-R1-W1-G1-I2	54	205	V1-F1-R1-W1-G1-I2	52	205	V1-F1-R1-W1-G1-I1	50	204
V2-F1-R1-W3-G3-I4	52	225	V2-F1-R1-W3-G3-I4	49	225	V1-F1-R1-W1-G1-I2	48	205
V1-F1-R2-W1-G1-I2	52	233	V2-F1-R1-W4-G3-I4	46	234	V2-F1-R1-W4-G3-I4	45	250
V2-F1-R1-W4-G3-I4	49	234	V2-F1-R1-W3-G4-I4	43	234	V2-F1-R1-W3-G4-I4	42	250
V2-F1-R1-W3-G4-I4	47	234	V1-F1-R1-W2-G1-I4	42	242	V2-F1-R1-W4-G4-I4	39	258
V1-F1-R1-W2-G1-I4	43	242	V2-F1-R1-W4-G4-I4	40	242			
V1-F1-R1-W3-G1-I4	41	246	V1-F1-R1-W3-G1-I4	39	246			
V1-F1-R1-W4-G1-I4	40	254	V1-F1-R1-W4-G1-I4	38	254			
V2-F2-R1-W3-G3-I4	35	270	V1-F1-R1-W2-G3-I4	30	275			
V1-F1-R1-W2-G3-I4	32	275	V1-F1-R1-W3-G3-I4	27	278			
V1-F1-R1-W3-G3-I4	29	278						
V1-F1-R1-W4-G3-I4	28	286						
V1-F1-R1-W3-G4-I4	26	287						

[1] The definition of the measures' identifiers is given in Table 2, and cells color to indicate the system as:

Gas Boiler	ASHP	GSHP	Electric Radiator

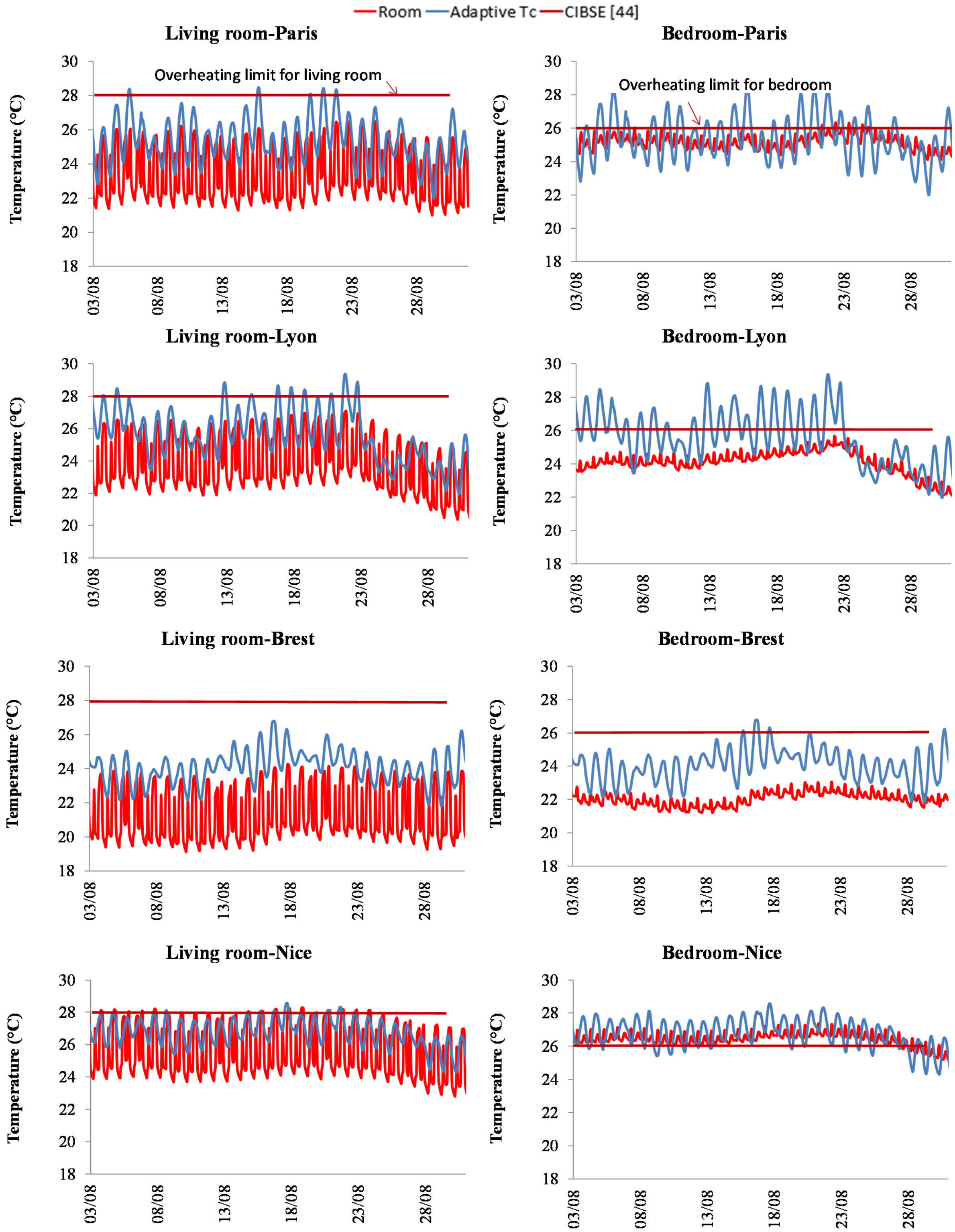

Fig. 10 Example of summer operative temperatures in the living room and bedroom for a most insulated and tight construction variant under the different climates

4. Discussion

Building energy optimization studies usually include a large size and wide ranges of parameters (typically ranges of continuous variables) that do not mind standardised elements provided by the construction trades. This, therefore, results in a mix of solutions which may assist tradesmen for designing and offering energy-efficient measures. However, the un-standardised elements cannot directly (or via practitioners) allow householders to confidently decide on the proper set of measures for immediate implementation. Furthermore, the mix between standardised and un-standardised variables can mislead the decision-making process. Therefore, in this work, the focus was on standardised measures offered in the French market to have direct impact on the decision-making process of selecting suitable retrofit measures for the French housing. The delivered energy, the quantity of interest for householders (i.e. used quantity for energy bills), was used with the energy and payback constraints. Realistic mortgage financial calculations were used in order to provide a reliable cost and payback analysis (easy to introduce to householders). The impact of each measure on energy saving was obtained with variance, when combined with other measures, to provide an understandable indicator for practitioners and householders on expected annual savings. The analyses showed that a 9 years loan period is not sufficient for most of the variants to provide payback. Such a loan offered in France, for home improvements, could only allow few interventions with gas boiler system to be economically viable. The assumed 15 years loan period with a cashback scheme could let other heating systems and wall insulation variants to be among candidate solutions. The wall insulation variants only got a few solutions that lied on the Pareto frontier (where the Parteo frontier is defined as the set of efficient solutions that consists of alternatives not dominated by any other alternative and lies on the solutions' frontier).

The impact of the used future energy prices (predicted price) was studied for the 15-years future average prices for an uncertainty band of ±10%. Fig. 11 shows the candidate solutions for +10% and -10% energy price on the right and left hand sides, respectively. As can be seen, the number of candidate solutions increased with the +10% increase and vice versa. The Pareto frontier also extends or shrinks up and down with the price increase or decrease. However, the obtained solutions on the frontier (Fig. 9) should, in best cases, remain optimum unless very dramatic changes could happen for the electricity price apart from oil and gas prices. It should be also noted that, the use of solar or wind renewable energy for onsite generation was not in the scope of this study and may have an impact on optimum solutions.

In the approach of this study, the heating systems were not simulated with the DTM but were accounted for using average annual standard efficiencies. This was for two reasons: a) to enforce standard relevant efficiencies to provide useful comparable results on systems' performance; b) to reduce the simulation time as simulating the system could significantly increase the runtime. The candidate solutions for Paris included only few oil boiler variants that were accompanied with wall insulation. Similarly, few electric heating variants with wall insulation were among the candidate solutions for Paris and Lyon. The vast majority of candidate solutions included gas boiler systems accompanied with other different fabric retrofit measures. This is mainly due to its low running cost and relatively higher efficiency compared to oil boiler. The ASHP system, as assumed to be used with low-temperature hydronic central heating systems, and accompanied with minor fabric changes, seemed to be a favourable choice (middle of the Pareto Frontier) for both objectives of energy and cost efficiency under the climate of Paris, Lyon and Brest. Further, although the ASHP was not among candidate solutions for Nice, it could be an optimum choice in case the cooling energy was accounted for in these analyses. The candidate solutions for Nice only included gas boiler accompanied with ground slab retrofit plus the assumed improvement of airtightness. The minimization of cooling energy and the use of a more representative extreme summer data set (or future weather data) may be necessary to reiterate the analysis for Nice.

Limitations

This study introduced a simple optimization approach using exhaustive-search with constraint-based filtering technique to find optimum market solutions with available financing options in France. The limitations of this study that needs to be highlighted:

1- The so-called design-summer-year weather file was not used for the overheating analysis instead of the typical-reference-year. A mix of these two files or a break-down of running periods are possible solutions to investigate in future work, especially for the case of Nice.

2- The assumed ground temperatures may have contributed to a higher impact shown by the floor insulation variants, especially for the case of Nice.

3- It is perhaps very important to account for the cooling energy, in case of Nice, with the minimisation problem of the objective function.

4- Studying renewable energy production options among retrofit variants is necessary for the concept of nearly-zero-energy buildings, in future work.

5- This study provided quantitative analysis and did not account for micro-economic rebound effects [46] resulted from behavioural comfort take-back and an increase in energy usage. Perhaps the loan amortization from energy-saving adopted in this study can help with this effect.

Recommendations

1- Practitioners and researchers, through many ongoing research projects and in contact with householders, need to use simple and reliable tools to monetize and demonstrate the benefits brought by the retrofit process.

2- Speeding up the retrofit process of the housing stock needs better financing options and other governmental incentives to help householders with this difficult decision.
3- Reaching deep renovation level (i.e. 60-90% or 75% less than current energy usage) for these categories of domestic old buildings is possible with a more efficient system such as ASHP or with wall insulation. Wall insulation retrofit can be a lengthy and invasive process compared to the option to change to ASHP, therefore, more governmental support is needed to encourage wall insulation options.

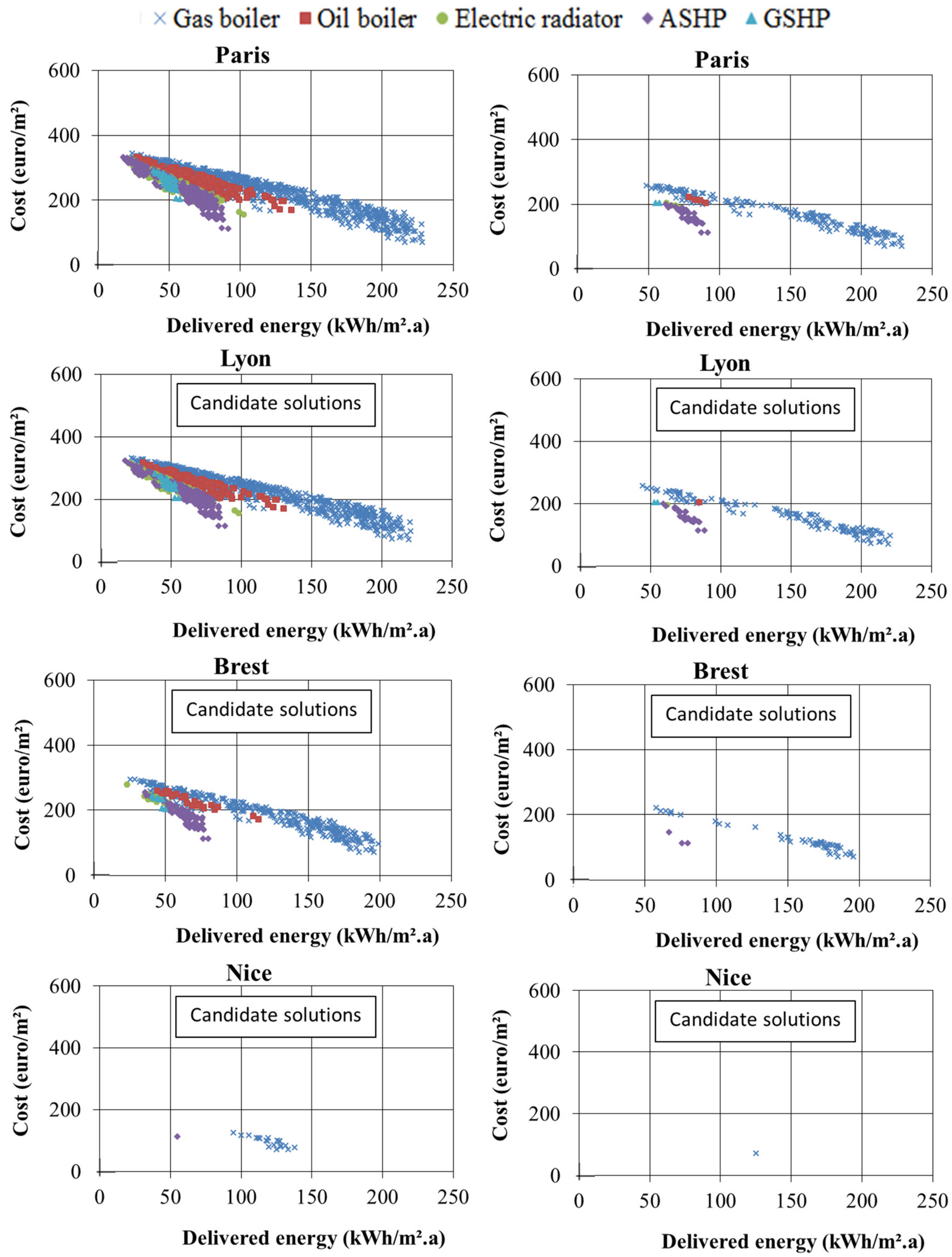

Fig. 11 Candidate solutions for the 4 cities with change in future energy prices +10% (left) and -10% (right)

5. Conclusions

This study presented a simple and practical optimization approach (exhaustive search with a filtering technique) that is focused on most popular retrofit measures (standardised) introduced for the French market. This included objectives of energy and cost efficiency subject to minimum limit of energy-saving, payback, and overheating risk constraints. The study aimed at supporting the decision-making process in selecting retrofit measures for the French housing stock, built before the year 1974. The approach introduced in this study can be implemented by French practitioners on a regular basis (updated with market measures and prices) to provide a helpful guidance on the retrofitting process, i.e. in favour of end-consumers or householders.

The impact of each retrofit measure on heating energy consumption was analysed independently under all variants' permutations. The offered home improvement loan in France for 9 years amortization period does not allow any deep renovation measures.

The external wall insulation had the highest impact, as would be expected, with an energy saving of 100 kWh/m^2.a.

The candidate solutions that fulfilled the energy saving, payback and comfort constraints varied with the different climates, where it included only a few solutions for Nice. The upper bound of optimum investement cost varied from 80 and 290 €/m^2 for Nice and Paris respectively. The energy saving objective was based on the delivered energy which is the energy quantity that householders are charged for in their energy bills. The number of candidate solutions varied significantly for the different climates. Candidate solutions on the Pareto frontier (the set of efficient solutions that is not dominated by any other alternative and lies on the solutions' frontier) did not include any oil boiler solutions. A few solutions were present on the Pareto frontier that included wall insulation accompanied with direct electric heating and ASHP system for Paris, Lyon and Brest cases. Several variants lied on the middle of the Pareto frontier comprised ASHP system with minor fabric change for Paris, Lyon and Brest. The frontier solutions also included a few GSHP system variants with very minor fabric retrofit measures for Paris and Lyon. An unceratinity band of ±10% of the estimated future energy prices was examined and showed that the obtained solutions on the frontier should, in normal situations, remain optimum.

The minimization of cooling energy and further overheating analysis may be necessary to implement for the Nice case. Future work may include further development of methods and scope.

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Appendix

This appendix provides references of the gathered information including prices of the different retrofit measures. These are listed in Table A.1 and Table A.2.

Table A.1 References of the retrofit measures information used in this study

Retrofit variable	Reference of used information
MV	1- http://www.prix-construction.info/renovation/ 2- https://www.travaux.com/guide-des-prix/
Window type	1- http://www.prix-construction.info/renovation/ 2- https://www.travaux.com/guide-des-prix/
External Wall and Roof-Loft	1- http://www.prix-construction.info/renovation/ 2- https://www.travaux.com/guide-des-prix/Labour costs were obtained from: 3- ANAH (Agence nationale de l'habitat), nd, 'Prix indicatifs et critère de Choix'; available at: http://www.anah.fr/fileadmin/anahmedias/eqtor/pdf/prix_indicatifs.pdf
Ground slab	1- http://www.prix-construction.info/renovation/ 2- https://www.travaux.com/guide-des-prix/ 3- Labour costs were obtained from: ANAH (Agence nationale de l'habitat), nd, 'Prix indicatifs et critère de Choix'; available at: http://www.anah.fr/fileadmin/anahmedias/eqtor/pdf/prix_indicatifs.pdf
Air-tightness	http://www.solagro.org/site/im_user/0278_$_11etancheite_air.pdf

Table A.2 References for the used heating systems and energy prices

	Reference prices
Oil boiler Gas Boiler Electric radiators ASHP& GSHP	*Sources of data are coming from BatiChiffrage 2018 (https://chiffrage.batiactu.com/)*
Energy prices main source	*Arrêté du 15 septembre 2006 relatif au diagnostic de performance énergétique pour les bâtiments existants proposés à la vente en France métropolitaine (Modifié par Arrêté du 1er décembre 2015) (https://www.legifrance.gouv.fr/affichTexteArticle.do;jsessionid=7BBCB2F1DDFE51B1EEB11339DB0D5B0E.tplgfr35s_3?idArticle=LEGIARTI000031582863&cidTexte=JORFTEXT000000788395&categorieLien=id&dateTexte=*