Energy performance analysis and low carbon retrofit solutions for residential buildings

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Abstract. The aim of this paper is to investigate the energy performance of residential buildings, through a case study of a typical domestic house located in Thessaloniki, Northern Greece. The building’s energy performance is simulated and analysed using the DesignBuilder software. The study then performs a parametric analysis, in which deviation in various parameters is compared against the current situation in the thermal, cooling load and total energy requirements. The significance of changing each parameter is evaluated by considering the energy balance. Finally, the study uses the Analytical Hierarchy Procedure (AHP) to choose the best sustainable retrofit option in order to reduce the carbon footprint in a domestic house. The alternatives considered are sealing the building envelope (installing cavity-wall insulation), on-site energy generation (solar PVTs), installation of energy efficient appliances, and home monitoring with smart meters. The procedure suggests a solution that best meets the criteria of cost, greenhouse gases emissions reduction, and ease of installation. The case study suggests that smart meters monitoring is the best option, followed by cavity-wall insulation.

1. Introduction

The shortage of energy resources combined with the increasing demand of energy consumption compose the well-known “energy problem”. As the world’s population is over 7 billion, the challenge of meeting global energy needs is as critical as ever. The challenge ahead is not only to supply energy to an ever-increasing demand; but also achieve this in a globally fair fashion. It is estimated that if everyone lived as the average EU citizen, 2.8 Earths would be needed to sustain the requirements for natural resources generated by such lifestyle (WWF, 2019). Continuing with a business as usual model would exceed what Earth can regenerate by 75% in 2020 (Global Footprint Network, 2019). At the same time, Earth’s natural resources for energy supply are depleting fast, with a slow rate of regeneration. Over-reliance on fossil fuels is not a viable long-term solution, and is also responsible for a plethora of problems, such as increased carbon emissions, air and water pollution, health problems, etc.

The building sector takes up an important share of the world’s energy consumption; according to European Commission, (2014) it accounts for approximately 40% of total energy consumption in the EU. Additionally, 36% of greenhouse gas (GHG) emissions is attributed to buildings. Along with the great share of the building sector in energy consumption, comes great potential in energy savings. Currently, about 35% of the EU’s buildings are over 50 years old, from which only 0.4-1.2% of it is renovated each year. An estimated 14 billion m² of existing buildings will need to be renovated over the next 30 years (Zhai, et al. 2011). Renovation of existing buildings can therefore lead to significant
energy savings and play a key role in the clean energy transition, as it could reduce the EU’s total energy consumption and CO2 emissions by 5-6% (European Commission, 2014).

It is thus concluded that sustainable and low energy building design is becoming urgently important. There is a growing need to address the inefficiencies in carbon-intensive buildings and invest in renewable energy solutions. Renewable tactics are proving to be a more sustainable, environmentally friendly, and many times cheaper solution. Progress towards sustainable buildings is advancing, and many policies have been set in global and national level. The UN has acknowledged this challenge ahead and has set a Sustainable Development Goal (SDG) for sustainable cities and green buildings by 2030. Adding to that, more and more countries are advocating for green buildings through national and international directives, certifications, CO2 reduction targets, minimum energy standards, and market incentives for building retrofits and renewables. The Energy Performance of Buildings Directive (EPBD) (2010/31/EU) and the Energy efficiency directive (2012/27/EU) are the main legislative framework aiming to improve the energy performance of buildings within the European Union. The directives contain a broad range of policies and guidelines for existing building stock and new construction. For instance, all new buildings are required to be nearly zero-energy buildings (NZEB) as of 31 December 2020, meaning that their low energy requirements will come mostly from renewable energy sources. In addition to these requirements, EU countries must make energy efficient renovations to at least 3% of the total floor area of buildings owned and occupied by central government. Regarding long-term strategies, EU has set an aim of decarbonising the national building stocks by 2050, with indicative milestones for 2030, 2040 and 2050. Additionally, these directives include a common European scheme for rating the energy performance of buildings, in a way that allow cross-national comparisons. Finally, energy performance certificates must be issued when a building is sold or rented, and inspection schemes must be established (European Commission, 2019).

Greece was the first EU Member State that was condemned by the Court of Justice of the European Union for not having brought into force laws and regulations necessary to comply with EPBD. EPBD was enacted officially by national law in 2008 with the “Regulation on the Energy Performance of Buildings – KENAK”. KENAK is the main Hellenic framework which sets guidelines for the energy performance of buildings, outlines the general calculation method of buildings energy assessment, introduces the use of a reference building for benchmarking, and the minimum energy performance requirements. The reference building is a copy of the studied building with the same architecture, geometry, orientation, use and operation, at the same location, but it automatically adapts the characteristics of the building elements and electromechanical (E/M) installations in accordance to the minimum energy efficiency requirements of KENAK. Then KENAK compares the studied building to the reference building in terms of primary annual energy consumption normalized per unit floor area (kWh/m²). Based on that comparison, the studied building is classified to 9 categories, ranging from A+, which is the best in terms of energy performance to G, which is the worst. The reference building in KENAK’s methodology is by definition class-B, and as of October 2010, all new buildings and existing ones that undergo major renovations must be at least class-B (Balaras et al., 2011).

Nevertheless, despite the recent advancements, energy efficient policies need to improve drastically in order to address the growing challenge of energy crisis. In order to meet the Paris Agreement and keep average global temperature increases below 1.5°C, we need to stop using up to 80% of our fossil fuel reserves – but globally, our reliance on fossil fuels is increasing (Ecotricity, 2019). To meet the SDG goals by 2030, building envelope measures – including near zero energy buildings construction and deep energy renovation of existing buildings – need to increase 3.5-fold (IEA, 2019). Energy policies often prove to be inefficient, too slow, or lack market incentives, which deters widespread adoption in case of non-mandatory policies. Even more they can be non-existent; two-thirds of countries around the world lacked mandatory building energy codes in 2017 (IEA, 2019).

This study aims to underline the importance of incorporating sustainable techniques into building construction and operation, in order to reduce the energy consumption of the building sector. It tries to fill a knowledge gap in understanding how energy is distributed at a domestic house and which retrofits
have the most potential in energy and carbon savings. It aims at producing solutions that significantly reduce the impact of built environment on the planet, whilst maximising occupant wellbeing. Recent policies are calling for a shift in traditional building design, and the need to include renewable energy solutions. Radical changes must be made in the way engineers plan the built environment in order to lessen fossil fuel reliance. It has become increasingly important to study options for reducing energy consumption and carbon emissions of buildings and to apply these findings to improve efficiency and mitigate climate change.

2. Methodology

This paper investigates the energy consumption of residential buildings, through a case study in Thessaloniki, Greece. For this purpose, a typical 2-storey house is used. Its energy performance is simulated using the software package DesignBuilder and its energy balance is calculated. Next, it is examined how changes in a number of parameters impact the energy balance of the house. Conclusions are drawn on how appropriately selecting or modifying these variables can help reduce the energy consumption. Next, 4 retrofit options are considered in order to choose the most sustainable solution to reduce the carbon footprint in domestic housing. The alternatives considered are sealing the building envelope (installing cavity-wall insulation), on-site energy generation (hybrid PVTs), installation of energy efficient appliances, and home monitoring with smart meters. The criteria used to make the choice are cost, reduction in greenhouse gases (GHG), and ease of installation. This multi-criteria decision-making analysis is performed using the Analytical Hierarchy Procedure (AHP).

2.1 Building energy performance analysis

2.1.1 Building characteristics. The building used for this paper is a typical residential building found in Thessaloniki, northern Greece. It is a 2-storey building with pilotis and a flat roof and it has 1 apartment in each floor. Its west and east side are adjacent to other buildings and it thus assumed that there is no heat exchange in these facades. The north and south side are free, with only the north side receiving significant shading from opposite buildings. The buildings across the south side are located in a distance greater than 20m; no shading is taken into consideration. The typical floor layout is shown in the following Figure 1.

The studied building complies with the minimum requirements of KENAK; it is classified as class-B. KENAK sets specifications for the building’s envelope by introducing lower heat transfer coefficients (U-values). The lower the U-value, the more slowly heat is transmitted through it, and so the building fabric performs as an insulator. The minimum specifications for the building’s E/M installations include heat recovery by at least 50% in central air-handling-units with fresh air supply greater than 60%, proper thermal insulation of all heat and cold distribution pipes, use of outdoor temperature compensation systems, hot water recirculation with variable speed pumps, coverage of the hot water load by 60% from renewable energy sources (RES), thermostatic control in different thermal
zones, independent heating and cooling with heat meters, etc (Balaras et al., 2011). For the purpose of this study, the thermal insulation used throughout the building is 7 cm of extruded polystyrene (XPS) positioned on the outside layer of wall sections, and the openings are set as double glazing with 13 mm void of air and 4 mm thick frame.

2.1.2 Energy modelling. Building energy modelling is a useful tool gaining popularity, since it offers the ability to adequately address building performance problems and suggest retrofits to reduce the energy requirements. Lately, with the advancement of computers, numerous studies have been performed on building energy simulation, using various techniques. This study uses the software ‘DesignBuilder’, a general-purpose simulation software that analyses the environmental performance of buildings. It can provide a fully integrated performance analysis including energy and comfort, HVAC, daylighting, CFD, BREEAM/LEED credits, and reports complying with several national building regulations and certification standards. DesignBuilder enables the user to compare the performance of design alternatives, optimise the building at any stage, and assist with sustainable building design and assessment. The simulations run according to EnergyPlus simulation engine, which is a widely used integrated building simulation programme. Its simplified model employs the user’s input to calculate the building’s thermal response, taking into account the building’s geometry, materials, equipment, location, shading, and daylight (DesignBuilder, 2019).

DesignBuilder uses activity templates as a source of default activity (building usage) data for the model. The data covers occupancy, equipment usage, suitable design internal temperatures, illuminance levels, and ventilation rates per person. For this study, we assume that most occupants are out of the house in the morning and return in the afternoon, thus the occupancy density (people/m²) varies according to the time of the day. The occupancy model set is significant since it determines the heat input of the building from occupancy gains. Next, we have to determine the heating, ventilation and air conditioning systems (HVAC) of the building. At this first stage of the study, no natural ventilation is employed. The heating system uses natural gas and the cooling electricity, and a schedule for their use is set based on the season, the occupancy, and the needs of the building. We also define the heating and cooling setpoint temperature (i.e. the ideal temperature, setting of the thermostat) and setback temperature (i.e. temperature during unoccupied periods to avoid overheating or over-cooling). Choosing an appropriate setback temperature can help avoid condensation, frost damage and reduce peak heating/cooling requirements. The building is heated, except for the stairway, elevator and air shaft, pilotis, and basement. As a result, the building has thermal bridges, which are areas with higher thermal conductivity than the surrounding materials, creating a path of least resistance for heat transfer. Thermal bridges are typically found where there is either a break in the insulation, less insulation or the insulation is penetrated by an element with a higher thermal conductivity. Research has shown that thermal bridging can be responsible for up to 30% of a dwelling's heat loss, as well as contribute to condensation and mould growth (BRE Group, 2019). The heat loss associated with thermal bridges is expressed as a linear thermal transmittance (Ψ-value), which is set according to different types of thermal bridges, based on the guidelines of KENAK. Regarding the lighting of the building, there is a lighting sensor in each apartment, which appropriately reduces the lights when there is sufficient daylight. Finally, we have to determine the infiltration, i.e. the involuntary air introduction through cracks and pores of the building envelope, since it is a significant parameter in the building’s energy performance.

2.2 Parametric analysis

Once the energy performance of the building is simulated and its consumption examined, we proceed to look at some input parameters that can be changed in order to reduce the energy consumption. For this purpose, we examine 6 parameters: orientation, thermal insulation layer position, thermal insulation layer thickness, glazing type, infiltration, and natural ventilation. We examine various values of these parameters and for each value we calculate the total energy requirements of the building. As a result, we can determine which is the optimal value of all these parameters that leads to the lowest possible energy load. The values examined for 3 parameters are presented in Table 1. Regarding the thermal
insulation position, we examined positioning it on the inside and outside layer of the wall section. Concerning the glazing type, we examined standard glazing (with an emissivity factor of $e=0.84$) and low-\textit{e} glazing ($e=0.04$). Finally, in relation to natural ventilation we examined a natural ventilation strategy which is activated based on the external temperature, internal temperature inside the building, and their temperature difference.

Table 1: Range of Values examined in the Parametric Analysis

| Parameter               | Maximum | Minimum | Interval |
|-------------------------|---------|---------|----------|
| Orientation             | $0^\circ$ | $360^\circ$ | $15^\circ$ |
| Thermal insulation thickness | $0$ cm  | $10$ cm  | $1$ cm   |
| Infiltration            | $0$ ac/h | $1.6$ ac/h | $0.1$ ac/h |

2.3 Low carbon retrofit solutions

Since the building sector accounts for $36\%$ of greenhouse gas emissions in the EU, investigating how we can reduce the carbon footprint of domestic buildings is becoming more and more important. For this study we aim to choose the best sustainable retrofit option to reduce the carbon footprint in a typical house. The criteria that will be examined are cost (capital and maintenance), reduction in greenhouse gases (GHG) emissions, and the ease of installation. The alternatives that will be considered are 1) sealing the building envelope (installing cavity-wall insulation), 2) on-site energy generation (solar PVTs), 3) installation of energy appliances, and 4) home monitoring with smart meters indicating performance and usage. In the end, the option which best meets most of the criteria will be selected.

Sealing the building envelope is achieved by installing cavity-wall insulation, which is often one of the most cost-effective measures to save energy in a domestic building. It should pay for itself in four years or less through the savings it’ll make on the heating bills. Energy generation is examined by installing hybrid photovoltaic thermal (PVT) panels, which integrate a heat exchanger and cooling fluid. They capture solar energy using PV technology combined with simple heat exchangers, generating a better combined-efficiency than much high-tech PV panels (Meggers et al., 2012). PVT panels are around $12\%$ more expensive to install than typical PV panels; nevertheless, they are more efficient and thus, are expected to pay for themselves in less than 3 years. The next alternative is replacing ordinary appliances (dishwasher, washing machine, refrigerator, laptop, television) with more efficient ones with high energy rating. Finally, we examine smart meters, i.e. gas and electricity meters that show how much energy is used in real time. They automatically send the readings, which can easily be accessed by dwellers using an interactive online tool. Smart meters are paving the way for a more energy efficient future, as they make it easier to identify situations of high energy consumption and find ways to mitigate it.

For the analysis, the Analytic Hierarchy Process (AHP) will be used, which is an effective tool for providing a framework for decision making. The process evaluates a set of possible courses of action across a set of criteria. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, AHP helps to capture both subjective and objective aspects of a decision. In addition, it incorporates a useful technique for checking the consistency of the decision maker’s evaluations, thus reducing the bias in the decision-making process (Saaty, 1987). The consistency ratio (CR) has been checked throughout the study and has been found lower than $10\%$, which shows that the inconsistency is acceptable.

The analysis commences by stating the objective, which is finding the best retrofitting solution to reduce the carbon footprint in domestic housing. Next, the criteria are compared in pairs, allocating an evaluation weight on each pair, showing their relative importance in the decision-making process. The
weights are codified on a 9-point intensity scale, which reflect the relative strength of preferences with 1 meaning that two elements have equal importance and 9 that one element is extremely more important than the other. Cost is chosen to be the most important factor; though only slightly more important than reduction of the GHG emissions. The first barrier why building owners are hesitant to upgrade their properties for energy efficiency is the initial cost of retrofitting, even with the knowledge that over time the savings from reduced operational costs far outweigh the upfront investment (Jesus, 2014). So, the final selection would be a trade-off between cost (capital and maintenance cost) and potential benefits. Homeowners will also consider ease of installation and want to mitigate any upheaval. However, this is a much less significant factor compared to the other two mentioned above. Using the same methodology, we compare the sub-criteria of capital and maintenance cost. The capital cost is moderately more important than the maintenance cost since building owners will not perform a retrofit if the capital cost is high. The maintenance cost is spread over a bigger period of time, so they will not attribute as much importance to it. The generated pairs and weights are listed in Table 2:

| Criterion A         | Criterion B                  | More Important | Intensity |
|---------------------|------------------------------|----------------|-----------|
| Cost                | Reduction in GHG emissions   | A              | 2         |
| Cost                | Ease of installation         | A              | 8         |
| Reduction in GHG    | Ease of installation         | A              | 7         |
| emissions           |                              |                |           |
| Capital Cost        | Maintenance Cost             | A              | 4         |

Then the weights of the 3 criteria are put in a 3x3 comparison matrix, which is later normalised, and the Eigen Vector is calculated. The same procedure is followed for the 2 sub-criteria as well. In the end, we have the final weights, or global priorities of all the criteria, which range from 0 to 1 depicting their importance, as can be seen in Table 3:

| Criterion              | Priority  |
|------------------------|-----------|
| Capital Cost           | 0.467     |
| Reduction in GHG       | 0.354     |
| emissions              |           |
| Maintenance Cost       | 0.117     |
| Ease of installation   | 0.062     |
| Sum                    | 1.000     |

Next, we move on to the pairwise comparison of all the alternatives. For a fixed criterion, AHP assigns a score to each option. The higher the score, the better the performance of the alternative with respect to the considered criterion. The score is codified again on a 9-point intensity scale. Appendix A, B, C, and D present the pairwise comparison of the alternatives in terms of capital cost, maintenance cost, reduction in GHG emissions, and ease of installation respectively. Finally, AHP combines the criteria weights and the options scores, and determines a global score for each option, and a consequent ranking. The global score for a given alternative is the weighted sum of the scores it obtained with respect to all the criteria, and it indicates its performance with respect to the ultimate objective of the analysis. The alternative with the highest weight coefficient value should be taken as the best alternative (Pohekar S. D.; Ramachandran, 2004).
3. Results

This section examines the energy performance of the studied building. First, the energy requirements of the building are presented. Next, the results of the parametric analysis are shown. Finally, the results of the AHP are presented and the best sustainable option to reduce the carbon footprint of a house is discussed.

3.1 Energy performance

The energy loads are averaged per building area (KWh/m²). The total energy requirements are shown in Figure 2. The annual heating requirement is 52 KWh/m² and is the biggest energy load of the building, followed by the equipment load. The cooling load is rather low, as it accounts for 30% of the total requirements. A reason for this is that the cooling system has been set to work only a few hours a day; far less than the hours the heating system is on. The lighting load is also comparatively insignificant because the house has an automated system to reduce the lights when there is sufficient daylight.

The energy balance diagram of the building is shown in Figure 3. The thermal gains consist of lighting, equipment use, occupancy, solar gains, and heating loads. The building receives the majority of its thermal gains (70%), equally from the heating system and solar irradiation. Heat from the sun absorbed and diffused in the building is significant, considering there are many south-facing openings at the house. The thermal losses consist of the cooling load and infiltration, i.e. involuntary air introduction typically through cracks in the building envelope. Infiltration losses account to 30% and can substantially affect the energy performance of the building. Note that the chart is not balanced; the values do not add up to zero. This is because DesignBuilder does not calculate the heat flux of the shell. These are the losses due to conduction and thermal radiation of the transparent and opaque elements of the shell, which exact value is quite high, at 91 KWh/m².
3.2 Parametric Analysis

Moving on to the parametric analysis, orientation is the first parameter examined. Orientation mostly determines the thermal solar gains. As it can be seen from Figure 4, the optimal orientation for the specific building configuration is the current one, since it maximizes the south-facing openings area. South facing windows provide direct sunlight into the building in winter, reducing the heating requirements. In summer, the solar angle is higher, meaning that the sun can be easily shielded through blinds or a horizontal canopy over the window.

Next, the impact of the thermal insulation layer is investigated. It is found that in the studied building the position of the insulation layer does not significantly alter the results. The total energy requirements are similar for layers positioned at the inside and outside area of the wall sections. Nonetheless, the thickness of the layer is important, and its impact is shown in Figure 5. As expected, the energy load decreases as the insulation thickness increases. However, this reduction becomes non-significant as we move over insulation layers of 10 cm thick. Having an insulation layer of 10 cm instead of 7 cm reduces the energy consumption only by 6%, whereas it increases significantly the price. As a result, there is an optimal insulation thickness that minimises the energy requirements, which is a combination of energy savings and cost. Very thick insulation layers are not ideal because they might protect the building in winter and reduce the heating load, but they also trap heat in the summer and increase the cooling requirements.

Glazing type is the next parameter examined. We investigate the energy performance of the building with standard glazing and with glazing with low emissivity. Low-e windows minimize the amount of light of certain spectra that can pass through glass, without compromising the amount of visible light that is transmitted; thus, they reduce solar gains. Indeed, it is found that low-e glazing reduces the cooling load in the summer by 35%. However, in winter the reduced solar gains increase the heating requirements by 18%, and the total energy requirement by 7%. When choosing glazing type, the
objective is to maximize winter solar gains and minimise the summer ones. As a result, since different windows have different orientation and receive different solar loads, they should have different glazing type. For example, applying low-e coating is beneficial to windows that mostly determine the summer solar gains.

We then study the impact of infiltration on the building’s energy performance. Increasing the air renewal rate has different effects in summer and in winter; but it generally increases the total energy requirement. A building with more pores in the envelope that allows double the air change rate from the studied building has increased energy loads by 31%. Nevertheless, it reduces the cooling load by 7%, since it allows the release of high temperatures in the summer. Finally, we employ a natural ventilation strategy and compare it with the original model. Just like infiltration, natural ventilation works differently on different seasons. As expected, it lessens the cooling requirements by 25%, but augments the heating load, and subsequently the total energy load. The ventilation schedule set is activated based on the external temperature, internal temperature, and their temperature difference. Applying a more thorough ventilation strategy might help avoid unnecessary use of it and increased heating loads. It is also deduced that natural ventilation is more effective in areas with greater cooling requirements.

3.3 Low carbon retrofits

In this section, we present the final stage of the decision-making process, which is the actual choice of a retrofit solution to reduce the carbon footprint of residential buildings. Following step-by-step the Analytic Hierarchy Process, we eventually obtain for each decision alternative an overall weight coefficient, which indicates its performance with respect to the ultimate objective of the analysis. The following table illustrates the results of the process.

| Alternatives                        | Overall Score |
|-------------------------------------|---------------|
| Home monitoring with smart meters   | 0.326         |
| Sealing the building envelope       | 0.254         |
| On-site energy generation           | 0.216         |
| Energy efficient appliances         | 0.203         |

Home monitoring with smart meters has obtained the highest total rating with respect to the objective, accounting for 32.6%. This alternative involves the least capital cost and zero maintenance cost (included in bills). Thus, and despite the fact that it does not have the biggest contribution to GHG emissions savings, the installation of smart meters constitutes the most favourable option. Research suggests that smart meters have the potential of cutting down 25% of CO2 emissions in a house (Smart Energy GB, 2019). Sealing the building envelope with cavity wall insulation has achieved the second-best position in the ranking, rated at 25.4%. The main reasons for its high performance are its relatively low capital cost, its zero maintenance cost, combined with its potential for moderate savings of CO2 emissions, while it requires a quite quick and easy installation process of minor disturbance for the household. On-site energy generation by Photovoltaic Thermal (PVT) panels ranked third at 21.6%, which is the most expensive option, but it achieves the biggest CO₂ savings. Finally, the least preferable option is installing energy efficient appliances, since it is less effective and has the biggest maintenance cost of all the alternatives.

4. Conclusion

This paper addresses the energy performance of residential buildings. A typical domestic house in northern Greece has been simulated using the DesignBuilder software in order to investigate its energy behaviour. Then, we examined how changes in a number of parameters affected the energy requirements
of the house. Studying in detail how these variables affect the energy performance can provide insights on how to properly modify them to improve energy efficiency and mitigate climate change. Finally, 4 retrofit alternatives were considered in order to choose the best option to reduce the carbon footprint of a typical residence.

As expected, heating requirements take up the biggest share of energy consumption. Heat losses from involuntary air infiltration were found to be significant. As the analysis suggests, when designing a sustainable house, choosing the appropriate orientation in the first stages of the design can make an important difference in its energy performance. Insulation is also important, but too thick insulation layers can have adverse effects in the summer. Low e glazing generally performs better, however it may not be suitable for every opening in a house. Finally, introducing natural ventilation can have multiple benefits, such as reduced cooling loads, as well as enhanced air quality.

Regarding retrofits for low-carbon housing, according to the results of this study the best option is home monitoring with smart meters, followed by cavity-wall insulation, and PVT panels. It is concluded that just monitoring the energy use in houses can pave the way for a low-carbon future. Sending real time information can enhance the homeowners’ awareness over their energy use and help them manage it in the most efficient way. However, it becomes clear that the results are largely based on the individual’s preferences, and on the importance we accord to each criterion. Nonetheless, AHP can assist people in making decisions, and can be helpful as a screening tool when the requirement is to refine a short-list of options for subsequent, more detailed appraisal and investigation.

Overall, this study has proven that changing a few design parameters can have a substantial impact on the energy performance of residential buildings. Moreover, it has shown that home monitoring with smart meters is the most preferable option to reduce the carbon footprint of a home, when we take into account the specific criteria mentioned above. Therefore, this work and further studies can be of interest to engineers, designers, and policy makers, for the development of sustainable building strategies, as well as for better understanding the energy performance of houses.

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6. References

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7. Appendices
Appendix A: Pairwise evaluation of alternatives based on capital cost

| Comparison                        | Capital cost (£) | Better capital cost | Under/Over average capital cost (£) | Better option | Intensity | Rationale                                                                 |
|-----------------------------------|------------------|---------------------|-----------------------------------|---------------|-----------|---------------------------------------------------------------------------|
| A                                 | B                | A                   | B                                 | A             |           |                                                                            |
| Sealing the building envelope     | On-site energy generation | 475 | 10,000 | A | 9,525 | 21.05 | 2,801 | 6,725 | A | 9 | B is a lot over average cost |
| Sealing the building envelope     | Energy efficient appliances | 475 | 2,500 | A | 2,025 | 5.26 | 2,801 | 776 | A | 5 | Both under average cost; strong cost advantage for A |
| Sealing the building envelope     | Home monitoring with smart meters | 475 | 130  | B | 345  | 3.65 | 2,801 | 3,146 | B | 2 | Both under average cost; slight cost advantage for B |
| On-site energy generation         | Energy efficient appliances | 10,000 | 2,500 | B | 7,500 | 4.00 | 6,724 | 776 | B | 4 | A cost is 4 times the cost of B |
| On-site energy generation         | Home monitoring with smart meters | 10,000 | 130  | B | 9,870 | 76.92 | 6,724 | 3,146 | B | 9 | A is a lot over average cost |
| Energy efficient appliances       | Home monitoring with smart meters | 2,500 | 130  | B | 2,370 | 19.23 | 776  | 3,146 | B | 7 | Both under average cost; very strong cost advantage for B |
Appendix B: Pairwise evaluation of alternatives based on maintenance cost

| Comparison | Maintenance cost (£/year) | Better maintenance cost | Under/Over maintenance cost (£/year) | Better option | Intensity | Rationale |
|------------|---------------------------|-------------------------|--------------------------------------|----------------|----------|-----------|
| A          | B                         | A 35 35 ∞               | 26.25 8.75                           | A              | 7        | No cost for B; B is strongly favored over A |
| Sealing the building envelope | On-site energy generation | 0 35 | A 35 ∞ | 26.25 8.75 | A | 7 | No cost for B; B is strongly favored over A |
| Sealing the building envelope | Energy efficient appliances | 0 70 | A 70 ∞ | 26.25 43.75 | A | 9 | No cost for B; B is extremely favored over A |
| Sealing the building envelope | Home monitoring with smart meters | 0 0 | equal 0 ∞ | 26.25 26.25 | equal | 1 | Both options have equal maintenance cost |
| On-site energy generation | Energy efficient appliances | 35 70 | A 35 2.00 | 8.75 43.75 | A | 4 | Both costs over average; moderate advantage for A |
| On-site energy generation | Home monitoring with smart meters | 35 0 | B 35 ∞ | 8.75 26.25 | B | 7 | No cost for B; B is strongly favored over A |
| Energy efficient appliances | Home monitoring with smart meters | 70 0 | B 70 ∞ | 43.75 26.25 | B | 9 | No cost for B; B is extremely favored over A |
Appendix C: Pairwise evaluation of alternatives based on reduction in GHG emissions

| Comparison | Reduction un CO₂ emissions (kg/year) | Better CO₂ savings amount (kg/year) | More CO₂ savings by ratio | Under/Over average CO₂ savings (kg/year) | Better option | Intensity | Rationale |
|------------|-------------------------------------|------------------------------------|---------------------------|------------------------------------------|---------------|-----------|-----------|
| A          | B                                   | A                                  | A                         |                                          |               |           |           |
| Sealing the building envelope | On-site energy generation | 670 | 2,000 | B | 1,330 | 2.99 | 510 | 820 | B | 6 | B significantly above average; strong savings advantage |
| Sealing the building envelope | Energy efficient appliances | 670 | 1,700 | B | 1,030 | 2.54 | 510 | 520 | B | 5 | B significantly above average; strong savings advantage |
| Sealing the building envelope | Home monitoring with smart meters | 670 | 350 | A | 320 | 1.91 | 510 | 830 | A | 3 | Both under average savings; slight advantage for A |
| On-site energy generation | Energy efficient appliances | 2,000 | 1,700 | A | 300 | 1.18 | 820 | 520 | A | 2 | Both over average savings; slight advantage for A |
| On-site energy generation | Home monitoring with smart meters | 2,000 | 350 | A | 1,650 | 5.71 | 820 | 830 | A | 9 | A significantly above average; strong savings advantage |
| Energy efficient appliances | Home monitoring with smart meters | 1,700 | 350 | A | 1,350 | 4.86 | 520 | 830 | A | 8 | A significantly above average; strong savings advantage |
Appendix D: Pairwise evaluation of alternatives based on ease of installation

| Comparison                          | Ease of installation                                                                 | Better option | Intensity | Rationale                                                                 |
|-------------------------------------|--------------------------------------------------------------------------------------|---------------|-----------|---------------------------------------------------------------------------|
| Sealing the building envelope       | Requires a professional installer for about a couple of hours. Usually (when cavity walls), it is barely disruptive. | A             | 7         | B takes significantly more time, and is much more disruptive.             |
| On-site energy generation           | Requires a professional team for about two days. Need for access inside the house.   |               |           |                                                                           |
| Sealing the building envelope       | Requires a professional installer for about a couple of hours. Usually (when cavity walls), it is barely disruptive. | B             | 3         | B can be done by the owner; moderate advantage over A.                    |
| Energy efficient appliances         | Installation is easy and can be done by the homeowner, without technical assistance. |               |           |                                                                           |
| Sealing the building envelope       | Installation, done by a professional takes up to 2 hours. Minor disturbance for the owner. | B             | 2         | Both options take approximately the same time; B is slightly favored, because under some circumstances A can be more disruptive. |
| Home monitoring with smart meters  |                                                                                      |               |           |                                                                           |
| Sealing the building envelope       | Requires a professional installer for about a couple of hours. Usually (when cavity walls), it is barely disruptive. | B             | 9         | B can be done by the owner, whereas A takes significantly more time, and is much more disruptive. A is extremely favored. |
| On-site energy generation           | Requires a professional team for about two days. Need for access inside the house.   |               |           |                                                                           |
| Energy efficient appliances         | Installation is easy and can be done by the homeowner, without technical assistance. | B             | 7         | A takes significantly more time, and is much more disruptive; B is significantly favored. |
| Home monitoring with smart meters  |                                                                                      |               |           |                                                                           |
| On-site energy generation           | Requires a professional team for about two days. Need for access inside the house.   | B             | 3         | B can be done by the owner; moderate advantage over A.                    |
| Energy efficient appliances         | Installation is easy and can be done by the homeowner, without technical assistance. |               |           |                                                                           |

