MULTI-OBJECTIVE OPTIMISATION FOR MULTI-RESIDENTIAL BUILDING RETROFIT: A METHOD AND AN APPLICATION

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Multi-Objective Optimisation for Multi-Residential Building Retrofit: A Method and an Application

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ABSTRACT

The building sector has been at the centre of the environmental protection policies of the European Union (EU). This is mainly due to its high energy consumption (40% of the total) among the EU Members. Residential buildings are responsible for two-thirds of that amount. Recently, the European Commission set radical targets for the reduction of greenhouse gas (GHG) emissions by 2030 (50-55% reduction compared with 1990 levels) and 2050 (climate neutrality) and the building sector, especially the existing building stock, is expected to play a critical role in achieving those goals.

Special consideration should be given to multi-residential buildings. Compared to other building types, they have limited suitable space for the installation of renewable energy systems and are governed by a complex legal framework, imposing additional challenges on decision-making.

Targeting multi-residential buildings, this study developed a method for the identification of optimal retrofit sets. It is a multi-objective simulation-based optimisation method for the performance assessment of 'whole building' retrofit interventions under two objectives: the minimisation of the operating GHG emissions and the life-cycle cost.

The innovation in the method is the integrated approach, considering energy supply, energy demand-side technologies and energy-saving measures. A dynamic building systems' modelling process was also introduced, based on part-load performances, to address the accuracy limitations of existing, monthly quasi-steady state methods.

The functionality of the method was illustrated through an application. The case study building is a 6-storey multi-family building, constructed before 1980. The performance of several retrofit sets of measures was compared to the 'base case' building, which is a comparable version of the case study building. To identify the way that various parameters of the building environment affect the method application and the obtained results, four locations were considered, one for each Greek climate zone.

It was found that for all Greek climate zones, the cost-optimal retrofit set consists of the roof and basement ceiling insulation, the installation of air-to-air heat pumps (HP)

for heating and cooling and solar thermal panels for domestic hot water (DHW). This way, the operating GHG emissions could be decreased from 59% to 67%, compared to 'base case', depending on the building location.

To achieve a retrofit that minimises the GHG emittions (almost 90% less operating GHG emissions compared to 'base case'), the obtained solution sets included wall, roof, basement ceiling insulation and window replacement with double or triple-glazed windows, central biomass boilers (locations without natural gas) or gas condensing boilers (locations with natural gas) for heating, air-to-air HPs for cooling and photovoltaic-thermal (PV/T) panels for DHW and electricity production. Net-zero carbon retrofit solutions could not be achieved for any location.

The findings of the study are in line with the observed market trends (envelope insulation, installation of double-glazed windows and air-to-air HPs, condensing gas boilers or biomass boilers). Gas absorption HPs and air-to-water HPs will be competitive alternatives when their purchase costs decrease. Similarly, solar thermal collectors for DHW are the common practice, however, when solutions that minimise GHG emissions are required, PV/T panels have great potential but limited market penetration.

The results obtained are specific to the financial situation, fuel, renewable energy sources and systems availability of the considered locations. They can be used as a guide for retrofitting similar buildings and construction types in urban areas of the Mediterranean climate, assisting policy makers and home owners.

Declarations

I declare that the thesis comprises only my work towards the PhD except where referred. The acknowledgement has been made in the text to all other material used. The thesis is less than 100,000 words in length, exclusive of tables, figures, bibliographies and appendices.

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List of publications arising from the research

Panagiotidou, M, Aye, L & Rismanchi, B (submitted September 9, 2020), 'Energy retrofit optimisation of multi-residential buildings: A 'whole-building' approach', *Applied Energy*.

Panagiotidou, M, Aye, L & Rismanchi, B (submitted August 22, 2020), 'Alternative heating and cooling systems for the retrofit of multi-residential buildings in Greece', *Energy*.

Panagiotidou, M, Aye, L & Rismanchi, B 2020, 'Solar driven water heating systems for medium-rise residential buildings in urban Mediterranean areas', *Renewable Energy*, vol. 147, pp. 556–569.

Panagiotidou, M & Aye, L 2018, 'Comparison of Multi-objective Optimisation Tools for Building Performance Simulation', in *Proceedings of BSO 2018: 4th Building Simulation and Optimisation Conference, Cambridge, UK: 11-12 September*, pp. 215–222.

Panagiotidou, M, Rishmanchi, B & Aye, L 2018, 'Low energy building retrofit: A review of objectives and solutions', in *ZEMCH 2018 International Conference Conference Proceedings, Melbourne, Australia: 29 January-1 February*, pp. 59–74.

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Abbreviations*

a-a	air-to-air
a-w	air-to-water
aNSGA-II	active non-dominated-and-crowding sorting genetic algorithm II
AHP	analytical hierarchy process
BDO	building design optimisation
BEPS	building energy performance simulation
CHP	combined heat and power
CMA-ES	covariance matrix adaptation evolution strategy
COP	coefficient of performance
DAG	discrete xiirmijo gradient
Dfa	hot summer continental climates (Köppen climate classification)
DH	district heating
DHW	domestic hot water
EEn	embodied energy
EPBD	Energy Performance of Buildings Directive
EPC	energy performance certificate
EPS	expanded polystyrene
ESM	energy-saving measure
EU	European Union
evMOGA	evolution strategy multi-objective genetic algorithm
FEn	final energy
GA	genetic algorithm
GA-RP	genetic algorithm – refine process
GHG	greenhouse gas
GSHP	ground source heat pump
GUE	gas utilisation efficiency
GWP	global warming potential
HDE	hybrid differential evolution algorithm
HP	heat pump
HPHW	heat pump hot water

HVAC	heating, ventilation and air-conditioning
IC	initial cost
IR	inconvenience rate
LCA	life-cycle assessment
LCC	life-cycle cost
LCEI	life-cycle environmental impact
LCPEn	life-cycle primary energy
low-e	low emissivity
MFH	multi-family house
MODA	multi-objective dragonfly algorithm
MODE	multi-objective differential evolution algorithm
MOGA	multi-objective genetic algorithm
NPV	net present value
NSGA-II	non-dominated-and-crowding sorting genetic algorithm II
nZEB	near-zero energy building
OC	operating cost
OEm	operating emissions
PBP	payback period
PCC	partial correlation coefficient
PLF	part-load factor
PLR	part-load ratio
pNSGA-II	passive non-dominated-and-crowding sorting genetic algorithm II
PRCC	partial rank correlation coefficient
PR-GA	preparation process – genetic algorithm
PSO	particle swarm optimization
PSOIW	particle swarm optimization inertia weight
PV	photovoltaic
PVC	polyvinyl chloride
PV/T	photovoltaic-thermal
RES	renewable energy sources
RESS	renewable energy supply system

SA-ASHP	solar-assisted air-source heat pump
SANM	simplex algorithm of Nelder-Mead
SANMOE	simplex algorithm of Nelder-Mead with the extension of O'Neill
SA-WSHP	solar-assisted water-source heat pump
SFH	single-family house
SRC	standardised regression coefficient
SRRC	standardised rank regression coefficient
SS	sequential search
TABULA	typology approach for building stock energy assessment
TC	thermal comfort
VoM	visibility of measures

*The nomenclature and abbreviations used in publications are included in the body of the published work.

Chapter 1 - Introduction

1.1 Introduction

Since the 1960s, the available data shows that there has been an uninterrupted link between economic growth, energy demand and energy-related emissions (World Bank 2020a, 2020b). In 2017, it was estimated that 68% of the greenhouse gas (GHG) emissions, which are responsible for global warming, came from the consumption of energy (IEA 2017). Despite the global agreements to reduce the energy-related environmental impact, emissions have been increased, as the energy supply is heavily relying on fossil fuels. Consequently, the International Panel on Climate Change (IPCC 2018) estimated that net-zero CO_2 emissions should be achieved by 2050 in order to limit global warming to 1.5 °C and the future climate-related risks.

From 1971 to 2010, the energy consumed by buildings, globally, followed an increasing trend of 1.8% annually (IEA 2013). In 2017, the building sector and the building construction activity were accountable for 36% of the global energy demand and almost 40% of the GHG emissions (UN Environment and IEA 2017). Therefore, buildings hold a great potential for reducing the GHG emissions and slowing global warming.

1.2 Problem statement

Following the global trend, in 2012, European buildings were responsible for 40% of the total final energy consumption. Residential buildings were accountable for two-thirds of that amount (Gynther, Lapillone & Pollier 2015). This is mainly attributed to the fact that Europe's building stock is aged and, most likely, not energy efficient. In fact, more than half of the European buildings were built before the 1970s and the introduction of thermal efficiency standards (Norris & Shiels 2004). At the same time, recent studies reported a low annual growth rate, about 1% (European Commission 2018), and a low annual retrofit rate, between 0.5% and 2.5% (BPIE 2011), for the residential sector. Therefore, most of the residential buildings of the future have already been built and are characterised by poor energy performance.

Among other residential building types, a special consideration should be given to multi-residential buildings. The main reason is the fact that a relatively high proportion of Europe's population is concentrated in cities. Europe has been radically transformed from rural to urban since the beginning of the 1950s. In 2018, 74% of its population lived in urban settlements, which was considerably larger than the world's average of 55% (United Nations 2018).

In addition, compared to other building types, multi-residential buildings are governed by a complex legislative framework, resulting from a complex tenure status. It should be mentioned that more than 75% of European households are owner-occupied (Eurostat 2016). Thus, the prospect of decision-making, regarding any type of building intervention, is more challenging for multi-residential buildings than single-family houses.

Another challenge that multi-residential buildings face is the limited areas suitable for the installation of renewable energy supply systems (RESS). The most widely used RESS is the photovoltaic (PV) panels, requiring unshaded rooftop or facade areas, while other RESS, such as horizontal loop geothermal heat pumps (HPs), occupy a large amount of site areas. On the other hand, the vertical loop occupies smaller ground area, of around 5-10 m^2 per kW. According to ASHRAE (1995), it is more suitable to small properties; however, it has high drilling costs.

Overall, multi-residential buildings present a great opportunity and at the same time a great barrier towards the 2030 climate target of the European Union (EU) for 40% cuts in GHG emissions, compared to 1990 levels.

Effective building retrofit has been seen as the way to reduce buildings' energy consumption and related emissions. The EU, trying to improve the energy performance of the building stock, launched the Energy Performance of Buildings Directive (EPBD) (EU 2018). It provides member states with a methodological framework for the calculation of the energy performance, both for new buildings and existing buildings that undergo a major retrofit process.

Optimising the building retrofit is not a simple process as various parameters, objectives and stakeholders are involved. To start with, the potential retrofit strategies, such as energy-saving measures, efficient space heating, cooling, domestic hot water

(DHW) systems and RESSs, are numerous. Dealing with a great number of parameters leads to a greater number of alternative retrofit sets. Concurrently, most of the times, the building retrofit does not involve single-objective but multi-objective decision making and might include environmental, financial and social criteria, based on the involved stakeholders. The development of a method to assist decision-makers, providing them with optimal sets of retrofit interventions, is essential. Policy makers can also be benefitted from the obtained empirical results of the method applications. Identifying a wide range of sets of retrofit interventions, from cost-optimal (as defined in EPBD) to those minimising the operating GHG emissions, they can introduce targeted retrofit incentives for the building owners. In turn, the GHG emissions produced by the residential sector will decrease, getting closer to the EU's 2030 and 2050 target.

1.3 Research questions

The main question that this research raises is:

> *How can the optimal sets of interventions that minimise both the environmental impact and the retrofit cost, be determined for the retrofit of a multi-residential building, considering the 'whole-building'?*

To answer the main question, a number of sub-questions follow:

1. *What are the appropriate indicators to measure the environmental impact and the retrofit cost?*

2. *How is optimality determined for the retrofit of multi-residential buildings?*

3. *What is the state-of-the-art of the retrofit practice?*

4. *What are the retrofit constraints?*

5. *What is the baseline performance of multi-residential buildings constructed before the 1970s?*

6. *What are the potential retrofit interventions and their performance?*

1.4 Research aim and objectives

This research aims to develop a method to support the residential building retrofit decision making, pursuing the conflicting objectives of reducing the operating GHG emissions of the building while minimising the retrofit life-cycle cost (LCC). This research focuses on multi-residential buildings, located in medium and high-density urban areas, as they have greater challenges to overcome compared to other building types. The key stakeholders are the residence owners, as they are the final decision-makers of the retrofit and, in most cases, the recipients.

The following research objectives are set to achieve the aim:

1. *Develop the retrofit optimisation framework.*
2. *Identify and model the retrofit strategies, based on the design parameters, the objective functions and the environment of the case study building.*
3. *Optimise the design parameters of the multi-residential building retrofit in terms of minimising the environmental impact and the retrofit cost.*

The first research objective builds the optimisation framework, identifying the methods and tools, as well as the optimisation variables and constraints. The second objective prepares the application of the developed framework to a case study building, after evaluating the performance of the last. It explores the feasibility of the potential retrofit interventions, considering the building's physical, financial, social and legislative environment. The performance of the proposed retrofit interventions is also pre-assessed, identifying synergies and limitations. The last research objective is the retrofit optimisation of the case study building, illustrating an application of the developed framework and obtaining application results.

1.5 Limitations

The scope of the study is limited to residential buildings because of their significant contribution to climate change. The method can potentially be applied to commercial buildings; however, the assumptions need to be adjusted to meet the requirements case-by-case.

The study is a simulation-based work. Results were verified through the data obtained from the building audit, the EU residential building typologies and the literature. Full-scale building monitoring data was not obtained due to practical and financial limitations. Finally, physical implementation and post-evaluation were not conducted.

1.6 Research method overview

This chapter is a window to the implemented method of the study. The scope is to provide a general description of the method. Explicit description is provided in Chapters 3 to 5. Figure 1 presents the research method and steps followed by the thesis, in terms of inputs, processes and outputs.

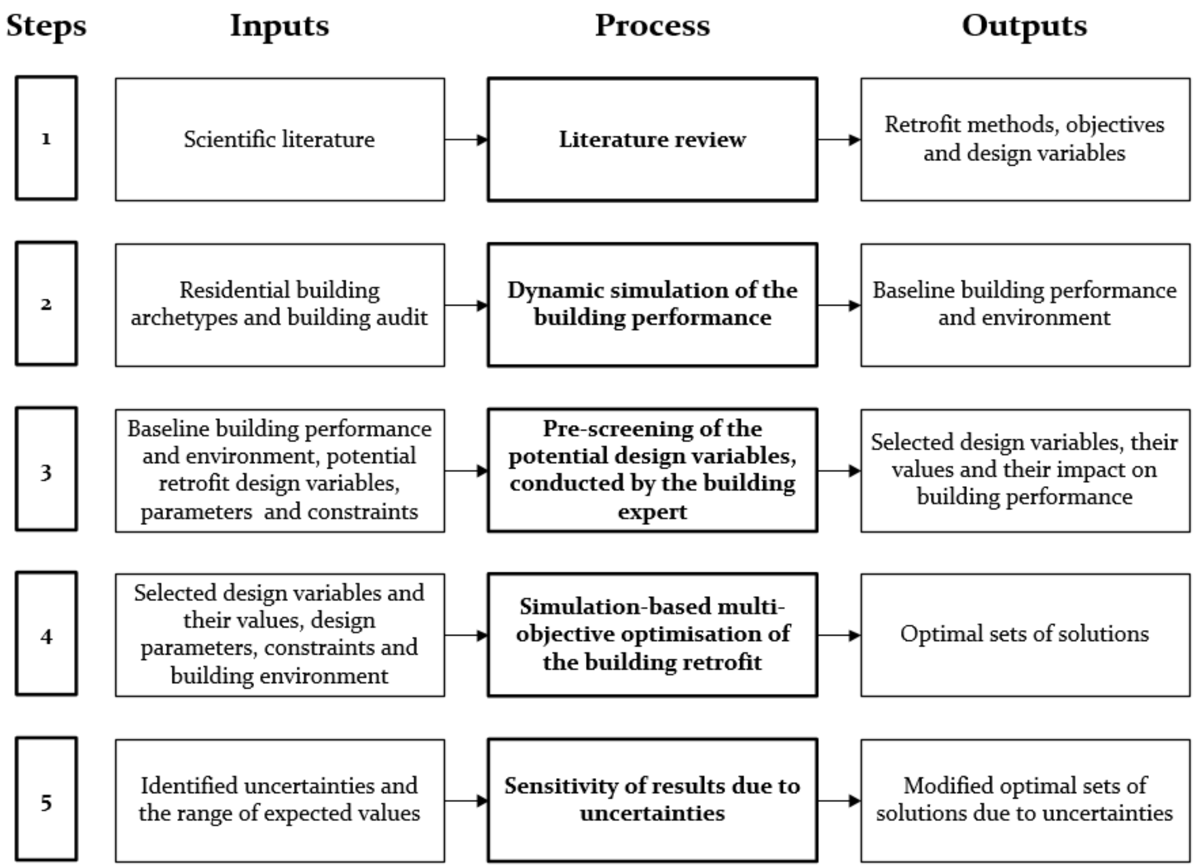

Figure 1. Steps of the thesis

At the first step, an academic literature search was conducted, using multiple databases, including Google, Google scholar and Web of Science. The search strategy followed was the construction of a compound query, using the Boolean operators 'AND' and 'OR'. More details for Step 1 and the structure of the conducted literature review can be found in Chapter 2.

In Step 2, the baseline performance of the case study building was determined. TRNSYS, a dynamic building performance simulation software, was employed for that purpose. Input data were extracted from the EU residential building archetype database 'TABULA'. A building audit was also conducted to assess the general condition of the building and verify TABULA parameter values and results. The audit involved building inspection that determined the condition of the building envelope and installed systems, as well as the collection of energy bills to estimate the energy consumption.

A building expert was involved in the Step 3, to pre-screen the potential design variables, based on the legislative, climatic, technological and financial environment of the building. The building performance, based on the individual retrofit interventions, was simulated and assessed.

Step 4 combined energy simulation and multi-objective optimisation to quantitatively analyse the optimal solutions with reference to the retrofit of existing multi-residential buildings. The selected building performance simulation tool was TRNSYS and the software tool that handled the optimisation process was DAKOTA. The Multi-objective Genetic Algorithm (MOGA) was employed instead of a brute-force calculation, reducing the computation time and resources required.

Finally, in Step 5, a sensitivity analysis of the optimisation results due to uncertainty was undertaken. The uncertainties were studied in the form of scenario analysis for the range of the expected values of the uncertain parameters.

1.7 Thesis overview

To fulfil the aim of the study, thesis chapters must achieve the objectives stated. A literature review, regarding the retrofit practice, was conducted in Chapter 2. The review considered all retrofit practice stages in order to determine the key aspects that impact the retrofit and identify the knowledge gaps. It also built a solid basis for developing the optimisation framework, which is the first objective of the study.

Addressing the second objective, in Chapter 3 and 4, the building's performance was evaluated and the feasibility of potential retrofit interventions was explored under the building environment. The chapters also provide preliminary results of the method application, accomplishing the third research objective. More specifically, Chapter 3 pre-assessed the alternative heating and cooling options of the building retrofit. Similarly, in Chapter 4, the alternative DHW systems, coupled with RESSs were identified and their performance was evaluated.

Chapter 5 describes the developed method and its application to the case study building and discusses the retrofit optimisation results, achieving the last thesis objective. Finally, Chapter 6 summarises the main conclusions of the study, highlighting the original contribution to knowledge made, while providing recommendations for further research.

1.8 References

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Chapter 2 - Literature review

2.1 Introduction

The National Institute of Building Sciences of the United States (2018) defined six fundamental principles of sustainable building design: optimise site potential, optimise energy use, protect and conserve water, optimise building space and material use, improve the indoor environmental quality, optimise operating and maintenance practices. Recently, Qu et al. (2020) developed a ‘holistic’ retrofit approach for multi-residential buildings, following three principles. The first principle is the reduction of building’s primary energy needs through energy-saving measures. The second principle is the renewable energy supply as an addition to the energy-saving measures. The last one is the avoidance of complex installation processes that cause disturbance to residents.

Under the umbrella of the aforementioned principles, the retrofit practices are reviewed, based on the scientific literature. The multi-residential building retrofit is a complex task. A large number and interactions between building components and the environmental, as well as financial and social context need to be considered. Breaking the retrofit practice into activities, as defined by Ma et al. (2012) and further developed, it involves: (1) building audit and performance assessment, (2) definition of the retrofit stakeholders, objectives and strategies, (3) performance assessment of the retrofit strategies against the selected objectives, (4) identification of the optimal solution(s), (5) uncertainty analysis and (6) measurement and verification of the energy savings. The structure of the literature review, based on the activities mentioned, is presented in Figure 2.

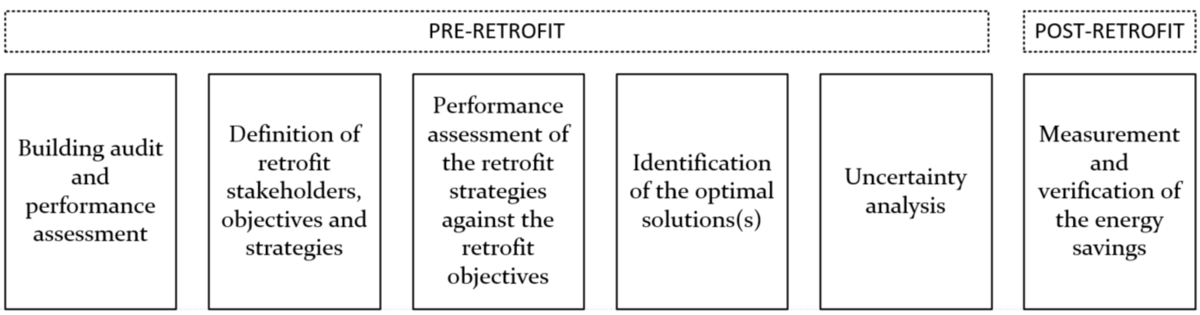

Figure 2. Activities of the retrofit practice

The purpose of the present literature review is to build a comprehensive understanding of the state-of-the-art of the retrofit practice that leads to the development of a robust optimisation framework. It is to understand the employed methods, the introduced objectives and the undertaken strategies. In order to obtain an overview, Chapter 2.2 considers other review works on building design and retrofit. Chapter 2.3 covers the retrofit activity (2), focusing on the stakeholders, the retrofit objectives and strategies, while Chapter 2.4 covers activity (3), discussing the methods and tools employed by researchers to assess the performance of the retrofit strategies against the selected objectives. Chapter 2.5 covers the most critical issues of activities (1), (4) and (5) of the retrofit practice. Most recent studies are reported in Chapter 2.6. Finally, in Chapter 2.7, conclusions summarise the major findings of the literature review, identifying the knowledge gaps.

2.2 Review studies

In accordance with national energy performance legislation or through the setting of higher energy efficiency goals, numerous residential building retrofit projects have been carried out. Holding different perspectives, projects employ methods to explore several retrofit strategies or scenarios against one or more assessment criteria. Some also consider possible uncertainties and risks involved in the retrofit process, including financial limitations, governmental policies, energy prices and the climate change.

De Boeck et al. (2015) conducted an extended literature review of residential building design projects, classifying the information accordingly to identify trends. Even though the review doesn't focus on building retrofit, it is worth mentioning the major findings, as the methods and processes employed for the design of new buildings and retrofits are similar. The classification categories considered for their analysis were: the building type and location, the design variables, the objective functions, the type of analysis performed, the method and the software used. As for the design variables, five major groups were identified: the 'whole building' (shape, orientation, infiltration, thermal mass, floor area and volume), envelope elements (walls, roofs, floors), windows and shadings, heating, ventilation and air-conditioning (HVAC) systems and

RESSs, as well as appliances and lighting. Studies considering aspects of all groups are rare. According to the authors, categories such as envelope elements, windows and shadings are the most investigated, while the HVAC systems have started gaining more attention after 2011. As for the retrofit objectives, the most common are the reduction of energy demand, GHG emissions, LCC and the payback period (PBP). Five types of analysis were identified: single or multi-objective optimisation, scenario analysis, economic analysis, sensitivity analysis and statistical analysis.

A recent literature review on multi-residential building retrofit was conducted by Hamid et al. (2018). They collected 115 research papers and projects of multi-family buildings in temperate climates. Among the considered strategies, the retrofit of the building envelope was the most common, whilst the retrofit of HVAC systems came second. Solar technologies and smart control systems were rarely introduced as retrofit strategies. Another worth-mentioning finding is that almost all studies set as a retrofit objective either the primary energy consumption or the GHG emissions, or both, followed by the indoor environmental quality and financial objectives. Most of the times, the retrofit impact was estimated through calculations or building performance simulations. The built case studies considered were limited and the impact estimation was through building audits and measurements. Finally, it was also noted that more than half of the studies held the building owner(s) as target stakeholder(s).

Other researchers investigated building retrofit projects from different perspectives. Ma et al. (2012) analysed several projects around the world, focusing on the retrofit interventions proposed, the assessment method used and their major results. Moran et al. (2015) limited the reviewed studies to those located in Europe and target a nearly zero-energy building (ZEB) retrofit outcome. Vilches et al. (2017) focused on life-cycle assessment (LCA) retrofit studies. Pombo et al. (2016) assessed the sustainability level of residential retrofit projects.

2.3 Stakeholders, objectives and solutions of building retrofit

This section aims to explore further and analyse how other studies have assumed the inter-relationships between the stakeholders' perspectives and the objective functions considered by the residential building retrofit projects, as well as to compare and discuss their results. The intention is to identify which objective functions are related to which specific stakeholders and how outcomes vary. Stakeholders are those who may influence the building retrofit, such as policymakers, public authorities at different levels, building or apartment owners and tenants, builders, engineers, architects and the local community.

A deeper investigation of the relationship between the stakeholders and the objective functions used was conducted by Lizana et al. (2016), to support the decision management of residential retrofit projects. They claimed that the assessment method is determined by the combination of the objective functions used and can be either a cost-benefit analysis, a multi-criteria analysis, a multi-objective optimisation analysis or an energy rating system. It is mentioned that most of the studies, aiming to reduce the problem complexity, used only two groups of objective function: financial and energy or financial and GHG emissions. There are not many studies that employed three or more objective functions. In addition, three major stakeholders were identified by Lizana et al. (2016): the 'private owner/user', the administrator as the 'public promoter' and the 'private promoter'. The private owner is mainly interested in the initial cost and the final energy savings. The public promoter focuses on GHG emissions reduction and meeting the environmental targets. Whereas, the private promoter focuses on the financial benefits of the investment.

The review of this section is based on a conference paper titled "Low energy building retrofit: a review of objectives and solutions", published in *Proceedings of ZEMCH 2018 International Conference, Melbourne: January 29 – February 1* (see Appendix A). Section 2.3.1 describes the literature search and selection strategy and Section 2.3.2 discusses the identified objective functions sets in association with the stakeholder's perspective and the major results. Findings are highlighted in Section 2.3.3.

2.3.1 Literature search and selection strategy

At the first place, an academic literature search was conducted, using multiple databases, including Google, Google scholar and Web of Science. The search strategy followed was the construction of a compound query, using the Boolean operators "OR" and “AND”. The search words used were: (“retrofit” OR “renovation”) AND “residential” AND “building” AND “assessment” AND “criteria” AND (“strategies” OR “interventions”). Various search combinations of the key words were also made.

From the identified scientific papers, a selection process was performed. The selected documents were those that use a single-criteria or a multi-criteria assessment method to evaluate retrofit strategies, or retrofit packages, for residential buildings, aiming to reduce the energy use or the GHG emissions. The selected information was classified and summarised in Table 1 and Table 2, in order to facilitate the correlation analysis. The studies were also limited to buildings located in Europe.

The location of the case study and the corresponding climate zone play a significant role in heating and cooling loads and the available energy sources and technologies utilised. A proposed retrofit approach could be unsuitable if applied in a different climate or urban characteristics (Li et al. 2017). Thus, the considered case studies were further classified according to the climate zone they belong to.

Building type is also a critical parameter for the determination of energy consumptions. Multi-storey buildings consume less energy for heating and cooling compared to detached low-rise buildings. Three building types were defined to facilitate the classification of the case studies: ‘single-family houses’ (SFH), ‘medium-rise multi-family houses’ (MFH) and ‘high-rise multi-family houses’. The construction period of each building was also noted, as older buildings tend to have higher energy consumptions. The overall target of each retrofit project was also taken into consideration. Projects that set high energy or GHG emissions reduction targets require not only high-efficiency levels of the proposed retrofit strategies but also a large number of them.

The selected stakeholder categories broadly follow the classification previously introduced by Lizana et al. (2016). These were: the ‘owner/user’, the ‘public promoter/legislator’ and the ‘private investor/developer’. It should be noted that a considerable number of the analysed projects did not declare the adopted stakeholder’s perspective and thus this field was left empty. On the other hand, there were studies declaring that they respond to all stakeholders’ requirements.

Case studies were also classified according to the so-called assessment criteria or the objective functions they considered. The major categories are the ‘environmental’, the ‘financial’ and the ‘social’ objective functions, while further categorisation was based, among others, on the life-cycle stage considered in calculations. Finally, the retrofit strategies were assigned into three categories, based on Pombo et al. (2016) classification: the ‘building envelope’, the ‘HVAC systems’ and the ‘RESSs’. The strategies were further sub-classified, as shown in Table 2. It is apparent that the residential building retrofit is a multi-factorial task and there is no straight comparison of the selected case studies, as results may vary, not only depending on the selected objective functions, but also on the climate conditions, the target set and the considered retrofit strategies.

2.3.2 Results

There are three major types of objective functions identified: a) the financial, b) the environmental and c) the combination of financial and environmental. Social objective functions were rarely used as assessment criteria. Most of the times, they were combined with environmental and/or financial objective functions, either as a third objective function or as a constraint.

According to Table 1, environmental objective functions were further sub-divided, based on the energy consumption or GHG emissions consideration and the building life-cycle stages included into the analysis. The categories are: the ‘Final Energy’ (FEn), the ‘Primary Energy’ (PEn), the ‘Embodied Energy’ (EEn), the ‘Operating Emissions’ (OEm), the ‘Life-Cycle Primary Energy’ (LCPEn) and the ‘Life-Cycle Environmental Impacts’ (LCEIs). The financial objective functions commonly employed are: the ‘Initial Cost’ (IC), the ‘Operating Cost’ (OC), the ‘Life-Cycle Cost’ (LCC) and the ‘Payback Period’ (PBP). The Social objective functions are the ‘Inconvenience Rate’ (IR), the ‘Visibility of Measures’ (VoM) and ‘Thermal Comfort’ (TC).

Table 1. Reviewed case studies classified based on climate zone, construction period, house type, target, stakeholders and assessment objectives

				House Type				Stakeholders			Assessment Objective functions: Environmental						Financial				Social		
No	**Reference**	**Climate Zone**	**Construction Period**	**SFH**	**Medium-rise MFH**	**High-rise MFH**	**Target**	**O/U**	**PP/L**	**PI/D**	**FEn**	**PEn**	**EEn**	**LCPEn**	**OEm**	**LCEIs**	**IC**	**PBP**	**OC**	**LCC**	**IR**	**VoM**	**TC**
1	Risholt et al. (2013)	Boreal	1980-1989	×			near-ZEB	×			×									×		×	×
2	Hasan et al. (2008)	Boreal		×			low energy				×									×			
3	Amstalden et al. (2007)	Continental	1948-1975	×			low energy	×			×									×			
4	Brown et al. (2013)	Boreal	a) 1963, b) 1973		×	×	low energy	×			×									×			
5	Kuusk and Kalamees (2015)	Boreal	1986			×	near-ZEB	×				×						×		×			
6	Penna et al. (2015)	Continental & Mediterranean	a) before 1976, b) after 1976	×	×	×	near-ZEB	×			×									×			×
7	Ferreira et al. (2014)	Mediterranean	1990			×	net-ZEB	×				×								×			
8	Hamdy et al. (2013)	Boreal		×			near-ZEB		×			×								×			(1)
9	Ballarini et al. (2017)	Mediterranean	a) before 1920, b) 1921-1945, c) 1946-1960, d) 1961-1975, f) 1991-2005, g) after 2005	×	×	×	low energy	×	×	×		×								×			
10	Lizana et al. (2016)	Mediterranean	1955			×	low energy		×			×								×		×	×
11	De Angelis et al. (2013)	Continental	1960-1979			×	low energy									×				×			
12	Cetiner and Edis (2014)	Mediterranean	1992			×	low energy	×								×				×			
13	Pombo et al. (2016)	Mediterranean	1960-1969			×	passive house		×							×				×			
14	Antipova et al. (2014)	Mediterranean					low environ. impact									×				×			
15	Ostermeyer et al. (2013)	Atlantic	1950-1960			×	75% primary energy reduction									×				×			
16	Verbeeck and Hens (2005)	Atlantic	1970-1979	×	×		low energy							×						×			
17	Ascione et al. (2015)	Mediterranean				×	low energy		×			×					×						×
18	Huws and Jankovic (2014)	Atlantic		×			zero carbon								×		×						×
19	Lizana et al. (2016)	Mediterranean	1955			×	low energy			×		×			×		×						
20	Assiego De Larriva et al. (2014)	Mediterranean	1983			×	low energy and carbon	×	×	×		×				×							
21	Wang et al. (2015)	Boreal	a) before 1945, b) 1946-1960, c) 1961-1975	×	×	×	low energy	×	×	×		×	×					(2)					
22	Dodoo et al. (2010)	Boreal	1995			×	passive house							×									
23	Desogus et al. (2013)	Mediterranean	1950-1959	×	×	×	low energy	×	×									×		×			
24	Salata et al. (2017)	Mediterranean	2000			×	class improvem.	×									×	×	×				
25	Lizana et al. (2016)	Mediterranean	1955			×	low energy	×									×		×		×		

SFH: Single-Family House, MFH: Multi-family House, O/U: Owner/User, PP/L: Public Promoter/Legislator, PI/D: Private Investor/Developer, FEn: Final Energy, EEn: Embodied Energy, LCPEn: Life-Cycle Primary Energy, OEm: Operating Emissions, LCEIs: Life-Cycle Environmental Impacts, IC: Initial Cost, PBP: Payback Period, OC: Operating Cost, LCC: Life-Cycle Cost, IR: Inconvenience Rate, VoM: Visibility of Measures, TC: Thermal Comfort, (1) restriction, (2) considered in a secondary assessment process.

Table 2. Reviewed case studies classified according to the retrofit strategies under consideration

No	Reference	Retrofit Strategies																
		Building Envelope						HVAC Systems									RESS	
		Wall Insulation	Roof Insulation	Ground Floor Insulation	Infiltration	Window Replacement	Shadings	Mechanical Ventilation	Control Systems	Existing System Retrofit	Electric Heater	Boiler	HP	CHP	DH	Cooling	Solar Thermal	PV
1	Risholt et al. (2013)	×	×	×	×	×					×		×				×	
2	Hasan et al. (2008)	×	×	×		×		×										
3	Amstalden et al. (2007)	×	×	×		×												
4	Brown et al. (2013)	×	×			×			×		×							
5	Kuusk and Kalamees (2015)	×	×	×		×				×							×	×
6	Penna et al. (2015)	×	×	×		×						×						
7	Ferreira et al. (2014)	×	×	×		×						×	×			×	×	×
8	Hamdy et al. (2013)	×	×	×		×		×			×	×	×		×	×	×	×
9	Ballarini et al. (2017)	×				×											×	
10	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×
11	De Angelis et al. (2013)	×	×	×		×												
12	Cetiner and Edis (2014)	×	×	×	×													
13	Pombo et al. (2016)	×	×	×		×												×
14	Antipova et al. (2014)	×	×			×											×	
15	Ostermeyer et al. (2013)	×	×	×		×					×	×					×	
16	Verbeeck and Hens (2005)	×	×	×		×					×	×	×				×	×
17	Ascione et al. (2015)	×	×			×			×			×				×		
18	Huws and Jankovic (2014)	×	×	×	×	×	×		×			×	×				×	×
19	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×
20	Assiego De Larriva et al. (2014)	×	×	×		×	×											
21	Wang et al. (2015)	×	×	×	×	×			×	×			×		×			
22	Dodoo et al. (2010)	×	×			×					×		×	×	×			
23	Desogus et al. (2013)	×	×			×												
24	Salata et al. (2017)	×				×			×			×	×	×	×		×	×
25	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×

HVAC: Heating, Ventilation and Air Conditioning, RESS: Renewable Energy Systems, HP: Heat Pump, CHP: Combined Heat and Power, DH: District Heating, PV: Photovoltaic

Financial Objective Functions

Projects that only employ financial objective functions, are not commonly met in building retrofit studies for the improvement of energy performance. When they are, they include financial indicators of energy consumption or GHG emissions mitigation criteria such as the return of investment. Purely financial criteria could be employed by the investor, who is, in most of building retrofit cases, the owner of the house. All three studies under this category adopted the owner/user's perspective.

Desogus et al. (2013) investigated the financial feasibility of the envelope retrofit, in terms of LCC and PBP, for three different building types in Italy. The aim of their investigation was to challenge the national legislation, claiming that it is strict and does not promote cost-effectiveness. According to the study's results, the combination of all proposed interventions, wall and roof insulation and window replacement had the lowest Net Present Value (NPV) and was not cost-effective. When subsidies were introduced, complete retrofit works were preferred to partial, despite the high IC.

Salata et al. (2017) conducted a research for a high-rise MFH retrofit case, located in Rome, focusing on financial objective functions. A large spectrum of retrofit interventions was considered: external wall insulation, window replacement, control systems such as sensors and thermostat settings, boiler substitution alternatives including Combined Heat and Power (CHP) technologies and Solar thermal and PV panels. The performance of all potential retrofit strategies and their combinations was assessed using three financial criteria: the IC, the annual economic return and the return of investments. Calculations showed that the envelope's thermal performance improvement did not have a considerable impact on energy demand reduction, while it had high installation cost and a PBP of more than 30 years. PV panels are more effective when combined with a HP instead of a condensing boiler, as HP uses electricity. However, the choice between a condensing boiler and a HP was also determined by the local electricity and gas prices. The installation of smart control systems was a high-scored strategy on all assessment objective functions, as it led to satisfactory annual energy savings and their amortisation period was less than 20 years. The combination of CHP and a HP, despite the high IC, had a PBP of 15 years and allowed the building to reach an 'A' energy class, according to national regulations for energy certification, based on the EPBD.

Finally, Lizana et al. (2016), employed financial assessment criteria in combination with social criteria, for a case study in Southern Spain. They looked at the IC, the annual economic return, the TC and the IR caused to occupants. Low investment retrofit interventions were identified as optimal; among them was the installation of water flow reducers in taps and the sealing of frames for the improvement of airtightness. Other proposed interventions were the installation of retractable window awnings, roof insulation, the replacement of the existing HPs with more efficient ones and the insulation of exterior walls.

Environmental Objective Functions

LCA is among the most popular decision-making support methods used for the selection of the optimal alternatives among the potential retrofit strategies. Several LCA studies explored alternative solutions for energy saving measures (ESMs), looking at their embodied energy and the influence they have on primary energy consumption of the building during its operating phase. The interest was focused on the environmental impact of different envelope insulation materials and window frames. High performance targets, such as Passive House standard or nearly ZEB, aimed for optimal solutions of all available intervention categories: ESMs, HVAC systems and RESSs. Table 1 shows that the majority of projects employing environmental objective functions claimed that they meet the requirements of all involved stakeholders (Wang, Laurenti & Holmberg 2015; Assiego De Larriva et al. 2014).

Assiego De Larriva et al. (2014) compared insulation and ventilation strategies to achieve global warming potential (GWP) reduction for the retrofit of a high-rise residential building in south Spain. Ventilation strategies were proven to have a lower GWP and thus they were preferred. The authors generalised the obtained results for buildings located in temperate climates.

Wang et al. (2015) investigated the trade-off between PEn savings and EEn for the retrofit interventions of three different building types in Sweden. The options considered were ESMs addressing the thermal insulation and airtightness of the envelope, efficient ventilation and the introduction of a low temperature heating system with connection to a district heating (DH) network when available. Results varied, depending on the building type. For the SFH and the low-rise MFH, the most effective retrofit strategy was the combination of small-scale retrofit of the building envelope, such as air-tightness improvement and window replacement, with a low-temperature heating system. For the high-rise MFH, additional envelope retrofit options should be implemented. The installation of a heat recovery system led to PEn savings and lower embodied GHG emission levels.

Dodoo et al. (2010) estimated the LCPEn consumption of a wood-frame apartment building in south Sweden, after being refurbished to Passive House standard. Several ESMs and the installation of mechanical ventilation systems with heat recovery were investigated under three different end-use heating systems (resistance heating, HP and DH). As expected, the heating system that demonstrated the greater PEn usage was resistance heating, because of its low energy efficiency. The installation of ventilation systems with heat recovery, followed by the replacement of windows and the insulation of external walls led to higher energy savings. It was also found that the EEn of materials increased by 17% when the building was retrofitted to Passive House standard.

Environmental and Financial Objective Functions

The identified trends of the studies that use multi-criteria assessment methods to evaluate retrofit alternatives are the combination of the LCC objective function with OEn, PEn and LCEIs. The driving force behind these trends is the EPBD methodology, considering the determination of the cost-optimal solutions for a nearly zero-energy building retrofit.

Life-Cycle Cost and Final Energy

Four out of the five reviewed studies that choose to minimise the LCC and the OEn were employed by researchers who looked at the building retrofit problem from the owners' perspective. This can be justified by the fact that energy bills are among the highest household expenses and energy savings can be used as an incentive for homeowners in order to retrofit their house.

Amstalden et al. (2007) considered envelope insulation and window replacement as energy efficiency improvement strategies for a SFH in Switzerland. They argued that the wall and roof insulation were the best strategies, since both floor insulation and window replacement had negative NPV. Hasan et al. (2008), also investigated a SFH in Finland, considering passive energy efficiency strategies and mechanical ventilation. Their findings were in agreement with that of Amstalden et al. (2007) on the insulation of walls and floor and the replacement of windows, but not on the roof insulation. Mechanical ventilation systems with heat recovery were also found to be cost-effective. Brown et al. (2013) compared three alternative packages for two different house types in Sweden, including passive measures, mechanical ventilation and additional system controls. They concluded that the balanced mechanical ventilation with heat recovery and the addition of thermostat settings to radiators, followed by high-efficiency window replacement, were the optimal retrofit interventions.

Life-Cycle Cost and Primary Energy

The objective functions set of LCC and PEn was not correlated with any specific stakeholder's perspectives. From the owners' perspective, Kuusk and Kalamees (2015) in Estonia, targeting a net-ZEB and exploring both ESMs and the installation of RESSs, found that the indoor climate requirements could be fulfilled using thermostats and mechanical exhaust ventilation system without heat recovery. The major energy-saving requirement was fulfilled with additional envelope insulation, window replacement and the installation of a two-pipe radiator heating system to replace the existing one-pipe system. Moving to the energy efficiency requirements for new buildings, additional ventilation units with heat recovery was the optimal retrofit intervention. A nearly ZEB was achieved by the installation of additional solar thermal collectors, while a net-ZEB with additional PV panels.

In Portugal, Ferreira et al. (2014) looked for the cost-optimal retrofit strategies to achieve a nearly ZEB MFH. They found that the cost-optimal option was the combination of low thickness Expanded Polystyrene (EPS) envelope insulation for the external walls and low thickness Extruded Polystyrene insulation for the roof and floor, with a high-efficiency gas boiler for heating and DHW. A net-ZEB target could be achieved with the additional installation of PV panels. They also pointed out that the introduction of high-level envelope performance requirements in the national building code could lead to retrofit strategies that deviate from the cost-optimal options. Retrofit interventions should improve the performance of all envelope elements, while ensuring thermal comfort levels and cost-optimality. In addition, renewable energy technologies can play a critical role when a net-zero level is required.

From the public promoter's perspective, the investigations that used LCC and PEn as assessment objective functions, took also TC into consideration, either as a constraint (Hamdy, Hasan & Siren 2013) or as a third objective function (Lizana et al. 2016; Penna et al. 2015). Hamdy et al. (2013), explored the nearly ZEB retrofit options for a SFH in Finland. A large number of variables were considered in a matrix, which eliminated mutually exclusive interventions. The included variables were ESMs, such as envelope insulation, air-tightness, window replacement and heat recovery options, heating, cooling and DHW systems, as well as RESSs, such as solar thermal and PV systems. The LCC-PEn consumption chart showed that clusters were formed based on the heating and cooling technologies used. The highest cost-operating system required high-level ESMs interventions and vice versa. It was noticed that investing in heating systems was more viable than in high cost ESMs. The optimal cost-efficient heating system was the ground source heat pump (GSHP) and could be combined with RESSs, which did not improve the financial performance of the GSHP strategy, but led to nearly ZEB performance. In addition, retrofit strategies, that did not consider cooling systems, were preferable to those that considered them; the latter could improve the energy performance of the building and the financial feasibility of the strategy when RESSs were installed. Both solar thermal and PV panel systems were selected, but PVs were more economically viable than solar thermal.

Lizana et al. (2016), from the public promoter's perspective, applied the weighted multi-criteria assessment method, employing a large number of assessment criteria. Among them, LCC, PEn consumption and TC were highly weighted. The considered retrofit strategies were ESMs, HVAC systems and RESSs. The cost-optimal and energy-efficient retrofit strategy idendified were the combination of the placement of retractable awnings, window replacement with aluminium frames and low emissivity (low-e) double glazing, external wall and roof insulation and the application of solar thermal collectors to cover energy for DHW.

Adding TC as the third objective function, Penna et al. (2015) provided three optimal retrofit solutions for each residential building type studied in two different climate zones in Italy. They noted the importance of window type selection and the installation of a mechanical ventilation system to improve TC. They also pointed out that the overuse of conventional ESMs, such as the addition of extended insulation of the building envelope, was responsible for summer overheating.

Ballarini et al. (2017), using IEE-TABULA project's (TABULA 2017) building typology, developed a multi-criteria assessment method for the evaluation of retrofit strategies, applicable to all building types of the Italian residential building stock. The strategies included envelope insulation, window replacement, heat generator replacement, thermal solar system installation and their combinations. Heating system replacement was the most cost-effective intervention, especially for warm climates (less than 1,400 heating degree days), due to low initial cost and short PBP. The retrofit package that combined envelope insulation, window replacement and heating system replacement was the cost-optimal one for medium and large size buildings that were constructed before 1975. The initial cost was high, but the PBP did not exceed 19 years.

Life-Cycle Environmental Impacts and Life-Cycle Cost

Life-cycle studies often combine LCEIs with LCC assessment criteria under a multi-criteria decision-making process, in order to look both at the environmental and financial point of view. Once more, there was no obvious correlation between that objective functions set and any stakeholder's perspective. De Angelis et al. (2013) and Cetiner and Edis (2014) both studied envelope insulation alternatives, in terms of materials and thickness, for the optimal retrofit of high-rise MFHs in Italy and Turkey, respectively. An interesting study of Pombo et al. (2016) investigated several retrofit scenarios of a high-rise residential building in Spain, from the 'business as usual' to Passive House standard, using ESMs. Environmental indicators were interpreted to monetary values to estimate the cost of the damage to the environment and humans. The best practice among the ESMs suggested thicker roof (24 cm) and wall insulation (16 cm), or a slightly thinner insulation and the addition of a second polyvinyl chloride (PVC) framed, low-e, double glazing window. The Passive House standard scenario was rejected as it involved high initial costs.

Antipova et al. (2014) evaluated a number of retrofit strategies for a residential building in central Portugal, under two objective functions: the LCC and the LCEIs, based on the LCA method. The major finding of the study was the high correlation among the different environmental impacts employed and their inversely proportional relation with the LCC. Verbeeck and Hens (2005) assessed a large variety of intervention categories (ESMs, HVAC systems and RESSs) under the same objective functions, LCEIs and LCC, using a typical Belgium detached and terraced houses as case studies. Their findings prioritised ESMs, with the insulation of the roof to be the most effective measure. Better performing glazing was also suggested, but the wall insulation was too expensive to be among the optimum strategies. In terms of LCEIs, gas boilers were preferred over electrical heating systems. It is also worth noting that RESSs were not part of the optimal solution set for any of the reference buildings.

Ostermeyer et al. (2013) introduced the concept of life-cycle sustainability assessment, using LCC, LCEIs and social acceptance criteria. However, the last criteria was limited to the identification of the driving retrofit technologies and their implementation consequences on residents. A multi-storey residential building in France was used as a case study and a number of ESMs, HVAC systems and RESSs were considered as potential retrofit interventions. A high thermal resistance envelope insulation, triple-glazed windows and mechanical ventilation were proposed under the high-score LCEIs scenario, whereas, lower thermal resistance insulation, double-glazed window replacement and natural ventilation under the LCC-LCEIs balanced scenario. A high-efficient condensing boiler was the optimal choice for heating in both scenarios.

Investment Cost and Primary Energy/Operating Emissions

From the private investor's perspective, Lizana et al. (2016) studied the same retrofit strategies under PEn consumption and IC. They found that the optimal strategy was the installation of an air-source HP for heating, cooling and DHW, that complimented the substitution of existing windows with aluminium framed, low-e double-glazed windows.

Adding TC as a third assessment objective function, Ascione et al. (2015) and Huws and Jankovic (2014) made retrofit proposals to achieve low energy consumption and net-ZEB level, respectively. For their case study in Italy, they assessed selected budget-based retrofit scenarios, that consist of EMSs and heating and cooling systems. The optimum strategy combined low-thickness EPS wall insulation with high thermal resistance rockwool roof insulation, a mechanical exhaust ventilation system without heat recovery, the replacement of the existing boiler with a condensing one and the replacement of the air-cooled chiller with a water-cooled one, characterised by higher efficiency.

In the United Kingdom, Huws and Jankovic (2014) assessed numerous variables of the three retrofit intervention categories, under the same criteria. According to them, a high-level external wall insulation stabilised the indoor temperature and increased the TC. Triple-glazed windows were the intervention that minimised GHG emissions, while quadruple-glazed windows provided the maximum TC conditions.

2.3.3 Discussion

When financial objective functions were considered, the improvement of the thermal properties of the building envelope was not a cost-effective retrofit strategy, especially for buildings located in temperate climates, because the estimated energy demand reduction was not enough to pay off the initial costs. On the other hand, low initial cost interventions, such as window frame sealing, retractable awnings and the installation of sensors were among the global optimal solutions.

When the minimisation of the environmental impact was the retrofit desired outcome, the envelope insulation, the airtightness and the replacement of existing windows with more efficient ones were among the optimal strategies, especially for cold climates. The embodied energy of these components was considerable; however, the lifetime final energy was also reduced, leading to net or positive energy mismatch. In temperate climates, natural ventilation can reduce the energy consumption for space cooling, while in cold climates heat recovery can reduce the space heating energy requirement. Having low embodied energy, natural and mechanical ventilation were considered among the optimal retrofit solutions. The installation of high-efficiency heating systems, such as HPs, was also considered as appropriate.

The majority of the investigations that consider LCC and LCEIs objective functions introduced balanced solutions, combining medium thermal resistance insulation of the envelope with high-efficiency heating systems. It should be noted that RESSs were not part of the optimal retrofit strategies, even though they were necessary in order to achieve a low energy/carbon retrofit target.

Similar balanced strategies are proposed by the investigations that employ LCC and FEn or PEn objective functions, prioritising efficient HVAC systems over high cost ESMs. The combination of medium envelope insulation levels with efficient HVAC systems formed the optimal solution. Among them, mechanical exhaust ventilation system with or without heat recovery and window replacement were the selected strategies. In general, heating systems were more cost-effective than high-cost ESMs. RESSs were introduced for nearly and net-ZEB retrofit targets but without improving the LCC objective function.

Considering TC as the third objective function, there was not a clear consensus in the literature over the role that the level of envelope insulation can play for building retrofit. Case studies located in temperate climate zones (Penna et al. 2015; Ascione et al. 2015) indicated that lower level of insulation, combined with a mechanical exhaust ventilation system, increased the thermal comfort, however, case studies located in colder climates (Hamdy et al. 2011; Huws & Jankovic 2014) called for higher thermal insulation levels of the envelope and higher R-value windows. It should be mentioned that shading systems were also considered under the ESMs and were selected among the optimal retrofit strategies.

Finally, despite being outside of the scope of this chapter, it is worth discussing the uncertainties that researchers identified. They can be classified in two major categories: uncertainties regarding the financial calculations and future climate uncertainties. The most commonly met are the discount rate or interest rate employed under the LCC calculations (Hasan, Vuolle & Sirén 2008; Ferreira et al. 2014; Pombo et al. 2016) and the considered lifespan (Ballarini et al. 2017b; Pombo et al. 2016; Ostermeyer, Wallbaum & Reuter 2013), while second comes the energy price escalation rates (Hamdy, Hasan & Siren 2013; Pombo et al. 2016). The uncertainty of the future climate was addressed, through a sensitivity analysis of results, by Desogus et al. (Huws & Jankovic 2014).

2.4 Applied methods and tools

Computer simulation has been emerged as a prevalent method for handling complex engineering problems. Dynamic simulation programs are widely used to analyse the performance of the building envelope and the integrated energy systems. Parametric simulation has also been used in order to see the effect of several variables to one or more design objectives. In addition, optimisation methods have been evolved to converge to the optimal solution of complex building design problems. The developed methods are most of the times automated because of the iterative nature of the process. They are called ‘simulation-based optimisation’ methods.

Retrofit problems are single or multi-objective problems in nature, where economic, scenario or sensitivity analysis are also performed (De Boeck et al. 2015). The following sections discuss the optimisation method and tools identified in literature.

2.4.1 Optimisation methods

In mathematics and sciences, ‘optimisation’ is the selection of the most appropriate solution to a problem from a set of alternatives. In BEPS, optimisation refers to a number of processes including iterative improvement of a simulation model, sensitivity analysis, expert-based optimisation and brute-force search.

In general, building design optimisation (BDO) is the process of minimising or maximising an objective function, by selecting a number of variables, under a number of constrains. A BDO problem can have both integer and discrete variables. Therefore, the objective function(s) can be discontinuous (Banos et al. 2010). Algorithms sensitive to those discontinuities or to multi-modal function, such as gradient-based algorithms and direct search algorithms, might fail to converge to the optimal solution (Wetter & Wright 2004). This behaviour limits the suitable optimisation algorithms to those that can handle result discontinuity, such as derivative-free algorithms. Optimisation problems can be constrained and unconstrained. Constraints can be imposed to variables, representing performance limitations or physical limitations. They are distinguished in equality and inequality constraints and can be variable's bounds, penalty and barrier functions. It is generally advised to convert equality constraints to inequality, as they are handled easier by the optimisation algorithms (Roy, Hinduja & Teti 2008).

Another important characteristic of most BDO methods is that optimisation algorithms treat the building performance simulation software as a 'black-box'. In that case, problem-depended optimisation methods, such as heuristic and gradient-based algorithms, that require information on the problem, cannot be implemented. Depending on the number of the objective functions (single-objective or multi-objective optimisation), there is one global optimal solution or a set of non-dominated optimal solutions, called Pareto optimal (Pareto 1896). A solution is non-dominated when there is no other solution that improves one objective function without deteriorating another one. The following sections discuss the commonly used algorithms, their performance and the available optimisation tools.

2.4.2 Optimisation algorithms and their performance

The selection of the optimisation algorithm for BDO is problem depended. If there is an analytical solution of the objective function, a problem can be solved with numerical methods. For BEPS, this is when calculations can be mathematically described. However, the evaluation of the objective function(s) with the use of a building performance simulation program is a non-linear problem and require the use of derivative-free algorithms (Machairas, Tsangrassoulis & Axarli 2014). In this section, a number of commonly used optimisation algorithms are described and discussed.

Direct search methods belong to the derivative-free algorithm family. They use heuristic principles to approach the optimal solution(s). The Hooke-Jeeves (H-J) algorithm (Hooke & Jeeves 1962) has often been applied to BDO problems. Peippo et al. (1999), who implemented the method to the optimisation of solar building design, stated that the algorithm requires problem specific programming. Less popular algorithms are the Simplex algorithm of Nelder-Mead (SANM) (Nelder & Mead 1965) and the Discrete Armijo Gradient (DAG) (Polak 1997). According to Bouchlaghem (2000), the SANM is more efficient than other direct search methods, however, its robustness is questioned. Among the three, Wetter & Wright (2004) claimed that H-J should be preferred as being more robust and having better quality of results. Those methods can be used even if the optimisation function has small-scale discontinuities, despite being sensitive to them.

Non-linear optimisation problems might have discontinuities in the objective functions that need to be handled by the optimisation software. Algorithms sensitive to those discontinuities or to multi-modal functions, such as gradient-based algorithms and direct search algorithms, might fail to converge to the optimal solution (Wetter & Wright 2003).

Evolutionary optimisation algorithms are the most frequently used among BDO problems. Being meta-heuristic, thus problem independent, they treat the optimisation problem as a 'black-box'. In order to approach the optimum solution(s), they generate a set of random numbers and use the principles of natural selection to evolve. However, their convergence to a global optimum or a set of optimal solutions cannot be guaranteed, especially for a small number of iterations. Genetic algorithms (GAs) are very effective when used for non-linear, discontinuous problems with many local minima. The Multi-Objective Genetic Algorithm (MOGA), the Non-dominated-and-crowding Sorting Genetic Algorithm II (NSGA-II) (Deb et al. 2002) and their variants are the most popular GAs (Wright et al. 2002; Palonen et al. 2009; Magnier & Haghighat 2010; Chantrelle et al. 2011; Evins et al. 2012; Hamdy et al. 2012; Hamdy et al. 2013; Yang et al. 2014; Yu et al. 2015; Ascione et al. 2015; Méndez Echenagucia et al. 2015; Manzan et al. 2016).

The Particle Swarm Optimization (PSO) algorithm, proposed by Eberhart & Kennedy (1995), belongs to the Swarm Intelligence category. Despite the fact that it is a meta-heuristic, population-based stochastic algorithm, it is not commonly met in literature (Rapone & Saro 2012; Delgarm et al. 2016).

Meta-heuristic algorithms have been widely used as the basis for hybrid optimisation algorithms. Being global-reach algorithms, they approach the optimal point. Then, a local optimiser is employed in order to refine the result. Hasan et al. (2008) used the PSO algorithm with construction coefficient J-H (PSO/J-H) algorithm for the LCC minimisation of a building design. Kämpf & Robinson (2009) proposed the combination of the covariance matrix adaptation evolution strategy with the hybrid differential evolution algorithm (CMA-ES/HDE) for a solar optimisation problems of buildings.

Despite the fact that the literature on BDO has been significantly increased the last two decades (Nguyen, Reiter & Rigo 2014), there are not many studies testing optimisation algorithms for this problem category. Thus, most BDO studies implement optimisation algorithms without looking at their performance. The following paragraphs review studies that compare optimisation algorithms applied in BDO problems.

For single-objective BDO problems, Wetter & Wright (2004) compared the performance of nine optimisation algorithms on a simple and a detailed simulation model. They tested the Coordinate Search algorithm (Audet, Dennis & Siam 2003), the H-J algorithm, PSO algorithm (Eberhart & Kennedy 1995) and the PSO that searches on a mesh, hybrid PSO/H-J algorithm, the simple GA (Press et al. 1993), the Simplex algorithm of Nelder-Mead with the Extension of O'Neill (SANMOE) (Nelder & Mead 1965; O'Neill 1971) and the DAG on the minimisation of the cost function. According to their findings, the hybrid PSO/H-J had the minimum cost. Sacrificing results accuracy, the simple GA reached close proximity to the maximum obtained cost reduction with a lower number of simulations. However, it was noted that if the number of simulations was small, algorithms that use stochastic operators might had failed to go close to the optimum solution. The SANMOE algorithm, requiring a large number of simulations, did not manage to come close to the optimum solution. The DAG algorithm failed and it is not recommended for discontinuous objective functions.

Based on the above results, Kämpf et al. (2010) compared two hybrid algorithms, the PSO/H-J and the CMA-ES/HDE. Their efficiency to optimise five benchmark functions was tested. Two buildings, that had one and several thermal zones equivalently, located at three different climate zones were simulated. Findings indicated that CMA-ES/HDE algorithm performed better on highly multi-modal, complex functions, while PSO/H-J gave better results when used for simple functions. The authors stated that the reason why both algorithms, having different model parameter combination, resulted in similar values of the objective functions is the multi-modal nature of the objective functions.

Tuhus-Dubrow & Krarti (2010) studied the design optimisation of a residential building envelope. They compared the performance of a GA, a PSO and a Sequantial Search method and found that the GA located the optimal solution, giving 0.5% accuracy on average, requiring half the number of iterations compared to PSO and the Sequential Search (SS) method.

Bichiou & Krarti (2011) compared the effectiveness and computational time of three optimisation algorithms, a GA, a PSO and a SS algorithm, when applied for the design optimisation of the building envelope and the selection of HVAC systems, targeting the minimisation of the LCC or the annual energy cost. The GA and the PSO algorithm reached the optimal solutions, saving 70% of the computation time, compared to the SS algorithm. The last one, optimising the building envelope first and then the HVAC systems, obtained the optimal solutions faster, by slightly sacrificing accuracy.

Futrell et al. (2015) studied the building design optimisation targeting the minimisation of lighting loads, testing a number of optimisation algorithms, namely:

SANMOE (Nelder & Mead 1965; O'Neill 1971), H-J, PSO using Inertia Weight (PSOIW) and the hybrid PSO/H-J algorithm. Results indicated that SANMOE and H-J algorithms reached convergence faster than PSOIW but they had inconsistent results. The PSOC/H-J demonstrated consistent solutions, while the PSOIW came closer to the global solution but only after performing a large number of iterations.

Si et al. (2016) used a set of indicators (robustness, stability, validity, coverage, speed and locality) to assess the performance of three commonly used algorithms for a design optimisation problem of six design variables, namely: H-J, Multi-Objective Genetic Algorithm II (MOGA-II) (Goldberg 1989), and PSO. They reported that MOGA-II method needed less iterations than PSO to reach convergence, while, in terms of locality index, the H-J performed the best among all selected algorithms. However, there was no algorithm demonstrating high-performance over all the indicators, which means that the algorithm selection should be made based on the nature of the problem.

Junghans & Darde (2015) developed a hybrid algorithm, which is a combination of a GA and a modified simulated annealing algorithm. Comparing the results with those obtained by using a GA, they found that the hybrid algorithm came closer to the global optimal without a significant increase of the calculation time.

Comparing multi-objective optimisation algorithms, Hamdy et al. (2009) claimed that a hybrid method can achieve faster solutions compared to a GA alone. They proposed two new methods, the preparation process and GA (PR-GA) and the GA with refine process (GA-RF). Results demonstrated an overall superiority of hybrid algorithms, in terms of both the optimisation of the objective functions and the computational time.

Hamdy et al. (2012) assessed the performance of three NSGA-II-based multi-objective optimisation algorithms (Deb et al. 2002), in terms of quality of result, diversity of solutions and convergence speed. Passive (pNSGA-II) and active (aNSGA-II) archiving strategies were added to NSGA-II in order to prevent the algorithm from failing to approach the Pareto optimal front. Results indicated that aNSGA-II and pNSGA-II outperformed NSGA-II in all of the evaluation criteria.

Another study of Hamdy et al. (2016) used a complex building energy model to compare seven multi-objective optimisation algorithms: a pNSGA-II, a PSO, a PR-GA, a non-dominated sorting evolution strategy, a Multi-Objective genetic algorithm employing the concept of epsilon dominance (evMOGA) (Reynoso-Meza 2014), a Multi-Objective Differential Evolution algorithm (spMODE-II) (Reynoso-Meza 2014; Xue, Sanderson & Graves 2003) and a Multi-Objective Dragonfly Algorithm (MODA) (Mirjalili 2016). The assessment criteria were the execution time, the convergence to the benchmarking optimal set, the diversity of the optimal set of solutions, the number of Pareto optimal solutions and the contribution of the algorithm's solutions to the Pareto front. The algorithms were executed using the same iteration numbers. The PR-GA method demonstrated high performance on convergence, time and number of non-dominated solutions, thus, was considered to be the best option. However, if an algorithm had to be selected, pNSGA-II, evMOGA and spMODE-II were competent choices, demonstrating acceptable performance in most of the indicators.

Finally, Li et al. (2017) compared the performance of four meta-heuristic multi-objective optimisation methods, the NSGA-II, the PSO, the MOGA and a Diferential Evolution (DE) algorithm, as for their execution time, the convergence to the optimal set and the diversity of the optimal set of solutions. Their results showed that the DE was superior in execution time and diversity of solutions indicators, while the MOGA and NSGA-II had an average performance through all tests.

Once more, there is no algorithm that outperforms the others, but it should be carefully selected based on the problem's characteristics. In general, meta-heuristic methods deal more effectively with building design optimisation problems. The GAs, the PSO algorithms and their variations are able to locate the optimal solutions faster. A better performance is noticed by methods based on meta-heuristic algorithms, such as the PR-GA and the GA-RF. The same is for hybrid algorithms that combine a meta-heuristic algorithm with a direct or graphic search algorithm.

2.4.3 Building energy performance simulation tools

It has already been mentioned that in the literature, BPO is usually coupled with building energy performance simulation (BEPS). Thus, it is useful to review the predominant BEPS tools before studying the available optimisation tools. Overall, they are divided in two major categories: the monthly quasi-steady state methods and the dynamic methods.

Monthly quasi-steady state methods are characterised by limited accuracy. Most of the building modelling tools employed by the EU member states, for EPC purposes, are based on monthly quasi-steady state methods. Their model inputs are simplified building information, while the dynamic effects are introduced using correlation factors. It has also been reported that they fail to accurately estimate the energy impact of common energy supply systems (Caceres & Diaz 2018).

Dynamic models consider the mass and energy rate of accumulation within the system, compared to an initial state. According to Attia et al. (2013), the most commonly used energy performance simulation tools are EnergyPlus, IDA ICE, TRNSYS and Esp-r. EnergyPlus (Crawley et al. 2000) is a free software, sponsored by the US Department of Energy. It does not have a graphical interface; third-party software tools, such as Design Builder or OpenStudio, are employed. ESP-r (William, Sc & Arch 2018) was created by the University of Strathclyde and is also free. Similar to EnergyPlus, it can be used for energy performance simulation of the building envelope, the HVAC systems and a number of renewable energy systems, such as PV (Sousa 2012).

IDA ICE (Kalamees 2004) and TRNSYS (Solar Energy Laboratory 2017) are commercial tools. While IDA ICE is easy to use, TRNSYS has a steep learning curve. On the other hand, TRNSYS is more flexible; its modular nature facilitates the addition of mathematical models, as well as the integration of components developed in other tools, such as Matlab and Excel.

2.4.4 Optimisation software tools

This section reviews optimisation tools that have been used for BPO. They can be classified in two major categories: special optimisation tools for building design and generic optimisation packages. They can be further sub-classified based on their capability to deal with single-objective or multi-objective optimisation problems, to handle discrete or continuous variables and constraint functions and to allow parallel computing. Attia et al. (2013) published an extended review on optimisation tools used for BPO problems.

Some of the special optimisation tools for building design are: Opt-E-Plus, GENE_ARCH, BEopt, MultiOpt2, jEPlus+EA and TRNSOPT. Opt-E-Plus was developed by NREL (Ellis et al. 2006) for EnergyPlus building simulation software. Thus, it is a free software. It is not designed for multi-objective optimisation problems and it is oriented towards the US context. GENE_ARCH (Caldas 2006) is also freeware and able to handle multi-objective optimisation problems. It was developed to couple DOE2.1 building simulation engine. BEopt was also created by NREL (Christensen et al. 2005) to be coupled both with DOE2.2 and TRNSYS. It was developed to explore design options for the envelope and the HVAC systems and calculate the energy savings. Once more, the program is restricted to the US context. MultiOpt2 (Chantrelle et al. 2011) is a commercially available multi-objective optimisation tool developed for TRNSYS 17. It uses the NSGA-II algorithm and comes with economic and environmental databases. The combined software jEPlus+EA (Zhang 2017) can be coupled with EnergyPlus , TRNSYS and DOE-2. In addition, all variables are discrete during optimisation. TRNSOPT is a TRNSYS software interface, introduced as a Type, that couples TRNSYS with GenOpt, a generic optimisation package. Overall, the special optimisation tools for building design are characterised by limited flexibility.

On the other hand, generic optimisation packages are more flexible, however, most of the times, they require advanced programming skills. Some of the most commonly used are GenOpt, DAKOTA, modeFRONTIER, MOBO, as well as Matlab, R and Python optimisation packages. GenOpt (Wetter 2001) is one of the most popular packages, being used to a plethora of BDO studies. It is a free, single-objective optimisation software that can be coupled with any simulation software that has text-based input and output files. DAKOTA is also a free software and its' optimisation algorithms can handle both single-objective and multi-objective optimisation problems. Even though it has the option of user interface, it has a steep learning curve. The modeFRONTIER (ESTECO 2017) is a commercial product with a large number of capabilities, regarding multi-objective optimisation, sensitivity analysis and parallel computing. MOBO (Palonen, Hamdy & Hasan 2013) is probably one of the most user's friendly environments for BPO problems as it is free and comes with a graphical user interface. It handles continuous and discrete variables, as well as derived variables. It is suitable for multi-objective optimisation and has an integrated library of the most commonly used algorithms, such as NSGA-II, aNSGA-II, OMNI-optimiser, J-H, the hybrid coupling of GA and J-H, along with random search and brute force processes. A comparison between MOBO and DAKOTA software was presented in the conference paper titled "Comparison of Multi-objective Optimisation Tools for Building Performance Simulation with TRNSYS", published in *Proceedings of BSO 2018: 4th Building Simulation and Optimisation Conference, Cambridge, UK: 11-12 September* (see Appendix B).

The programming languages Matlab, R and Python also provide optimisation capabilities, however, their use require advanced programming knowledge. Matlab environment, a commercial platform, has been widely used in BDO studies because of its flexibility and its extended capabilities to handle both single and multi-objective optimisation problems, discrete and continuous variables and parallel computing, while providing a variety of algorithms. Python language was used for the automation of building energy simulation workflows by Miller et al. (2012) and for the optimisation of the building envelope by Echenagucia et al. (2015). R language, even though it has packages for optimisation and sensitivity analysis, has not been used, to the best of the author's knowledge, for BDO problems.

2.5 Other aspects that influence building retrofit

The present section briefly discusses the on-going scientific research around the most critical issues of retrofit activities (1) building audit and performance assessment, (4) identification of the optimal solution(s) and (5) uncertainty analysis. Studies on post-retrofit measurement and verification are limited and won't be discussed under the present review.

2.5.1 Building audit and performance assessment

The first activity of the retrofit practice is the building audit and performance assessment. According to ASHRAE (2018) building audit can be conducted in three levels. Level 1 involves building inspection that determines the condition of the building envelope and installed systems. Level 2 requires the collection of energy bills to estimate the energy consumption for heating, cooling, DHW, lighting and appliances. Level 3 is the detailed building monitoring of occupancy, lighting and equipment schedules, internal loads and hot water draw profiles, as well as setpoint temperatures for heating, cooling and DHW, lighting levels and equipment efficiency.

In EU, energy performance certificates (EPCs) were widely introduced in 2010 with the EPBD-recast (European Commission 2012). Along with the building audit process, the building modelling process and modelling tools were provided. Modelling results are used for building energy labelling and the selection of retrofit actions suggested to homeowners.

Building audit is most of the times conducted in order to verify simulated energy consumption results or to calibrate building models. It should be mentioned that most standards and regulations developed for energy performance calculations assume standard operating conditions in order to enable easier comparisons between buildings. However, occupants' energy-related behaviour can have a great impact on building's energy consumption (Wallis, Nachreiner & Matthies 2016). By opening and closing the windows, modifying the thermostat settings or turning heating and cooling equipment on and off, occupants influence energy bills (Hong et al. 2016).

Serrano-Jim Enez et al. (2019) conducted building audit and occupant surveys that they normalised in order to develop three energy consumption profiles (high, medium and low) and compare them with the standard operating conditions (EU 2010). Based on their findings, the annual primary energy consumption of the standard operating conditions was the higher of all scenarios. The authors tested the influence of each energy consumption profile on the NPV of alternative retrofit interventions, in order to identify the preferable options. Results showed that for the same retrofit intervention there were significant variations of energy savings and NPV among the alternative energy consumption profiles, indicating that further investigation is required.

2.5.2 Identification of the optimal retrofit solution(s)

When the retrofit decision making involves more than one assessment criteria, it becomes a multi-criteria assessment problem. As mentioned in Section 2.3.2, multi-objective optimisation problems do not have one global solution but a set of optimal solutions. There are several ways to rank the optimisation results. The most common among studies on energy management problems is the Analytical Hierarchy Process (AHP) (Mardani et al. 2017; Nielsen et al. 2016). The method prioritises criteria through pairwise comparisons, conducted by the decision-maker or based on quantitative measured data.

When the assessment criteria are financial and energy or environmental, the cost-optimal approach can be employed. The EPBD (EU 2018) introduced the cost-optimal building design/retrofit concept that was defines as the solution of the lower LCC among the trade-off set of solutions (Pareto front). Moving along the Pareto front curve, a further reduction of the primary energy consumption or the GHG emissions would lead to LCC increase. Since 2010, a large number of studies employed the method to select the cost-effective one among the optimal global cost and primary energy retrofit alternatives (Kurnitski et al. 2014; Delmastro, Mutani & Corgnati 2016; Ferreira, Almeida & Rodrigues 2016).

Serrano-Jimenez et al. (2017) took the EPBD cost-optimal methodology a step further. After estimating the LCC and the annual primary energy consumption of a number of retrofit alternatives and packages, they conducted a survey among the multi-residential building residents in order to define additional socioeconomic parameters related to residents' preferences and needs. For example, according to the authors' report, residents prioritise cost against comfort and efficiency, passive against active retrofit measures and half of them were willing to pay between €1,500 - €3,000, while only 19% were willing to pay more than €3,000. Based on those findings, they defined three levels of intervention: mild, moderate and intense. Each intervention level had four alternative retrofit packages. The authors gave a score to the packages under nine equally weighted assessment categories (energy consumption reduction, cost-optimal ratio, comfort, affordability, PBP, revaluation of the property, usefulness of the measure, execution time and visibility of work), based on the energy and cost calculations and the conducted survey. That way, they managed to address the variety of needs among the different groups of residents.

2.5.3 Sensitivity and uncertainty analysis

This section discusses the main sensitivity and uncertainty analysis methods and factors related to building performance assessment.

Sensitivity analysis

Sensitivity analysis has been broadly used in BEPS applications such as early building design, sizing of heating, cooling and power building systems, building retrofit and climate change adaptation models. In building energy models, sensitivity analysis can identify the critical variables that affect model's performance on the design objectives. There are two types of sensitivity analysis methods, the local and global. The difference between local and global methods is that while local methods can get results for different locations of the parameter space, global methods can provide results for the entire sampled space. The last one is the main reason why global methods are preferable to building performance analysis applications. However, global sensitivity analysis methods are computationally demanding, compared to local.

Global methods can be further categorised to regression, variance-based, screening-based and meta-model sensitivity analysis (Tian 2013). The most popular method among building performance analysis studies is the regression method. Commonly used indictors of the regression method are the Standardised Regression Coefficient (SRC), the Standardised Rank Regression Coefficient (SRRC), the Partial Correlation Coefficient (PCC) and the Partial Rank Correlation Coefficient (PRCC). SRC and PCC are used for linear models, while SRRC and PRCC are used for non-linear, monotonic models, converting them to linear (Helton et al. 2006). At the same time, SRC and SRRC are used for uncorrelated data, while PCC and PRCC for correlated. Screening-based methods assess one parameter at a time, investigating how extreme values influence the outputs. They are used as a pre-process of sensitivity analysis to reduce the number of parameters that the main sensitivity analysis will evaluate (Eisenhower et al. 2012).

Another important parameter of sensitivity analysis is the probability distribution of the inputs and the inputs sampling method, in case that the selected sensitivity analysis method is a sampling-based method. According to Heiselberg et al. (2009) there are three commonly used probability distributions met in building performance applications: uniform, standard and lognormal. Building design studies use uniform distributions for their inputs, due to the fact that all possible values of the design variables are equally likely to be selected in the design phase. Studies of existing buildings use normal distribution for their inputs, because they look at the natural variations, such as the quality of insulation or construction. Building retrofit is a more complex case, as both design and natural variations of inputs are considered. According to Tian (2013) there are two approaches. The first one is the use of the two-dimensional Monte Carlo method. However, this method is computationally demanding. The second approach is to ignore the natural variations, provided the fact that their effect is not significant.

Selecting the appropriate sensitivity analysis method and tool is not a straightforward process. According to Nguyen & Reiter (2015), there must be a certain level of knowledge of the outputs. In general, the outputs of building simulation processes are, most of the times, non-linear and discontinuous. There are several tools used for sensitivity analysis. Among them, Dakota (Adams et al. 2014), Simlab and R sensitivity packages are free and can be used with BEPS.

Uncertainty analysis

Uncertainty analysis has received lots of attention in the field of building performance assessment and economic viability of energy efficiency solutions in buildings. This is because several inherently uncertain factors impact both the building performance and the investment feasibility indicators.

As for the building performance assessment, there are three types of uncertain parameters identified: design, physical and scenario parameters (Hopfe & Hensen 2011). Design parameters refer to design variations of the building properties, like geometry and orientation. Design parameters are outside the scope of the present study as they are more relevant to the design of new buildings than the retrofit of existing buildings. Physical uncertainties are related to physical material properties, such as density, thermal conductivity and thickness. They are also categorised as inverse uncertainties, as they can be determined through data measurement and model calibration.

Scenario uncertainties, which can also be referred to as uncertainties in boundary conditions, are more relevant to building retrofit projects and can be subdivided into internal and external. Internal uncertainties refer to the building operation and occupants' behaviour. They can be occupancy, lighting and equipment schedules, shading and window control strategies, as well as set-point temperatures for heating and cooling. External scenario uncertainties are related to weather data or climate change.

Scenario uncertainties are also characterised as forward uncertainties because their variation will influence the uncertainty of the study outputs, such as the energy use and the GHG emissions. The developed methods for forward uncertainty quantification are divided in probabilistic and non-probabilistic. Probabilistic methods are further subdivided in sampling based and non-sampling based. Sampling based methods are commonly used in building performance assessment problems because they treat the original deterministic model as a 'black-box', running it many times with different samples. Monte Carlo method and it's variations are widely used in building performance assessment problems (Santos Silva & Ghisi 2014). Non-sampling based methods and non-probabilistic methods are rarely used in building performance assessment problems (Tian et al. 2018).

The impact of climate change on building performance has also been studied (De Wilde & Tian 2011; Tian & De Wilde 2011). For those studies, future weather data were created by shifting variables of the current weather data files, based on climate projections. Tian & De Wilde (2011) employed UKCP09 probabilistic climate change predictions (Murphy et al. 2010) to assess building thermal performance under three future emission scenarios (low, medium and high) in years 2020, 2050 and 2080.

As for the building retrofit as an energy-related investment, uncertainties arise from excessive investment costs, the unpredictable increase of the maintenance cost and the unreliable forecast of the expected savings. In a macroeconomic study of energy-related projects, uncertain parameters are the energy price, the energy inflation rate and the discount rate. For example, LCC increases with the increase of energy price and energy inflation rate and decreases with the increase of discount rate. Copiello et al. (2017) integrated Monte Carlo method with LCC analysis to study the uncertainty caused by the energy price and the inflation rate for the retrofit of a social housing building. They found that the discount rate had four times higher influence than the energy price on project's LCC.

Rysanek & Choudhary (2013) combined a building performance simulation method under economic and technical uncertainties (energy price, IC, installation cost, government tariffs and subsidies and carbon intensity of the electricity grid) distinguished in two scenarios, the optimistic and the pessimistic, for retrofit optimisation. Optimisation under uncertainty is a promising method to treat real building design problems of non-deterministic input parameters (Hoes et al. 2011; Ramallo-González, Blight & Coley 2015; Bamdad et al. 2018).

2.6 Recent studies

This chapter reports recent studies on residential building retrofit, published in years 2019 and 2010, as they were not included in the literature review the time it was conducted. It is not an exhaustive review, but a review to identify the current trends and major findings in the researched field.

An increasing number of studies, regarding the impact of future climate on residential building retrofit, was observed (Shen, Braham & Yi 2019; Ayikoe Tettey & Gustavsson 2020). Shen et al. (2019) developed a method and a tool for the performance evaluation of several retrofit interventions targeting the building energy savings and the NPV, under climate change. The method employed a data tree algorithm for model training as it requires less computational resources. The ranking as well as the ranking change of optimal retrofit sets were obtained for the present and future climate conditions. To illustrate the method's applicability, two building types, a residential and an office building, located in two locations, San Francisco and Philadelphia, were considered as case studies. Results indicated that the optimal retrofit solutions heavily rely on the future climate change potential, thus, the impact of climate change in building retrofit should be considered.

Tettey and Gustansson (2020) explored the primary energy savings potential of several energy efficiency measures, including energy demand and supply measures, under the current and three future climate scenarios, for a multi-residential building retrofit in Southern Sweden. Results showed that heating and cooling demand vary significantly depending on the considered climate scenarios. Therefore, the performance of heating and cooling systems should be assessed together.

Regarding the retrofit of multi-residential buildings, several research studies were undertaken over the last couple of years (Rosso et al. 2020; La Fleur, Rohdin & Moshfegh 2019; Yuan, Nian & Su 2019). In the Mediterranean climate, Rosso et al. (2020) carried out a study on the multi-objective optimisation of building retrofit, considering four objective functions: the investment cost, the annual cost of primary energy, the annual primary energy demand and the annual CO_2 emissions. The method was applied to a multi-residential building in Rome, considering a number of retrofit interventions: ESMs (envelope insulation, window replacement, shadings, conversion of the balcony or the courtyard or the ground floor into a greenhouse) and renewable energy systems (solar thermal collectors and PV panels), but not HVAC systems. The identified optimal solution suggests the implementation of high thickness envelope insulation, double-glazing windows, conversion of balconies into greenhouses, reflective envelope finishing layer, solar thermal collectors and PV panels.

In the cold climate of Sweden, La Fleur et al. (2019) presented an optimisation study to identify the cost-optimal energy retrofit set, considering envelope insulation, window replacement and mechanical ventilation with heat recovery system, for several energy saving targets. It was found that cost-optimality can be achieved within a range of 20% to 40% energy saving target and includes window replacement with aluminium framed argon filled windows and wall and attic insulation or mechanical ventilation with heat recovery. Interestingly, the recurrent cost of energy is a small part of the LCC, which makes the ESMs less attractive. Thus, low energy price becomes a barrier to the building energy retrofit.

Finally, Yuan, Nian & Su (2019) developed a method for the ranking of building retrofit strategies regarding their performance on energy consumption and LCC. To evaluate the sensitivity of results due to uncertainty, a sensitivity analysis was carried out for a range of energy price escalation rates and discount rates. It was noticed that the ranking of cost-effective retrofit sets was the same for all energy price escalation rates but modified for the considered range of discount rates, indicating a stronger impact.

2.7 Conclusions

The undertaken literature review addressed part of thesis research Objective 1:

1. Develop the retrofit optimisation framework.

By addressing the first objective, this chapter seeks to build the basis for the development of a robust retrofit optimisation framework. The review followed the breakdown of the retrofit activities: (1) building audit and performance assessment, (2) definition of the retrofit stakeholders, objectives and strategies, (3) performance assessment of the retrofit strategies against the selected objectives, (4) identification of the optimal solution(s) and (5) uncertainty analysis.

The building audit is conducted to collect data for the assessment of the baseline performance of the building and, in some cases, to calibrate the building models and verify modelling results. Less often, authors use the collected information to update the building occupancy, heating, cooling, ventilation, lighting and equipment schedules and set points, in order to calculate the energy consumption more accurately.

The literature review of the retrofit activity 2 'definition of the retrofit stakeholders, objectives and strategies' indicated that most of the studies hold as major retrofit stakeholder the building/apartment owner(s). A combination of cost and energy or emissions indicators is used to assess the retrofit alternatives, while social criteria are less often considered. The retrofit, most of the times, targets the building envelope and less often the HVAC and the RESSs. A 'whole-building' approach is missing from the literature review. This identified knowledge gap was addressed by the present study.

Moving to the retrofit activity 3, the review identified the simulation-based optimisation, single or multi-objective, as the dominant method for performance assessment of the retrofit strategies. Additional methods might also be employed in order to calculate the cost or the environmental impact, based on the selected assessment criteria. GAs are the most popular among optimisation algorithms used by BPO, as they can handle multi-objective optimisation and they do not need to know the mathematical expression of the model, treating the performance simulation software as a 'black box'.

The optimisation process of a multi-objective building retrofit problem provides a set of optimal solutions. The selection of the final retrofit out of the sets of optimal interventions needs to be undertaken by the decision-maker. Most of the times, a weighting method, such as the AHP, is employed. Studies that follow a participatory approach, involving the decision-makers through surveys, are rarely met it the literature. However, the present study doesn't cover this step of the decision-making process. Future work on this topic is advised.

Finally, it was noticed that a large share of the reviewed building design or retrofit studies conducted uncertainty analysis, either regarding the financial calculations or the future climate. Despite the fact that the focus of the present study is not the uncertainty analysis, uncertainties that have a great impact on building retrofit were considered.

By determining the key aspects that impact retrofit and identifying the knowledge gap, a solid basis was built towards the development of the retrofit optimisation framework. The following two chapters address the second thesis objective.

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Chapter 3 – Alternative space heating and cooling systems

3.1 Introduction

The purpose of the previous chapter was to obtain a comprehensive understanding of the state-of-the-art of multi-residential building retrofit, as reported by the scientific literature, that is required for the development of a robust retrofit optimisation framework. The literature review highlighted, among other factors, the need to address the accuracy limitation of monthly quasi-steady state methods, as well as to simulate the performance of heating and cooling systems together.

The aim of this chapter is to select and compare alternative space heating and cooling systems in terms of minimising the GHG emissions and the LCC for a low-energy efficiency multi-residential building that was introduced as a case study.

The research Objective 2, as stated in Chapter 1, is addressed under this chapter:

> *2. Identify and model the retrofit strategies, based on the design parameters, the objective functions and the environment of the case study building.*

The retrofit strategies regarding space heating and cooling are discussed here. Strategies regarding the DHW and RESSs are investigated in Chapter 4.

The case study building was selected from 'Typology Approach for Building Stock Energy Assessment' (TABULA), an EU funded program for the development of a common database of the residential archetypes of the building stock in 20 European countries. While most of the information about the case study building was extracted from TABULA, a building audit was conducted to verify TABULA and identify the variations between the archetype and reality. The audit involved a building inspection that determined the condition of the building envelope and the installed systems, as well as the collection of energy bills to estimate the energy consumption. The collected information from the building audit is presented in Appendix C.

Appendix D provides the calculation of heat losses of the central hydronic system and the energy consumption of the circulation pump. The TRNSYS Types developed (Type 252, Type 253, Type 254, Type 255) are presented in Appendix E. The content of this chapter was submitted as a manuscript with the title "Alternative heating and cooling systems for the retrofit of medium-rise residential buildings in Greece” to *Energy*. The structure, the format and the referencing system followed the journal style.

3.2 Publication #1

Alternative heating and cooling systems for the retrofit of medium-rise residential buildings in Greece

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ABSTRACT

More than half of European households' energy consumption is accounted for space conditioning. Although the European average cooling load is negligible, over the past decade, southern European countries have experienced a growing trend in demand for cooling systems. This article compares the performance of market-available heating and cooling systems that can replace the existing low-efficiency systems in multi-residential buildings located in four Greek climate zones. The study objectives are to minimise the operating greenhouse gas (GHG) emissions and the life-cycle cost (LCC). Results demonstrated that air-to-air heat pumps have the lowest LCC. In areas where natural gas is not available, the replacement of the diesel-oil boiler with a biomass boiler leads to a decrease in the operating GHG emissions between 50% and 70%, depending on the heating load. In areas where natural gas is available, the gas absorption heat pump (GAHP) has the lowest operating GHG emissions, demonstrating a reduction between 30% and 50%, when compared to a conventional gas boiler. However, GAHP has a high LCC, making it less attractive compared to heat pumps and condensing gas boilers. The findings are in line with the current residential space conditioning market, while indicating the potential of biomass boilers and GAHPs.

Keywords: space cooling; space heating; medium-rise buildings; residential buildings; retrofit.

Nomenclature

Symbols

CE	annual cost of energy (€)
CI	initial cost (€)
CM	annual cost of system maintenance (€)
CR	annual cost of system component replacements (€)
r	real discount rate
t	project life (a)

Abbreviations

a-a HP	air-to-air heat pump
a-w HP	air-to-water heat pump
CC	correlation coefficient
CHP	combined heat and power
COP	coefficient of performance
CVRMSE	coefficient of variation of root mean square error
EU	European Union
GAHP	gas absorption heat pump
GHG	greenhouse gas
GUE	gas utilisation efficiency
HP	heat pump
LCC	life-cycle cost
MAE	mean absolute error
MBE	mean bias error
NPV	net present value
PLF	part-load factor
PLR	part-load ratio
PM	particulate matter
PM2.5	particles that have aerodynamic diameters less than or equal to 2.5 µm
RMSE	root mean square error
TABULA	Typology Approach for Building Stock Energy Assessment
TMY	typical meteorological year
TRNSYS	TRaNsient SYstem Simulation program

1. Introduction

In 2012, the building sector was responsible for 40% of the total energy consumption and 36% of the greenhouse gas (GHG) emissions in Europe [1]; these figures were reflected on the global scene [2]. Recently, the European Commission set radical targets for the reduction of GHG emissions by 2030 (50-55% reduction compared with 1990 levels) and 2050 (climate neutrality) and the building sector, especially the existing building stock, is expected to play a critical role in achieving these goals [3,4]. The reason is that 75% of the existing buildings are not energy efficient, with only 0.4% to 1.2% of the building stock is renovated annually [5]. The European Green Deal requires the existing renovation rates to double in order to reach the European Union's (EU) targets [4].

Among the building types, special consideration should be given to the residential sector because of its large share both in total floor area (75% of the total in 2010 [5]) and the final energy use (26% of the total in 2018 [6]). For EU households, heating was responsible for 64% of the total household energy consumption in 2017 [7]. The average annual heating energy consumption was about 118 kWh m^{-2} a^{-1}. North European countries had higher heating energy requirements (210 kWh m^{-2} a^{-1}), while countries of the Mediterranean had less (90 kWh $m^{-2}a^{-1}$) [8]. The average European energy consumption for space cooling was not significant (around 1% of the total household energy consumption), however, southern European countries have increased cooling demand that was projected to grow further [9].

The total household energy consumption is determined dictated by the selected space conditioning equipment and fuel type [10,11]. There are numerous studies that compare alternative heating systems for new or existing buildings. A recent one by Martinopoulos et al. [12] compared alternative heating systems for residential buildings in European countries, analysing their operating costs, based on seasonal energy efficiency. Results indicated that ground coupled heat pumps (HPs) had the lowest energy consumption cost, while electric heating systems had the highest followed by diesel oil fired boilers. The annual operating cost of a biomass boiler was almost twice compared to a ground-source HP, yet, the initial cost of the installation was significantly smaller [12]. For urban buildings, the most financially attractive and environmentally friendly heating system was the low-temperature condensing gas boiler [12]. The authors claimed that in the absence of a natural gas distribution infrastructure, diesel oil systems could be used, despite the higher fuel cost and GHG emissions.

Martinopoulos and Papakostas [13] compared the LCC of various, commonly used, heating systems for residential buildings in the Mediterranean climate. System energy efficiency, investment cost, fuel cost and environmental impact were considered. The results indicated that the climate and fuel availability have a great influence on system selection. The identified cost-optimal solution was the condensing gas boiler. HPs were the second choice, followed by the biomass pellet boiler, a system that is prohibited in large cities. Finally, the diesel oil and the electric boilers were ranked last. An earlier study, conducted by Papadopoulos et al. [14], assessed the economic and environmental performance of three heating systems: a central diesel oil boiler with a single-pipe distribution system, an autonomous natural gas boiler and autonomous air-to-water (a-w) HPs. The study is for a typical multi-residential building, located in the two major Greek cities, Athens and Thessaloniki. Their results are in line with those of Martinopoulos and Papakostas [13], indicating that the autonomous natural gas boiler minimises both the annual energy cost and the annual primary energy consumption. They are also relevant to the primary energy factors considered.

Fuel availability plays an important role in heating system selection. Just like the availability of natural gas urban infrastructure determines the use of gas-burning systems, the same can be said for biomass distribution and biomass-burning systems. Areas with large biomass residue availability, such as southeast European countries, can therefore benefit [15,16]. At the same time, the increased use of biomass is one of the objectives of the EU in order to achieve its strategic carbon emissions reduction targets [17–19]. Few studies [20–23] have explored the potential of biomass in the residential sector. Modern biomass boilers have efficiencies ranging between 85% and 90%, and are user-friendly, as they come with automatic pellet feeding features. However, according to Vicente et al. [24], there is a major concern regarding their particle matters (PM) emissions coming from small scale outdated biomass heating systems, as they are responsible for almost 50% of the total PM2.5 emissions in Europe.

Other parameters, such as the GHG emission factor of several energy sources, play an important role on system performance. Pineau et al. [25] compared the primary energy consumption and GHG emissions of a range of various heating technologies, including condensing gas boilers, biomass boilers, micro combined heat and power (CHP) systems, electric a-w HPs, a-w gas absorption heat pumps (GAHPs) and electric air-to-air (a-a) HPs. The technologies were located in various countries with different electricity generation energy mix, including France, Germany and Italy. Under system sizing following the European Standard EN12831 [26], the micro-CHP and the GAHP have higher energy efficiencies than conventional systems, however, small sizes, suitable for residential use, are not available on the market. In terms of environmental impact, biomass boiler systems produce significantly less emissions than conventional systems. In France, where electricity has a lower GHG emission factor, compared to Germany and Italy, electricity-driven systems have lower annual GHG emissions than gas-burning systems [25].

As identified, a large number of studies compare alternative heating systems for residential buildings. However, to the best of our knowledge, there is a limited number of studies on alternative cooling systems, and importantly research that investigates the combined performance of heating and cooling alternative options. Indeed, further research into these systems is critical, given the increased market penetration of reverse-circuit HPs that can handle both heating and cooling. It would be especially beneficial to residential buildings located in temperate climates (such as the Mediterranean) which require both heating and cooling.

Therefore, the aim of this article is to compare alternative heating and cooling systems in terms of minimising the GHG emissions along with the life-cycle costs (LCC). A low-energy efficiency multi-residential building was employed as a case study, due to the increased challenges at this building category encounters. The performance parameters of alternative cooling and heating systems for the case study building were quantified for one location in each climate zone of Greece (Table 2). The investigation of alternative hot water heating systems and their interaction with the heating and cooling systems is outside the scope of the study. Results obtained are specific to the economic situation, technology and fuel availability, the fuel and electricity prices and the national GHG emission factors. They can be used as a guide for similar construction and building types located in urban Mediterranean climate areas.

1.1 Space conditioning systems and challenges of the Greek residential sector

The residential buildings constructed before the 1960's in Greece do not have a central heating system. Heating is supplied either by unitary oil-fired stoves or low efficiency electric-driven devices [14]. For multi-residential buildings constructed after the 1960's, the most common heating systems is the centralised high-temperature hydronic system. Low temperature hydronic systems with floor slab pipes may also be found in new buildings.

Central forced-air heating systems are rarely installed in multi-residential buildings, mainly because their increased weight impacts the seismic performance of the building [14]. They also require extensive ductwork and space above the ceiling or below the floor. On the other hand, reverse-circuit HPs, that have dominated the cooling market due to their simple installation and low cost, are also used for heating if there is no hydronic system installed or in use. It should be mentioned that the way electricity charges apply - electricity tariffs follow a stepwise pattern over the 4-monthly consumption - is a barrier for the installation of central electricity-driven heating (and cooling) systems in multi-residential buildings. Other cooling technologies, such as the evaporative cooling, demonstrated high performance meeting the thermal comfort requirements when applied in a typical building in Athens (Greek climate zone B) [27], however, its market penetration is limited. Solar thermal systems were exclusively used for domestic water heating; and geothermal energy in building sector was almost non-existent [14].

The traditional boiler, widely available all over the country, is a central oil-fired boiler that combusts diesel oil [28]. Diesel oil is transferred on-site by vehicles and is stored in tanks. In the cities of Athens and Thessaloniki, natural gas was introduced to retail consumers in 2001. Since then, the use of diesel oil boilers has drastically decreased in those areas. They are being replaced by conventional gas boilers or, more recently, with condensing gas boilers, while for the rest of the country the use of biomass has increased [29]. Another noticeable trend in locations where natural gas urban infrastructure is available, is the change of the central heating system to autonomous hydronic systems, using condensing gas boilers [30].

Multi-residential buildings have more challenges compared to single-family houses. One of the reasons is the limited available land and rooftop space for the installation of renewable energy technologies, such as solar or horizontal loop ground coupled heat pump. Another challenge is the complex ownership nature and legislation that governs the building operation and decision-making. For example, the equal operating cost allocation favours the apartments located at the top and bottom floors, which have the greatest heating loads, discouraging owners from taking energy saving measure.

Finally, energy poverty emerged as a critical problem over the years of the financial crisis in Greece, following similar trends that occurred in other European countries [31] and globally [32,33]. The financial crisis put additional pressure on the existing problems of high energy prices and low energy efficiency of the building stock [34,35]. According to Hellenic Statistical Authority [36–38], in 2008, 76% of multi-residential buildings had the central heating system operating, while in 2017, only 37.7% of them were in use (Table 1). Law 4495/2017 allowed apartments to disconnect from the central heating system of the building, without the approval of the other owners, after insulating the pipes that heat the apartment.

Table 1.
Heating system used (%) by Greek households from the years 2008-2017 [38].

Heating system	2008	2011	2014	2017
Hydronic heating system with radiators (diesel oil)	68.2	64.4	35.4	41.3
Hydronic heating system with radiators (natural gas)	5.0	7.7	9.2	12.1
Burning stove (fuel oil)	5.3	4.2	2.7	2.0
Burning stove (liquefied petroleum gas)	0.6	1.5	2.2	1.4
Burning stove (wood)	6.1	6.7	11.1	8.8
Electric thermal storage heater	2.8	2.3	2.2	2.0
Electric heater	4.4	4.4	13.5	13.1
Reverse-circuit heat pump	4.0	4.7	12.8	8.8
Other means	2.6	3.8	9.2	9.9
No heating	0.4	0.2	1.8	0.5

2. Method

The developed method is presented through its application in a multi-residential building case study. The case study building was selected from the 'Intelligent Energy Europe' programme

‘Typology Approach for Building Stock Energy Assessment’ (TABULA) [39], an EU funded program for the development of a common database of the residential archetypes of the building stock in 20 European countries. While most of the information about the case study building was extracted from TABULA, a building audit was conducted to verify TABULA and identify the variations between the archetype and reality.

The selected building was modelled for four cities, located in each of the Greek climate zones. For every city, a reference (Case Ø) heating and cooling system was identified, based on widespread use and fuel availability, and several market-available alternative options were selected and compared. The annual GHG emissions and the net present value (NPV) of LCC of the selected alternatives were estimated. Table 2 presents the four cities and their Greek climate zones [40], the corresponding Köppen climate classification [41] and the natural gas availability.

Table 2.
The selected cities and the Greek and Köppen climate zone classification [40,41].

City	Greek climate zone	Köppen climate zone[1]	Natural gas availability
Heraklion	A	*Csa*	Not available
Athens	B	*Csa*	Available
Thessaloniki	C	*Csa/Cfa*	Available
Florina	D	*Cfa/Dfa*	Not available

[1] *C* = temperate, *D* = continental; *s* = dry summer, *f* = no dry season; *a* = hot summer.

To estimate annual GHG emissions, the annual energy consumptions of heating and cooling systems were multiplied by the corresponding GHG emission factors of the fuels utilised (Table 3). To estimate the annual cost, the annual energy consumption was multiplied by the current energy price (Table 4). The electricity and fuel prices provided are the final retail prices, including taxes.

Table 3.
Greenhouse gas (GHG) emission factors in Greece.

Fuel type	GHG emissions factor (kg CO_2-e kWh^{-1})	Reference
Electricity	0.810	Koffi et al. (2017) [42]
Natural gas	0.240	Koffi et al. (2017) [42]
Diesel oil	0.306	Koffi et al. (2017) [42]
Biomass pellet	0.063	Bertoldi et al. (2010) [43]

Table 4.
Electricity and fuel prices in Greece.

Fuel type	Price (€ kWh^{-1})	Reference
Electricity	0.1800[1]	PPC (2018) [44]
Natural gas	0.0509	Eurostat (2019) [45]
Diesel oil	0.1000	POPEK (2019) [46]
Pellet	0.0500[2]	Hellas pellet (2019) [47]

[1] Based on average electricity consumption of 2,000 kWh per four months.
[2] The pellet has heating value of 5 kWh kg^{-1} and costs 0.250 € kg^{-1}.

The discounted cash flow method which followed ISO 15686-5:2008 was applied to estimate the NPV of LCC (Eq.(1)).

$$LCC = C_I + \sum_{n=1}^{t} \frac{C_{E_n} + C_{M_n} + C_{R_n}}{(1+r)^n} \quad (1)$$

where C_I is the initial cost (€), t is the project life in years, r is the real discount rate (-), C_E is the annual cost of energy (€), C_M is the annual cost of system maintenance (€), C_R is the annual cost of system component replacements (€). The operating cost is a function of the fuel costs, the energy efficiencies of the heating and cooling systems and the building heating and cooling requirements. TRNSYS [48] was employed for system simulations and estimations of the energy consumptions. The simulation period was one year with a timestep of one hour.

The project life was assumed to be 20 years, as this is within the lifespan of most systems [49]. The discount rate applied has a significant effect on the value of LCC and it differs depending on the stakeholder. A discount rate between 2% to 4% has been advised for energy efficiency investments made by building occupants, as it reflects the actual building owners' benefits, over the entire lifetime in Europe [50]. According to Buildings Performance Institute Europe, the applicable discount rate for heating and hot water of a household is 3.1% to 3.7% [51,52]. The real discount rate 4% was applied assuming greater uncertainty in future.

2.1 Description of the case study building and estimation of the heating and cooling loads

According to the last national census data (2011), almost 50% of the Greek dwellings were in multi-residential buildings, located in urban areas, while 50% of the multi-residential buildings were built before 1980 [53] and the introduction of the thermal insulation legislation [54]. Similar are the numbers in EU, where more than 60% of the building stock was constructed before 1980 and the introduction of mandatory thermal insulation in most national regulations [55].

According to TABULA [39], The Greek building typology [56] includes 32 categories: four construction periods (pre-1980, 1981-2000, 2001-2010 and post-2011), four climate zones and two sizes (single-family and multi-family houses). The case study building (Fig. 1) is a 6-storey multi-family building, constructed in 1961 (before 1980) and is located in Athens (Greek climate zone B).

Fig. 1. 'Google Street View' of the case study building [57].

The selected building type can be found around Europe between 1945 and 1975. It is characterised by a reinforced concrete frame, brick masonry walls and wood-frame single-glazed windows [58]. Table 5 provides details of the construction types, the building envelope elements and their U-values and Table 6 presents the building's heat losses and gains. Occupant, lighting and equipment schedules are based on ASHRAE Standard 90.1 [59] for multi-family buildings and are presented in Fig. 2.

Table 5.
Construction types and thermal transmittance of the case study building [39].

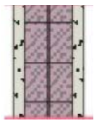
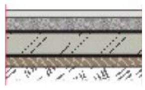
Elements	Wall 1	Wall 2	Wall 3	Roof	Floor	Window
Construction type	Brickwork 20 cm - plastered on both sides	Load bearing structure - reinforced concrete - plastered on both sides	Load bearing structure - reinforced concrete - unplastered on one or both sides	Flat roof	Slab on grade	Single-glazed, wooden or synthetic frame
Schematic						
U-value ($W\ m^{-2}\ K^{-1}$)	2.20	3.40	3.65	3.05	3.10	4.70
Area (m^2)	422	149	50	320	88	424

Table 6.
Building heat losses and gains.

Parameter	Value	Unit	References
Thermal bridge	0.15	$W\ m^{-2}\ K^{-1}$	TABULA (2017) [39]
Infiltration	0.40	hr^{-1}	
Fresh air	0.75	$m^3\ hr^{-1}\ m^{-2}$	Technical Chamber of Greece (2010) [60]
Occupants' thermal power	4.00	$W\ m^{-2}$	
Lighting capacity	64.00	$W\ m^{-2}$	
Lighting in-parallel use factor	0.50	-	
Equipment capacity	4.00	$W\ m^{-2}$	
Equipment operation factor	0.75	-	
Equipment in-parallel factor	0.50	-	

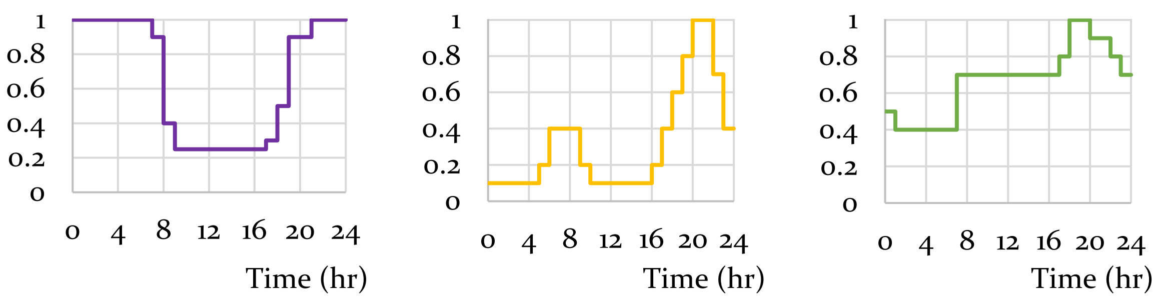


Fig. 2. Building occupation schedule (left), lighting schedule (centre) and equipment schedule (right) [59].

The ground floor of the building has three apartments and two retail shops and all upper floors has only apartments. For modelling purposes, the building was divided into fifteen zones. The 15 zones (three zones for the ground floor, two zones for each upper floor, and one zone for the staircase exit) model was based on the floor level and the usage.

For heating, the daytime (8:00 – 24:00) thermostat set-point temperature is 20 ̊C [60] and the night setback temperature is 18 ̊C. Heating season for Greek climate zones A and B begins on 28 October and ends on 15 April, whereas for Greek climate zones C and D it starts on 15 October and finishes on 30 April. The thermostat set-point temperature for cooling is 26 ̊C. Cooling season begins on 15 May and ends on 15 September for all Greek climate zones.

For building performance simulations, the weather data files used are in a TMY2 format, created using Meteonorm software [61]. The selected time stamp for TMY2 weather file is solar time. The difference between solar time and local standard time for each city was estimated using the equations provided in Duffie and Beckman [62]. It should be noted that the difference between longitude of the city and that of the standard meridian is 4.8-8.6 degrees. The estimated differences in times are not substantial compared to one-hour timestep. Therefore, the schedules (Fig. 2) in local standard time were used without conversion.

2.2 System parameters, assumptions and part-load performance

The existing double-pipe distribution system has been used as a reference for the proposed retrofit strategies. Those systems are representative of the heating systems installed in residential buildings in Greece until the early 1980s [14]. Several assumptions were made for the heating system configuration. Vertical hot water pipes provide hot water to a couple of cast iron radiators at each floor. The pipes located in the basement are insulated with a 13 mm thick elastomeric rubber insulation. The ratio of the annual distribution system losses to the annual heating load was found to be about 5.5% (align with the minimum distribution system efficiency of 96% required by the regulations [40]). Therefore the heat distribution losses were neglected. Autonomy of all zones was introduced to Case Ø system via the installation of water valves in every radiator, controlled by the thermostat in each zone.

Since the existing heating system was designed to operate for a few hours in a day, it is oversized and 80 ˚C supply temperature was used to be able to meet the heating load. A site-visit revealed that the existing boiler is 45% oversized (200 kW) compared to the peak load estimated (137 kW) using TRNSYS for a continuous operation. Provided the oversized system components, a lower distribution temperature (55 ˚C) was assumed for the alternative retrofit heating systems.

Heating and cooling systems are sized for full load design conditions, however, during most of the season, they operate at part-load. For most of the heating and cooling systems, manufacturers are required to inform their seasonal performance. By using the building's load and the part-load performance of the heating or cooling equipment and other parameters, the energy consumption and the seasonal performance can be estimated. Normalised part-load efficiency curves were produced, calculating the part-load ratio (PLR) and part-load factor (PLF) for all alternative heating and cooling systems investigated. PLR is defined as the ratio between the operating capacity and the rated capacity. PLF is defined as the ratio between the operating efficiency/coefficient of performance (COP) and the rated efficiency/COP. The performance curves are illustrated in Section 2.3. They were created using the performance data for one model of each system, however, they are used to calculate systems' performance for a range of capacities, depending on system's sizing.

Boiler's energy efficiency is a function of the water return temperature and the on/off operation when the load is below the minimum capacity [63]. High efficiency boilers have modulating capabilities that limit the on/off operation energy losses to loads lower than the modulating range. For equipment supplied in EU, the rated conditions for hot water boilers are according to Council Directive 92/42/EEC. The rating conditions for biomass boilers are provided by IS EN 303-5:2012. Manufacturers need to provide full and part-load (30%)

efficiency information. The part-load efficiency during on/off operation was calculated based on DOE-2 boiler curve [64]. The coverage was expanded for a range of return water temperatures, using the method developed by Cockroft, Samuel & Tuohy [65].

HP's COP is a function of the fluid supply temperature, the ambient air temperature and the on/off operation when the load is below the minimum capacity. Similar to boilers, the modulating capabilities of the HP's compressor limit the on/off operations energy losses to loads lower than the modulating range. For equipment supplied in the EU, the rating conditions of a-a and a-w HPs are defined by IS EN 14511-2:2013, while for GAHPs by IS EN 12309-3:2014. Manufacturers, following IS EN 14825:2016, need to provide the HP's COP for four ambient air temperatures that represent a range of part-load conditions. To calculate the part-load efficiency, the method developed by Schibuola et al. [66,67] has been used and expanded to integrate a range of ambient air temperatures.

2.3 Alternative heating and cooling systems

For each location, alternatives for heating and cooling were compared to a reference system (Case Ø). For locations without natural gas (Greek climate zone A and D), a diesel oil conventional boiler is Case Ø heating system. While for locations with natural gas (Greek climate zone B and C), a natural gas conventional boiler is Case Ø. A-a HPs is Case Ø cooling system for all locations. The selected systems for the locations without/with natural gas are presented in Table 7 and 8, respectively.

Table 7.

Case Ø system configuration and the alternatives for the locations without natural gas.

Case	Heating	Cooling
Ø	Diesel oil conventional boiler (central)	
1	Diesel oil condensing boiler (central)	Air-to-air HPs (autonomous)
2	Biomass pellet boiler (central)	
3	Air-to-water HP (autonomous)	
4	Air-to-air HP (autonomous)	

Table 8.

Case Ø system configuration and the alternatives for the locations with natural gas.

Case	Heating	Cooling
Ø	Natural gas conventional boiler (central)	
1	Natural gas condensing boiler (central)	Air-to-air HPs (autonomous)
2	GAHP (central)	
3	Air-to-water HP (autonomous)	
4	Air-to-air HPs (autonomous)	

The limited rooftop areas were assumed to be utilised for solar water heating systems; details may be found in [68]. Thus, solar energy supply technologies were not considered. At the same time, due to the limited exposed ground area, ground coupled HPs were not considered in this investigation.

System sizing follows the method reported by Lhendup [69] and market available capacities are also considered. In heating mode, the water supply temperature of the hydronic systems was assumed to be 55 °C. In cooling mode, the supply water temperature of the autonomous a-w HP system was assumed to be 7 °C. A 5% of the peak load has been set as the cut-down load. It should be mentioned that in case of future building insulation, the heating and cooling system should be resized to the reduced heating and cooling load. The following sections present the selected alternative systems.

2.1.1 Diesel oil and natural gas conventional boilers

As mentioned before, Case Ø in Greek climate zone A and zone D is a diesel oil conventional boiler, while in climate zone B and zone C is a conventional natural gas boiler. The capacity control of the boiler is handled via on/off operation. The assumed rated efficiency of standard oil boilers is 85%, while for a standard gas boiler 90% [70] The assumed electrical power absorbed is 0.25 kW. PLF for various return water temperatures were calculated based on the method presented in Section 2.2.1. Fig. 3 shows the diesel oil and natural gas boilers' PLF as a function of return water temperature and PLR.

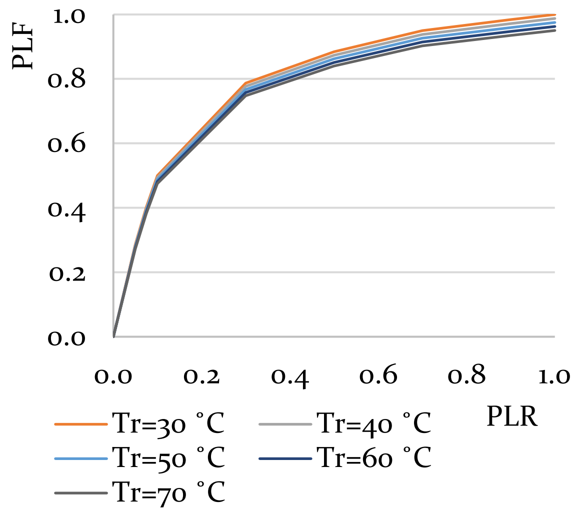


Fig. 3. Normalised part-load performance of a typical diesel oil conventional boiler (rated heating capacity 100 kW, rated efficiency of 85%) and a typical natural gas conventional boiler (rated heating capacity 100 kW, rated efficiency of 90%).

2.1.2 Diesel oil and natural gas condensing boiler

The modelled diesel oil condensing boiler is De Diedrich GTU C200 and C300 series [71], while natural gas condensing boiler is Ariston Genus Premium EVO HP [72]. Both systems' capacity control is modulating. The modulating operation is modelled based on the method developed by Cockroft, Samuel & Tuohy [65]; PLF as a function of return water temperature and PLR. For PLR smaller than the modulating capacity the boiler operates in on/off mode as described in Section 2.2.1. The normalised part-load performances of the boilers are illustrated in Fig. 4.

2.1.3 Biomass pellet boiler

A biomass pellet boiler is an alternative to the existing diesel oil boiler, for Greek climate zone A and D. According to Ministerial Decision 189233:2011, biomass pellet boilers are permitted in urban areas of Greece. The modelled biomass pellet boiler is Mavil Primus [73]. The system capacity control is on/off. The normalised part-load performance illustrated in Fig. 3 was assumed.

2.1.4 Gas absorption heat pump

The modelled GAHP is Robur GAHP-A [74]. As the model comes in only one capacity, the system is an assembly of more than one unit, connected in parallel. When operating alone, the unit's capacity can be modulated up to 50%, however, when more than one unit are operating in parallel the capacity control of each unit is on/off. The method for the calculation of part-load efficiency, uses data provided by the manufacturer's testing under the IS EN 14825:2016. For the GAHP, the PLF is defined as the ratio between the operating gas utilisation efficiency (GUE) and the rated GUE. Fig. 5 shows the PLR-PLF for on/off capacity control and for modulating capacity control operation.

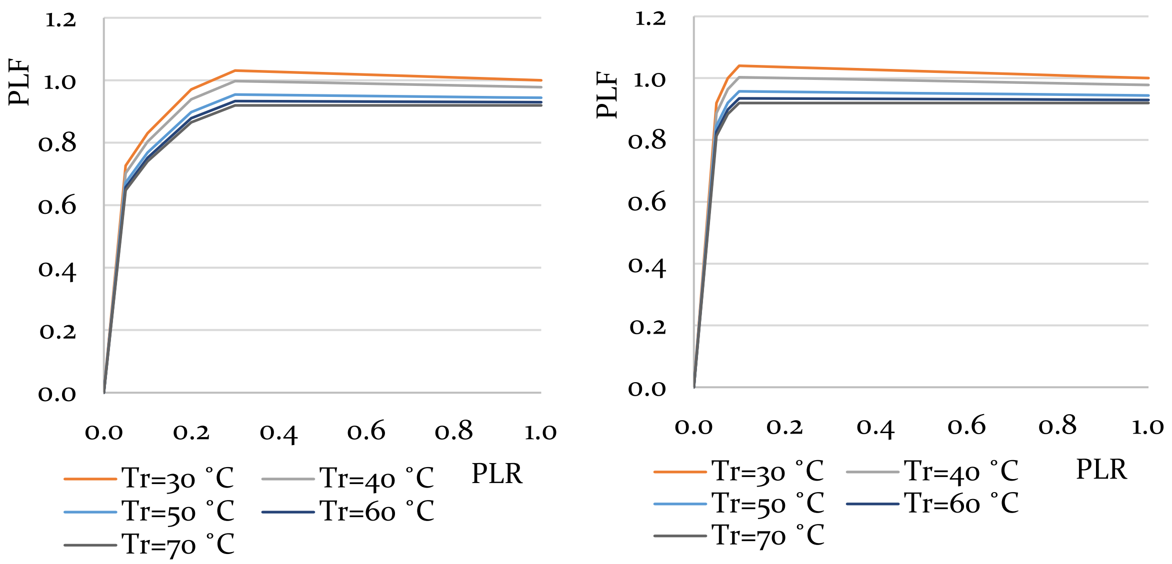


Fig. 4. Normalised part-load performance of the diesel oil condensing boiler (De Diedrich GTU C334) (left) and the natural gas condensing boiler (Ariston Genus Premium EVO HP 100) (right).

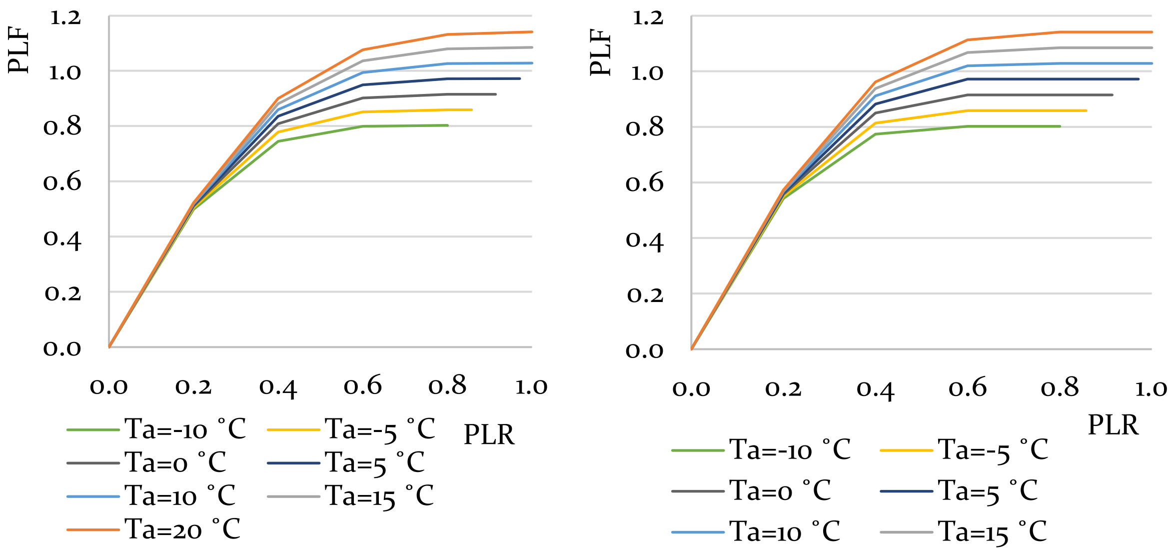


Fig. 5. Normalised part-load performance of the GAHP (Robur GAHP-A) under on/off capacity control (left) and modulating capacity control (right).

2.1.5 Air-to-water heat pump

The autonomous a-w HP for heating and cooling system we used in our model is Ariston Pocket M Net [75]. The a-w HP has modulating capacity control. Fig. 6 shows the PLR-PLF for a range of ambient temperatures. Under the operation of this system, each apartment is disconnected from the central heating system and a new distribution system is installed. Three fan coil units are allocated to each apartment, sized to meet the respective apartment's peak heating load.

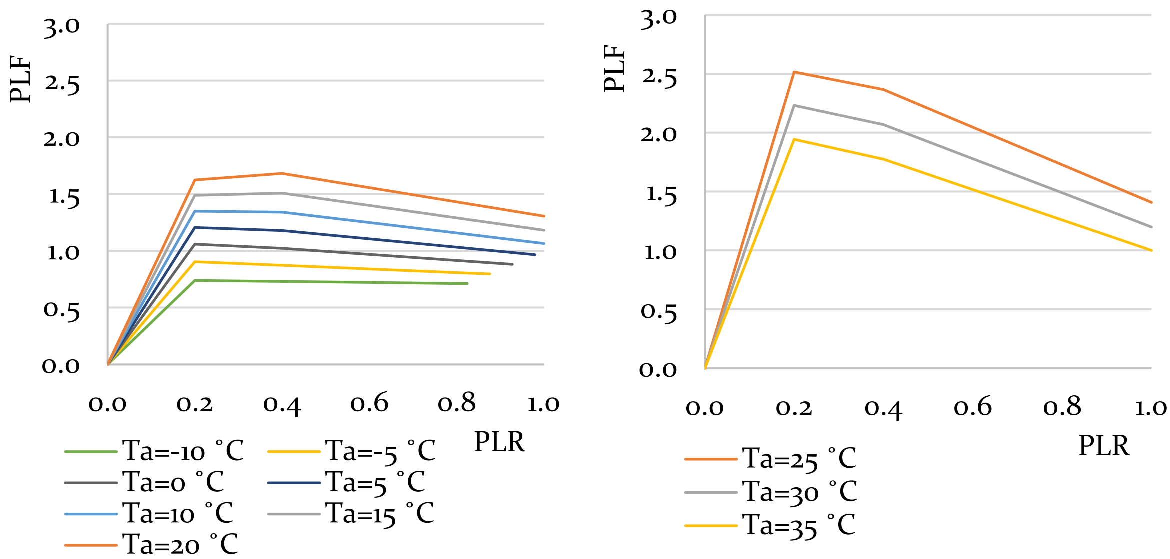


Fig. 6. Normalised part-load heating performance (left) and cooling performance (right) of a typical a-w HP (Ariston Pocket M Net 40).

2.1.6 Air-to-air reverse-circuit heat pump

Two reverse-circuit a-a HP units are introduced as heating and cooling alternatives for each apartment. NREL [76] testing results of Mitsubishi FE12NA a-a HP are used as input data of system's performance map. Fig. 7 shows the PLR-PLF for a given ambient temperature under heating and cooling mode.

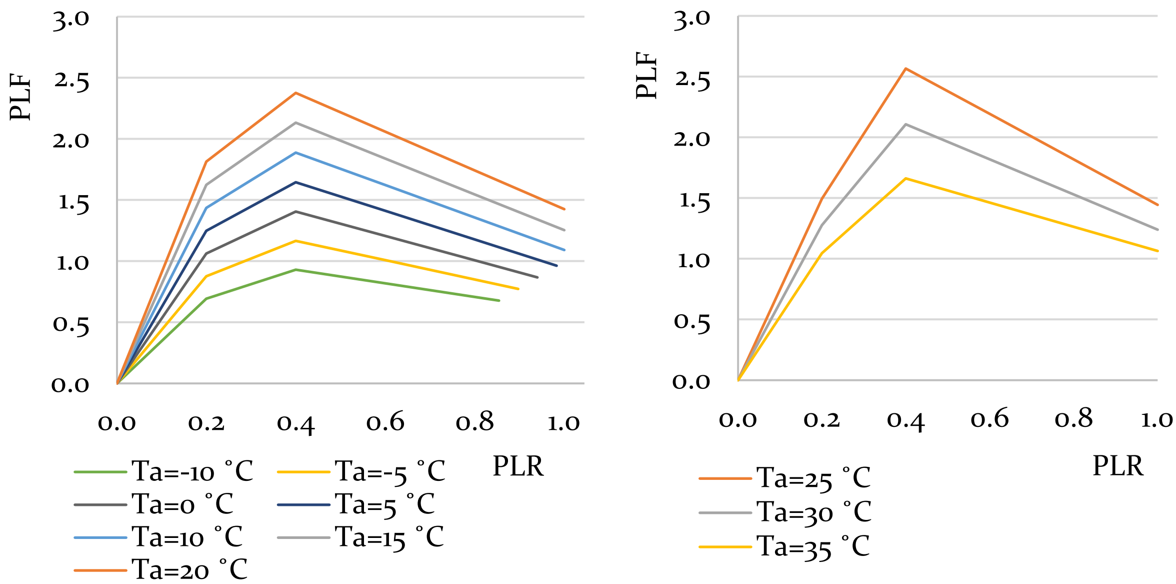


Fig. 7. Normalised part-load heating performance of a typical a-a HP (left) and cooling performance (right) (Mitsubishi FE12NA).

2.2 Verification and validations of the models

In general building models are validated comparing the simulated results with the measured data. A number of apartments of the case study building had their building envelope modified. Measurement on the current building is not appropriate. Therefore simulated results for heating were compared with TABULA data. The simulated annual heating load per floor area of the building is 97.6 kWh m^{-2} a^{-1} and that of cooling is 76 kWh m^{-2} a^{-1}. The annual heating load presented in TABULA (using a static calculation method) is 70.5 kWh m^{-2} a^{-1} [note no data available for cooling]. We could say that the building model developed in TRNSYS is verified. It should be noted that TRNSYS Type 56, which was used for the modelling of the case study building, was validated by Mazzeo et al [77] for Rome (Mediterranean climate). They reported that Type 56 is highly accurate (the coefficient of determination, R^2 ranges from 0.854 – 0.990) for the internal air temperature, the glass internal and external surface temperatures.

For the validations of three developed TRNSYS Types the performance parameters of the heating and cooling systems (boiler, a-a HP, a-w HP, GAHP) were simulated and the results were compared with Manufacturers' and test reports' data. One may say that the available two testing points for the boilers (full capacity and 30% capacity as required by standards) are not sufficient for validation. The justification is that the PLFs of boilers do not vary significantly (see Fig. 3 & 4). The accuracy indices found are presented in Appendix A.

3. Results

The operating GHG emissions and LCC of the selected alternative heating and cooling systems were compared with that of Case Ø. The GHG emissions results are presented in Section 3.1, while the LCC results are presented in Section 3.2.

3.1 Annual operating GHG emissions

Section 3.1.1 presents annual operating GHG emissions for locations without natural gas and Section 3.1.2 presents those for locations with natural gas.

3.1.1 Locations without natural gas

The results for locations without natural gas (Greek climate zone A and D) are provided in Fig. 8. Case 2 produces the smaller amount of GHG emissions. Case 4 and Case 3 follow; their performance is comparable in climate zone A where heating load is smaller than zone D but cooling load is much larger. In climate zone D, the performance of Case 4 is significantly better than Case 3. This is attributed by the higher efficiencies of Case 4 in heating mode, when compared to Case 3. Systems that rely on oil-fired boilers for heating produce the largest amount of annual GHG emissions amongst the systems compared.

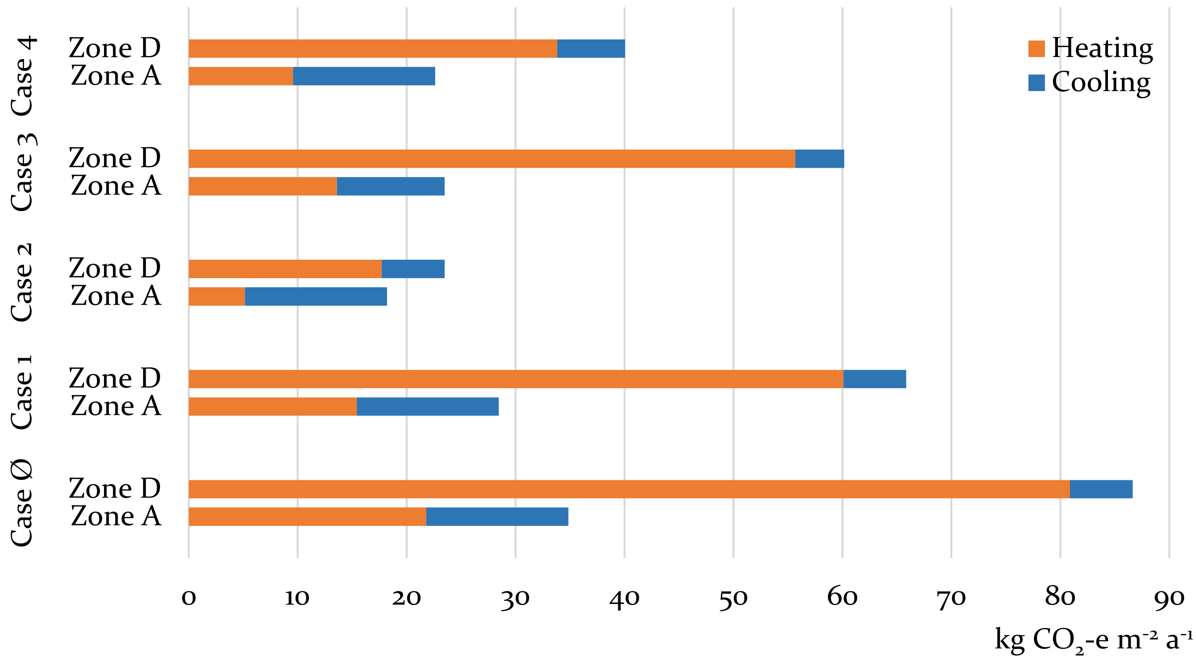


Fig. 8. Annual GHG emissions of alternative systems for location without natural gas (Greek climate zone A and D).

3.1.2 Locations with natural gas

The results for locations with natural gas (Greek climate zone B and C) are presented in Fig. 9. Case 2 has the lower annual GHG emissions, as it is benefited from the high COP of HPs and the low GHG emissions of natural gas. Case 4 has the second lower GHG emissions. In climate zone B, the performance of Case 1 is comparable to Case 3, however, in climate zone C, Case 1 outperforms Case 3. Once more, all four alternative systems have less GHG emissions compared to Case Ø.

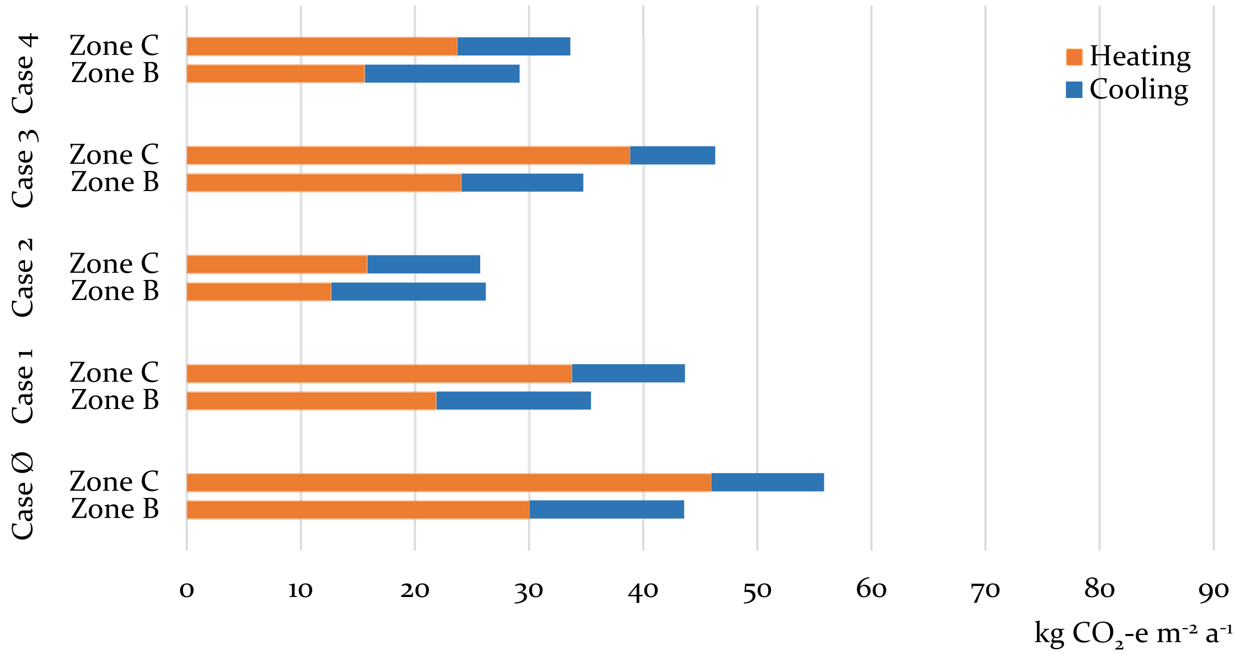


Fig. 9. Annual GHG emissions of alternative systems for locations with natural gas (Greek climate zone B and C).

3.2 Life-cycle cost

The NPV of LCC of the system comprises of the initial cost and the discounted annual operating and maintenance cost. Table 9 provides a breakdown of the initial cost and Table 10 provides the maintenance cost per unit of conditioned area for the alternative systems. It can be seen that, except for the GAHP, the initial cost of central heating systems is much less than the autonomous systems.

3.2.1 Locations without natural gas

The initial cost and the NPV of recurrent cost of the compared systems in locations without natural gas are presented in Fig. 10. For both climate zones, Case 4 minimises the LCC as it has both low initial and recurrent costs. The recurrent cost is determined by the system's efficiency and the cost of the energy. The high efficiency of Case 4 system compensates for the high price of electricity. On the other hand, despite the high efficiency of Case 3, its LCC is higher due to the high initial cost. For climate zone A, the initial cost of Case 3 is about 50% of the LCC. Case 2 comes second, after Case 4, for both climate zones. Despite the low efficiency, compared to HPs, the low prices of biomass boiler and pellet lead to lower LCC. All proposed systems have lower LCC than Case Ø.

Table 9.
Initial cost per unit of conditioned area[7] (€ m^{-2}) breakdown of the alternative systems for climate zone B.

Item/service cost	Diesel oil non-cond. boiler	Natural gas non-cond. boiler	Diesel oil cond. boiler	Biomass boiler	Natural gas cond. boiler	GAHP	a-w HP	a-a HP
Installation of thermal autonomy	4.47[4]	4.47[4]	4.47[4]	4.47[4]	4.47[4]	4.47[4]	-	-
Pipe insulation of non-cond. zones	0.37[1]	0.37[1]	0.37[1]	0.37[1]	0.37[1]	0.37[1]	-	-
Dismantling of the existing central heating system	-	-	0.19[1]	0.19[2]	0.19[2]	0.19[2]	-	-
Chimney replacement	-	-	1.20[1]	-	1.20[2]	-	-	-
Secondary circuit water pump			0.60[1]	0.60[1]	0.60[1]	0.60[1]	-	
Installing of piping for the autonomous system	-	-	-	-	-	-	11.91[1]	-
Fan coils	-	-	-	-	-	-	11.91[5]	-
New system installation	1.25[1]	1.25[1]	1.25[1]	1.05[1]	1.25[1]	3.16[1]	8.93[1]	3.18[5]
New system	1.10[5]	1.26[5]	11.83[6]	2.73[5]	3.31[2]	26.91[3]	56.57[2]	19.26[5]
Total initial cost	7.19	7.35	19.91	9.41	11.39	35.70	89.32	22.44

[1] (Lafogiannis 2019, personal communication, 11 October), [2] (Psarros 2019, personal communication, 14 October)
[3] (Pavlidou 2019, personal communication, 26 September), [4] (Delatolas 2019, personal communication, 27 August)
[5] Average prices calculated from on-line shopping web sites, [6] (Armiros 2020, personal communication, 3 January)
[7] Conditioned building area: 1360.4 m^2, -: Not applicable

Table 10.
Cost of maintenance per unit of conditioned area (Psarros 2019, personal communication, 14 October).

System	Cost per unit conditioned area[1] (€ m^{-2})
Natural gas cond. boiler	0.11
Biomass boiler	0.11
GAHP	0.11
A-w HP	1.59
A-a HP	1.19

[1] Conditioned area of the building: 1360.4 m^2

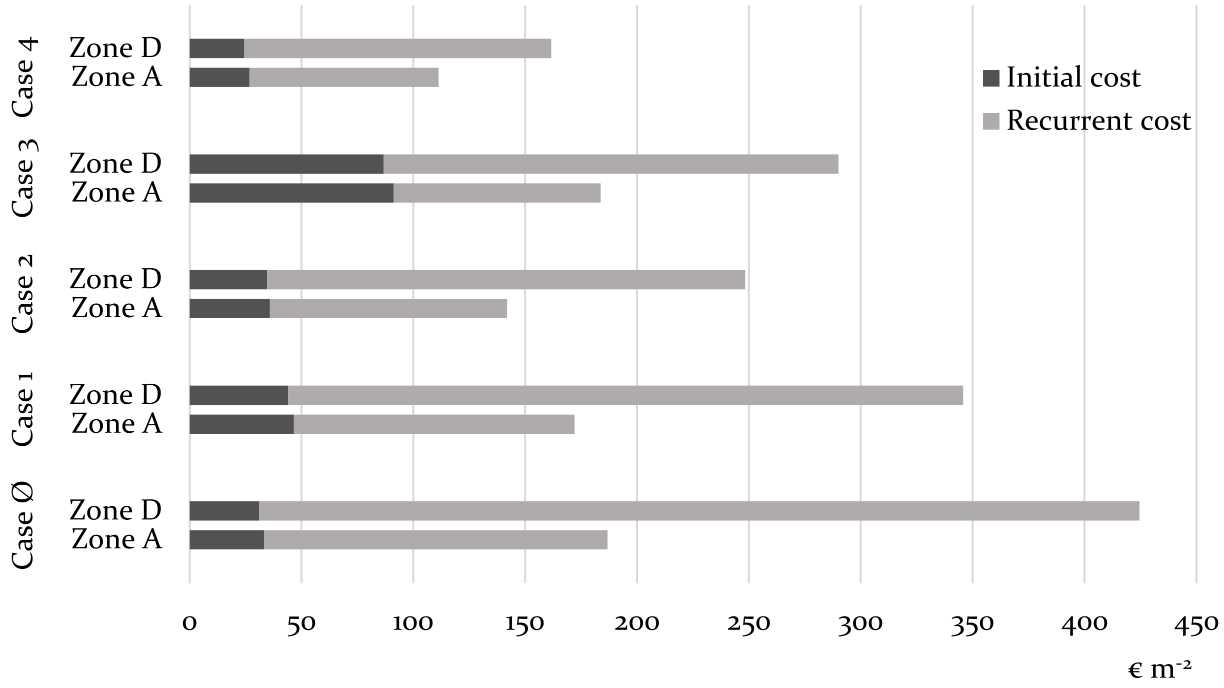


Fig. 10. Initial costs and NPV of recurrent costs for alternative systems investigated for locations without natural gas (Greek climate zone A and D).

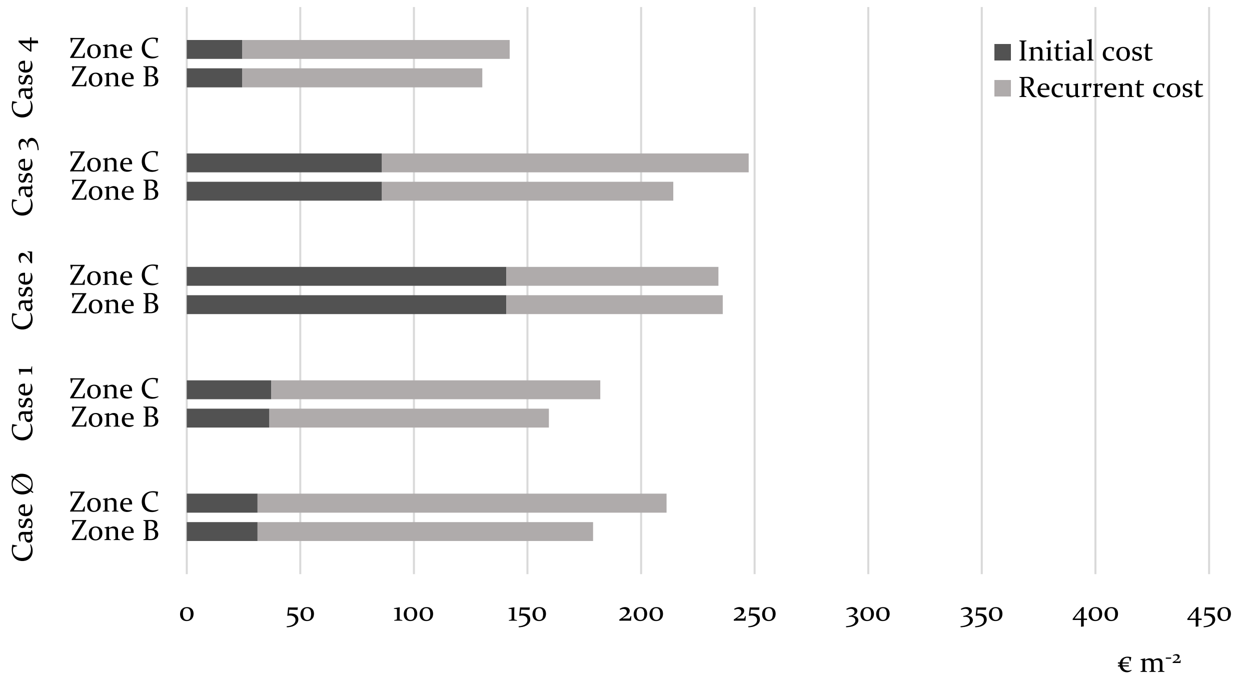


Fig. 11. Initial costs and NPV of recurrent costs for alternative systems investigated for locations with natural gas (Greek climate zone B and C).

3.2.2 Locations with natural gas

The initial and the NPV of recurrent costs for the compared systems in locations with natural gas are presented in Fig. 11. The low gas price compensates for the lower efficiencies of Case 1 and Case 2, compared to Case 3 and Case 4 where the high systems' efficiencies compensate for the high electricity price.

The high initial costs of Case 2 and Case 3 are responsible for their higher LCC compared to Case 1 and 4, for both Greek climate zones. The a-w HP requires the replacement of the existing radiators with fan coil units, fact that increases the initial cost significantly. GAHP commercial products are relatively expensive, which makes them less competitive when compared to other gas-burning central heating systems. Case 4 has the lower LCC, when compared to the rest of the systems, for both climate zones.

4. Discussion

Several parameters, such as the GHG emission factor, the initial cost, the energy cost, the fuel type and the heating and cooling load, influence the annual GHG emissions and the LCC of the systems. In some cases, the effects of those parameters counteract each other. For example, electric-driven HPs have high efficiency that decreases the amount of annual GHG emissions and LCC, however, the high GHG emission factor and energy cost of electricity have the opposite effect. On the other hand, less efficient systems, such as conventional and condensing boilers might have lower annual GHG emissions than Case Ø, if they combust fuels with lower GHG emission factors.

Biomass-fired systems that replace the conventional diesel oil boiler have a great potential to decrease the annual GHG emissions (up to 73%), depending on the heating load. The larger the heating and cooling load the greater the reduction was found. However, when a conventional gas boiler is replaced, the alternative systems have better performance, decreasing the annual GHG emissions but to a lesser extend (29% to 53%).

Systems' initial cost influences the LCC, especially for climate zones with low heating loads. Central heating systems of low initial cost, such as biomass or condensing gas boilers, have comparable results (locations without natural gas) or better results (locations with natural gas) to autonomous systems of high initial cost, such as a-w HPs, even though the efficiency of the central heating systems are lower than the autonomous systems. Although the GAHP is a central heating system, it is not considered among the optimal solutions. Only when its initial cost decreases significantly, could it be a cost competitive alternative.

The results presented agree with the current market's trend: high penetration of condensing gas boilers and a-a HPs in the residential sector. Systems of low initial and operating costs are more competitive against both the existing systems and systems characterised by high-efficiency and high initial costs, such as the GAHPs and the a-w HPs.

In urban areas where natural gas distribution infrastructure does not exist, biomass pellet boilers are a reasonably more desirable replacement of the diesel oil boilers. This is in line with the heating in the rural areas of Greece which have a long tradition of biomass combustion systems such as wood-fired stoves.

4.1 Sensitivity of results due to uncertainty in the real discount rate used

The future operating and maintenance cost depend on the energy price growth rate and the inflation rate. The results of a recent study on building energy retrofit evaluation under uncertainty demonstrated that the discount rate had four times higher influence than the energy price on project's LCC [78]. Thus, a sensitivity analysis of the optimisation results was undertaken, considering a range of real discount rates from 2% to 6%, which is in line with the range used by other studies on residential building retrofit in Europe [79].

The results of the sensitivity analysis are shown in Fig. 12. As expected, systems that have low recurrent costs are less sensitive to the real discount rate. In climate zone A, considering a high discount rate makes Case Ø more attractive than Case 3, while in climate zone C, Case 2 and Case 3 become equally attractive. However, no change of the optimal solutions regarding the LCC was noted over the range of real discount rates analysed.

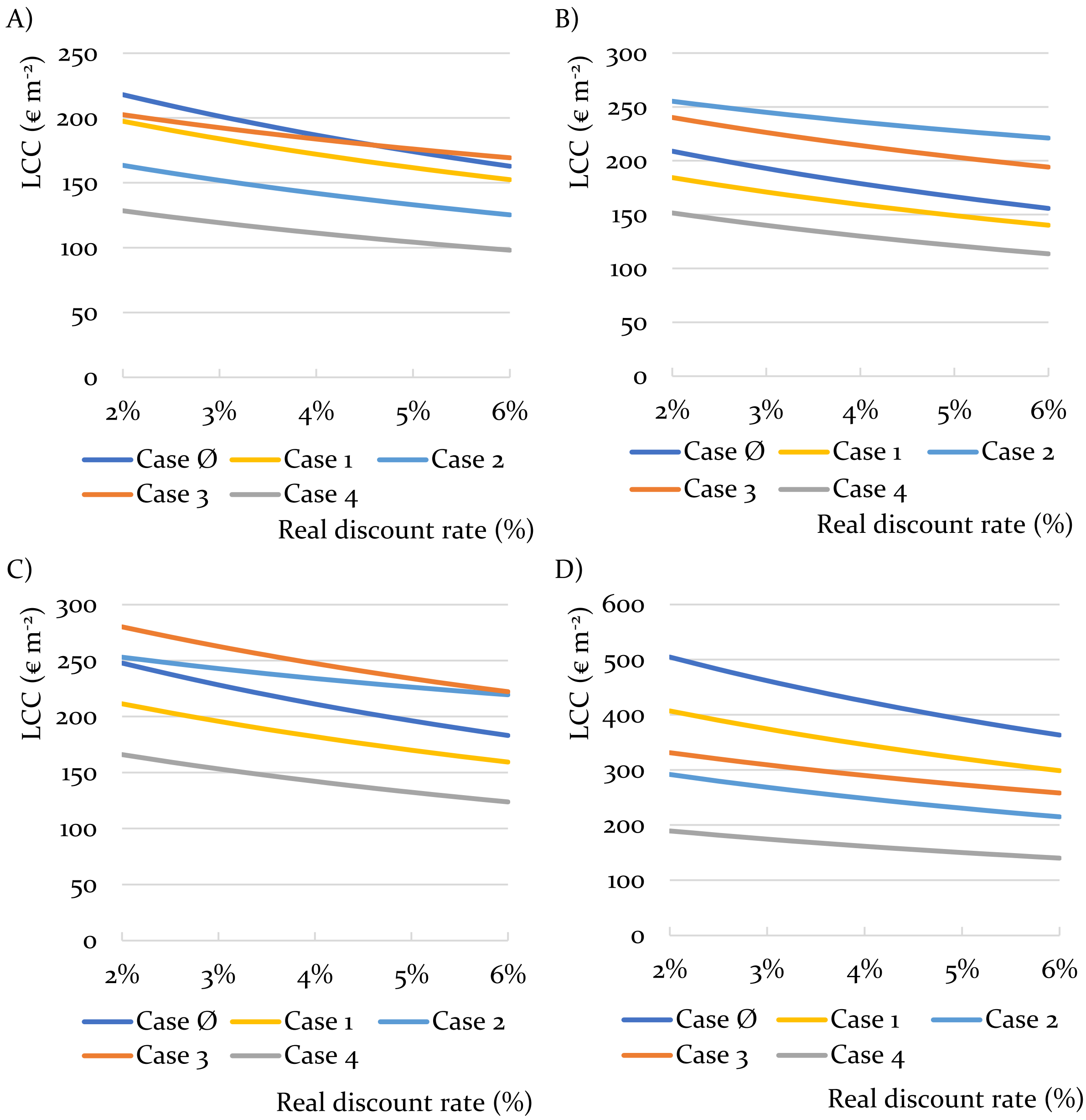


Fig. 12: Sensitivity analysis for a range of real discount rates, for climate zones: A) Heraklion, B) Athens, C) Thessaloniki and D) Florina.

4.2 Further research recommended

In this investigation, only the alternative heating and cooling systems for the building retrofit were studied. The interactions of the systems with other elements, such as water heating and mechanical ventilation, or envelope insulation and window replacement were outside the scope. In addition, only the uncertainty analysis of the real discount rate was conducted. Uncertainties of other parameters, such as the energy price growth rates and future GHG emission factors were not considered. These interactions and uncertainties mentioned were identified as further research in the future.

5. Conclusions

This article compared the performance parameters of market-available alternative heating and cooling options that can replace the existing low-efficiency systems in multi-residential buildings of the four Greek climate zones. These options were designed to reduce both the greenhouse gas (GHG) emissions and the life-cycle cost (LCC).

For locations where natural gas is not available (Greek climate zones A and D), the replacement of the existing system can lead to a significant GHG emissions reduction, which is proportional to the heating and cooling loads. Case 2 (biomass pellet boiler for heating and a-a HPs for cooling) was the most beneficial alternative, followed by Case 3 (a-w HP for heating and cooling) and Case 4 (a-a HPs for heating and cooling) in warmer climate zones and Case 4 in colder climate zones. Case 4 minimised the LCC, followed by Case 2, in both Greek climate zones.

In urban areas where natural gas distribution infrastructure is available (Greek climate zone B and C), Case 2 (GAHP for heating and a-a HPs for cooling) had the lowest GHG emissions, followed by Case 4 and Case 1 (natural gas condensing boiler for heating and a-a HPs for cooling). Nevertheless, Case 2, along with Case 3, had the highest LCC compared to the other two systems that demonstrated lower LCCs. The GAHP and the a-w HP will be competitive alternatives when their purchase cost decreases.

Condensing gas boilers and a-a HP units are the most common space conditioning systems in Greece. Having low initial and operating costs are more competitive against other high-performing but high initial cost systems, such as the GAHP and the a-w HP. The results of the present study are in line with the observed market trends. Results obtained are specific to the financial situation, state of the technologies and fuel availability of the locations considered. However, they can be used as a guide for the retrofit of similar construction and building types located in urban areas of the Mediterranean climate. They are also specific to the selected systems and the current electricity GHG emissions of the grid in Greece. However, future decarbonisation of the grid, as planned by EU, will have a strong impact on systems' GHG emissions, favouring electricity-driven systems.

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Appendix A: Validation of the developed TRNSYS types for the HP performance

The developed HPs and GAHP TRNSYS Types were validated by comparing the simulated and catalogued/measured COP for heating and, in case of the a-a and a-w HPs, cooling. The description of the measured data and their sources are provided in Table A.1.

Table A.1.
Description of test data and their sources

System type	System model	Data description	Reference
Air-to-air HP	Mitsubishi FE12NA	COP (heating and cooling)	NREL. Laboratory Test Report for Fujitsu 12RLS and Mitsubishi FE12NA Mini-Split Heat Pumps 2011.
Air-to-water HP	Ariston Pocket M Net 40	COP (heating and cooling)	Psarros 2019, personal communication, 14 October
GAHP	Robur GAHP-A	COP (heating)	Giuberti 2019, personal communication, 2 August

Accuracy indices: the Root Mean Square Error (RMSE), the Coefficient of Variation of Root Mean Square Error (CVRMSE), Mean Bias Error (MBE), the Mean Absolute Error (MAE) and the Correlation Coefficient (CC) were applied for quantifying the agreement between simulated and measured temperatures. Each index serves a deferent purpose. The RMSE indicates the absolute fit of the model to the data. The CVRMSE normalises the RMSE by the average dependent variable value, which is the measured COP/GUE. MAE measures the average magnitude of the errors in a set of simulated values, without considering their direction, while MBE calculates the average bias in the simulations. Finally, the CC measures the strength and direction of a linear relationship between the dependent and the independent variables.

The scatter plots of the simulated values versus catalogued/measured of the COP/GUE for the a-a HP, the a-w HP and the GAHP are presented in Figures A.1 to Fig. A.3. Most of the differences in COP/GUE values were found to be within a ±10% range. Table A.1 shows the statistical parameters of the comparisons between the simulated and catalogued/measured COP/GUE values for the three heating and cooling systems. Overall, results indicate acceptable accuracies.

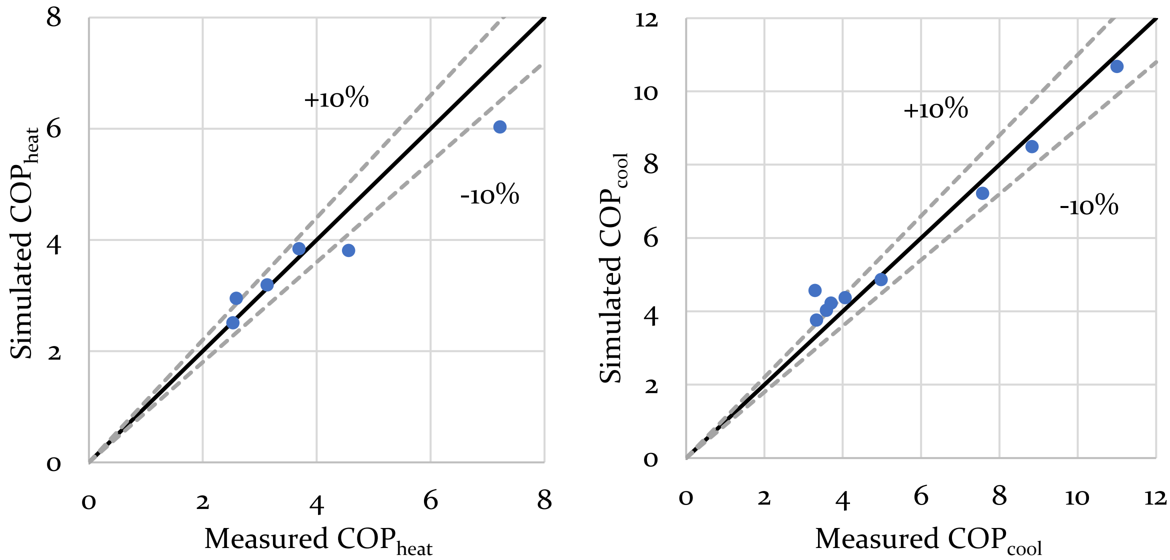

Fig. A.1. Simulated vs. measured COP for heating (left) and cooling (right) mode of the air-to-air HP.

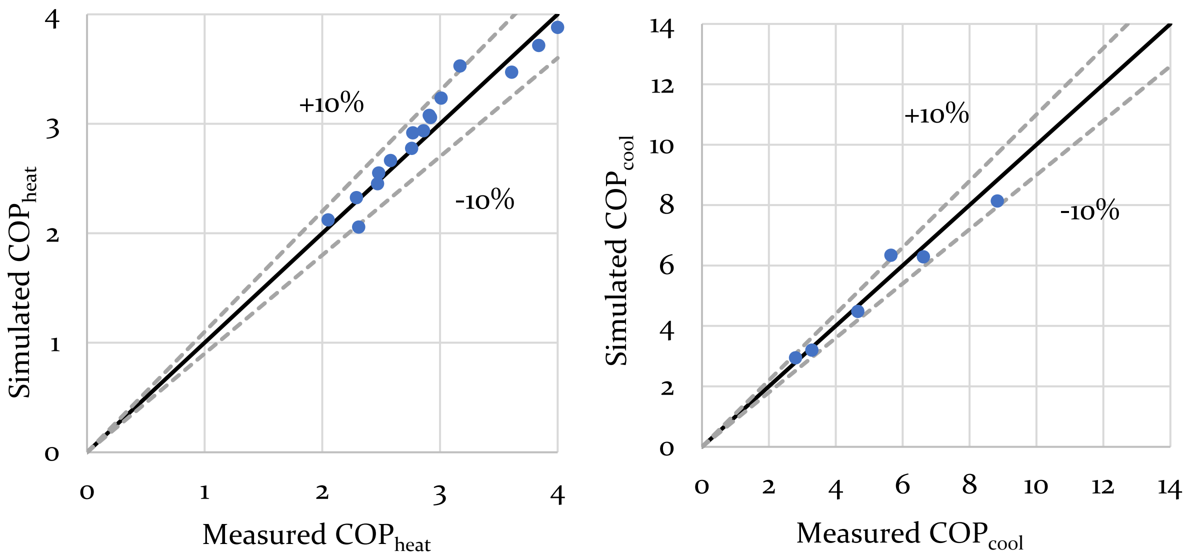

Fig. A.2. Simulated vs. measured COP for heating (left) and cooling (right) mode of the air-to-water HP.

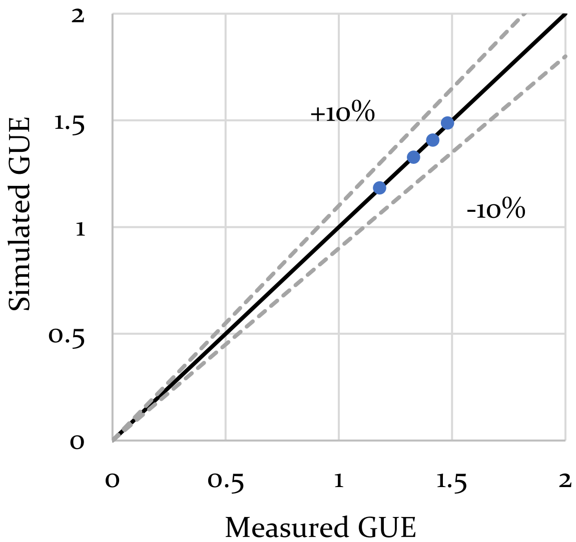

Fig. A.3. Simulated vs. measured COP for heating mode of the GAHP.

Table A.1.
Statistical parameters of the comparisons between measured and simulated for COP values for the space heating and cooling systems.

Variables	RMSE	CVRMSE	MAE	MBE	CC
Air-to-air HP COP$_{heat}$	0.06	0.02	0.42	-0.23	0.98
Air-to-air HP COP$_{cool}$	0.43	0.08	0.46	0.21	0.99
Air-to-water HP COP$_{heat}$	0.02	0.01	0.12	0.03	0.98
Air-to-w HP COP$_{cool}$	0.07	0.01	0.36	-0.07	0.98
GAHP - GUE	0.00	0.00	0.01	0.00	1.00

HP: heat pump, GAHP: gas absorption heat pump, RMSE: Root Mean Square Error, CVRMSE: Coefficient of Variation of Root Mean Square Error, MAE: Mean Absolute Error, MBE: Mean Bias Error, CC: Correlation Coefficient

Chapter 4 – Alternative DHW and RESSs

4.1 Introduction

The purpose of the previous chapter was to select and compare alternative space heating and cooling systems in terms of minimising the GHG emissions and the LCC for a low-energy efficiency multi-residential building that was introduced as a case study. The aim of this chapter is to select and compare alternative DHW and RESSs that minimise the annual 'net' electricity consumption and the LCC for the same multi-residential building. It should be mentioned that all DHW systems are autonomous, studied at apartment level. Only electricity-driven DWH systems were considered.

The chapter addresses part of the research objectives 2, as stated in Chapter 1:

> *2. Identify and model the retrofit strategies, based on the design parameters, the objective functions and the environment of the case study building.*

The content of this chapter was published with the title "Solar driven water heating systems for medium-rise residential buildings in urban Mediterranean areas" in *Renewable Energy*, vol. 147 (2020), p. 556-569. The structure, the format and the referencing system followed the journal style.

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Solar driven water heating systems for medium-rise residential buildings in urban mediterranean areas

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International Energy Agency reported that buildings are accountable for one-third of the global final energy demand in 2017. On-site renewable energy generation can reduce buildings' grid electricity consumptions. Medium-rise buildings located in urban areas have limited available rooftop or facade surfaces, thus solar driven technologies such as solar thermal, photovoltaics (PV) or photovoltaics/thermal (PV/T) are in competition for the available space. This investigation aims to compare available solar driven water heating systems in the market, suitable to replace the conventional electric water heater for a multi-residential building. Under the present study, solar PV electric water heating system (S1), solar thermal water heating system with electric boosting (S2), solar PV/T water heating system with electric boosting (S3) and integrated solar PV and heat pump water heating system (S4) are investigated. The performance parameters compared are the annual net electricity consumption from the grid and the net present value of life-cycle cost (LCC) for 20 years life. Results reveal that S3 and S4 have 'net' positive electricity production but higher initial costs, compared to the other systems. For buildings located in colder climates, S2 has lower LCC compared to S3 but for warmer climates the LCC of S3 is the lowest.

1. Introduction

Buildings are responsible for 38% of the total final energy consumption in the European Union (EU), two-thirds of which is for residential buildings [1,2]. They present a great opportunity and at the same time, they are a significant barrier towards the 2030 climate target of the EU for 40% cuts in greenhouse gas (GHG) emissions, compared to 1990 levels. To meet the target, special consideration must be given to multi-residential buildings, due to the limited unshaded rooftop and façade areas for the installation of renewable energy systems (RES).

The commonly applied technologies for on-site production of renewable energy in buildings are the solar thermal collectors and the photovoltaic (PV) panels. Solar thermal collectors convert solar radiation into usable heat, with a typical efficiency of up to 80% [3], while solar PV panels have an energy conversion efficiency of 12%–18% [4]. Due to higher efficiencies, solar thermal technologies are applied for space and water heating, which are the most energy-intensive end-uses in residential buildings [1]. Many support schemes for PV development have been launched in most European countries, leading to rapid growth over the last decades. Even though photovoltaics/thermal (PV/T) systems provides combined efficiencies they are not commercially attractive solutions yet [5].

Various studies compared the performance and costs of various water heating systems, or combination with electricity production: PV and PV/T [5–8]; PV and solar thermal [9]; solar thermal, PV and PV/T [10–13]; PV/T [14] and solar assisted heat pump systems [15–17]. Results mainly depend on the end use, the climate and the prices in the country of application. The higher the solar radiation available, the better the financial viability of the project [18]. Low-temperature applications, such as domestic hot water (DHW), show financial improvements [9].

In general, the individual electrical and thermal efficiencies of PV/T systems are lower compared to side-by-side PV and solar water-heating systems [10,19]. According to da Silva and Fernandes [17], to obtain the same thermal and electric yields with side-by-side PV and solar thermal panels, an additional 60% roof area is required.

Good, Andresen and Hestnes [20] addressed the issue of

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Abbreviations

Cfa	humid subtropical climates
Csa	Mediterranean hot summer climates
Csb	Mediterranean warm/cool summer climates
Dfa	hot summer continental climates
DHW	domestic hot water
DX-SAHP	direct expansion solar-assisted heat pump
EU	European Union
GHG	greenhouse gas
GSHP	ground-source heat pump
HP	heat pump
HPWH	heat pump water heating
LCC	life-cycle cost
NPV	net present value
PV	photovoltaic
PV/T	photovoltaic/thermal
RES	renewable energy systems
SA-ASHP	solar-assisted air-source heat pump

buildings' limited rooftop area for the installations of RESs for water heating. They compared annual net electricity consumption of three solar energy systems for a Norwegian single-family house. They reported that high-efficiency PV modules had better performance among market-available technologies. The combined use of solar thermal collectors and PV modules came second. The limited rooftop area issue was also addressed by Herrando et al. [8] and Herrando and Markides [5]. Both investigations compared the performance of a PV/T system with a PV system installed in a typical three-bedroom terrace house in London. The PV/T system had more energy output and less GHG emissions. It met more than 50% of the total electricity demand and 36% of the DHW demand, while the PV system met only 49% of the electricity demand. However, PV system had the half the discounted payback time of the PV/T system.

To select among the competing solar technologies for DHW loads of a 40 m^2 roof area of a house in Montreal, Delisle and Kummert [11] compared PV/T collectors with solar thermal and PV modules, based on the energy produced and financial benefits. They argued that the benefits of the PV/T system depend on the end-use of the thermal and electrical energy and the type of equipment it replaces.

To identify the solar panel area requirement for a 160 L DHW load in Prague, Matuska and Sourek [9] compared a PV water heating and a solar thermal system in terms of the energy yields and financial parameters. The PV water heating system requires 13.2 m^2 area, while the solar thermal system requires 4.5 m^2. They found that the solar thermal system achieved 61% solar fraction, supplying 25% more energy than the equivalent PV-DHW system. They reported that solar thermal DHW systems were financially better than PV-DHW systems available at the market. Matuska [12] also compared the performance and cost of a market available PV/T system with a solar thermal system, a PV system and their combination in several configurations, for a multi-residential building in Wurzburg, Germany. The PV/T system outperformed all compared systems in terms of energy production. However, its market price needed to be halved in order to be financially competitive.

Seven solar-assisted water heating systems, with the same solar collector area (6 m^2) and the same water storage tank capacity (280 L), were compared by Li and Yang [17] for Hong Kong, in terms of financial viability and total equivalent warming impact. The water heating systems investigated are a conventional electric, a conventional gas, a solar electric boosted, a solar gas boosted, a solar-assisted air-source heat pump (SA-ASHP), a solar-assisted water-source heat pump (SA-WSHP) and a direct expansion solar-assisted heat pump (DX-SAHP). They found that the payback period of the solar water heater boosted by electricity is 3.4 years and that of the solar water heater boosted by gas is 3.8 years, compared to the conventional electric water heater. The SA-ASHP' payback time was 4.3 years and that of SA-WSHP was 6.9 years. As for the total equivalent warming impact, the conventional electric water heater has the highest, followed by the DX-SAHP and the SA-WSHP. The solar water heater boosted by gas has the lowest, followed by the conventional gas water heater.

Aye, Charters and Chaichana [15] investigated the effects of location and climate on the performance of alternative water heating systems. They compared a thermosyphon solar water heater, an air-source heat pump water heater (HPWH) and a solar heat pump (HP) water heater in several Australian cities, in terms of grid electricity consumption, GHG emissions and life-cycle cost (LCC). The thermosyphon water heater was the most appropriate system for locations of high solar radiation, producing less GHG emissions. In areas of lower solar radiation, a solar HPWH was found to be preferable due to the decreased LCC.

Biaou and Bernier [16] examined four renewable energy systems for producing DHW in two climates (Montreal and Los Angeles), by identifying the required solar panel areas to achieve net zero energy consumption. The study was applied in a detached home of 156 m^2 floor area. The alternatives were: a regular electric hot water tank, the de-superheater of a ground-source heat pump (GSHP) with electric boosting, thermal solar collectors with electric boosting and a HPWH indirectly coupled with a space conditioning GSHP. The electricity consumed by the electric booster was supplied by PV panels. Based on the simulation results, heating DHW with solar thermal collectors was the best solution for both climates. Optimising the size of the solar thermal and PV panels, the authors concluded that for Los Angeles, 4.5 m^2 thermal solar collectors and 2.06 m^2 PV panels were needed. The system's payback period was found to be 11 years. For Montreal, 12 m^2 of solar thermal collectors and 5.2 m^2 of PV panels had to be installed. However, this system was not cost-effective, having a payback period of 29 years.

Even though cities' population density increases and the ratio of available rooftop area per habitable area decreases, the problem of optimising the use of the limited roof area for the on-site production of solar energy has not been sufficiently addressed. The present study responds to this issue by comparing alternative solar driven water heating systems for DHW, meeting hot water loads in a cost-effective way.

2. Method

This investigation compared market available solar driven water heating systems suitable to replace the conventional electric water heaters for a typical multi-residential building in four cities, one for each Greek climate zone. The annual net electricity consumptions from the grid and the net present values of LCC of the selected alternatives for 20 years life were estimated. Results were generalised for the Mediterranean climate zones (Csa and Csb of Köppen classification [21]).

2.1. Assessment criteria

An electric water heating system was considered as the reference (Baseline). The following systems were compared with it:

S1 Solar PV electric water heating system,

S2 Solar thermal water heating system with electric boosting,
S3 Solar PV/T water heating system with electric boosting, and
S4 Integrated solar PV and heat pump water heating system.

Energy and financial parameters have been commonly applied to assess the performance of DHW systems [11,15,16,22]. The two assessment criteria considered in this investigation are the annual electricity consumption and the LCC. The first one demonstrates the energy production potential of the systems, while the second one indicates the cost-effectiveness.

A discounted cash flow analysis was conducted. The calculation method for LCC follows ISO 15686–5:2008 (Eq. (1)):

$$LCC = C_I + \sum_{n=1}^{t} \frac{C_{E_n} + C_{M_n} + C_{R_n}}{(1+d)^n} \quad (1)$$

where C_I is the initial cost (€), t is the project life in years, d is the real discount rate, C_E is the annual cost of electricity (€), C_M is the annual cost of system maintenance (€), C_R is the annual cost of component replacements (€).

The discount rate applied has a significant impact on the value of LCC and it varies depending on the nature of the project. A discount rate higher than 4% is used for commercial, short-term investments, while a lower rate between 2% and 4% is advised to be used for energy efficiency investments made by building occupants, as it reflects the actual owners' benefits, over the entire building's lifetime [23]. According to Buildings Performance Institute Europe, the applicable discount rate for space heating and hot water of a household is 3.1%–3.7% [24,25]. This investigation used the real discount rate of 4%. Sensitivity analysis was performed for a discount rate range from 2% to 6%.

The project life was assumed to be 20 years, as it covers the lifetime of most systems and beyond this it is hard to forecast energy prices [26]. The salvage values were not considered because they typically represent a small percentage of the LCC. TRNSYS 18 software tool [27] was employed for the system simulations and the estimation of electricity consumptions. The simulation period is one year with 1 min timestep to accurately represent the hot water load.

2.2. Case study

Solar energy technologies could play a major role in on-site renewable energy production in Greece. In Athens, the daily average solar radiation received on the horizontal plane is 15.7 MJ m^{-2} [28]. Greece is the second country among EU-15 in terms of total installed solar thermal collector capacity (2,301 MW_{th}) [29]. On the other hand, the total installed PV panels' capacity is among the lowest of EU-15.

According to Hellenic Statistical Authority [30], the DHW production is dominated by conventional electric water heaters with a share of 74.5%. Solar thermal collectors are also popular, having a share of 37.6%. It should be noted that, according to Greek building code [31], all new buildings and existing buildings that undergo a major renovation process must have solar thermal systems supplying at least 60% of the DHW energy needs.

The case study building is a 6-storey multi-family residential building with a basement floor. Fig. 1 shows the building in Google Street View. It was selected from the 'Intelligent Energy Europe' programme 'Typology Approach for Building Stock Energy Assessment' [32], which is an EU funded program for the development of a common database of the residential building stock typologies in 20 European countries. It was constructed prior to 1980 in Athens (Greek climate zone B). The 1980 was selected as 55% of residential

Fig. 1. Google Street View of the case study building [35].

buildings built before that year have inefficient heating and hot water systems [33,34].

The monthly mean global and diffuse solar radiation on a horizontal plane and the monthly mean ambient air temperature of each city are presented in Fig. 2 [36]. All four Greek climate zones are characterised by high solar irradiation, which makes them suitable for solar energy technologies. Table 1 presents the list of cities, the Greek climate zones [37] and the corresponding Köppen climate classification categories they belong.

2.3. DHW load profile

According to Greek regulations for building energy efficiency [37], the average daily hot water consumption for residential dwellings is 50 L per person. Assuming that every apartment of the building has an average of three occupants, the daily hot water demand of an apartment is considered to be 150 L. It should be noted that the national regulation does not prescribe hot water draw-off profiles used in performance analysis of DHW systems. Similar studies have applied profiles based on measurements [38] or the profiles prescribed by Standard EN 15450:2007 for the design of heat pump heating systems [39]. For this investigation, the guidelines provided by the National Renewable Energy Laboratory (NREL) was used as it is more appropriate and modified to fit the local lifestyle [40]. Table 2 shows the applied DHW end-use event characteristics of a 2-bedroom apartment. Fig. 3 presents the assumed daily hot water consumption schedule of a 2-bedroom apartment in Greece. It is based on the end-use, temperature, duration and events of Table 2.

2.4. System parameters and assumptions

The building's roof area is 246 m^2, of which 23.24 m^2 is occupied

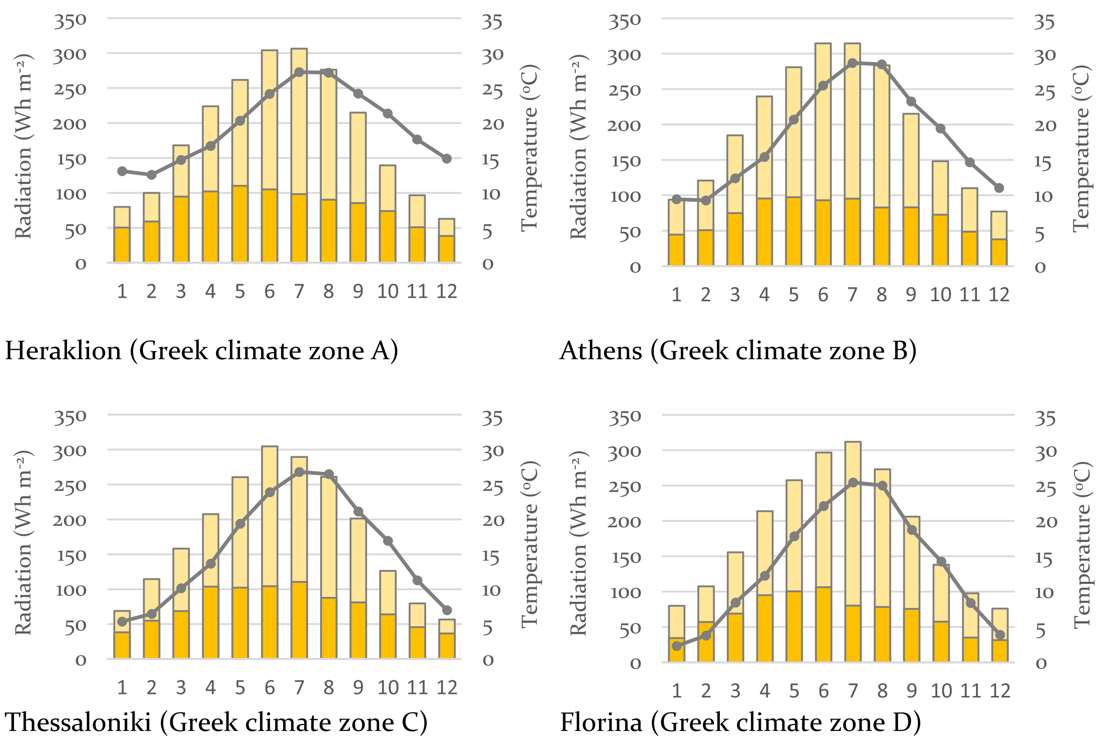

Fig. 2. Monthly average diffuse (bar graph-darker colour) and total solar radiations (total stacked columns) and ambient air temperature (line graph) of the four selected cities. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
The selected cities and the Greek and Köppen climate zone classification.

City	Greek climate zone	Köppen climate zone
Heraklion	A	Csa
Athens	B	Csa
Thessaloniki	C	Csa/Cfa
Florina	D	Dfa

Table 2
Daily DHW end-use draw-off pattern.

End-use	Temperature (°C)	Flow rate (L hr^{-1})	Duration (min)	Events (–)
Shower	40	479	6	3
Sinks	40	161	1	3

by the staircase exit to the roof. The area of a typical solar panel is 1.6 m^2 (1.6 m × 1.0 m). Panels were assumed to be installed facing the south and having a fixed tilted angle of 25°, as suggested by Ref. [41]. To estimate the horizontal distance between panels, the solar incidence angle at solar noon on the 22nd of December (when the sun is lowest in the sky) was used. The solar incidence angle is 126.8°, the solar angle is 28.20° and the horizontal distance between panels is estimated to be 1.25 m. Considering the rooftop geometry and orientation, the maximum panel area which can be installed on the roof is 81 m^2. Divided equally for the 27 apartments, each one has about 3 m^2 panel area. This restriction is applied to all systems investigated: PV panels, solar thermal panels and PV/T panels.

A 200 L cylindrical storage tank was selected for all water heating systems. The tank volume to panel area ratio is 0.067 m^3m^{-2} and the target annual solar fraction 78% [42]. The setpoint temperature was 60 °C, with a deadband of 3 °C.

2.5. Electric water heating system (baseline)

The existing water heating system is an old electric heater. A new double element electric water heater was considered as the reference system and was compared against other retrofit alternatives. The rated heating capacity of each element is 3.6 kW.

The TRNSYS project is presented in Fig. 4. For system modelling, Type 158 was employed to model the water storage tank. The dual electric element is modelled using TESS Type 2270 and is controlled by two thermostats (TESS Type 1502).

2.6. Solar PV electric water heating system (S1)

An array of PV panels located at the rooftop of the building provides electricity to system. A 270 W_p rated capacity polycrystalline panel (1.6 m^2) was selected [43]. The specifications of the panel are shown in Table 3. The system configuration is presented in Fig. 5. The electric water heater is the same as the Baseline system. The PV panels are connected to a 13 kW inverter with 98% efficiency. The PV array has been simulated using Type 103b and Type 48a has been used to model the inverter.

2.7. Solar thermal water heating system with electric boosting (S2)

S2 consists of a flat-plate solar collector, a water storage tank with electric boosting, a pump, an on/off controller and insulated connecting pipes. The controller signals the pump to circulate the fluid from the storage tank to the solar collector, through the pipes, based on the temperature of the collector outlet water. The thermostat triggers the auxiliary heater when necessary.

Type 158 was selected for the modelling of the water storage tank. The tank was divided into six temperature nodes to account for the stratification. There are two output points, one towards the solar collector and the other towards the end-use. The first input is

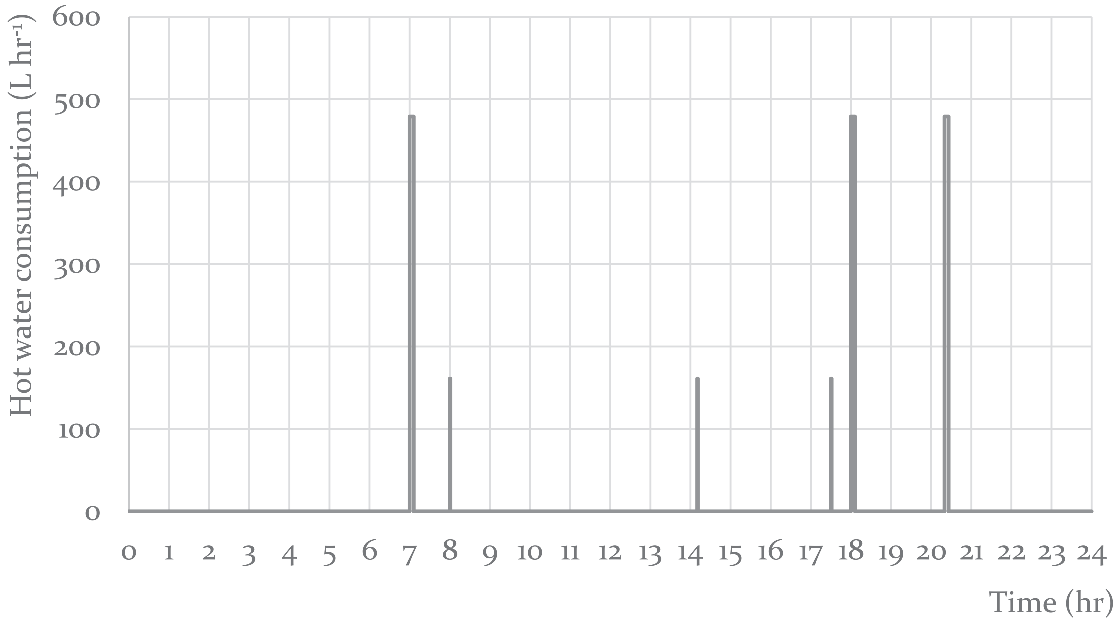

Fig. 3. Daily DHW load profile for a 2-bedroom apartment in Greece.

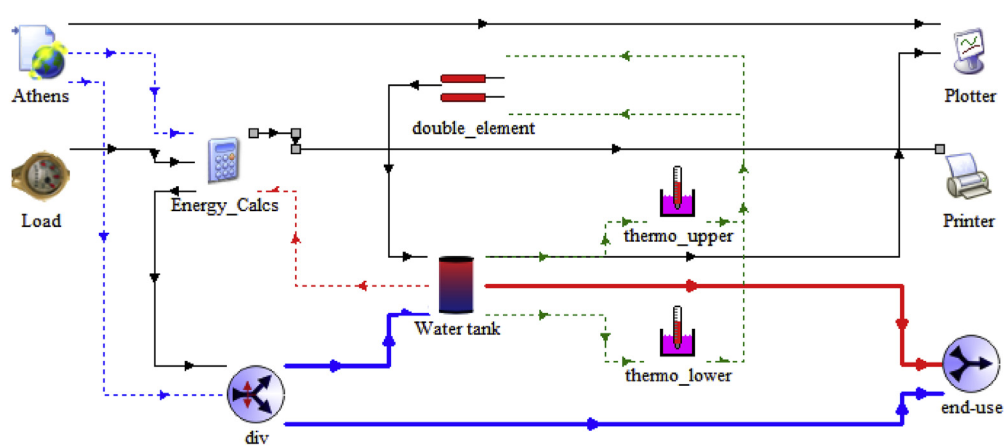

Fig. 4. TRNSYS project for the reference system (Baseline).

Table 3
Specifications of the selected polycrystalline PV panel [43].

Parameter	Value
Maximum power at standard test conditions (P_{max})	270 W
Optimum operating voltage (V_{mp})	31.1 V
Optimum operating current (I_{mp})	8.69 A
Open circuit voltage (V_{oc})	37.9 V
Short circuit current (I_{sc})	9.15 A
Module efficiency	16.5%
Nominal operating cell temperature (NOCT)	45 °C
Temperature coefficient of I_{sc}	0.00067 K^{-1}
Temperature coefficient of V_{oc}	−0.0033 K^{-1}
Panel gross area	1.64 m^2

located at the middle of the tank and the output at the bottom, while the second input at the bottom and the output at the top. Auxiliary heating has a rated heating capacity of 3.6 kW.

The specifications of the selected flat-plate solar collector [44] are provided in Table 4. The collector was assumed to be south facing and the assumed slope was 25° (same as the PV panels). The configuration of S3 is presented in Fig. 6. The flat-plate collector has been modelled using Type 1b. To calculate the heat losses of the pipes, Type 31 has been used. Pipes are located on the rooftop and inside the conditioned zones. Type 1 has been used to model the heat pump and Type 165 to model the controller of the pump. Instead of a double heating element, a single element has been modelled, using TESS Type 1226.

2.8. *PV/T – electric booster system (S3)*

The PV/T system integrates the photovoltaic technology for electricity production and solar thermal technology for heat production. The selected panel [45] was modelled using Type 50a. It has a polycrystalline PV collector with an extruded metal heat exchanger. The specifications of the collector are provided in Table 5.

The PV part of the system is connected similarly to Section 2.6. Based on the panel's electrical power of 150.4 W m^{-2}, the total

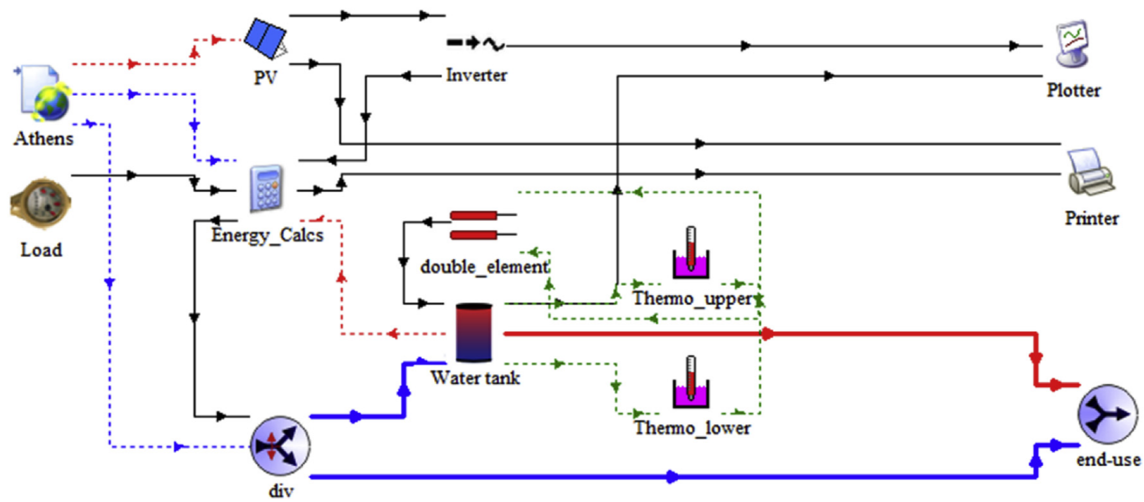

Fig. 5. TRNSYS project for the solar PV electric water heating system (S1).

Table 4
Specifications of the selected flat-plate solar collector [44].

Parameter	Value
a_o *	0.716
a_1 *	14.58 kJ h^{-1} m^{-2} K^{-1}
a_2 *	0.02232 kJ h^{-1} m^{-2} K^{-2}
b_o (IAM)*	0.16
b_1 (IAM)*	−0.0065
Water flow rate	180 kg h^{-1}
Modelled module area	3.0 m^2
*According to BS EN 12972–2 2006	

system's installed electrical power is 11,549 W and is connected with a 12 kW inverter. Fig. 7 shows the TRNSYS project developed. Type 50a has been used to model the PV/T collector. The rest of the components are similar to S1 and S2.

2.9. PV – HPWH system (S4)

The same PV array as Section 2.6 was selected to provide part of the electricity needed for the operation of a HPWH system. The produced energy is provided to a HPWH system. The HP has been modelled using Type 938. The HP performance data were derived from experiments done on a Geospring [46] HPWH (Table 6) by Khalaf [47]. The TRNSYS project is shown in Fig. 8. The working fluid exiting the compressor enters the condenser tube, which forms a “wrap around” helical coil on the circumference of the water storage tank. For the simulation of the “wrap around” storage tank, Type 1237 has been used. Twenty temperature nodes in the tank, which is the same as the number of loops of the heat exchanger coil, were considered. The heat exchanger coil is a D25 copper pipe of 22.35 m total length. Type 938 has been used to model the water-to-water heat pump.

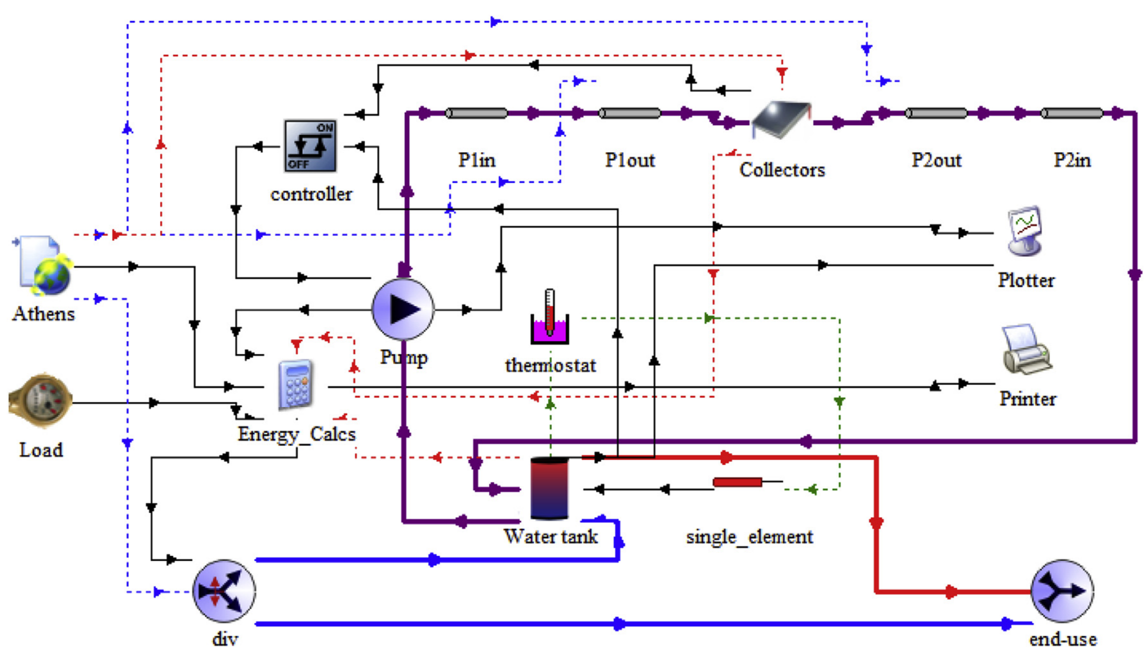

Fig. 6. TRNSYS project for the solar thermal water heating system with electric boosting (S2).

Table 5
Specifications of the selected PV/T polycrystalline flat plate solar collector [45].

Parameter	Value
Maximum electrical power at STC (P_{max})	200 W
Voltage maximum power (V_{mp})	24.5 V
Current maximum power (I_{mp})	8.05 A
Module electrical efficiency	15.26%
Nominal operating cell temperature (NOCT)	48 °C
Temperature coefficient of I_{sc}	+0.0004 K^{-1}
Temperature coefficient of V_{oc}	- 0.0034 K^{-1}
Fin efficiency factor	0.96
Collector plate absorptance	0.93
Collector loss coefficient	34.32 kJ h^{-1} m^{-2} K^{-2}
Cover transmittance	0.9
Temperature coefficient of solar cell efficiency	0.0048 K^{-1}
Cell efficiency	0.178
Water flow rate	90 L h^{-1}
Area of each module	1.31 m^2

Table 6
Specifications of the selected HPWH [46].

Parameter	Value
Rated Power	0.55 kW
Air flow rate	150 L s^{-1}
Rated $COP_{heating}$	3.24

3. Results

Net electricity consumptions and LCCs of the systems compared are presented in Section 3.1 and 3.2 respectively (see Fig. 11).

3.1. Net electricity consumptions

Net electricity consumptions for all investigated systems are presented in Figs. 9-12. The same energy consumption pattern applies to all four climate zones. Diffuse solar radiation is similar for all climate zones, leading to comparable amounts of electricity production of each system. Cities of lower dry bulb temperature, such as Florina (zone D), have increased electricity consumption, compared to cities of higher dry bulb temperature, such as Heraklion (zone A).

As expected, the highest grid electricity consumption is for the reference system. When PV panels are installed on the building's rooftop and combined with the electric hot water heater (S1), they can generate up to 50% of the system annual electricity demand. For S2, flat-plate solar thermal collectors provide 80%–85% of the system annual energy demand. These findings are in line with the findings of Matuska and Sourek [9]. S3 and S4 systems have no grid net electricity consumption (S4 in zone D is excepted) as their decreased electricity demands are satisfied by the PV electricity production. S3 has the highest performance in all climate zones, with 'net' positive electricity production. The energy performance of the PV/T system is found to be better compared with the PV system of the same area. This finding agrees with the finding of Herrando [8]. Finally, S4 has significantly lower energy consumption compared to S1. Recent research [48] focused only on design optimisation of S4.

3.2. Life cycle cost (LCC)

The LCC of the system comprises of the initial cost and the discounted operating and maintenance cost. The initial cost includes the costs of additional parts required, the engineering and the labour for installation. The operating cost is the cost of electricity consumed over the project lifespan. The maintenance cost includes the costs of labour and system parts that need to be repaired or replaced.

3.2.1. Initial costs

The Baseline system is a new dual element electric water heating system. S1 has a rooftop PV array added to the Baseline system. A breakdown of the initial cost is presented in Table 7. The cost of the PV panels, including their installation, has been equally divided to all 27 apartments. It is 39% of the total initial cost of S2.

The installation of solar thermal panels on the rooftop and a water storage tank inside the apartment has increased expenses, mainly because of the additional piping works involved. The same is for the S3 that combines both the expenses of the PV panel installation and connections and the hydraulic piping and connections of the solar thermal panels. As Table 7 shows, S4 has the

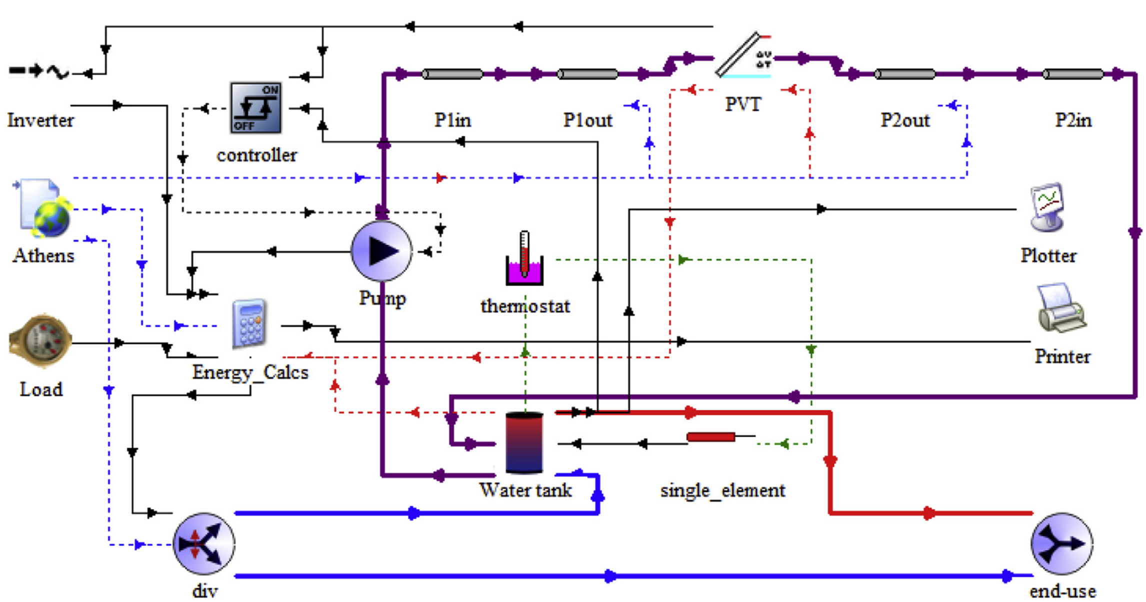

Fig. 7. TRNSYS project for the solar PV/T water heating system with electric boosting (S3).

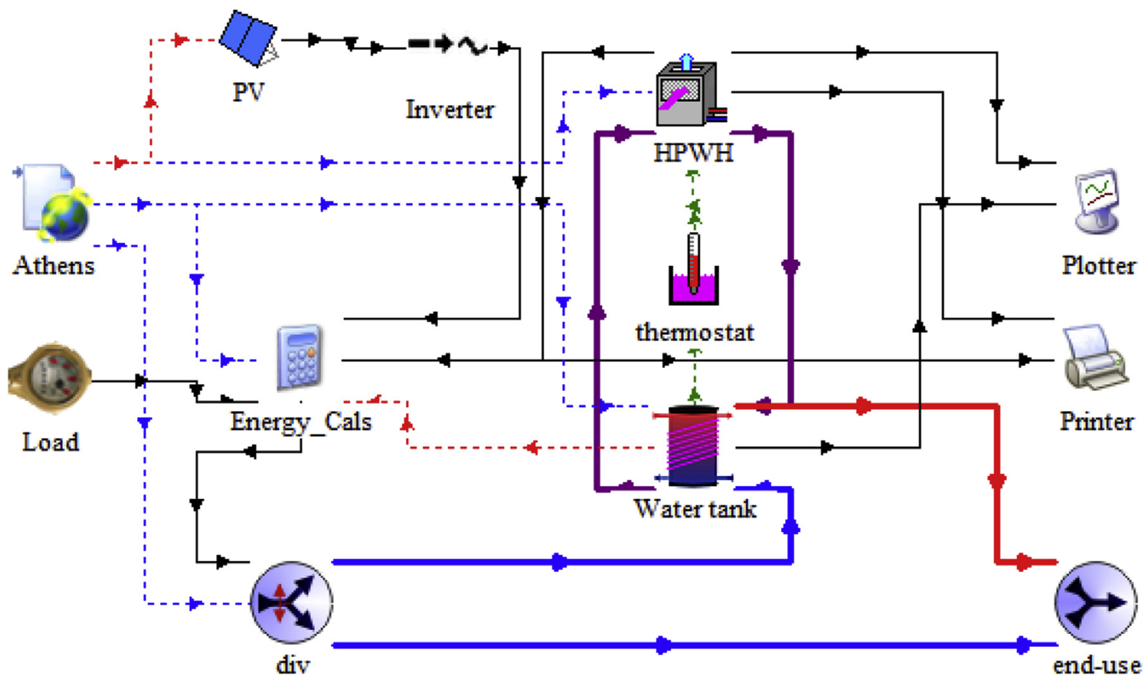

Fig. 8. TRNSYS model of the integrated solar PV and heat pump water heating system (S4).

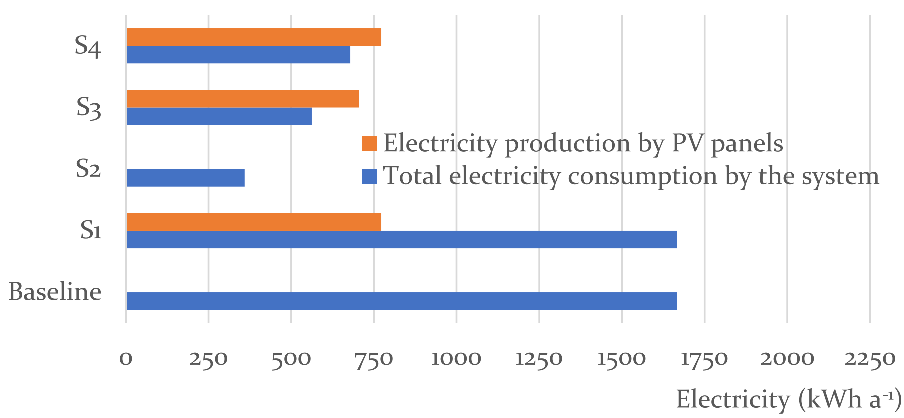

Fig. 9. DHW systems' electricity production/consumption for Heraklion (Greek climate zone A).

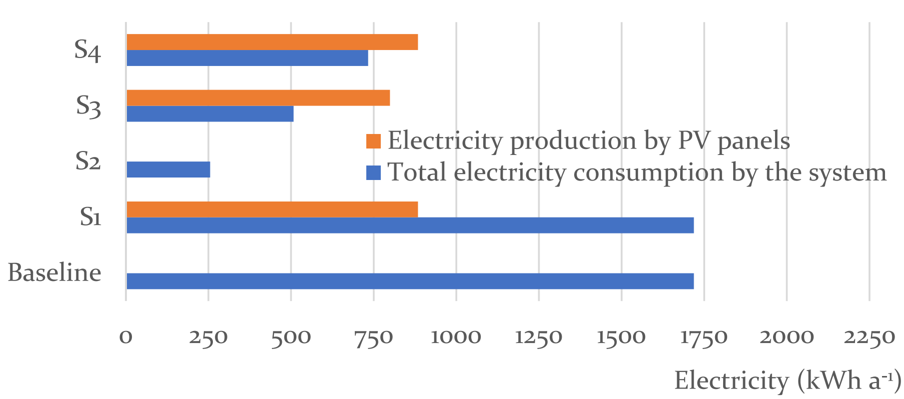

Fig. 10. DHW systems' electricity production/consumption for Athens (Greek climate zone B).

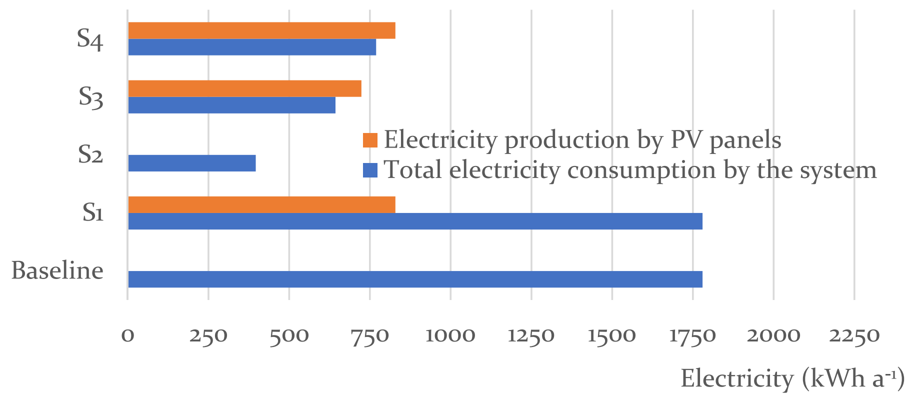

Fig. 11. DHW systems' electricity production/consumption for Thessaloniki (Greek climate zone C).

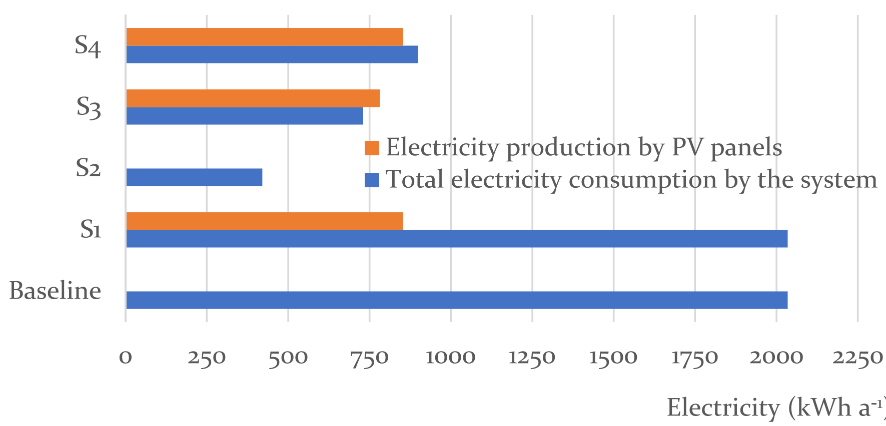

Fig. 12. DHW systems' electricity production/consumption for Florina (Greek climate zone D).

highest initial capital.

3.2.2. Maintenance and replacement cost

Maintenance of the water storage tank and the PV panels or the solar thermal collectors is an annual process while the replacement of system parts takes place every three years (Psarros 2018, personal communication, 08 August). A breakdown of the maintenance and replacement cost is shown in Table 8.

3.2.3. Operational cost

Since 2014, new household PV applications for connection to the electrical grid are operating under the 'net-metering' scheme [49]. A recent regulation allows residents of a multi-residential building to form an energy community and virtually split the produced electricity to multiple bi-directional meters [50]. This system is called 'virtual net-metering'. Under 'net-metering' scheme, the prosumers offset the consumed electricity by the electricity produced by the PV panels. As this may happen at different times, the electrical grid acts as an energy storage system. In the case of Greek regulations, when the electricity produced is less than the electricity consumed, the prosumer needs to pay for the 'net' electricity consumption and an additional charge for transmission and distribution grid services. When the electricity produced is higher than the electricity consumed, the prosumer is not reimbursed for the excess electricity.

According to HELAPCO [51], the credit received by the prosumer for the electricity exported to the grid is estimated from 0.10 € kWh^{-1} to 0.125 € kWh^{-1}. For the present study, 0.12 € kWh^{-1} will be assumed. The calculated electricity cost for a household is 0.18 € kWh^{-1}, based on the Public Power Corporation [52] price list. That means that the prosumers need to pay 0.18 € kWh^{-1} for the 'net' electricity consumed and an additional 0.06 € kWh^{-1} for the electricity supplied to the grid and used back.

3.2.4. Results from the discounted cash flow analysis

A discounted cash flow analysis was performed to estimate the LCC of each DHW heating system. The values of initial costs and the net present value (NPV) of all recurrent costs, for all cities, are presented in Figs. 13-16. IC of every system is assumed to be the same for all cities. However, the NPV of all recurrent costs varies depending on the total annual electricity consumption.

Baseline system has a higher LCC of all systems. S1 is the least preferable alternative. S4 is less preferable than S2 and S3 from the LCC point of view, for all climate zones, mainly because of the increased initial cost. S2 and S3 are the most preferable systems, having similar LCC. S2 has lower initial cost than S3 but the NPV of recurrent costs varies, making the one preferable than the other, depending on the climate zone they are tested. Warmer climate zones equally favour S3 over S2, while colder climate zones favour S2 over S3. This result agrees with Kalogirou and Tripanagnostopoulos [7] and Axaopoulos and Fylladitakis [18] who reported that PV/T systems are financially better in locations with higher solar radiations.

Even though both PV module prices have been significantly

Table 7
Initial cost (€) breakdown for the reference and alternative systems.

Item	Baseline	S1	S2	S3	S4
Storage tank	700[e]	700[e]	1,000[a]	1,000[a]	2,050[a]
Tank installation (hydraulic)[a]	350	350	350	350	350
Tank installation (electric)[a]	70	70	70	70	70
Parametrisation[a]	–	–	60	60	–
Refrigerant connection[a]	–	–	–	–	50
Start-up and customisation of HPWH[a]	–	–	–	–	60
Connection from roof to apartment (hydraulic)[a]	–	–	360	360	–
Solar thermal panels[a]	–	–	471	–	–
PV panels[b]	–	333	–	–	333
PV/T panels[c]	–	–	–	728	–
Panel support system[b]	–	100	100	100	100
Panel hydraulic connection parts[a]	–	–	92	92	–
Inverter[b]	–	93	–	93	93
Electric parts of PV panels[b]	–	63	–	63	63
Connection to grid expenses[d]	–	14	–	14	14
Installation of panels[b]	–	55	40	95	55
Engineering[b]	–	37	–	37	37
Other expenses[b]	–	22	–	22	22
Total initial cost	1120	1838	2543	3006	3297

- = Not applicable.
[a] (Lafogianis 2018, personal communication, 08 August).
[b] (Routzios 2018, personal communication, 24 July).
[c] (Browne 2019, personal communication, 01 September).
[d] HEDNO [53].
[e] The assumed price of the dual element electric water heaters based on equivalent tanks available at the US and Australian market.

Table 8
Costs (€) of maintenance and replacement.

Maintenance type	Baseline	S1	S2	S3	S4
Storage tank annual maintenance (labour)[a]	75	75	75	75	75
Storage tank 3-year parts replacement[a]	150	150	150	150	20
Panel annual maintenance[b]	–	25	25	25	25

- = Not applicable.
[a] (Psarros 2018, personal communication, 08 August).
[b] (Routzios 2018, personal communication, 24 July).

reduced over the last decade, solar thermal systems remain financially better compared to PV systems for water heating. This fact was reported by Matuska and Sourek [9].

3.2.5. Sensitivity analysis

As mentioned before, a sensitivity analysis was performed for the real discount rate applied, as it has a high impact on the LCC. A range of 2%–6% was selected in climate zone B (Fig. 17). As expected, systems with high recurrent costs are more sensitive with respect to the real discount rate. Systems that have low recurrent costs, such as S3 and S4, are less sensitive to real discount rate fluctuation. It should be mentioned that as real discount rate increases, S2 LCC becomes lower than S3 LCC, making it financially more attractive.

4. Discussion on applicability of results in other locations in mediterranean climate zones

As mentioned before, three out of four cities investigated fall into the Csa (Hot-summer Mediterranean climate) zone of Köppen classification [21]. The classification is based on threshold values and seasonality of monthly ambient air temperature and precipitation. To generalise the results of the present study for the Mediterranean climate zones (Csa and Csb), solar radiation data from 37 cities (see Table 9) located within these climate zones were generated using the POWER Data Access Viewer (DAV) Web Mapping Application [54,55] and analysed.

As shown in Fig. 18, all 37 cities are within latitude 31°–44° and their annual average solar radiation falls within 14.0 MJ m^{-2} to 20.6 MJ m^{-2}. The mean of the annual average daily solar radiation for the 37 cities is 17.4 MJ m^{-2}. The coefficient of variation of the data set is low (9.3%), which means that all locations received similar solar radiation intensity. This is also confirmed by Fig. 19, which shows the monthly average daily solar radiation of the 37

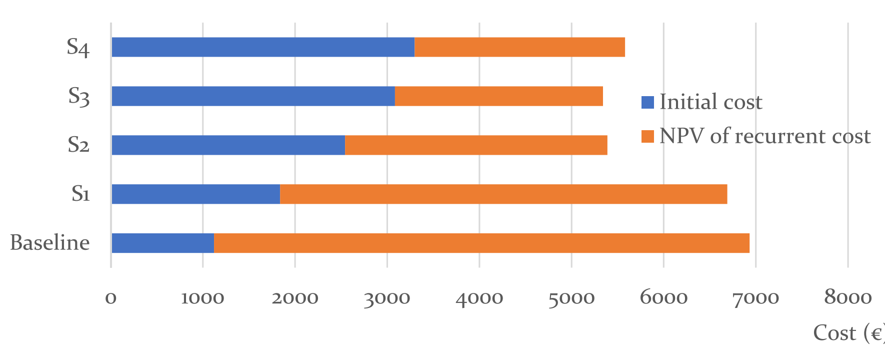

Fig. 13. Initial costs and NPV of recurrent costs for all DWH heating systems investigated in Heraklion (Greek climate zone A).

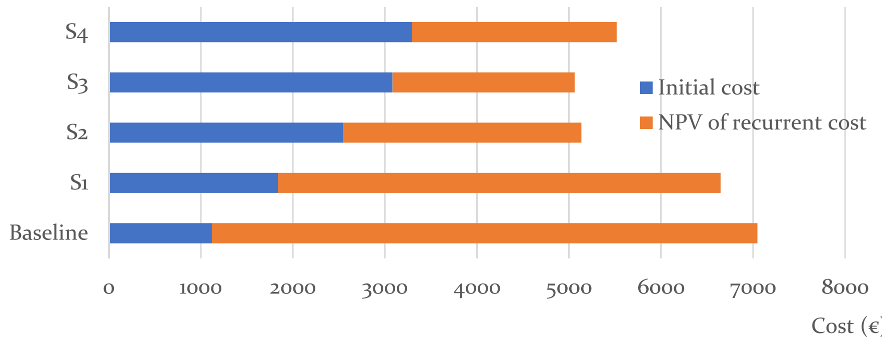

Fig. 14. Initial costs and NPV of recurrent costs for all DWH heating systems investigated in Athens (Greek climate zone B).

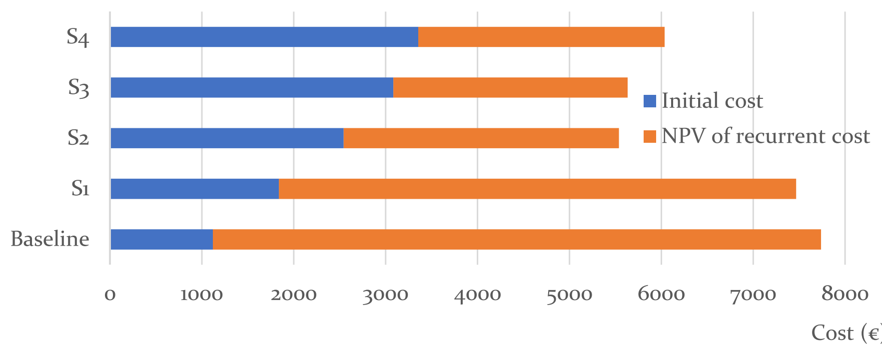

Fig. 15. Initial costs and NPV of recurrent costs for all DWH heating systems investigated in Thessaloniki (Greek climate zone C).

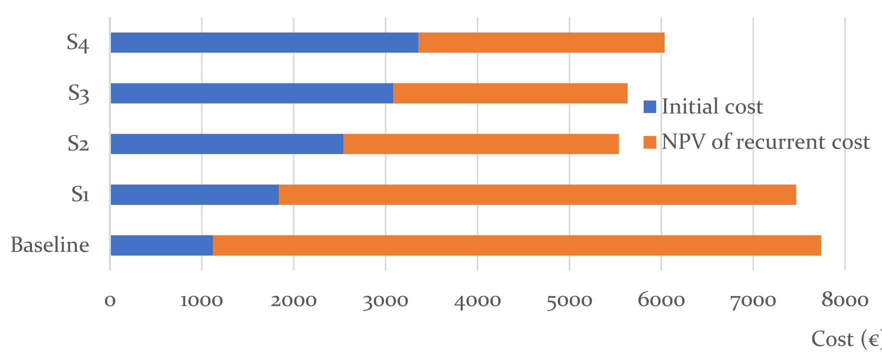

Fig. 16. Initial costs and NPV of recurrent costs for all DWH heating systems investigated in Florina (Greek climate zone D).

cities. It should be noted that month 1 for the cities in southern hemisphere corresponds to July in Fig. 19. This observation means that the solar systems installed in climate zones Csa and Csb will have similar energy outputs. In that sense, the 'net' electricity consumption results of the solar driven hot water heating systems obtained are also valid for equivalent systems located within the Mediterranean climate zones Csa and Csb.

5. Conclusions

The problem of limited available rooftop or facade surfaces for the installation of solar technologies is common for buildings located in urban areas. Solar thermal, PV or PV/T technologies compete for the available space. The present study compared four solar driven water heating systems with a reference system for a multi-residential building, located in urban areas of the four Greek climate zones. All systems can be assembled with commercially available components. The selected systems are an electric water heating system combined with a PV electricity supply system (S1), a solar thermal water heating system (S2), a PV/T water heating and electricity supply system (S3) and a HPWH system combined with a PV electricity supply system (S4). An electric hot water heating system (Baseline) is considered as the reference system. System performance simulations and financial analysis were performed for the four climate zones of Greece. The net annual grid electricity consumption and LCC were estimated and compared.

The case study building is a six-storey residential building, which has 27 apartments and a limited 245.72 m^2 rooftop area. The maximum panel south-facing non-shaded area equals to 3 m^2 per apartment. It has been found that the maximum possible installed

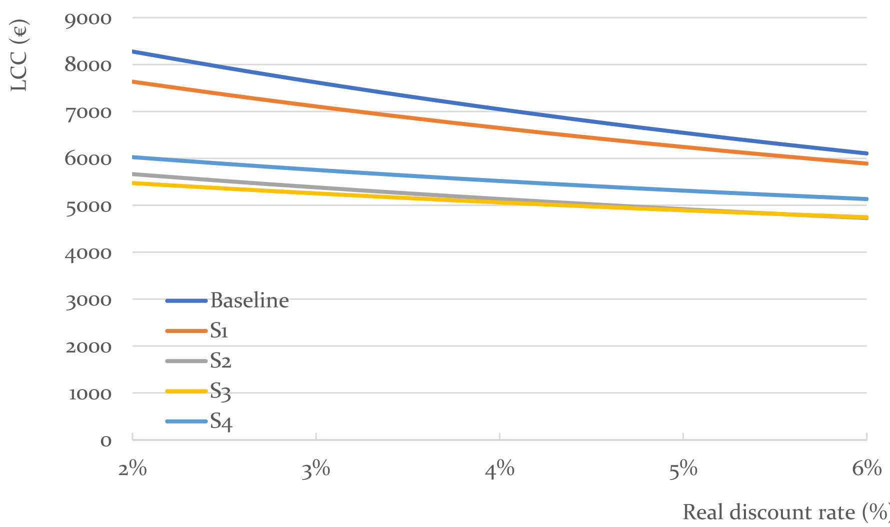

Fig. 17. Effects of real discount rate on LCC.

Table 9
Annual average daily solar radiation (MJ m^{-2}) for cities with Mediterranean climates.

No.	City	Country	Köppen classification	Latitude (deg N)	Longitude (deg E)	MJ m^{-2}
1	Essaouira	Morocco	Csb	31.509	−9.759	20.4
2	Jerusalem	Israel	Csa	31.768	35.214	18.5
3	Perth	Australia	Csa	−31.950	115.861	20.0
4	Tel Aviv	Israel	Csa	32.085	34.782	20.6
5	Santiago	Chile	Csb	−33.449	−70.669	19.7
6	Casablanca	Morocco	Csa	33.573	−7.590	18.8
7	Beirut	Lebanon	Csa	33.894	35.502	19.2
8	Cape Town	South Africa	Csb	−33.925	18.424	19.5
9	Los Angeles	US	Csa/Csb	34.052	−118.244	19.5
10	Santa Barbara	US	Csb	34.421	−119.698	19.1
11	Adelaide	Australia	Csa	−34.928	138.601	16.7
12	Heraklion	Greece	Csa	35.339	25.144	19.2
13	Latakia	Syria	Csa	35.541	35.795	19.4
14	Tangier	Morocco	Csa	35.760	−5.834	18.1
15	Málaga	Spain	Csa	36.717	−4.426	17.2
16	Algiers	Algeria	Csa	36.754	3.059	17.2
17	Tunis	Tunisia	Csa	36.819	10.166	16.3
18	Antalya	Turkey	Csa	36.897	30.713	16.3
19	Faro	Portugal	Csa	37.019	−7.930	17.6
20	Seville	Spain	Csa	37.389	−5.984	17.7
21	San Francisco	US	Csb	37.775	−122.419	16.5
22	Athens	Greece	Csa	37.984	23.728	16.5
23	Izmir	Turkey	Csa	38.424	27.143	16.8
24	Dushanbe	Tajikistan	Csa	38.560	68.787	16.7
25	Sacramento	US	Csa	38.582	−121.494	18.3
26	Lisbon	Portugal	Csa	38.722	−9.139	17.5
27	Valencia	Spain	Csa	39.470	−0.376	16.2
28	Thessaloniki	Greece	Csa/Cfa	40.640	22.944	14.5
29	Potenza	Italy	Csb	40.640	15.806	15.1
30	Naples	Italy	Csa	40.852	14.268	17.1
31	Porto	Portugal	Csb	41.158	−8.629	15.7
32	Tashkent	Uzbekistan	Csa	41.300	69.240	16.5
33	Barcelona	Spain	Csa	41.385	2.173	15.5
34	Rome	Italy	Csa	41.903	12.496	16.7
35	Marseille	France	Csa	43.297	5.370	15.6
36	Corunna	Spain	Csb	43.362	−8.411	14.0
37	Nice	France	Csa	43.710	7.262	15.5
Average						17.4
Minimum						14.0
Maximum						20.6
Standard deviation						1.7

Csa = Hot-summer Mediterranean; Csb = Warm-summer Mediterranean.

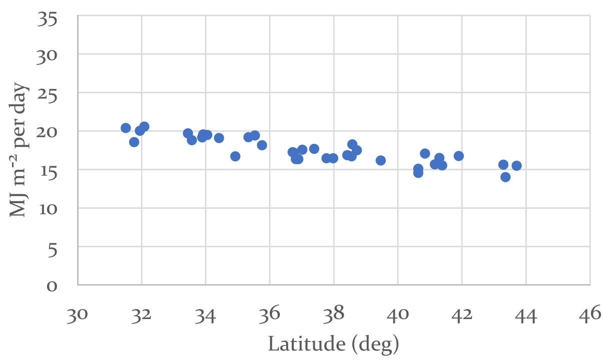

Fig. 18. Annual average daily solar radiation vs. Latitude for 37 cities within Mediterranean climate zones.

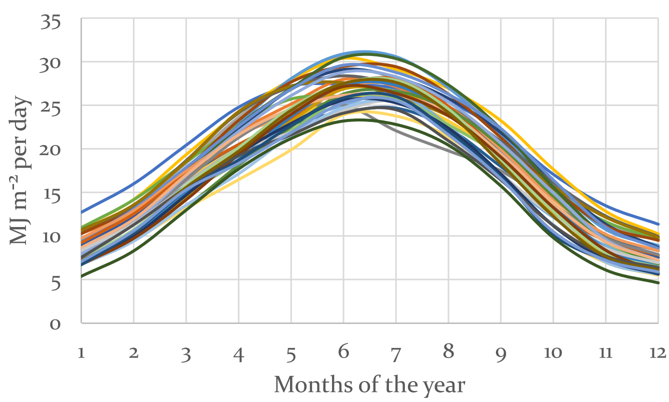

Fig. 19. Monthly average daily solar radiation for 37 cities within Mediterranean climate zones.

renewable energy technology when designed to cater for the DHW requirement, covers from 45% up to more than 100%, depending on the solar driven water heating system used.

More specifically, the energy produced by each system is similar for all considered Greek cities, however, the total electricity consumption of the systems varies based on the ambient air and water mains temperature. S3 has the lowest 'net' grid electricity demand, followed by S4. S4 has the highest initial cost, followed by S3 and S2. S2 and S3 have lower LCC. For colder climate zones, S2 is preferable to S3, while for warmer, S3 is preferable to S2. Due to the significant decrease in the PV module price, solar thermal technologies remain the most cost-effective water heating solutions. However, if the minimisation of GHG emissions is prioritised, PV/T modules show competitive results. Policy makers should consider ways to overcome the initial cost barrier of the system. Similar but less attractive is S4.

Results obtained are specific to the roof area investigated, the climatic conditions and the economic situation of the selected location. They can be used as a guide for the retrofit of similar buildings. The Köppen climate classification for the three out of four cities investigated in Greece is mainly Csa. Electricity consumption, electricity generation and heat output results can be generalised for cities in the Mediterranean climate zones, in assisting policy makers and home-owners in system selection for hot water.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2019.09.020.

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Chapter 5 – Retrofit optimisation

5.1 Introduction

The purpose of the previous chapter was to select and compare alternative DHW and RESSs that minime the annual 'net' electricity consumption and the LCC for the case study multi-residential building. This chapter presents the development of a robust multi-objective optimisation method for the building retrofit. It is a 'whole building' optimisation for the minimisation of the operating GHG emissions and the LCC. The application of the developed method and the results obtained are also presented and discussed. The chapter addresses the research objectives 1 and 3, as stated in Chapter 1:

1. *Develop the retrofit optimisation framework.*

3. *Optimise the design parameters of the multi-residential building retrofit in terms of minimising the environmental impact and the retrofit cost.*

The content of this chapter was submitted as a manuscript with the title "Energy retrofit optimisation of multi-residential buildings: a 'whole-building' approach" to *Applied Energy*. The structure, the format and the referencing system followed the journal style.

5.2 Publication #3

Energy retrofit optimisation of multi-residential buildings: A 'whole-building' approach

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Abstract

The European Union's building stock is characterised by low energy efficiency and slow growth rates. To achieve EU's greenhouse gas (GHG) emission targets, doubling building retrofit rates is one the focuses of The European Green Deal. In this article a multi-objective optimisation procedure, which can be applied for building retrofits, was developed for the minimisation of the operating GHG emissions and the life-cycle cost. The method was applied to a typical multi-residential building, in the four Greek climate zones. It was found that the cost-optimal retrofit set consists of roof and basement ceiling insulation, installation of air-to-air heat pumps (HP) for heating and cooling and solar thermal collectors for domestic hot water (DHW). This way, more than 60% reduction in GHG emissions compared to the base case is achieved. To reduce the GHG emissions by 90% additional measures are required, such as the installation of double or triple-glazed windows, wall insulation, a central biomass boiler (in locations without natural gas) or a gas condensing boiler (in locations with natural gas) for heating and photovoltaic-thermal panels for DHW and electricity production. Net-zero-carbon retrofit could not be achieved within the building premises, mainly due to space limitations for the installation of renewable energy systems. However, considering the future decarbonisation of the grid electricity, operating GHG emissions could be reduced below 95% or more, approaching a net-zero-carbon, in case efficient electricity-driven systems are installed.

Keywords: medium-rise building; residential building; multi-objective optimisation; genetic algorithm; greenhouse gas emissions; life-cycle cost.

Nomenclature

Symbols

C_E	operating cost (€ m-2)
C_I	initial cost (€ m^{-2})
C_M	maintenance cost (€ m^{-2})
C_R	replacement cost (€ m^{-2})
EF	greenhouse gas emission factor (kg CO_2-e kWh^{-1})
EI	energy input (kWh m^{-2})
EM	annual greenhouse gas emissions (kg CO_2-e m^{-2} a^{-1})
LCC	life-cycle cost (€ m^{-2})
r	real discount rate (-)
t	project lifespan (a)

Subscripts

n	index for the year
j	index for the fuel type

Abbreviations

COP	Coefficient of Performance
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
EPS	Expanded Polystyrene
ESM	Energy Saving Measures
EU	European Union
GA	Genetic Algorithm
GAHP	Gas Absorption Heat Pump
GHG	Greenhouse Gas
HP	Heat Pump
HPWH	Heat Pump Water Heating
HVAC	Heating, Ventilation and Air-Conditioning
KENAK	Greek Regulation for Energy Performance of Buildings
LCC	Life-Cycle Cost
MOGA	Multi-Objective Genetic Algorithms
nZEB	nearly Zero Energy Building
PLF	Part-Load Factor
PLR	Part-Load Ratio
PV	PhotoVoltaic
PV/T	PhotoVoltaic-Thermal
RESS	Renewable Energy Supply System
SHGC	Solar Heat Gain Coefficient
TABULA	Typology Approach for Building Stock Energy Assessment
uPVC	Unplasticised Poly Vinyl Chloride

1. Introduction

In recent decades, the building sector has been at the centre of attention of the environmental protection policies of the European Union (EU). The primary reason is its high final energy consumption (40%) and related greenhouse gas (GHG) emissions (36%) [1]. Almost 75% of the existing European buildings are not energy efficient [2]. One of the reasons is that more than 40% of the building stock is over 50 years old [3,4]. Residential sector dominates the building stock (75% of the total built area in the EU [5]), holding a large share of the total final energy consumption (26% of the total in 2018) [6]. Its annual growth rate across Europe is about 1%, while the average annual refurbishment rate is between 0.5% and 2.5% [7]. About 75% of the projected buildings in 2050 have already been built [8]. Therefore, there is a clear opportunity to retrofit the existing buildings, leading to significant energy savings and GHG emissions reduction. Among the residential building types, special consideration should be given to multi-residential buildings, as they encounter increased challenges minimising their GHG emissions, mainly due to their limited available land and rooftop space for the installation of renewable energy technologies, such as solar or geothermal.

Retrofit has been seen as a way to address the low energy efficiency problem of the building sector, especially after being introduced by the 'Energy Performance of Buildings Directive' (EPBD) [9] that requires all new buildings and buildings that undergo a major retrofit to have a nearly zero-energy demand. Recently, the European Commission set radical targets for the reduction of GHG emissions by 2030 (50-55% compared with 1990 levels) and 2050 (climate neutrality). To achieve those targets, the building stock is expected to play a critical role, doubling its retrofit rates [10].

Retrofit is a complex process that involves the analysis of multiple interactions between all components of a building and its environment. The process of identifying the optimal retrofit solution(s), among a variety of alternative measures, involves the reconciliation of environmental, energy-related, financial, legal and social factors. In accordance with energy performance legislation, such as the EPBD, or under environmental performance assessment schemes, several building design and retrofit optimisation studies have been published and various quantitative models have been developed.

The most commonly employed methods, and often overlapping, are: single or multi-objective optimisation, scenario analysis, economic analysis, sensitivity analysis and statistical analysis [11]. The multi-objective optimisation enables the identification of trade-offs between the competing objective functions. The essential concept of multi-objective optimisation is Pareto optimality [12]. Pareto optimal are the feasible solutions for which no improvement of all objective functions is possible simultaneously. This is factual for real-world problems, where a large number of non-dominated solutions are likely to exist.

Retrofit optimisation, being a process that involves a large number of variables, is computationally demanding in terms of time and resources. Optimisation algorithms can identify the optimal solutions, avoiding exhaustive computing time. Recent reviews of research studies on simulation-based optimisation methods applied in building performance analysis showed that genetic algorithms (GAs) were employed by more than 40% of the studies [13,14]. The main reason is their ability to tackle non-linear, discontinuous problems with many local minima, compared to classic optimisation methods [15], since they are less susceptible to the shape of the non-dominated front [16]. However, they cannot guarantee that the optimal solutions will be found. An extended literature review on algorithms for building design optimisation was conducted by Machairas et al. [15].

Optimisation tools are classified into two major categories: special tools for building design and generic packages. The special optimisation tools are coupled with a specific building simulation software. The most popular of them are: Opt-E-Plus, GENE_ARCH, BEopt, MultiOpt2, jEPlus+EA and TRNSOPT. Generic optimisation tools are more flexible; however, they require programming skills. Some of the commonly used software tools are: GenOpt, DAKOTA, modeFRONTIER, MOBO and MATLAB® Optimisation Toolbox [13,17].

Optimisation tools are coupled with building performance simulation software, which runs iteratively. Dynamic simulation programs are widely used to analyse the performance of the building envelope and the installed systems. On the other hand, most of building modelling tools employed by the EU member states use quasi-steady state methods. Their model inputs are simplified building information, while dynamic effects are introduced. The monthly quasi-steady state methods have lower accuracy to estimate the energy impact of common types of building systems compared to transient methods [18]. The most widely used building performance simulation tools include TRNSYS, EnergyPlus and DOE-2 [11,13,17].

The retrofit variables, considered in the literature, can be classified in three groups, namely the energy saving measures (ESM) targeting the building envelope (wall, roof and floor insulation, window replacement and shading), the installation of heating, ventilation and air-conditioning (HVAC) systems and the renewable energy supply systems (RESS), such as solar thermal and photovoltaic. According to the authors' previous investigation [19], as well as recent reviews of building retrofit studies [20], there is a lack of retrofit methods that address the building as a 'whole'. Rysanek and Choudhary [21] introduced a 'whole-building' analysis method for the identification of the optimal retrofit solutions, however, only environmental objectives were considered. In addition no optimisation process was introduced. Other identified studies that consider a large number of interventions were conducted either for the retrofit of simplified hypothetical buildings [22,23], the design of new buildings [24] or the performance assessment of a developed computational method [25].

This article presents the development of a robust multi-objective optimisation method for building retrofit, targeting the minimisation of operating GHG emissions and LCC. It is an application-oriented method that provides the targeted stakeholders: the policy makers and building owners, with optimal sets of commercially available solutions. The innovation in the method is the integrated approach, considering ESMs, as well as energy supply and demand-side technologies. The method introduces a dynamic building systems' modelling process, based on part-load performances, to address the accuracy limitations of existing, monthly quasi-steady state methods. The applicability of the method is illustrated through a multi-residential case study building. The following sections describe the structure of the method, upon which the case study is demonstrated.

2. The optimisation method

The developed method quantitatively analyses the cost-optimal solutions and the solutions that minimise the annual GHG emissions, with reference to the retrofit of existing multi-residential buildings. It combines energy simulation and multi-objective optimisation. A building expert is involved in an early design stage to pre-screen the potential design variables, based on the legislative, climatic, technological and financial environment of the building.

A GA, namely the Multi-objective Genetic Algorithm (MOGA) [26], handles the optimisation process, instead of a brute-force calculation, reducing the required computation time and resources. Within the optimisation process, three primary functions are performed: (1) the assignment of input parameters; (2) the execution of the 'whole-building' simulation; and (3) the assessment of simulation results and the generation of new input parameters, as required. At each iteration, the GA assigns new values to the design variables that are later combined and/or mutated, in order to obtain new values and potentially improve results. The procedure goes on until convergence is achieved or a 'stopping criterion' is satisfied. Along with the iterations' results summary, Pareto front is obtained.

At the end of the process, an uncertainty analysis is performed for a range of real discount rates (2% to 6%) and fuel and electricity prices (increased by 10% and 20%). In addition to that, the impact of the electricity grid decarbonisation is also calculated through an uncertainty analysis for future GHG emission values (for the years 2030 and 2040, assuming carbon neutrality by 2050).

2.1. Objective functions and design variables

The candidate demand-side measures and energy supply systems are chosen from the list of Table 1. The considered measures are those that affect the energy consumption and related emissions for heating, cooling and DHW. The energy demand for lighting, equipment and plug loads wasn't considered. During the pre-screening process, the building expert assesses the competency and applicability of the design variables and decides on their value range. Further, decisions must also consider the legislative, climatic, technological and financial constraints applied.

Table 1.
Indicative 'whole-building' energy retrofit measures.

Category	Retrofit measure
Energy saving	Insulation of external walls Insulation of roof Insulation of basement ceiling Window replacement Installation of shadings
Energy supply	Replacement of HVAC systems Installation of HVAC control systems Replacement of DHW systems Installation of RESSs (PV panels, wind turbines, ground source HPs, etc.)

HVAC: heating, ventilation and air-conditioning, DHW: domestic hot water, RESS: renewable energy supply system, PV: photovoltaic, HP: heat pump

A multi-objective optimisation approach was selected for the performance assessment of the retrofit combinations. Considering more than two objective functions would increase the complexity in the outcome interpretation [27]; hence, two objective functions were employed: the amount of annually produced GHG emissions per unit of floor area (kg CO_2-e m^{-2} a^{-1}) and the retrofit LCC (€ m^{-2}). For the calculation of the annual GHG emissions, the energy input for heating, cooling and DHW systems was multiplied by the GHG emissions factor of each fuel type, using Eq. (1):

$$EM = \sum_{j=1}^{J} (EI_j EF_j) \quad (1)$$

where *EM* is the annual GHG emissions (kg CO_2-e m^{-2} a^{-1}), j is the fuel type, EI_j is the energy input (kWh m^{-2}) and EF_j is the GHG emissions factor of each fuel (kg CO_2-e kWh^{-1}).

For the calculation of LCC, the discounted cash flow of each year is determined at the starting point of the project, according to Eq. (2):

$$LCC = C_I + \sum_{n=1}^{t} \frac{C_{E_n} + C_{M_n} + C_{R_n}}{(1+r)^n} \quad (2)$$

where C_I is the initial cost (€ m^{-2}), t is the project life in years, r is the real discount rate (-), C_E is the annual operating cost (€ m^{-2}), C_M is the annual cost of system maintenance (€ m^{-2}), C_R is the annual cost of component replacements (€ m^{-2}). Offers from local contractors and construction material retailers were used for the accurate estimation of the current market prices. The proposed lifespan for the calculation of the global cost of residential buildings is 30 years (EU regulation 244/2012). However, provided the fact that the method is developed for an existing building, the considered lifespan is 20 years and is within the lifespan of most systems. The lifespan of retrofit measures follows the EN 15459:2014 guidance, as well as the information provided by manufacturers.

2.2. The optimisation process

DAKOTA [28] software is employed to initiate and handle the optimisation process, while TRNSYS [29] is the environment for the transient simulation of the building and systems. DAKOTA sees TRNSYS as a black box; thus, the gradient information is not available. A Python script is used to interface them. MOGA is available in DAKOTA. According to the developed methodology, a preparation process is conducted prior to optimisation. During the preparation process, the energy consumed or produced by the water heating systems and RESSs is calculated. Results are saved in '.csv' format files in order to be accessed later. The main optimisation process contains the optimisation routine that calls the simulation sub-processes iteratively. It consists of two discrete calculation models. Each model is self-contained; the first one estimates the building energy demand and the peak heating and cooling loads that are determined by the ESMs and the second calculates the building's annual GHG emissions and LCC. The overall process is illustrated in Fig. 1.

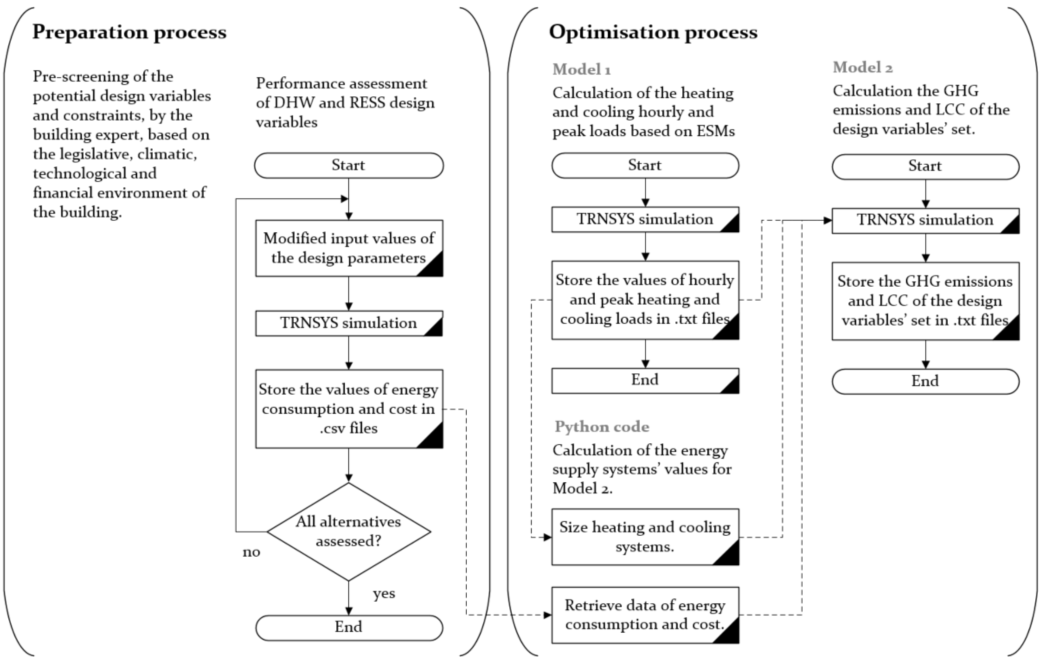

Fig. 1. Schematic view of the developed preparation and optimisation process.

Model 1, shown in Fig. 1, is responsible for the calculation of building's energy demand. The values of the building ESMs are the model inputs. TRNSYS Type 56 multi-zone building is employed for the calculation of the energy demand. The 3D layout of the case study building is developed using TRNSYS Google SketchUp plug-in. The building design and parameters are defined in TRNSYS, using text-based format input files (file extensions '.b18' and '.dck'). Each variable that corresponds to a design decision of the ESMs is parametrised and encoded as a delimiter inside the template files. The results are the heating and cooling energy demand and the peak loads, necessary for system sizing.

Model 2 gets inputs from Model 1 and the '.csv' format files, in the form of heating and cooling hourly demand profiles, the selection of the heating and cooling systems' type, size and costs, as well as the energy consumed or produced by the DHW and the RESSs. The appropriate template file, that corresponds to the modelled heating and cooling systems, is selected for the calculation of the energy input. The values of the optimisation objective functions are calculated for each combination of the design variables. Finally, Python script converts the TRNSYS output files (file extension '.out') into a DAKOTA compatible file, in order to be red by MOGA and restart the iteration.

Most building design and retrofit optimisation studies calculate the energy consumption of heating and cooling systems based on single-value average system efficiencies [23,24,30], which are either the nominal efficiency or the seasonal efficiency. A limited number of studies [21,31] make use of the software capability to simulate the transient system performance, using empirical models based on experimental performance data. This investigation employs empirical system performance curves for the modelling of heating and cooling systems. The modelling of other building systems, such as DHW and the RESSs, is handled by analytical modelling, using the fundamental laws of thermodynamics, heat and mass transfer.

Overall, the proposed modelling process resembles a reverse Sankey diagram, having the building energy needs on the left and the amount of input energy (and equivalent operating GHG emissions) required to satisfy them on the right side. Each model carries out annual simulations at a time step of one hour. The TRNSYS simulations for the calculation of the DHW energy needs required a timestep of one minute, due to the small timestep of the water draw schedule.

3. Case study

The case study building is a six-storey multi-residential building, constructed prior to the year 1980 (year 1961) and is located in Athens (Greek climate zone B, see Table 2). It was selected from the 'Intelligent Energy Europe' programme 'Typology Approach for Building Stock Energy Assessment' (TABULA) [32], which is an EU funded program for the development of a common database of the residential building stock typologies in 20 European countries. Fig. 2 shows the building in 'Google Street View' and a typical floorplan. In order to identify the way that various parameters of the building environment might affect the method application and obtained results, four locations were considered, as listed in Table 2.

Table 2.
The selected cities and the Greek and Köppen climate zone classification [33,34].

City	Greek climate zone	Köppen climate zone
Heraklion	A	Csa
Athens	B	Csa
Thessaloniki	C	Csa/Cfa
Florina	D	Cfa/Dfa

Csa: Mediterranean hot summer climates, Cfa: Humid subtropical climates, Dfa: Hot summer continental climates

The annual heating load calculated in TABULA was 70.5 kWh m^{-2} a^{-1}. The modelled annual heating load per floor area of the building was 97.6 kWh m^{-2} a^{-1}. For DHW, the calculated TABULA input electrical energy was 18.3 kWh m^{-2} a^{-1}, while the modelled was 21.2 kWh m^{-2} a^{-1}. The modelled annual cooling load per floor area was 76 kWh m^{-2} a^{-1}. No data for the cooling load was available in TABULA. The difference between TABULA and simulated results was mainly attributed to the deferent calculation methods employed; TABULA uses a static calculation method, while TRNSYS uses a dynamic approach. The energy consumption figures of the residential building stock reported in the literature [35,36] were also used to verify the simulated performance of the case study building.

Fig. 2. 'Google Street View' of the case study building [37] (left), Level 3 floorplan (right).

3.1. Characteristics of the Greek residential building stock and previous studies

In Greece, the residential sector accounts for about 30% of the total final energy consumption [38], 65% of which is dedicated to heating and cooling and 5.7% to DHW [39]. According to the last national census data (2011), 50% of multi-residential buildings were built before 1980. Looking at the multi-residential buildings constructed prior to 1980, approximately 90% have no wall insulation, more than 60% have single-glazed windows and almost 60% have a central heating system. Those figures justify the selection of the case study building as a representative of its category, as well as the considered energy end-uses (heating, cooling and DHW).

The analysis of energy performance certificates (EPC) of residential buildings or units [20] indicated that, for multi-residential buildings being constructed prior to 1980, the primary energy consumption for heating is about 150 kWh m^{-2} a^{-1} in Greek climate zone A and about 370 kWh m^{-2} a^{-1} in Greek climate zone D. The numbers for space cooling are about 50 kWh m^{-2} a^{-1} for climate zone A and 20 kWh m^{-2} a^{-1} for climate zone D, while for DHW about 50 kWh m^{-2} a^{-1} for all climate zones. Recognising the significant deviations among calculated and measured energy consumption, Balaras et al. [41] compared the calculated and measured primary energy for heating, using data from the EPCs. Results indicated that multi-residential buildings consume 43% less energy than the amount calculated using 'KENAK' software. According to the authors, the conducted field survey confirmed poor indoor thermal comfort conditions, resulting from reduced heating operating hours and lower thermostat settings that deviate from the calculation assumptions used by 'KENAK'.

The most popular retrofit interventions in multi-residential buildings are the replacement of single-glazed windows with double-glazed and the central diesel oil conventional boiler with a natural gas central or local boiler, saving 15% and 21% of primary energy respectively [41]. Kolaitis et al. [36] compared the impact of an external to an internal insulation system on the heating and cooling load, for an apartment located in a mid-floor of a multi-residential building, in two Köppen climate zones; warm Mediterranean (Csa) and temperate Oceanic (Cfa). Both configurations significantly reduced the total energy needs, however, external insulation outperformed internal by 8% for both climate zones.

Based on the Greek TABULA residential building typology, Dascalaki et al. [42] modelled the energy savings of the Greek building stock, resulting from a number of retrofit scenarios, in order to assess the prospect of achieving the EU targets for GHG emissions and final energy consumption mitigation. There were two scenarios considered: one scenario for ESMs (envelope scenario) and one for heating and DHW systems (system scenario). Results indicated that both envelope and system scenarios fell short to meet the GHG emissions mitigation targets, even when considering unrealistically high retrofit rates. Only when the envelope and system scenarios were combined the EU targets could be achieved.

Kakaras et al. [43], studied the comparative impact of a large number of design and retrofit interventions on the minimisation of the annual primary energy use and the NPV of LCC, considering both existing and new buildings, located in climate zones B and C. For multi-residential buildings of climate zone B being constructed before 1980, results indicated that gas condensing boiler heating solutions dominated the cost-optimal area, while HPs (low/high temperature and ground source) dominated the nearly zero-energy building (nZEB) area. For the same building types located in climate zone C, the cost-optimal and nZEB solutions followed similar patterns with climate zone B.

3.2. Pre-assessment of the potential design variables

The pre-screening of the design variables was performed considering the legal, climatic, technological and financial environment of the case study building. For this purpose, a building audit was conducted to assess the general condition of the building and verify TABULA parameter values and results. The following sections present the design variables of the optimisation process in two categories: (1) ESMs and (2) measures considering the energy supply systems.

3.2.1. Energy saving measures

Information about the building was extracted from TABULA [32] and the national building codes [44]. Table 3 provides the details of the construction types of the building envelope, while Table 4 indicates details regarding the building thermal gains and losses. According to the national building code of the construction year (prior to 1980), there was no insulation requirements for the envelope [45]. Currently, 'KENAK' requires buildings that undergo a major retrofit to meet the maximum allowed thermal conductivity (Table 5), to the extent that it is technically and financially feasible. Thus, the design variables regarding the thermal conductivity of the building envelope were constrained by these regulations.

Table 3.

Construction types and their thermal conductivity (U-value) (W m-2 K-1) of the case study building, TABULA [32].

Elements	Construction type	U-value
Wall 1	Double brickwork - plastered on both sides	2.20
Wall 2	Load bearing structure – reinforced concrete - plastered on both sides	3.40
Roof	Flat roof	3.05
Floor	Slab on grade	3.10
Window	Single glazed, wooden or synthetic frame	4.70

Table 4.
Case study building thermal losses and gains.

Parameter	Value	Unit	References
Thermal bridge	0.15	W m^{-2} K^{-1}	TABULA [32]
Infiltration	0.40	hr^{-1}	
Ventilation	0.75	m^3 hr^{-1} m^{-2}	Technical Chamber of Greece [44]
Occupants' thermal power	4.00	W m^{-2}	
Lighting capacity	6.40	W m^{-2}	
Lighting in-parallel use factor	0.50	-	
Equipment capacity	4.00	W m^{-2}	
Equipment operation factor	0.75	-	
Equipment in-parallel factor	0.50	-	

The values of Table 5 were used as lower constraints of the ESMs (envelope insulation and window replacement). The upper constraint and step of each variable were defined by the market availability of the product and common practice. Expanded Polystyrene (EPS) panels were selected as the insulation material due to their low thermal conductivity and low environmental impact [46]. Their mechanical (compressive strength) and physical (moisture resistance) properties allow their use for the insulation of all external and internal building surfaces. Table 6 provides the range and step of the envelope insulation design variables.

The windows of the case study building have a high thermal conductivity value, higher than the building code requirements for existing buildings that undergo major retrofit, leading to significant heat losses during the heating season and gains during the cooling season. The market available window frame materials are mainly aluminium and Unplasticised Poly Vinyl Chloride (uPVC). The prior has inferior thermal properties and a higher cost than the later. Thus, two window replacement options were selected, using uPVC as frame material; the first one is double-grazed while the second is triple-grazed, as presented in Table 7. No further ESMs were considered. It has been estimated that the existing shadings adequately cover the shading building needs.

3.2.2. Measures considering the energy supply systems

The case study building has a double-pipe high temperature central hydronic heating system, coupled with a natural gas non-condensing boiler and radiators. During the heating season, heating is supplied to the conditioned zones for a few hours during midday and evening. This is the traditional way central heating systems were designed to operate in Greece. There is no central cooling system, however, most of the apartments have air-to-air HPs installed to key apartment areas, such as the master bedroom and/or living room. DHW is supplied by electric water heaters located in each apartment. No renewable energy supply systems was installed.

Table 5.
Maximum thermal conductivity (W m^{-2} K^{-1}) of building envelope elements of existing buildings that undergo a major retrofit, for each Greek climate zone.

Building envelope element	Greek climate zone			
	A	B	C	D
Horizontal or sloped roof – outdoors boundary condition	0.50	0.45	0.40	0.35
Wall - outdoors boundary condition	0.60	0.50	0.45	0.40
Wall – non-conditioned space boundary conditions	1.50	1.00	0.80	0.70
Floor - outdoors boundary condition	0.50	0.45	0.40	0.35
Floor – non-conditioned space boundary conditions	1.20	0.90	0.75	0.70
Windows - outdoors boundary condition	3.20	3.00	2.80	2.60

Table 6.
ESMs design variables and values for commercially available envelope insulation.

Building envelope element	EPS 80 insulation panel thickness (mm) alternatives Greek climate zone A	B	C	D	Code
External walls – outdoors boundary condition	1) no insulation 2) 50 3) 60 4) 70 5) 80 6) 90 7) 100	1) no insulation 2) 60 3) 70 4) 80 5) 90 6) 100	1) no insulation 2) 70 3) 80 4) 90 5) 100	1) no insulation 2) 80 3) 90 4) 100	WLØ WL1
Horizontal roof – outdoors boundary condition	1) no insulation 2) 60 3) 70 4) 80 5) 90 6) 100	1) no insulation 2) 70 3) 80 4) 90 5) 100	1) no insulation 2) 80 3) 90 4) 100	1) no insulation 2) 90 3) 100	RFØ RF1
Basement ceiling – non-conditioned space boundary conditions	1) no insulation 2) 30 3) 40 4) 50 5) 60 6) 70 7) 80 8) 90 9) 100	1) no insulation 2) 30 3) 40 4) 50 5) 60 6) 70 7) 80 8) 90 9) 100	1) no insulation 2) 40 3) 50 4) 60 5) 70 6) 80 7) 90 8) 100	1) no insulation 2) 50 3) 60 4) 70 5) 80 6) 90 7) 100	FLØ FL1

Table 7.
ESMs design variables and U-values (W m^{-2} K^{-1}) for window replacement.

Window type	Frame	Glazing	SHGC	Code
1) No replacement	2.2	5.6	0.8	WDØ
2) uPVC frame, argon filled double glazing (4 x 15 x 5 mm)	1.1	1.1	1.1	WD1
3) uPVC frame, lowE argon filled triple glazing (4LowE x 15 x 5 x 15 x 5 mm)	1.0	0.6	0.6	WD2

SHGC = Solar Heat Gain Coefficient

HVAC systems

For the purpose of this study, several assumptions were made. The reference building, that the retrofit cases were compared to, was named ‘base case’. The 27 apartments were grouped in 7 conditioned zones, one for each flour. Apartment autonomy was introduced through the installation of water valves in every radiator, controlled by thermostats in each apartment. During the heating season (from the 28th of October to the 15th of April for climate zones A and B, and from the 15th of October to the 30th of April for climate zones C and D), the heating system was designed to operate in two modes. The daytime heating set-point temperature was 20 °C [44]. The set-back temperature for night-time was 18 °C. To facilitate comparison, a 55 °C water supply temperature was assumed for all heating systems, including ‘base case’. During the cooling season (from the 15th of May to the 15th of September for all climate zones) the set-point temperature for cooling was 26. For the hydronic system, water supply temperature was 7 °C.

Buildings located in South European countries have moderate heating demand while cooling demand is significant [47]. Thus, heating and cooling were studied together, grouping the alternative systems into one design variable. System selection was constrained by the climate conditions, market availability, common practice, fuel availability and space limitations. Table 8 lists the existing and selected alternative system combinations. It should be mentioned that mechanical ventilation wasn't considered a competent retrofit measure as the case study building lacks adequate ceiling or underfloor space for the required ductwork.

For the calculation of systems' energy consumption, part-load performance curves were employed, based on empirical or manufacturer's supplied data [48]. We particularly highlight the method developed by Schibuola, Scarpa & Tambani [49]. Using HP products' EN 14825:2016 test reports (HP efficiency for a range of part-load conditions for four ambient temperatures), they produced the part-load ratio (PLR) – part-load factor (PLF) curves. We extended the method to include additional space conditioning systems. Fig. 3 illustrates systems' efficiency/coefficient of performance (COP), as a function of the heating or cooling PLR.

Table 8.
Energy supply design variable for heating and cooling systems.

	Locations with natural gas		Locations without natural gas		Code
	Heating	Cooling	Heating	Cooling	
1)	Natural gas non-condensing boiler		Diesel oil non-condensing boiler		HCØ
2)	Natural gas condensing boiler (central)	A-a HP (autonomous)	Diesel oil condensing boiler (central)	A-a HP (autonomous)	HC1
3)	GAHP (central)		Biomass pellet boiler (central)		HC2
4)	A-w HP (autonomous)				HC3
5)	A-a HP (autonomous)				HC4

GAHP: gas absorption heat pump, HP: heat pump, a-a: air-to-air, a-w: air-to-water

Domestic hot water systems

The most commonly used domestic water heater is the electric. At the same time, the total installed solar thermal collector capacity in Greece is 2,301 MW_{th}, placing the country at the second rank among the EU-15 [50]. However, rooftop space limitations apply in multi-residential buildings. For the case study building, it was estimated that the available rooftop space is not enough to accommodate RESSs that, combined with a conventional auxiliary system, can cover more than 20% of the heating requirement. However, the estimated heat production can cover 85% of the hot water required by the DHW system [51].

Table 9 lists the considered 'base case' and alternative DHW systems. The heat pump water heating (HPWH) systems were proposed as an alternative to the traditional electric water heater. It should also be mentioned that the hot water produced by the solar thermal panels (a retrofit alternative under the design variable of RESSs presented in the following section) will be supplied to the electric water heating system (HW1). For the purpose of this study, the setpoint water temperature of 60 ℃ and a 200L cylindrical storage tank were assumed for all water heating systems. A detailed study of the systems was conducted by the authors [51].

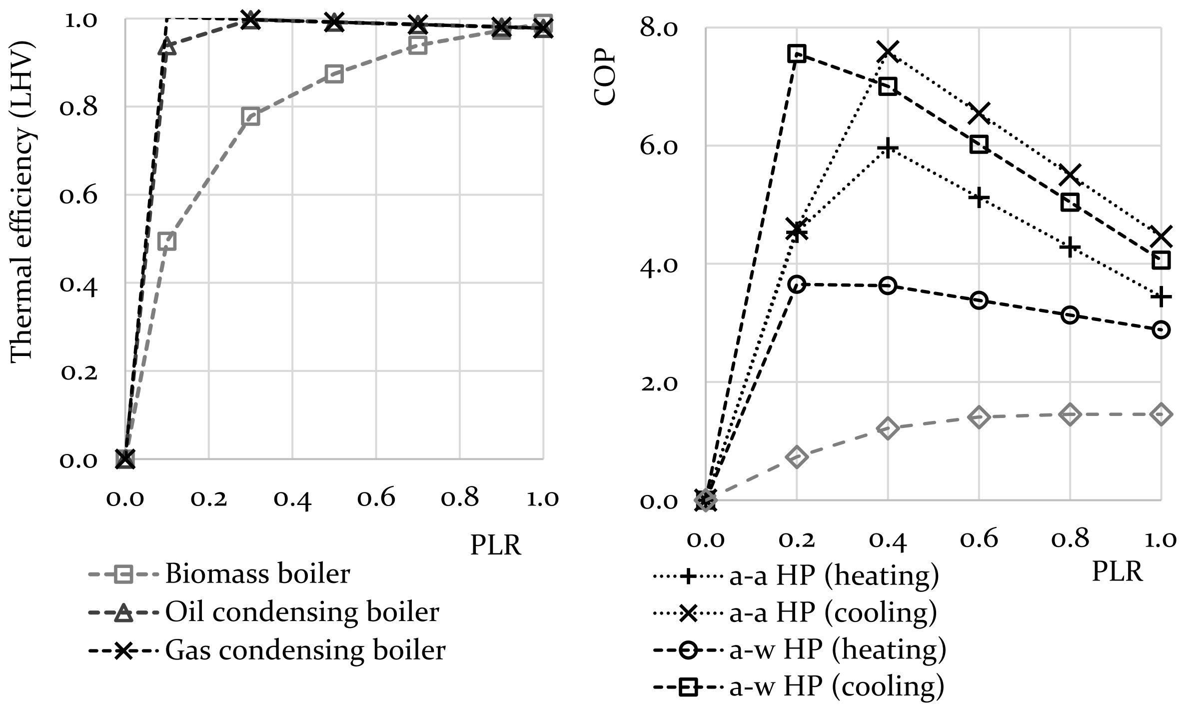

Fig. 3. PLR-Thermal efficiency (LHV)/COP curves of selected HVAC systems (boilers: left, HPs: right).

Table 9.
Energy supply design variable for DHW systems.

DHW system	Code
1) Electric water heating system	HW1
2) HPWH	HW2
HPWH: heat pump water heating	

Renewable energy supply systems
Space and market limitations make the PV, the solar thermal and the photovoltaic-thermal (PV/T) panels the competent alternatives under this design variable. The three systems compete for the building's available rooftop area. The maximum panel area that can be installed on the unshaded area of the rooftop is 80 m^2; thus, a 3 m^2 solar thermal panel area was considered for each household. One inverter was assumed for the electrical installation. The produced electrical energy was equally divided into the 27 apartments through virtual net-metering [52]. In case of solar thermal or PV/T panels, the produced hot water was directly supplied to the DHW cylinder of each apartment. In case the HPWH system is selected for the DHW system design variable, the solar thermal panels and the PV/T panels are not considered. A detailed study of the considered RESSs was conducted by the authors [51].

Table 10.
Renewable energy supply systems.

System	Code
1) no RESSs	REØ
2) PV panels	RE1
3) Solar thermal panels	RE2
4) PV/T panels	RE3
PV: photovoltaic, PV/T: photovoltaic-thermal	

3.3. Optimisation settings

For the calculation of the annual GHG emissions, the required energy input was multiplied by the GHG emission factor of each electricity/fuel type, provided in Table 11. For the calculation of the annual energy cost, the energy input was multiplied by the energy price of Table 12.

The real discount rate applied has a significant impact on the LCC and it varies depending on the stakeholders. A discount rate between 2% to 4% was advised to be used for energy efficiency investments made by building occupants, as it reflects the actual building owners' benefits, over the entire lifetime [53]. According to Buildings Performance Institute Europe, the applicable discount rate for space heating and hot water of a household is 3.1% to 3.7% [54,55]. This investigation used the real discount rate of 4% assuming uncertainty.

Table 11.
Greenhouse gas (GHG) emission factors (kg CO_2-e kWh^{-1}) for Greece.

Fuel type	Factor	Reference
Electricity	0.810	[56]
Natural gas	0.240	[56]
Diesel oil	0.306	[56]
Biomass pellet	0.063	[57]

Table 12.
Energy prices (€ kWh^{-1}) in Greece.

Fuel type	Price	Reference
Electricity	0.1800[1]	[58]
Natural gas	0.0509	[59]
Diesel oil	0.1000	[60]
Biomass pellet	0.0500[2]	[61]

[1] Based on the average electricity consumption of 2,000 kWh per four months.
[2] The pellet has a calorific value of 5 kWh kg^{-1} and costs 0.250 € kg^{-1}.

The steps of a GA application are initialisation, selection of individuals, crossover, mutation and termination. The GA control parameters can significantly affect its performance, in terms of speed and reliability. For example, a high mutation rate might lead to the loss of good solutions, while a high crossover rate to an early convergence. MOGA control parameters were set as shown in Table 13. The values were chosen based on previous studies [62] and tests carried out by the authors in order to obtain the best trade-off between the computational time and reliability of results.

Table 13.
MOGA control parameters.

Parameter	Value
Initialisation type	random
Population size	12
Crossover type	random
Crossover rate	0.8
Mutation type	uniform
Mutation rate	0.08
Selection type	elitism
Maximum number of evaluations	1,000

4. Results

The building environment has a considerable influence on the building retrofit, constraining its variables and shaping results' area. Thus, the obtained results are presented and discussed considering two major parameters: climate zone and the availability of natural gas infrastructure. Non-dominated sets of retrofit measures are presented using different colours for the design variable of heating and cooling systems. A list of the optimal solution sets is also provided for every climate zone. For simplicity purposes, envelope insulation alternatives were grouped into two major categories; non-insulated envelope elements are marked with zero and insulated elements with 1.

4.1. Locations without natural gas

Two locations are under this section; Heraklion (Greek climate zone A) and Florina (Greek climate zone D). As natural gas infrastructure is not available, diesel oil, biomass and electricity-driven heating and cooling equipment were in competition.

As expected, when comparing the optimisation results of Fig. 4 and Fig. 5, along with the optimal solution sets of Table 14 and Table 15, we noted a differential impact of the climate on the optimal solution sets. High savings, both for operating GHG emissions and LCC, can be achieved in Florina, as Florina has much higher heating load compared to Heraklion. However, lower annual operating GHG emissions (minimum of 23.6 kg CO_2-e m^{-2} a^{-1}) can be reached in Heraklion, compared to Florina (minimum of 33.6 kg CO_2-e m^{-2} a^{-1}).

The cost-optimal solutions for both locations require the insulation of roof and basement ceiling, a-a HPs for heating and cooling and solar thermal panels for DHW. No wall insulation or window replacement are included in Heraklion, as a result of the milder winter. The cost-optimal solution set has 62% less annual GHG emissions compared to 'base case'. The equivalent number for Florina was 66%.

When more ESMs are applied, such as wall insulation and window replacement, the biomass boiler for space heating becomes part of the Pareto optimal solutions, for both locations. For retrofit solutions that minimise the GHG emissions, 89% reduction compared to 'base case' can be achieved. In Heraklion, the a-w HP for heating and cooling is among the optimal retrofit sets when the minimisation of GHG emissions is required, increasing significantly the LCC.

In both locations, the optimal solutions for RESSs are clearly divided in two groups: the cost-optimal is solar thermal panels while PV/T panels dominate the optimal solution space from the middle part of Pareto front until the retrofit sets that minimise the GHG emissions.

4.2. Locations with natural gas

For locations with natural gas infrastructure network, Athens and Thessaloniki, optimisation results are presented in Fig. 6 and Fig. 7 equivalently. Table 16 and Table 17 present the list of optimal retrofit sets. Natural gas and electrical-driven systems competed for the replacement of the conventional gas boiler.

It was noticed that optimisation results follow a similar pattern for both locations. The cost-optimal retrofit set consists of roof and basement ceiling insulation, a-a HPs for heating and cooling and solar thermal panels for DHW. In Athens (climate zone B), the operating GHG emissions of the cost-optimal solution are 24.3 kg CO_2-e m^{-2} a^{-1} (67% reduction compared to 'base case'), while in Thessaloniki (climate zone C) they are slightly increased to 34.5 kg CO_2-e m^{-2} a^{-1} (59% reduction compared to 'base case').

When lower annual GHG emissions are targeted, retrofit solutions are a combination of wall, roof and basement ceiling insulation, installation of double-gazed windows, replacement of the conventional gas boiler with a condensing for heating, a-a HPs for cooling and PV/T panels for DHW and electricity production. The annual GHG emissions that this combination can achieve is 9.5 kg CO_2-e m^{-2} a^{-1} (87% reduction compared to 'base case') in Athens and 16.5 kg CO_2-e m^{-2} a^{-1} (81% reduction compared to 'base case') in Thessaloniki. Slightly lower emissions can be achieved installing an a-w HP for heating and cooling, however, the LCC is significantly increased as a result. The optimisation results indicate that net zero-carbon targets cannot be achieved in any of the locations, primarily due to the limited available area for the installation of RESSs. However, it should be mentioned that the results are within the system boundaries of the considered technologies and the current fuel and GHG emission factors of fuel and electricity. The impact that the future decarbonisation of the electricity grid has on results is discussed in Section 5.1.3.

5. Discussion

The identified cost-optimal retrofit solutions are in line with the observed market trends: the insulation of building envelope, the replacement of single with double-glazed windows and the installation of a-a HPs and condensing gas boilers in areas where natural gas is available [41]. At the same time, results that minimise the annual GHG emissions, down to almost 90% compared to 'base case', include envelope insulation and window replacement with double or triple-glazed windows, central biomass boilers (locations without natural gas) or central gas condensing boilers (locations with natural gas) for heating, a-a HPs for cooling and PV/T panels for DHW and electricity production. For Greek climate zones A, B and C, a-w HPs for heating and cooling are also part of the optimal solutions, having the minimum GHG emissions; however, they have a significant increase in LCC. Moving towards carbon neutrality, there is a noticeable market penetration potential for energy-efficient systems, such as a-w HPs and PV/T panels, providing the reduction of their initial cost.

The obtained results rely heavily on a large number of parameters, such as the building type and construction period, the climate of the building location, the selected retrofit measures and technologies, the fuel and electricity availability, price and GHG emission factors. Consequently, the comparison of results with state-of-the-art studies is challenging.

Comparing the present results of climate zone B with the results of Kakaras et al. [43] for a 3-storey multi-residential building of the same construction period and climate zone, strong similarities are identified. Their cost-optimal solution space is dominated by condensing gas boiler for heating and a-a HPs for cooling, however, the study did not consider the use of a-a HPs for both heating and cooling. Similar to the results of this study, a-w HPs for heating and cooling are part of their nearly zero-energy solutions. The cost-optimal results between the studied differ by 80 € m^{-2}. The mismatch is attributed to several reasons; the use of different simulation assumptions and methods (quasi-steady and dynamic), different price of materials, systems and energy, different discount rates, and most importantly different lifespan.

Another comparable study [30] targeting net-zero-energy retrofit of a multi-residential building in Porto, considering heating, cooling and DHW, holed as the cost-optimal solution the insulation of the envelope with EPS panels of low thickness (around 50 mm), the installation of PVC framed double-glazed windows, the replacement of the existing systems (electric for heating and DHW) with a natural gas boiler for DHW and a-a HPs for heating and cooling. The global cost of that solution, for a lifespan of 30 years was 430 € m^{-2}. According to that study [30], when cooling is not considered, the cost-optimal heating system is a natural gas boiler. Those results are in agreement with the results of this study.

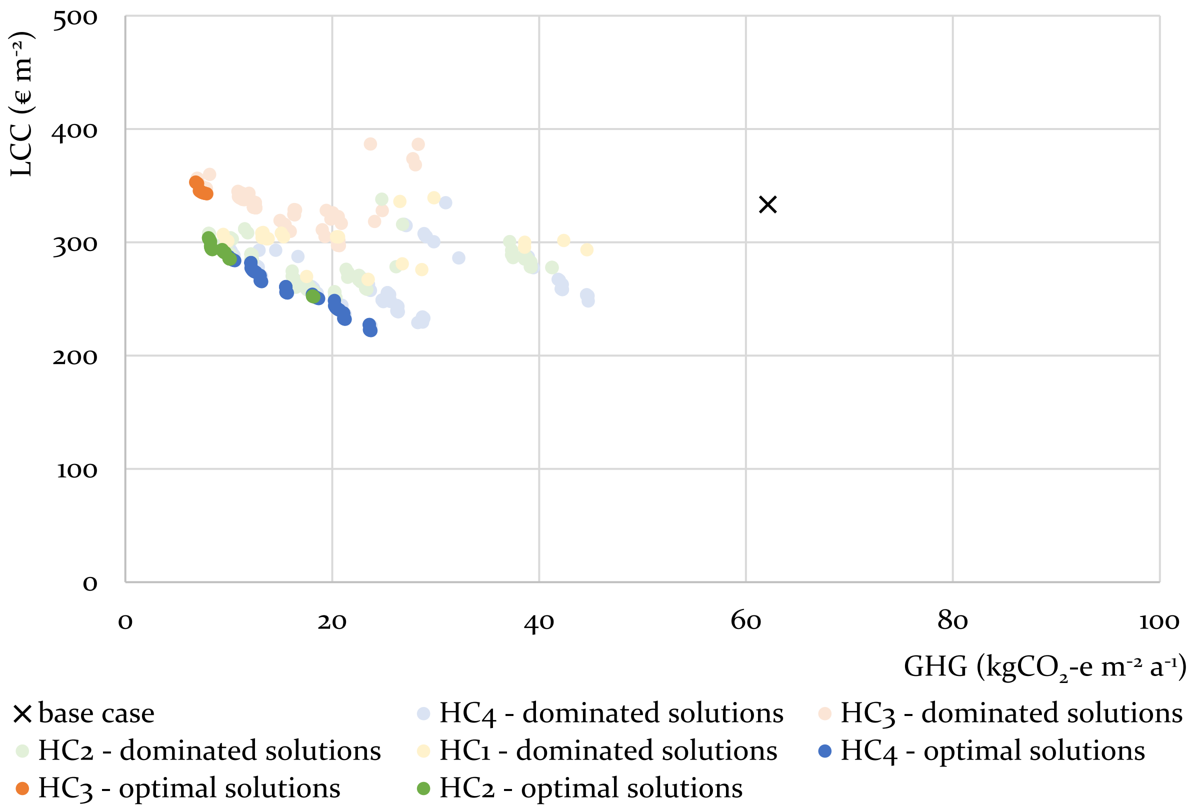

Fig. 4. Retrofit optimisation results for Greek climate zone A (Heraklion).

Table 14.
List of optimal solutions for Greek climate zone A (Heraklion).

Solution set code	Annual GHG emissions ($kg\ CO_2$-e $m^{-2}\ a^{-1}$)	LCC (€ m^{-2})
WLØ-RF1-FL1-WDØ-HC4-HW1-RE2	23.6	222.8
WLØ-RF1-FL1-WD1-HC4-HW1-RE2	21.1	232.9
WL1-RF1-FL1-WDØ-HC4-HW1-RE2	20.5	240.9
WL1-RF1-FL1-WD1-HC4-HW1-RE2	18.5	250.9
WLØ-RF1-FL1-WD1-HC2-HW1-RE2	18.2	252.1
WLØ-RF1-FL1-WDØ-HC4-HW1-RE3	15.5	260.3
WLØ-RF1-FL1-WD1-HC4-HW1-RE3	13.1	266.1
WL1-RF1-FL1-WDØ-HC4-HW1-RE3	12.4	275.0
WL1-RF1-FL1-WD1-HC4-HW1-RE3	10.5	284.2
WLØ-RF1-FL1-WD1-HC2-HW1-RE3	10.1	285.3
WL1-RF1-FL1-WDØ-HC2-HW1-RE3	9.5	291.3
WL1-RF1-FL1-WD1-HC2-HW1-RE3	8.3	295.3
WL1-RF1-FL1-WD2-HC2-HW1-RE3	8.1	303.1
WL1-RF1-FL1-WD1-HC3-HW1-RE3	7.4	344.1
WL1-RF1-FL1-WD2-HC3-HW1-RE3	6.8	352.6

WL: wall insulation, RF: roof insulation, FL: ground floor (basement ceiling) insulation, WD: window replacement, HC: heating and cooling system, HW: hot water heating system, RE: renewable energy supply system.

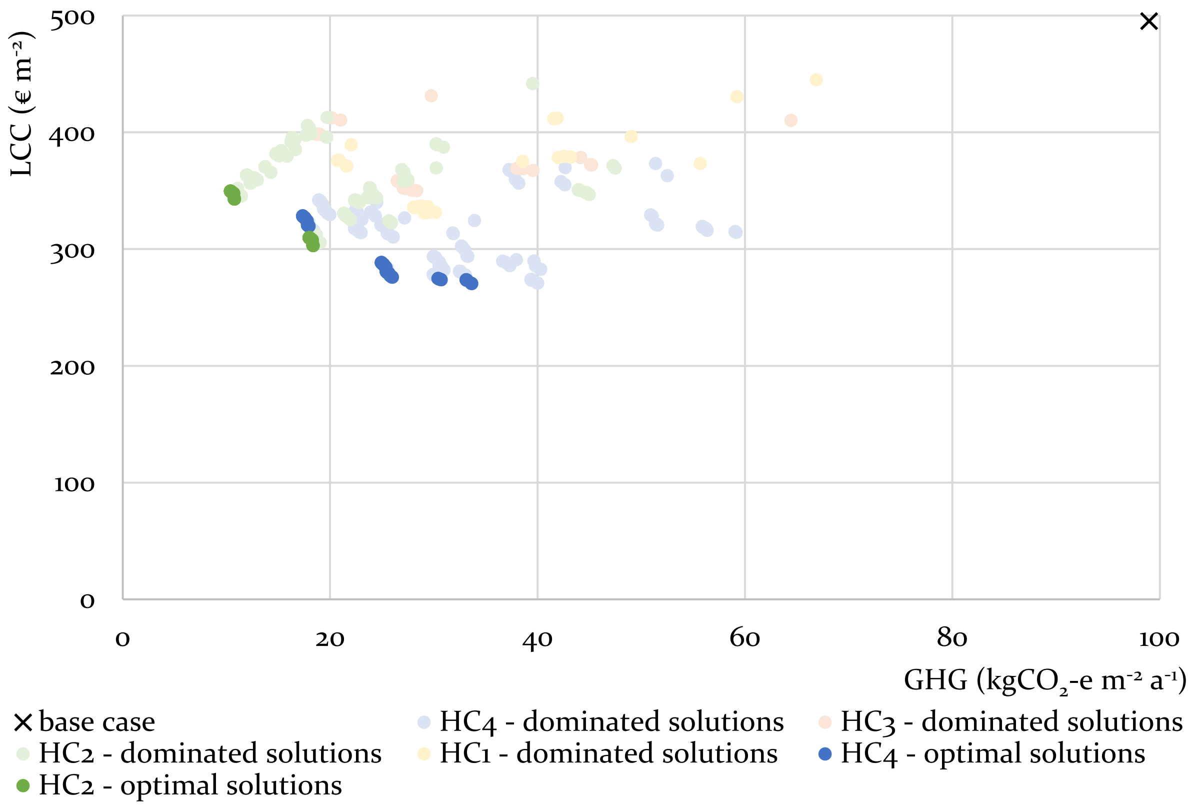

Fig. 5. Retrofit optimisation results for Greek climate zone D (Florina).

Table 15.
List of optimal solutions for Greek climate zone D (Florina).

Solution set code	Annual GHG emissions (kg CO_2-e m^{-2} a^{-1})	LCC (€ m^{-2})
WLØ-RF1-FLØ-WD1-HC4-HW1-RE2	33.6	270.6
WLØ-RF1-FL1-WD1-HC4-HW1-RE2	33.2	273.3
WL1-RF1-FLØ-WDØ-HC4-HW1-RE2	30.5	274.3
WL1-RF1-FL1-WD1-HC4-HW1-RE2	25.5	279.8
WL1-RF1-FLØ-WD2-HC4-HW1-RE2	25.3	284.8
WL1-RF1-FL1-WD2-HC4-HW1-RE2	25.1	287.2
WL1-RF1-FL1-WD1-HC2-HW1-RE2	18.4	303.1
WL1-RF1-FLØ-WD2-HC2-HW1-RE2	18.3	307.8
WL1-RF1-FL1-WD2-HC2-HW1-RE2	18.0	309.3
WL1-RF1-FLØ-WD2-HC4-HW1-RE3	17.7	324.7
WL1-RF1-FL1-WD2-HC4-HW1-RE3	17.5	327.1
WL1-RF1-FL1-WD1-HC2-HW1-RE3	10.8	343.0
WL1-RF1-FLØ-WD2-HC2-HW1-RE3	10.6	347.6
WL1-RF1-FL1-WD2-HC2-HW1-RE3	10.4	349.3

WL: wall insulation, RF: roof insulation, FL: ground floor (basement ceiling) insulation, WD: window replacement, HC: heating and cooling system, HW: hot water heating system, RE: renewable energy supply system.

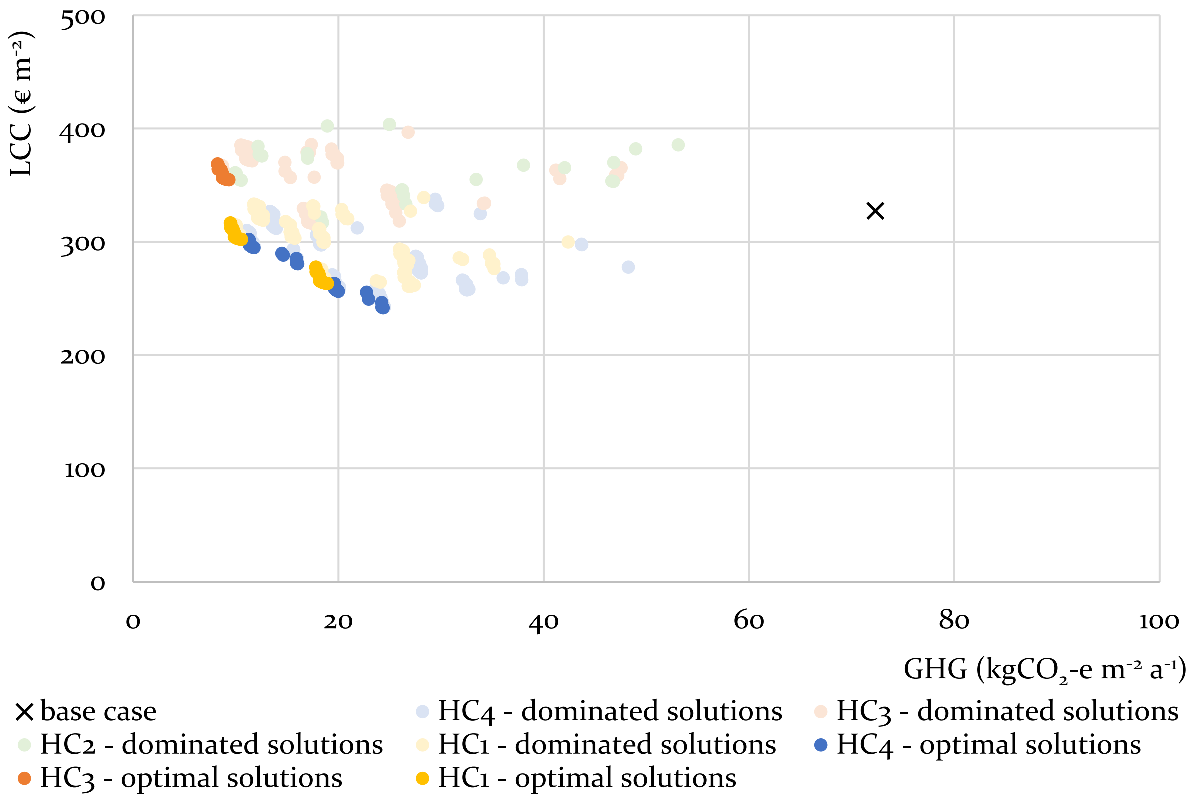

Fig. 6. Retrofit optimisation results for Greek climate zone B (Athens).

Table 16.
List of optimal solutions for Greek climate zone B (Athens).

Solution set code	Annual GHG emissions ($kg\ CO_2\text{-}e\ m^{-2}\ a^{-1}$)	LCC ($€\ m^{-2}$)
WLØ-RF1-FL1-WD1-HC4-HW1-RE2	24.3	242.1
WL1-RF1-FL1-WDØ-HC4-HW1-RE2	22.8	255.4
WL1-RF1-FL1-WD1-HC4-HW1-RE2	19.6	263.1
WL1-RF1-FL1-WD1-HC1-HW1-RE2	18.4	264.5
WL1-RF1-FL1-WD2-HC1-HW1-RE2	17.8	277.5
WLØ-RF1-FL1-WD1-HC4-HW1-RE3	16.0	180.5
WL1-RF1-FL1-WDØ-HC4-HW1-RE3	14.5	289.8
WL1-RF1-FL1-WD1-HC4-HW1-RE3	11.5	296.2
WL1-RF1-FL1-WD1-HC1-HW1-RE3	10.0	303.5
WL2-RF1-FL1-WD2-HC4-HW1-RE3	9.5	316.3
WL2-RF1-FL1-WD1-HC3-HW1-RE3	8.9	355.5
WL2-RF1-FL1-WD2-HC3-HW1-RE3	8.3	368.2

WL: wall insulation, RF: roof insulation, FL: ground floor (basement ceiling) insulation, WD: window replacement, HC: heating and cooling system, HW: hot water heating system, RE: renewable energy supply system.

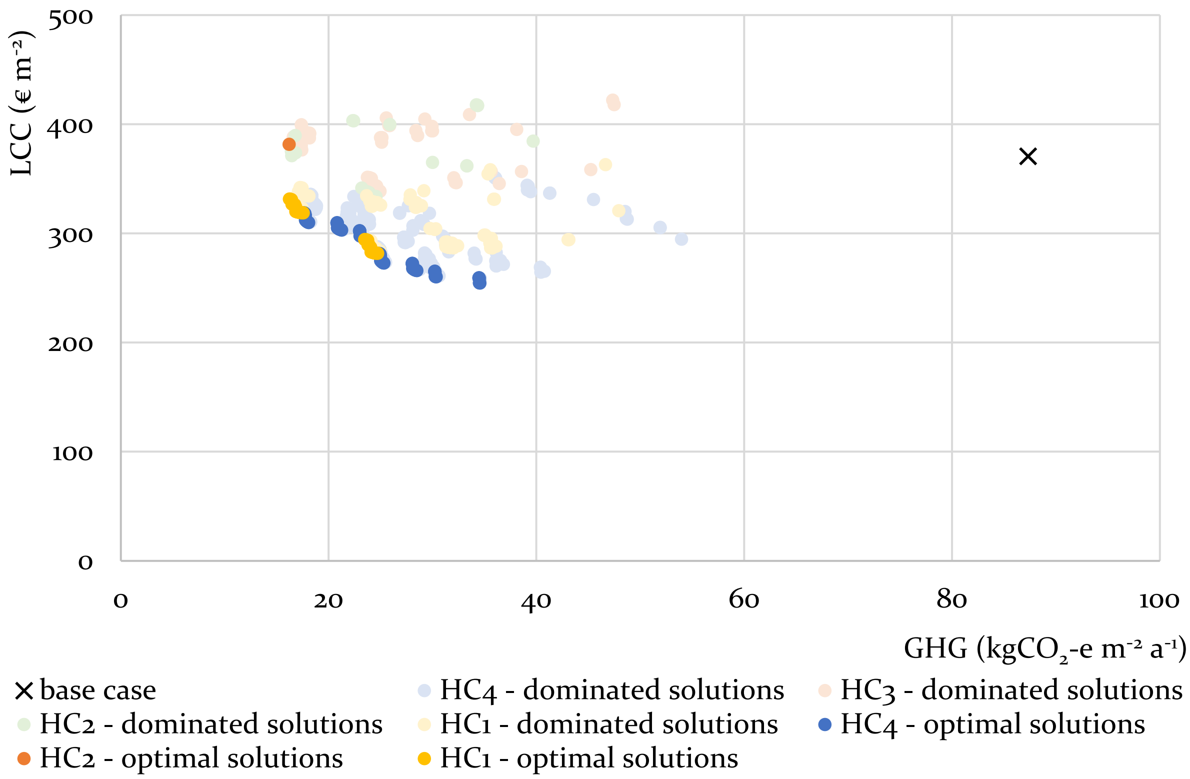

Fig. 7. Retrofit optimisation results for Greek climate zone C (Thessaloniki).

Table 17.
List of optimal solutions for Greek climate zone C (Thessaloniki).

Solution set code	Annual GHG emissions ($kg\ CO_2$-e $m^{-2}\ a^{-1}$)	LCC (€ m^{-2})
WLØ-RF1-FL1-WDØ-HC4-HW1-RE2	34.5	258.9
WLØ-RF1-FL1-WD1-HC4-HW1-RE2	30.3	260.5
WL1-RF1-FL1-WDØ-HC4-HW1-RE2	28.2	267.0
WL1-RF1-FL1-WD2-HC4-HW1-RE2	24.9	281.3
WL1-RF1-FL1-WD1-HC4-HW1-RE2	25.0	279.6
WL1-RF1-FL1-WD1-HC1-HW1-RE2	24.5	281.9
WL1-RF1-FL1-WD2-HC1-HW1-RE2	23.8	293.5
WLØ-RF1-FL1-WD1-HC4-HW1-RE3	23.0	301.7
WL1-RF1-FL1-WDØ-HC4-HW1-RE3	20.8	309.7
WL1-RF1-FL1-WD1-HC4-HW1-RE3	17.9	311.1
WL1-RF1-FL1-WD1-HC1-HW1-RE3	17.1	319.4
WL2-RF1-FL1-WD2-HC4-HW2-RE3	16.5	326.7
WL2-RF1-FL1-WD2-HC3-HW1-RE3	16.2	381.5

WL: wall insulation, RF: roof insulation, FL: ground floor (basement ceiling) insulation, WD: window replacement, HC: heating and cooling system, HW: hot water heating system, RE: renewable energy supply system.

Regarding the ultimate target of carbon neutrality, most studies did not achieve a net-zero-energy or emissions retrofit, under the determined building system boundaries and the considered interventions [22,27,63,64]. With respect to the retrofit of multi-residential buildings, Ascione et al. [27] minimised the primary energy down to 25 kWh m^{-2} a^{-1}, while Kakaras et al. [43] reduced it lower to 10 kWh m^{-2} a^{-1}. On the other hand, Salata et al. [31] minimised the energy used for heating, cooling and DHW from 59.62 kWh m^{-2} a^{-1} to 0.33 kWh m^{-2} a^{-1}, by replacing the conventional boiler with an a-w HP and installing a large area of PV panels on the building rooftop. The ratio of PV panel area to conditioned floor area of their case study building was 0.093 (112/1204), while the one of this study is 0.059 (80/1360).

5.1. Sensitivity of results due to uncertainty

The building retrofit, being a financial study, is sensitive to investment-related uncertainties, such as the energy price growth rate, the inflation and the discount rate. Thus, a sensitivity analysis of the optimisation results was undertaken, considering a range of real discount rates from 2% to 6%, resulting from the numbers used by other studies on residential building retrofit in Europe [65]. As for the fuel and electricity prices, the sensitivity analysis was undertaken for prices increased by 10% and 20%, considering the national energy price escalation [66–69] as well as similar studies [70–72].

At the same time, the building retrofit, being an environmental impact study, is sensitive to fuel and electricity GHG emission factors. While fuel GHG emission factors do not change drastically over time, there is an effort towards the decarbonisation of the electricity grid. The electricity GHG emission factor range used for the sensitivity analysis derived from the EU 2050 targets for carbon neutrality and the lifespan of the LCC calculation. Assuming a linear decarbonisation process, the electricity GHG emission factor will not exceed 0.54 kgCO_2-e kWh^{-1} by 2030 and 0.27 kgCO_2-e kWh^{-1} by 2040.

5.1.1 Effects of uncertainty in real discount rate

The sensitivity analysis results due to uncertainty in the real discount rate are presented in Fig. A.1 of Appendix A. For Florina, which is the location of the higher heating load (Greek climate zone D), when the real discount rate is 6%, the cost-optimal solution does not include window replacement, which is not the case for lower real discount rates. On the other hand, for Thessaloniki (Greek climate zone B), when the real discount rate decreases down to 2%, wall insulation or window replacement is required under the cost-optimal solution, while for higher real discount rates none of these are necessary. It is also interesting that, for locations of lower heating load (Greek climate zones A and B), when the real discount rate is high (6%), the cost-optimal retrofit set includes the PV/T panels, instead of the solar thermal panels. For Heraklion, the biomass pellet boiler outperforms the a-a HPs for heating. Overall, only modifications of the cost-optimal retrofit sets were noticed. The solutions that minimise the GHG emissions remain the same for the range of real discount rate studied, for all locations.

5.1.2 Effects of uncertainty in fuels and electricity prices

The increase of fuel and electricity prices does not have an impact on the ranking of the optimal retrofit set of solutions. A 10% increase of the prices will increase the LCC of the optimal solutions by 2% to 4%, while a 20% increase will cause a 5% to 10% LCC increase (Fig. A.2 of Appendix A). The sensitivity analysis results are in agreement with Copiello et al. [73] that compared the uncertainty due to the discount rate, the energy price and the energy inflation rate in building energy retrofit projects and concluded that the discount rate affects the results four times more than the energy price.

5.1.3 Effects of uncertainty in electricity GHG emission factors

The sensitivity analysis results due to uncertainty in electricity GHG emission factors are presented in Fig. A.3 of Appendix A. It is noticed that for locations with natural gas (climate zone B and C), triple-glazed windows are not only part of the solution sets that minimise the

GHG emissions but they can be met at the middle of the Pareto front, combined with a-a HPs for heating and cooling and solar thermal panels for DHW. Condensing gas boilers for heating are not part of the Pareto front, which is dominated by a-a HPs and a-w HPs for heating and cooling. In locations without natural gas (climate zone A and D), the optimal solution sets are similar for the different levels of electricity grid decarbonisation. In climate zone D, the biomass boilers are not part of the retrofit solution sets that minimise GHG emissions. In climate zone A, triple-glazed windows, combined with a-a HPs for heating and cooling and solar thermal panels for DHW, are among the cost-optimal solutions. The combination of envelope insulation, double or triple glazed windows, a-a HPs for heating and cooling and PV/T panels for DHW and electricity production is very close to achieve a net-zero-carbon balance.

6. Conclusions

We developed a new method for the identification of cost-optimal solutions and solutions that minimise the annual greenhouse gas (GHG) emissions and the global cost, for the retrofit of multi-residential buildings. The method employs simulation and multi-objective optimisation procedures, evaluating the performance of a large number of retrofit interventions. The innovation in the method is the integrated and application-oriented approach, targeting the 'whole building'. A dynamic building systems' modelling process, based on hourly components' part-load performances, is also introduced to provide better accuracy than the monthly quasi-steady state methods.

The software tools that facilitate the method are DAKOTA and TRNSYS. To avoid a large number of simulations, a Multi-Objective Genetic Algorithm (MOGA) is applied instead of a brute-force approach. A case study application illustrated the functionality of the developed method. The selected case study building is a six-storey multi-residential building, being constructed before 1980 in Athens. To identify how various parameters of the existing building might affect the application and the obtained results, the building was optimised for the four Greek climate zones.

It was found that, for all Greek climate zones, the cost-optimal retrofit set consisted of roof and basement ceiling insulation, the installation of air-to-air heat pumps (a-a HPs) for heating and cooling and solar thermal collectors for domestic hot water (DHW). This way, the operating GHG emissions can decrease between 59% and 67%, compared to 'base case', depending on the climate zone. To achieve a retrofit that minimises the annual operating GHG emissions (between 80% to 90% less compared to 'base case'), the solution sets include envelope insulation and window replacement with double or triple-glazed windows, a central biomass boiler (locations without natural gas) or a central gas condensing boiler (locations with natural gas) for heating, a-a HPs for cooling and PV/T panels for DHW and electricity production. The use of air-to-water (a-w) HPs for heating and cooling was part of the optimal solutions that minimise the GHG emissions, for Greek climate zones A, B and C, however, those solutions have a significant increase in LCC.

It was revealed that a net-zero-carbon retrofit could not be achieved for any locations, within the premises and the assumptions made, mainly due to the limited available roof space for the installation of renewable energy supply systems. However, considering the future decarbonisation of the grid electricity, operating GHG emissions can be reduced below 95% or more, approaching a net-zero-carbon retrofit, in case efficient electricity-driven systems are installed. Together with the decarbonisation of the grid electricity, a-a HPs and a-w HPs for heating and cooling dominate the optimal solutions.

The cost-optimal results are in line with observed market trends: the insulation of building envelope, the replacement of single-glazed windows with double-glazed windows and the installation of a-a HPs and condensing gas boilers in areas where natural gas is available.

Considering the EU 2030 and 2050 (carbon neutrality) targets for the reduction of GHG emissions, there is a noticeable market penetration potential for the identified retrofit solutions that minimise the GHG emissions, such as the a-w HPs and the PV/T panels, providing the reduction of their high initial cost.

The results obtained from the optimisation are specific to the market situation, available fuels and systems at the locations considered. These results could guide the retrofitting of similar buildings and construction types in urban areas of the Mediterranean climate.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Sensitivity analysis of results due to uncertainty

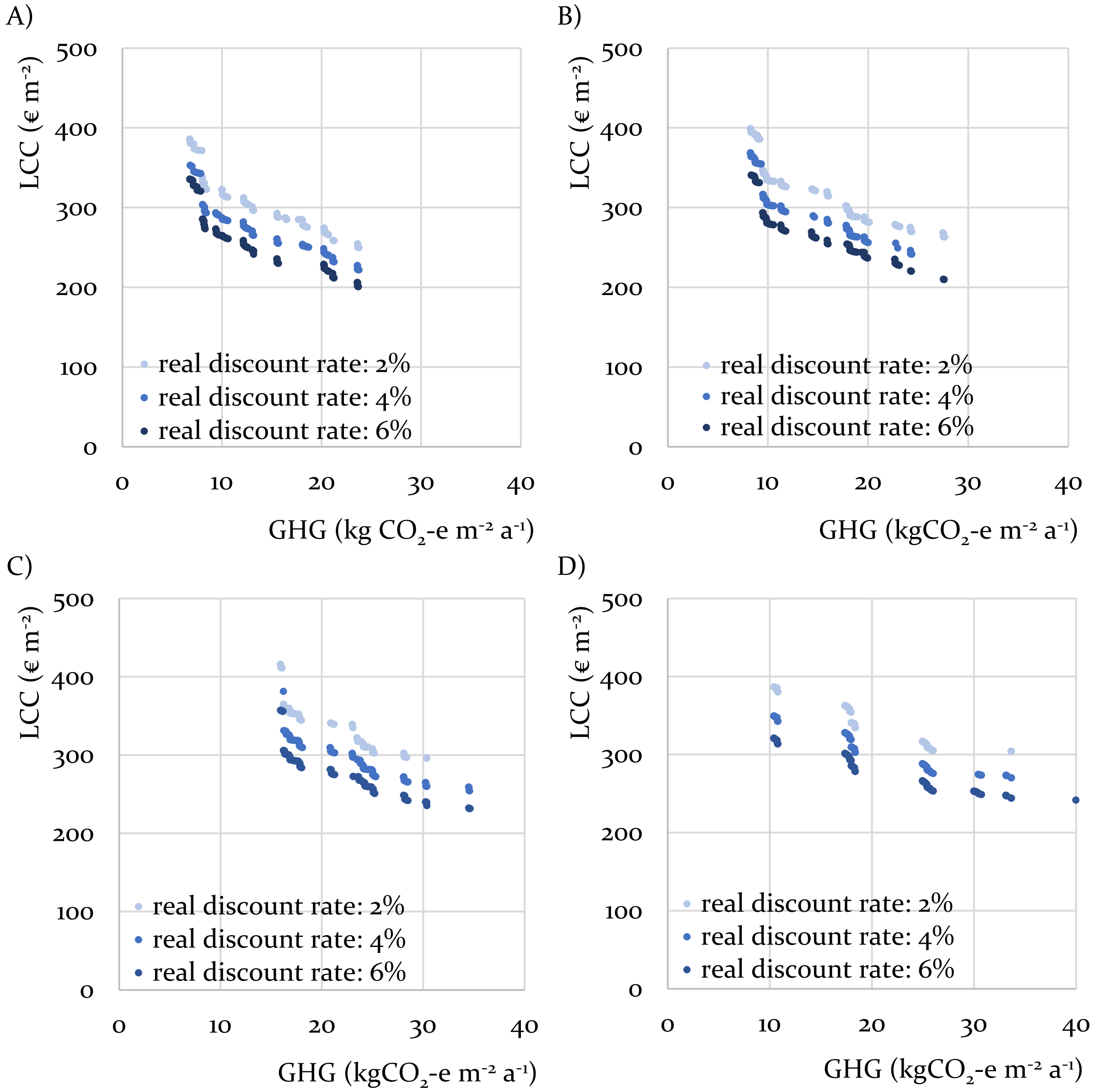

Fig. A.1. Sensitivity analysis for a range of real discount rate values: A) Heraklion, B) Athens, C) Thessaloniki and D) Florina.

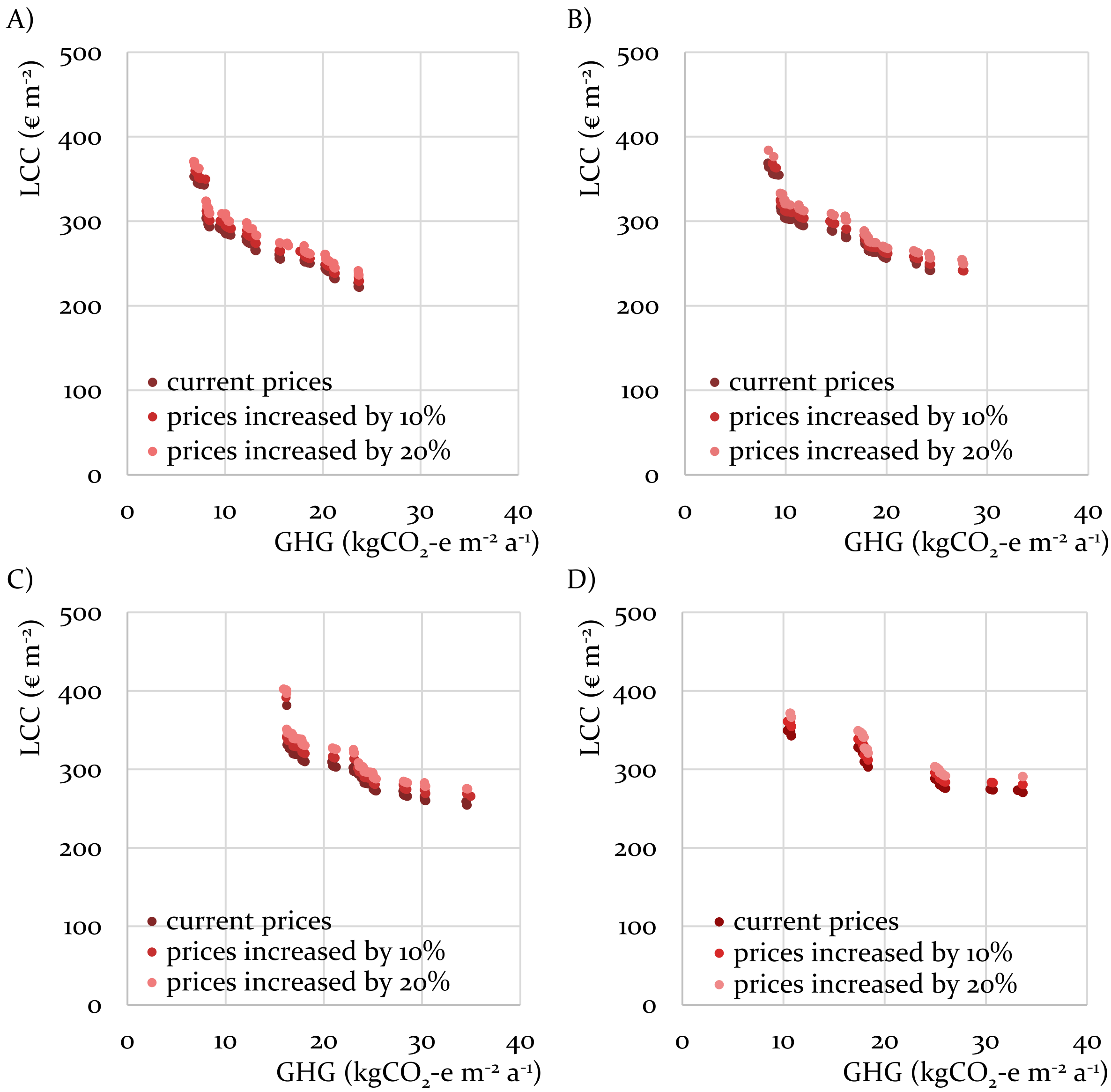

Fig. A.2. Sensitivity analysis for a range of fuel and electricity price increase: A) Heraklion, B) Athens, C) Thessaloniki and D) Florina.

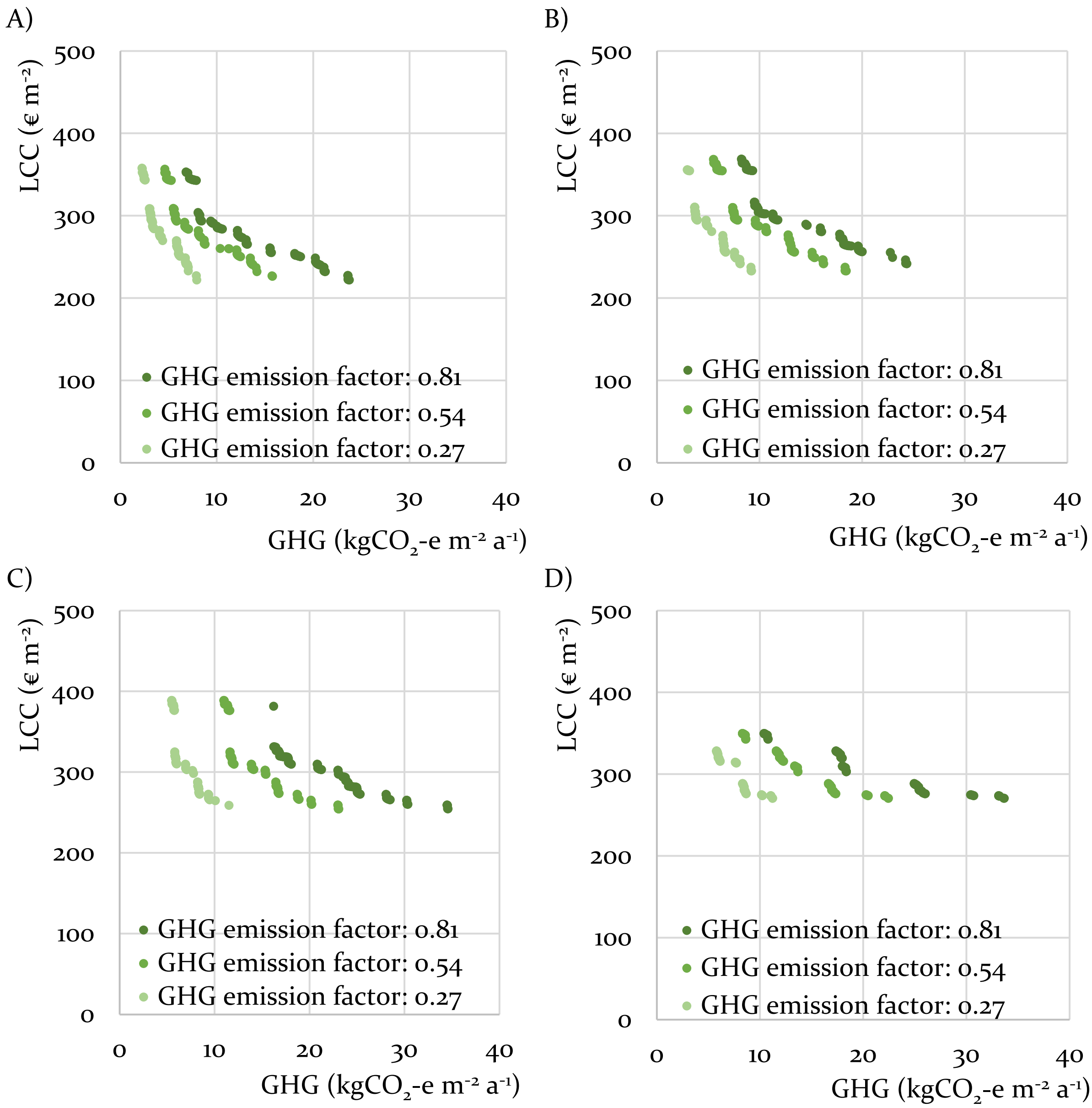

Fig. A.3. Sensitivity analysis for a range of electricity GHG emission factors ($kgCO_2$-e kWh^{-1}): A) Heraklion, B) Athens, C) Thessaloniki and D) Florina.

Chapter 6 – Conclusions and Recommendations

6.1 Introduction

This chapter summarises the findings presented in Chapter 2, Chapter 3, Chapter 4 and Chapter 5, highlighting the original contribution to knowledge made. Based on the results obtained and the limitations of the study acknowledged, future research paths were also identified and recommended at the end of the chapter.

The first step is to compare the results with the aim of the study, as stated in Chapter 1:

> *"The research aims to develop a method to support the residential building retrofit decision making, pursuing the conflicting objectives of reducing the operating GHG emissions of the building while minimising the retrofit life-cycle cost. The research focuses on multi-residential buildings, located in medium and high-density urban areas, as they have greater challenges to overcome compared to other building types. The key stakeholders are the residence owners, as they are the final decision-makers of the retrofit and, in most cases, the recipients."*

The following research objectives were introduced in Chapter 1 to achieve the aim:

1. *Develop the retrofit optimisation framework.*
2. *Identify and model the retrofit strategies, based on the design parameters, the objective functions and the environment of the case study building.*
3. *Optimise the design parameters of the multi-residential building retrofit in terms of minimising the environmental impact and the retrofit cost.*

The first objective, which is the development of the retrofit optimisation framework, was addressed after a thorough literature review was conducted in Chapter 2. The second objective, which is the identification of the potential retrofit interventions, was addressed in Chapter 3 and Chapter 4. Finally, the developed optimisation method (first objective), its application and the obtained results (third objective) were presented in Chapter 5.

6.2 Main findings of the study

This section presents some of the major findings and the way they respond to the aim and objectives of the research, highlighting the original contribution to knowledge made. The findings are divided into four sections, one for each chapter of the study. The results map is provided in Figure 3.

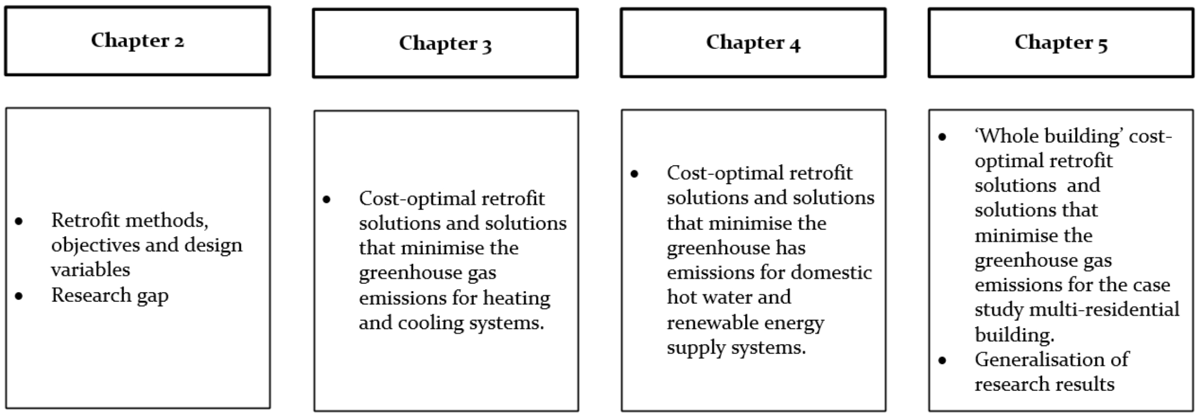

Figure 3. Results map

6.2.1 Findings from Chapter 2

Literature review

The literature review was conducted, following the identified retrofit practice activities: (1) the building audit and performance assessment, (2) the definition of the retrofit stakeholders, objectives and strategies, (3) the performance assessment of the retrofit strategies against the selected objectives, (4) the identification of the optimal solution(s) and (5) uncertainty analysis.

Building audit is the first activity of the retrofit practice. It is conducted by the building expert who collects information of the building characteristics, occupancy and service schedules, as well as energy consumption bills, when available. The data is used to access the building condition and, when possible, calibrate and validate the building model. In EU, EPCs were widely introduced in 2010 with the EPBD. Along with the building audit process, the building modelling process and modelling tools were provided. Modelling results are used for building energy labelling and the selection of retrofit actions suggested to homeowners. Most of the building modelling tools employed by the EU member states for EPC purposes use monthly quasi-steady state methods, characterised by limited accuracy. The model inputs are simplified building information, while the dynamic effects are introduced using correlation factors. Monthly quasi-steady methods also fail to accurately estimate the energy impact of common types of energy supply systems.

The second activity of the retrofit practice is the definition of the retrofit problem, the stakeholders, the objectives and strategies. The literature review indicated that most of the studies hold as a major retrofit stakeholder the building/apartment owner. This is justified from the fact that the owner is the final decision-maker of the retrofit and, in most cases, the recipient. A combination of cost and energy or emissions indicators is used to assess the retrofit alternatives, while social criteria are less often introduced. The retrofit target is most of the times the building envelope and less often the HVAC and the RESSs. A comprehensive 'whole-building' approach is missing from the literature review.

The third activity is the performance assessment of the retrofit strategies against the selected objectives. The dominant method used for building performance is the simulation-based optimisation, single or multi-objective. According to published literature, studies that consider more than two objective functions are characterised by increased outcome interpretation complexity. Since those processes are computationally demanding, a large number of algorithms have been developed to limit exhaustive calculations. GAs are the most popular among optimisation algorithms as they can handle multi-objective optimisation problems and they do not need to know the mathematical expression of the simulation model, treating it as a 'black box'.

The fourth activity is the selection of the final retrofit from the sets of optimal interventions. Most of the times, a weighting method, such as the AHP, is employed. Studies that follow a participatory approach, involving the decision-makers through surveys are rarely met in the literature. However, the identification of the final optimal solution is outside the scope of this study as the selection needs to be made by the decision-maker.

The last activity is the uncertainty analysis. It has been noticed that, despite the large number of studies conducting uncertainty analysis of building design projects, uncertainty analysis is not a common practice for residential building retrofit studies, even though the same uncertainties can be met. Uncertainties regarding the physical material properties, the building operation and occupants' behaviour, the weather data and climate change, the energy price growth rates, the energy inflation and the discount rate are commonly met in building retrofit projects. According to the literature review, the selection of the discount rate can significantly influence the results of the macroeconomic study and has been addressed by the present study.

Overall, the literature review highlighted the need for the development of a 'whole-building' retrofit multi-objective optimisation method that minimises the conflicting objectives of cost and emissions. To avoid exhaustive computation, the developed method should employ an optimisation algorithm, that approaches the optimal solution sets, dealing effectively with multi-objective, non-linear problems. Dynamic building modelling should also be introduced, instead of monthly quasi-steady state modelling, in order to improve accuracy and address the increased simulation difficulty of the building systems. Finally, the method should perform a sensitivity analysis of the results for the most important uncertainties, such as the discount rate used by macroeconomic calculations.

6.2.2 Findings from Chapter 3

Alternative space heating and cooling systems

In the first part of Chapter 3, a case study building was presented, and its performance was modelled and verified. The building was selected out of the program TABULA (2017), that was conducted for the development of a common typology database for the residential building stock in 20 European countries. It is a 6-storey multi-residential building, constructed in 1961 and located in Athens (Greek climate zone B). The building and its related TABULA category were selected after a thorough literature review of the Greek building stock and its characteristics. The review indicated that more than 50% of the dwellings in Greece were constructed before the 1980s and the introduction of the thermal insulation legislation. The building selection is also justified on the basis that, multi-residential buildings face increased challenges, compared to single-family houses, due to their complex tenure status and the limited available land and rooftop space for the installation of RESSs.

A building audit was conducted (see Appendix C), obtaining data for the characteristics of the building envelope, the installed systems and their operation, as well as the energy consumption for space heating.

The space conditioning requirements of the case study building were modelled using TRNSYS dynamic simulation software. For building modelling purposes, information about the building was extracted from TABULA and updated through the performed building audit, as well as the national integration of EPBD for EPC (Technical Chamber of Greece, 2010a, 2010b, 2010c). Results for space heating were verified by comparison with TABULA modelling results and the literature.

In the second part of Chapter 3, the performance parameters (the operating GHG emissions and the LCC) of market-available space heating and cooling alternative options that can replace the existing low-efficiency systems of the multi-residential buildings, were compared. To respond to the identified knowledge gap for the combined performance of space heating and cooling systems for areas of increasing cooling demand, such as the Mediterranean, space heating and cooling retrofit alternatives were assessed in groups. The research was conducted for four cities, located in the four Greek climate zones, to evaluate the influence of climate, systems and fuel availability.

To calculate systems' energy input, normalised part-load efficiency curves were produced, providing the PLF (the ratio between the operating efficiency/COP and the rated efficiency/COP of the system) based on the PLR (the ratio between the operating capacity and the rated capacity of the system), for the simulated alternative heating and cooling systems, using manufacturers' data or data from the literature.

The conducted literature and market review for the available and commonly used heating and cooling systems helped to eliminate the competing alternatives. For locations where natural gas is not available (Greek climate zones A and D), a diesel oil condensing boiler (Case 1), a biomass pellet boiler (Case 2) for space heating, combined with a-a HP units for space cooling, an a-w HP (Case 3) and a-a HP units (Case 4) for space heating and cooling competed for the replacement of the existing diesel oil conventional boiler for space heating, combined with a-a HP units for space cooling (Case Ø). Results indicated that the replacement of the existing system can lead to a significant GHG emissions reduction, which is proportional to the heating and cooling loads. In warmer climate zones, Case 2 was the most beneficial alternative, followed by Case 3 and Case 4, while in colder climate zones Case 4 outperformed all alternatives. Case 4 had the minimum LCC, followed by Case 2 in both Greek climate zones A and D.

In urban areas where natural gas is available (Greek climate zones B and C), a natural gas condensing boiler (Case 1), a GAHP (Case 2) for space heating, combined with a-a HP units for space cooling, an a-w HP (Case 3) and a-a HP units (Case 4) for space heating and cooling competed for the replacement of the existing natural gas conventional boiler for space heating, combined with a-a HP units for space cooling (Case Ø). Case 2 had the lowest GHG emissions, followed by Case 4 and Case 1. Nevertheless, Case 2, along with Case 3, had the highest LCC compared to the other two systems that demonstrate low LCC.

Findings of Chapter 3 are in line with the observed market trends. According to literature, condensing gas boilers and a-a HP units are the most common space conditioning systems in Greece. Having low initial and operating costs are more competitive against other high-performing but high initial cost systems, such as the GAHP and the a-w HP. GAHPs and a-w HPs will be competitive alternatives when their purchase costs decrease.

6.2.3 Findings from Chapter 4

Alternative DHW and RESSs

In Chapter 4, the performance parameters (‘net’ annual grid electricity consumption and LCC) of market-available solar-assisted water heating systems were compared for the ‘base case’ building. In addition to that, the problem of limited available rooftop or facade areas for the installation of solar technologies for buildings located in urban areas was addressed. Once more, the comparison was conducted for the 'base case' building, presented in Chapter 3, for the same urban areas of the four Greek climate zones.

Based on the conducted literature review and the building limitations, several calculations and assumptions were made. For the installation of solar RESSs, the maximum panel south-facing non-shaded area was 3 m^2 per apartment. It was found that the energy produced by the panel area could not meet the total energy needs of the 27 apartments. However, when designed to cater for the DHW requirement, it covered from 45% to more than 100%. Thus, the electric or heat gains of the competing solar systems were supplied to the DHW needs. The selected solar-assisted water heating systems were an electric water heating system combined with a PV electricity supply system (S1), a solar thermal water heating system (S2), a PV/T water heating and electricity supply system (S3) and a HPHW heating system combined with a PV electricity supply system (S4). An electric hot water heating system was considered the baseline system. A 200 litres cylindrical storage tank and 60 °C supply water temperature were assumed for all water heating systems.

The energy produced by each system was similar for all considered Greek urban areas, however, the total electricity consumption of the systems varied based on the ambient air temperature. Systems in Heraklion (Greek climate zone A) had the lower electricity consumptions while systems in Florina (Greek climate zone D) had the higher. According to the obtained results, S3 had the lowest 'net' grid electricity demand, followed by S4. S4 had the highest initial cost, followed by S3 and S2. S2 and S3 had the lower LCC. For warmer climate zones the preferable option was S3, while for colder climate zones was S2. The findings of Chapter 4 are in line with the observed high market penetration of solar thermal collectors for DHW. At the same time, results indicate that PV/T panels have great potential but limited market penetration, while HPHW systems will be a competitive alternative to electric water heating systems when their purchase costs decrease.

6.2.4 Findings from Chapter 5

Retrofit optimisation

In Chapter 5, the developed multi-objective optimisation method, for the evaluation of the cost-optimal retrofit sets of solutions and optimal solutions that minimise the GHG emissions, was applied to the reference multi-residential building. The objectives were the minimisation of the operating GHG emissions and the LCC, while the considered retrofit interventions covered the 'whole building'. The energy-saving measures were the envelope insulation (walls, roof, basement ceiling) and the window replacement. The installation of external shading was not considered as it was estimated that the existing shadings are sufficient. Natural ventilation techniques were not considered as their impact on space heating and cooling loads cannot be calculated with TRNSYS. The selected HVAC and RESSs alternatives were presented in Chapter 3 and Chapter 4. Optimisation results were compared to the 'base case' building of each Greek climate zone.

The employed software tools were DAKOTA and TRNSYS. DAKOTA initiated and controlled the optimisation process, while TRNSYS performed the building and systems' performance simulations. A Python script interfaced the software tools. To avoid exhaustive computation, MOGA, available in DAKOTA, was applied instead of a brute-force approach.

The more interesting optimisation results were those regarding two solution areas: the cost-optimal and the solutions that minimise the GHG emissions. They indicated that for all Greek climate zones, the cost-optimal retrofit sets consisted of roof and basement ceiling insulation, the installation of a-a HP units for space heating and cooling and solar thermal collectors with electric boosting for DHW requirements. In some cases, the replacement of the single-glazed windows with double-glazed was also required. However, the insulation of walls was not part of the cost-optimal solution for all Greek climate zones. Adopting that solution, the operating GHG emissions were decreased between 59% to 67%, compared to 'base case', depending on the building location.

Solutions that minimise the GHG emissions achieved reduction of almost 90% for all Greek climate zones, compared to ‘base case’. The obtained solution sets included wall, roof and basement ceiling insulation and window replacement with double or triple-glazed uPVC framed windows, central biomass pellet boilers (locations without natural gas) or gas condensing boilers (locations with natural gas) for space heating, a-a HP units for space cooling and PV/T panels for DHW and electricity production. The use of a-w HP systems for space heating and cooling were part of optimal solutions that minimise the LCC for Greek climate zones A, B and C, however, those solutions had a significant increase of LCC. A net-zero carbon retrofit solution could not be achieved for any location due to the limited available space for the installation of RESSs.

Findings of Chapter 5 were in line with the observed market trends, which are the insulation of the building envelope, the replacement of single with double-glazed windows and the installation of condensing gas boilers and a-a HP units in areas where natural gas is available. They also revealed the great potential that biomass pellet boilers have for space heating in areas where natural gas is not available. A-w HPs for space heating and cooling minimise the GHG emissions, however, they will become competitive when their purchase cost decrease. Similar to findings of Chapter 4, solar thermal collectors for DHW are the common market practice, however, when the minimisation of GHG emissions is required, PV/T panels have great potential but limited market penetration

The optimisation results are specific to the financial situation, systems and fuel availabilities of the locations considered. They can be used as a guide for retrofitting similar buildings and construction types in urban areas of the Mediterranean climate, assisting policy makers and home-owners.

6.3 Recommendations for future research

This section addresses the limitations of the study, regarding the retrofit uncertainties. In this thesis, the uncertainties caused by the real discount rate, the future fuel and electricity prices and future decarbonisation of the electricity grid were included in the developed method. Uncertainties regarding the building operation and occupants’ behaviour were not considered in this thesis. Those uncertainties can be considered through building monitoring and model calibration. A method that supports the development of case-specific occupation and system operation schedules is suggested, not only to integrate the present schedules but also those that will occur in the future.

Climate change poses new challenges to building retrofit. The method developed calculates the annual GHG emissions and LCC, assuming that the present TMY data will remain typical for the many years in the future. However, the global temperature increase, caused by the climate change, was not considered. Future research on climate change forecasting and integration into the method is recommended.

Finally, it has already been noted that one of the major findings of the application of the method is the difficulty to achieve net-zero carbon retrofit for multi-residential buildings. Additional research is required to identify the potentials of reaching this target.

6.4 References

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Appendix A – Conference Paper #1

LOW ENERGY BUILDING RETROFIT: A REVIEW OF OBJECTIVES AND SOLUTIONS

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Abstract: *Worldwide, the building sector is accountable for one-third of final energy consumption. This is expected to increase in the future. It is due to the continuing growth in demand for new buildings and the poor energy efficiency of the existing building stock. In developed countries, the ratio of new to old buildings is around 1% per year. According to the European Energy Performance of Buildings Directive Recast (Directive 2010/31/EU), optimal solutions towards low and near-Zero Energy Building (near ZEB) retrofit is of critical importance in order to achieve European Union (EU) climate and energy objectives. This has led to a large number of projects on deep building retrofit during the last 20 years. Each project has specific objective functions, depending on the adopted stakeholder's perspective and the selected retrofit strategies are dictated by the objective functions set. This study investigates stakeholders (legislators, investors, owners and users), objectives and optimal retrofit strategies and their interrelationships. The focus is on residential buildings due to the significant opportunity for reducing their Greenhouse Gas (GHG) emissions. A matrix has been developed to classify information in order to facilitate comparison and apparent correlations to be identified. The expected outcome is the better understanding of stakeholders' perspectives on financial, energy, GHG emissions, thermal comfort and the resulted optimal strategies.*

Keywords: *Residential Buildings, Building Stock, Deep Retrofit, Energy Efficiency, Europe*

Abbreviations and acronyms

CHP	combined heat and power	LCEIs	life cycle environmental impacts
DH	district heating	LCPEn	life cycle primary energy
DHW	domestic hot water	low-e	low emissivity
EEn	embodied energy	MFH	multi-family house
EPBD	energy performance of buildings directive	near ZEB	near-zero energy building
EPS	expanded polystyrene	net ZEB	net-zero energy building
ESMs	energy saving measures	NPV	net present value
EU	European Union	OC	operational cost
GHG	greenhouse gas	OEm	operational emissions
GSHP	ground source heat pump	OEn	operational energy
GWP	global warming potential	PBP	payback period
HP	heat pump	PEn	primary energy
HVAC	heating, ventilation and air conditioning	PV	photovoltaic
IC	initial cost	RES	renewable energy systems
IR	inconvenience rate	SFH	single-family house
LCA	life cycle assessment	TC	thermal comfort
LCC	life cycle cost	VoM	visibility of measures

1 Introduction

Among all building types, residential buildings hold great potential to reduce Greenhouse Gas (GHG) emissions, as they account for one-quarter of global final energy demand and 73% of the total energy demand of the building sector (IEA 2013). Buildings are the largest energy consumers in Europe. They are responsible for the 40% of the total final energy consumption, two-thirds of which is for residential buildings (Gynther et al. 2015). At the same time, the annual growth rate of the residential sector across Europe is low, around 1%, while the average annual refurbishment rate is between 0.5% and 2.5% (BPIE 2011).

Building retrofit has been seen as a key way to reduce buildings' energy consumption and related emissions of the existing building stock. Despite the fact that the large variety of residential buildings across Europe does not facilitate a consistent retrofitting approach (BPIE 2011), the EU, trying to address this issue, launched the Performance of Buildings Directive (EPBD) Recast (EU 2010). It provides member states with a methodological framework for the calculation of the energy performance, both for new buildings and existing buildings that undergo a major retrofit. However, the details are defined by the individual member states, in a national, regional or local level. Local characteristics, such as the climate conditions or the available solar radiation, can play a critical role in setting the legislative framework in each country (Cansino et al. 2011). The maturity of each member in implementing the energy efficiency measures depends on the established practice of the country in adopting building energy regulations and on the established commitment in achieving EU targets (Annunziata et al. 2013).

In accordance with national and EU energy performance legislation or through the setting of higher energy efficiency goals, various residential building retrofit projects have been carried out. Holding different perspectives, projects employ methods to explore a number of retrofit strategies against one or more assessment criteria. Some also consider possible uncertainties and risks involved in the retrofit process, including, financial limitations, governmental policy change, energy prices and climate change.

An early systematic review on building retrofit was conducted by Ma et al. (2012). Their work analysed a number of projects around the world, focusing on the retrofit interventions proposed, the assessment method used and their major results. After that, De Boeck et al. (2015) conducted an extended literature review of residential building retrofit projects, classifying the information accordingly to identify trends. The classification categories were: the building type and location, the design variables, the objective functions, the type of analysis performed, the methodology and software used.

Other researchers, investigated building retrofit projects from different perspectives. Moran et al. (2015) limited the reviewed studies to those located in Europe and target a near ZEB retrofit outcome and Vilches et al. (2017) focused on Life Cycle Assessment (LCA) retrofit studies. Pombo et al. (2016) assessed the sustainability level of residential retrofit projects. They reported that the environmental and the economic dimension of sustainability had been addressed but the social was absent from the assessment criteria.

The findings of the aforementioned reviews show that while passive renovation strategies are widely introduced, Heating, Ventilation and Air Conditioning (HVAC) systems and Renewable Energy Systems (RES) are less often considered among the retrofit strategies. Retrofit strategies are similar throughout the works analysed, however, assessment criteria differ. Location is also a key factor, since local databases are used for cost, energy and GHG emissions estimations, and issues differ depending on climate conditions.

The decision support tools used for the residential building retrofit were addressed by Ferreira et al. (2013). It was pointed out that the selection of the assessment criteria is the most important step of the retrofit process; if they are being modified, final results differ. They also noted that financial analyses are conducted from the specific decision maker's perspective, while environmental impacts are mainly assessed by the LCA method.

A deeper investigation of the relationship between the decision maker and the objective functions used was conducted by Lizana et al. (2016), in order to support the decision management of residential retrofit projects. They claimed that the assessment method is determined by the combination of the objective functions used and can be either a cost-benefit analysis, a multi-criteria analysis, a multi-objective optimisation analysis or an energy rating system. It is mentioned that most of the studies, aiming at reducing the problem complexity, use only two objective functions, which are: financial and energy or financial and GHG emissions. However, there are not many studies that employ three or more objective functions. Three major stakeholders were defined in Lizana et al. (2016): the 'private owner/user', the administrator as the 'public promoter' and the 'private promoter'. The private owner is mainly interested in the initial cost and the possible operational energy savings. The public promoter focuses on GHG emissions reduction and meeting the environmental targets. Whereas, the private promoter focuses on the financial benefits of the investment.

Based on the existing literature, the aim of this review is to further explore and analyse the inter-relationships between the stakeholders' perspectives and the objective functions used by the residential building retrofit projects, as well as to compare and discuss results. More specifically, the intention is to identify which objective functions are related to which specific stakeholders and how outcomes vary among the conducted optimisations. Local characteristics, such as climate conditions, are considered, however, other economic, environmental or political aspects of each case study are outside the scope of this research. Section 2 describes the review method and Section 3 discusses the identified objective functions sets in association with the stakeholder's perspective and major results. Findings are highlighted in Section 4.

2 Method

The selected documents are those that use a single-criteria or a multi-criteria assessment method to evaluate retrofit strategies, or retrofit packages, for residential buildings, aiming to reduce the energy used or their GHG emissions. The selected information is classified and summarised in Table 1 and Table 2, in order to facilitate correlation analysis.

The reviewed studies are limited to buildings located in Europe. Case study location and the corresponding climate zone play a significant role in heating and cooling loads and the available energy sources and technologies utilised. A proposed retrofit approach could be unsuitable if applied in different climate or urban characteristics (Li et al. 2017). Thus, the case studies considered are further classified according to the climate zone they belong.

Building type is also a critical parameter for the determination of energy consumptions. Multi-storey buildings consume less energy for heating and cooling compared with detached low-rise buildings. Three building types have been defined to facilitate case studies' classification: 'single-family houses' (SFH), 'medium-rise multi-family houses' (MFH) and 'high-rise multi-family houses'. Construction period for each building is also noted down, as older buildings tend to have higher energy consumptions. The overall target of each retrofit project is also taken into consideration. Projects that set high energy or GHG emissions reduction targets require not only high-efficiency levels of a proposed retrofit strategy but also an increased number of retrofit actions.

The selected stakeholder categories broadly follow the classification previously introduced by Lizana et al. (2016). These are: the 'owner/user', the 'public promoter/legislator' and the 'private investor/developer'. It should be noted that a considerable number of projects analysed do not declare the adopted stakeholder's perspective and thus this field has been left empty. On the other hand, there are studies declaring that they respond to all stakeholders' requirements.

Case studies are also classified according to the so-called assessment criteria or objective functions they consider. The major categories are the 'environmental', the 'financial' and the 'social' objective functions, while further categorisation is based, among others, on the life cycle stage considered in calculations. Finally, the retrofit strategies are assigned into three categories, based on Pombo et al. (2016) classification: 'building envelope', 'HVAC systems' and 'RES'. The strategies are further sub-classified, as shown in Table 2. It is apparent that the residential building retrofit is a multifactorial task and there is no straight comparison of the selected case studies, as results may vary not only depending on the selected objective functions, but also on the climate conditions, the target setting and the retrofit strategies under consideration.

Table 1: Literature review case studies classified according to climate zone, construction period, house type, target, stakeholder's perspective and assessment objective functions.

				House Type				Stakeholders			Assessment Objective functions												
											Environmental						Financial				Social		
No	Reference	Climate Zone	Construction Period	SFH	Medium-rise MFH	High-rise MFH	Target	O/U	PP/L	PI/D	OEn	PEn	EEn	LCPEn	OEm	LCEIs	IC	PBP	OC	LCC	IR	VoM	TC
1	Penna et al. (2015)	Continental & Mediterranean	a) before 1976, b) after 1976	×	×	×	near ZEB	×			×									×			×
2	Risholt et al. (2013)	Boreal	1980-1989	×			near ZEB	×			×									×		×	×
3	Hasan et al. (2008)	Boreal		×			low energy				×									×			
4	Amstalden et al. (2007)	Continental	1948-1975	×			low energy	×			×									×			
5	Brown et al. (2013)	Boreal	a) 1963, b) 1973		×	×	low energy	×			×									×			
6	Kuusk and Kalamees (2015)	Boreal	1986			×	near ZEB	×				×						×		×			
7	Ferreira et al. (2014)	Mediterranean	1990			×	net ZEB	×				×								×			
8	Hamdy et al. (2013)	Boreal		×			near ZEB		×			×								×			(1)
9	Ballarini et al. (2017)	Mediterranean	a) before 1920, b) 1921-1945, c) 1946-1960, d) 1961-1975, f) 1991-2005, g) after 2005	×	×	×	low energy	×	×	×		×								×			
10	Lizana et al. (2016)	Mediterranean	1955			×	low energy		×			×								×		×	×
11	De Angelis et al. (2013)	Continental	1960-1979			×	low energy									×				×			
12	Cetiner and Edis (2014)	Mediterranean	1992			×	low energy	×								×				×			
13	Pombo et al. (2016)	Mediterranean	1960-1969			×	passive house		×							×				×			
14	Antipova et al. (2014)	Mediterranean					low environ. impact									×				×			
15	Ostermeyer et al. (2013)	Atlantic	1950-1960			×	75% primary energy reduction									×				×			
16	Verbeeck and Hens (2005)	Atlantic	1970-1979	×	×		low energy							×						×			
17	Ascione et al. (2015)	Mediterranean				×	low energy		×			×					×						×
18	Huws and Jankovic (2014)	Atlantic		×			zero carbon								×		×						×
19	Lizana et al. (2016)	Mediterranean	1955			×	low energy			×		×			×		×						
20	Assiego De Larriva et al. (2014)	Mediterranean	1983			×	low energy and carbon	×	×	×		×				×							
21	Wang et al. (2015)	Boreal	a) before 1945, b) 1946-1960, c) 1961-1975	×	×	×	low energy	×	×	×		×	×					(2)					
22	Dodoo et al. (2010)	Boreal	1995			×	passive house							×									
23	Desogus et al. (2013)	Mediterranean	1950-1959	×	×	×	low energy	×	×									×		×			
24	Salata et al. (2017)	Mediterranean	2000			×	class improvem.	×									×	×	×				
25	Lizana et al. (2016)	Mediterranean	1955			×	low energy	×									×		×		×		

SFH: Single-Family House, MFH: Multi-family House, O/U: Owner/User, PP/L: Public Promoter/Legislator, PI/D: Private Investor/Developer, OEn: Operational Energy, EEn: Embodied Energy, LCPEn: Life Cycle Primary Energy, OEm: Operational Emissions, LCEIs: Life Cycle Environmental Impacts, IC: Initial Cost, PBP: Payback Period, OC: Operational Cost, LCC: Life Cycle Cost, IR: Inconvenience Rate, VoM: Visibility of Measures, TC: Thermal Comfort, (1) restriction, (2) considered in a secondary assessment process.

Table 2: Literature review case studies classified according to the retrofit strategies under consideration.

		Retrofit Strategies																
		Building Envelope						HVAC Systems									RES	
No	Reference	Wall Insulation	Roof Insulation	Ground Floor Insulation	Infiltration	Window Replacement	Shadings	Mechanical Ventilation	Control Systems	Existing System Retrofit	Electric Heater	Boiler	HP	CHP	DH	Cooling	Solar Thermal	PV
1	Penna et al. (2015)	×	×	×		×						×						
2	Risholt et al. (2013)	×	×	×	×	×					×		×				×	
3	Hasan et al. (2008)	×	×	×		×		×										
4	Amstalden et al. (2007)	×	×	×		×												
5	Brown et al. (2013)	×	×			×			×		×							
6	Kuusk and Kalamees (2015)	×	×	×		×				×							×	×
7	Ferreira et al. (2014)	×	×	×		×						×	×			×	×	×
8	Hamdy et al. (2013)	×	×	×		×		×			×	×	×		×	×	×	×
9	Ballarini et al. (2017)	×				×											×	
10	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×
11	De Angelis et al. (2013)	×	×	×		×												
12	Cetiner and Edis (2014)	×	×	×	×													
13	Pombo et al. (2016)	×	×	×		×												×
14	Antipova et al. (2014)	×	×			×											×	
15	Ostermeyer et al. (2013)	×	×	×		×					×	×					×	
16	Verbeeck and Hens (2005)	×	×	×		×					×	×	×				×	×
17	Ascione et al. (2015)	×	×			×			×			×				×		
18	Huws and Jankovic (2014)	×	×	×	×	×	×		×			×	×				×	×
19	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×
20	Assiego De Larriva et al. (2014)	×	×	×		×	×											
21	Wang et al. (2015)	×	×	×	×	×			×	×			×		×			
22	Dodoo et al. (2010)	×	×			×					×		×	×	×			
23	Desogus et al. (2013)	×	×			×												
24	Salata et al. (2017)	×				×			×			×	×	×	×		×	×
25	Lizana et al. (2016)	×	×		×	×	×	×				×	×	×			×	×

HVAC: Heating, Ventilation and Air Conditioning, RES: Renewable Energy Systems, HP: Heat Pump, CHP: Combined Heat and Power, DH: District Heating, PV: Photovoltaic

3 Analysis

There are three major types of objective functions identified: a) the financial, b) the environmental and c) the combination of financial and environmental. Social objective functions are rarely used as assessment criteria. In general, they are combined with environmental and/or financial objective functions, either as a third objective function or as a constraint.

According to Table 1, environmental objective functions are further sub-divided based on the energy consumption or GHG emissions consideration and the building life cycle stages included into analyses. The categories are: the 'Operational Energy' (OEn), the 'Primary Energy' (PEn), the 'Embodied Energy' (EEn), the 'Operational Emissions' (OEm), the 'Life Cycle Primary Energy' (LCPEn) and the 'Life Cycle Environmental Impacts' (LCEIs). The financial objective functions commonly employed are: the 'Initial Cost' (IC), the 'Operational Cost' (OC), the 'Life Cycle Cost' (LCC) and the 'Payback Period' (PBP). The Social objective functions are the 'Inconvenience Rate' (IR), the 'Visibility of Measures' (VoM) and 'Thermal Comfort' (TC).

3.1. Financial Objective Functions

Projects that employ financial objective functions only, are not commonly met at building retrofit studies for the improvement of energy performance. If they are, they include financial terms of energy consumption or GHG emissions mitigation criteria such as the return of investment. Purely financial criteria could be employed by the investor, who is, in most of building retrofit cases, the owner of the house. All three studies under this category adopt the owner/user's perspective.

Desogus et al. (2013) investigated the financial feasibility of the envelope retrofit, in terms of LCC and PBP, for three different building types in Italy. The aim of their investigation is to challenge national legislation, claiming that it is too strict and not cost-effective for homeowners. According to the study's results, the combination of all proposed interventions, wall and roof insulation and window substitution, has the lowest Net Present Value (NPV) and is cost-ineffective. When subsidies are introduced, complete retrofit works are preferred to partial, despite the high IC.

Salata et al. (2017) conducted a research, focusing on financial objective functions, for a high-rise MFH retrofit case, located in Rome. A large spectrum of retrofit interventions was considered: external wall insulation, window replacement, control units installation, such as sensors and thermostat settings, boiler substitution alternatives, including Combined Heat and Power (CHP) technologies and Solar thermal and Photovoltaic (PV) panels. The performance of all potential retrofit strategies and their combinations was assessed using three financial criteria: the IC, the annual economic return and the return of investments. Calculations showed that the envelope's thermal performance improvement does not have a considerable impact on energy demand reduction, while it has high installation cost and a payback period of more than 30 years. PV panels are more effective when combined with a Heat Pump (HP) instead of a Condensing Boiler, because HP uses electricity. However, the choice between a Condensing Boiler and a HP is also determined by the local electricity and gas prices. The installation of smart control systems is a high-scored strategy on all assessment objective functions, as it leads to satisfactory annual energy savings and their amortisation period is less than 20 years. The combination of CHP and a HP, despite the high IC, has a PBP of 15 years and allows the building to reach an 'A' energy class, according to national regulations for energy certification which are based on the EPBD.

Finally, Lizana et al. (2016), employed financial assessment criteria in combination with social criteria, for a case study located in Southern Spain. They look at IC, the annual economic return, the TC and the IR caused to occupants. Low investment retrofit interventions have been identified as optimal, among them water flow reducers in taps installation and the sealing of frames for the improvement of air-tightness. Other proposed interventions are the installation of retractable window awnings, roof insulation, the replacement of HPs with more efficient ones and the insulation of exterior walls.

3.2. Environmental Objective Functions

LCA is among the most popular decision-making support methods used for the selection of the optimal alternatives among the retrofit strategies available. A number of LCA studies explore alternative solutions for Energy Saving Measures (ESMs), looking at their embodied energy and the influence they have on primary energy consumption of the building during its operational phase. The interest is focused on the environmental impact of different envelope insulation materials and window frames. High performance targets, such as Passive House standard or near ZEB, aim for optimal solutions at all available intervention categories: ESMs, HVAC systems and RES. Table 1 shows that the majority of projects employing environmental objective functions claim that they meet the requirements for all involved stakeholders (Wang et al. 2015; Assiego De Larriva et al. 2014).

Assiego De Larriva et al. (2014) compared insulation and ventilation strategies to achieve Global Warming Potential (GWP) reduction for the retrofit of a high-rise residential building in South Spain. Ventilation strategies are proved to have a lower GWP and thus are preferred. They generalised results saying that for buildings located in temperate climates, the design that enables better ventilation leads to less GHG emissions.

Wang et al. (2015) investigated the trade-off between PEn savings and EEn for the retrofit interventions of three different building types in Sweden. The options considered are ESMs addressing the thermal insulation and air-tightness of the envelope, efficient ventilation and the introduction of a low temperature heating system with connection to a District Heating (DH) network when available. Results vary, depending on the building type. For the SFH and the low-rise MFH, the most effective retrofit strategy is the combination of small-scale retrofit of the building envelope, such as air-tightness improvement and window replacement, with a low-temperature heating system. For the high-rise MFH, additional envelope retrofit options should be implemented. The installation of a heat recovery system leads to PEn savings and embodied GHG emission levels.

Dodoo et al. (2010) estimated the LCPEn consumption of a wood-frame apartment building in south Sweden, after being refurbished to Passive House standard. A number of ESMs, the installation of efficient water taps and mechanical ventilation systems with heat recovery were investigated under three different end-use heating systems, which are resistance heating, HP and DH. As expected, the heating system that shows the biggest PEn usage decrease is resistance heating, because of its low energy efficiency. The installation of ventilation systems with heat recovery, followed by the replacement of windows, the use of efficient hot water taps and the insulation of external walls lead to higher energy savings. It was also found that the EEn of materials has increased 17% when the building is retrofitted to Passive House standard. However, the operational phase is still responsible for the largest PEn consumption share.

3.3. Environmental and Financial Objective Functions

The identified trends of the studies that uses multi-criteria assessment methods to evaluate retrofit alternatives are the combination of the LCC objective function with OEn, PEn and LCEIs. The driving force behind these trends is the EPBD Recast methodology, considering the determination of the cost-optimal solutions for a near zero energy or zero carbon emissions building retrofit.

3.3.1. Life Cycle Cost and Operational Energy

Four out of five studies reviewed that choose to minimise LCC and OEn are employed by researchers who look the building retrofit problem from the owners' perspective. This can be justified by the fact that energy bills are among the highest household expenses and energy savings can be used as an incentive for homeowners in order to initiate retrofitting their houses.

Amstalden et al. (2007) considered envelope insulation and window replacement as potential energy efficiency improvement strategies for a SFH in Switzerland. They argued that the wall and roof insulation are the better strategies, since both floor insulation and window replacement have negative NPV. Hasan et al. (2008), also investigated a SFH in Finland, considering passive energy efficiency strategies and mechanical ventilation. Their findings agree with that of Amstalden et al. (2007) on the insulation of walls and floor and the replacement of windows, but not with the insulation of the roof. Mechanical ventilation systems with heat recovery were also found to be cost-effective. Brown et al. (2013) compared three alternative packages for two different house types in Sweden, including passive measures, mechanical ventilation and additional system controls. They concluded that the balanced mechanical ventilation with heat recovery and the addition of thermostat settings to radiators, followed by high-efficiency window replacement, are the optimal retrofit interventions.

Different owner types, the 'aesthetic homeowner', the 'well-kept homeowner' and the 'do it yourself homeowner', were defined by Risholt et al. (2013) in order to indirectly introduce social criteria. Adding TC as the third objective function, Penna et al. (2015) provided three optimal retrofit solutions for each residential building type studied in two different climate zones in Italy. They mentioned the importance of window type selection and the installation of a mechanical ventilation system to improve TC. They also pointed out that the overuse of conventional ESMs, such as the addition of extended insulation of the building envelope, is responsible of summer overheating.

3.3.2. Life Cycle Cost and Primary Energy

The objective functions set of LCC and PEn are not correlated with any specific stakeholder's perspectives. From the owners' perspective, Kuusk and Kalamees (2015) in Estonia, targeting a net-Zero Energy Building (net ZEB) and exploring both ESMs and the installation of RES, found that the indoor climate requirements can be fulfilled using thermostats and mechanical exhaust ventilation system without heat recovery. The major energy saving requirement is fulfilled with additional envelope insulation, window replacement and the installation of a two-pipe radiator heating system to replace the existing one-pipe system. Moving to the energy efficiency requirements for new buildings, additional ventilation units with heat recovery is the optimal retrofit intervention. A near ZEB is achieved with the installation of additional solar thermal collectors, while a net ZEB with additional PV panels.

In Portugal, Ferreira et al. (2014) looked for the cost-optimal retrofit strategies to achieve a near ZEB MFH. They found that the cost-optimal option is the combination of low thickness envelope Expanded Polystyrene (EPS) insulation for the external walls and low thickness Extruded Polystyrene insulation for the roof and floor, with a high-efficiency gas boiler for heating and Domestic Hot Water (DHW). A net ZEB target is achieved with the addition of PV panels. They also pointed out that the introduction of high-level envelope performance requirements in the national building code can lead to retrofit strategies that deviate from the cost-optimal options. Retrofit interventions should improve the performance of all envelope elements, while ensuring thermal comfort levels and cost-optimality. In addition, renewable energy technologies play a critical role when a net-zero level is required.

From the public promoter's perspective, the investigations that uses LCC and PEn as assessment objective functions, take also TC into consideration, either as a constraint (Hamdy et al. 2013) or as a third objective function (Lizana et al. 2016). Hamdy et al. (2013), explored the near ZEB retrofit options for a SFH in Finland. A large number of variables were considered in a matrix, which eliminates mutually exclusive interventions. The included variables are ESMs, such as envelope insulation, air-tightness, window replacement and heat recovery options, heating, cooling and DHW technologies, as well as RES, such as solar thermal and PV systems. The LCC-PEn consumption chart shows that clusters are formed based on the heating and cooling technologies used. The highest cost-operating system requires high-level ESMs interventions and vice versa. It was noted that investing in heating systems is more viable than high cost ESMs investment. The optimal cost-efficient heating system is the Ground Source Heat Pump (GSHP) and can be combined with RES, which does not improve the financial performance of the GSHP strategy, but leads to near ZEB building performance. In addition, retrofit strategies that do not consider cooling systems are more preferable than those that do consider; the latter can improve the energy performance of the building and the financial feasibility of the strategy when RES are installed. Both solar thermal and PV panel systems are selected, but PVs are more economically viable than solar thermal.

Lizana et al. (2016), from the public promoter's perspective, applied the weighted multi-criteria assessment method, employing a large number of assessment criteria. Among them LCC, PEn consumption and TC were highly weighted. The considered retrofit strategies are ESMs, HVAC systems and RES. The cost-optimal and energy-efficient retrofit strategy is the combination of the placement of retractable awnings, window replacement with aluminium frames and low emissivity (low-e) double glazing, external wall and roof insulation and the application of solar thermal collectors to cover energy for DHW.

Ballarini et al. (2017), using IEE-TABULA project's (Anon n.d.) building typology, developed a multi-criteria assessment method for the evaluation of retrofit strategies, applicable to all building types of the Italian residential building stock. The strategies include envelope insulation, window replacement, heat generator replacement, thermal solar system installation and their combinations. Heating system replacement is the most cost-effective intervention, especially for warm climates (less than 1400 heating degree days), due to low initial cost and short payback period. The retrofit package that combines envelope insulation, window replacement and heating system replacement is the most cost-effective and cost-optimal for medium and large size buildings that have been constructed before 1975. The initial cost is high but the payback period does not exceed 19 years.

3.3.3. Life Cycle Environmental Impacts and Life Cycle Cost

Life Cycle studies often combine LCEIs with LCC assessment criteria under a multi-criteria decision making process, in order to look both at the environmental and financial point of view. Once more, there is no obvious correlation of this objective functions set with any stakeholder's perspective. De Angelis et al. (2013) and Cetiner and Edis (2014) both studied envelope insulation alternatives, in terms of materials and thickness, for the optimal retrofit of high-rise MFH in Italy and Turkey, respectively. An interesting study of Pombo et al. (2016) investigated several retrofit scenarios of a high-rise residential building in Spain, from the 'business as usual' to Passive House standard, using ESMs. Environmental indicators were interpreted to monetary values to estimate the cost of the damage to the environment and humans. The best practice among the ESMs suggests high thickness roof (24 cm) and wall insulation (16 cm), or a slightly thinner insulation and the addition of a second PVC frame, low-e, double glazing window. The Passive House standard scenario was rejected as it involves high initial costs.

Antipova et al. (2014) evaluated a number of retrofit strategies for a residential building in central Portugal, under two objective functions: the LCC and the LCEIs, based on the LCA method. The major finding of the study is the high correlation among the different environmental impacts employed and their inversely proportional relation with the LCC objective function. Verbeeck and Hens (2005) assess a large variety of all intervention categories (ESMs, HVAC systems and RES), under the same objective functions, LCEIs and LCC, using typical Belgium detached and terraced houses as case studies. Their findings prioritise ESMs, with the insulation of the roof to be the most effective measure. Better performing glazing is also suggested, but the wall insulation is too expensive to be among the optimum strategies. In terms of LCEIs, gas boilers are preferred over electrical heating systems. It is also worth noting that RES are not part of the optimal solution set for any of the reference buildings.

Ostermeyer et al. (2013) introduced the concept of Life Cycle Sustainability Assessment, using LCC, LCEIs and social acceptance criteria. However, the last criteria was limited in identifying the driving retrofit technologies and taking into account their implementation consequences on residents. A multi-storey residential building in France was used as a case study and a number of ESMs, HVAC systems and RES were considered as potential retrofit interventions. A high thermal resistance envelope insulation, triple glazing windows and mechanical ventilation was proposed under the high-score LCEIs scenario. Whereas, lower thermal resistance insulation, double glazing window replacement and natural ventilation under the LCC-LCEIs balanced scenario. A high-efficient condensing boiler is the optimal choice of heating system for both scenarios.

3.3.4. Investment Cost and Primary Energy/Operational Emissions

From the private investor's perspective, Lizana et al. (2016) studied the same retrofit strategies under PEn consumption and IC. They found that the optimal strategy is the installation of an air-source HP for heating, cooling and DHW, that compliments the substitution of existing windows with aluminium framed, low-e double glazing windows.

Adding TC as a third assessment objective function, Ascione et al. (2015) and Huws and Jankovic (2014) made retrofit proposals in order to achieve a low energy consumption and a Zero Carbon Building level, respectively. Their case study in Italy, assessed selected budget based retrofit scenarios, that consist of EMSs and heating and cooling systems. The optimum strategy combines low-thickness EPS wall insulation with high thermal resistance rockwool roof insulation, a mechanical exhaust ventilation system without heat recovery, the replacement of the existing boiler with a condensing one and the replacement of air-cooled chiller with a higher coefficient of performance water-cooled one.

In the United Kingdom, Huws and Jankovic (2014) assessed numerous variables of all three retrofit intervention categories, under the same criteria. According to them, a high-level external wall insulation stabilises the internal temperature and increases TC. Triple glazing windows provide the minimum GHG emissions, while quadruple glazing windows provide the maximum TC conditions.

4 Results and Discussion

When financial objective functions are considered, the improvement of the envelope thermal properties is not a cost-effective retrofit strategy, especially for buildings located in temperate climates, because the energy demand reduction is not enough to pay off the initial cost. On the other hand, low initial cost interventions, such as frame sealing, retractable awnings and the installation of sensors are among the global optimal solutions.

When environmental objective functions optimisation is the desired outcome, the envelope insulation and air-tightness and the replacement of existing windows with more efficient ones are among the optimal strategies, especially for cold climates. The embodied energy of these components increases, however, the life time operational energy reduces more which makes the net energy saving. Natural ventilation saves cooling energy in temperate climates while heat recovery saves heating energy in cold climates. Having low embodied energy, natural and mechanical ventilation are considered among the optimal retrofit solutions. The installation of high-efficiency heating systems, such as HPs, are also appropriate.

The majority of investigations that consider LCC and LCEIs objective functions introduce balanced solutions, combining medium thermal resistance insulation for the retrofitted envelope parts with efficient heating systems. It should be noted that RES are not part of the optimal retrofit strategies, despite the fact that they are necessary in order to achieve a low energy/carbon target.

Similar balanced strategies are proposed by investigations that employ LCC and OEn or PEn objective functions, prioritising efficient HVAC systems over high cost ESMs. The combination of medium envelope insulation levels with efficient HVAC systems form the optimal solution. Among them, mechanical exhaust ventilation system with and without heat recovery and window replacement are the selected strategies. In general, heating systems are more cost-effective than high-cost ESMs. RES are introduced for near and net ZEB retrofit targets but without improving the LCC objective function.

Considering TC as the third objective function, there is not a clear consensus in the literature over the role of the level of envelope insulation. Case studies located in temperate climate zones (Penna et al. 2015; Ascione et al. 2015) argue that lower level of insulation, combined with mechanical exhaust ventilation system, increase thermal comfort, however, case studies located in colder climates (Hamdy et al. 2011; Huws & Jankovic 2014) call for higher thermal insulation levels of the envelope and higher R-value windows. Finally, at those studies, shading systems are also considered as ESMs and selected among the optimal retrofit strategies.

5 Conclusions

This paper presents a literature review related to retrofit investigations on residential buildings, located in European countries. It is to address the issue of high contribution of the residential building stock to the GHG emissions. The aim is to identify the sets of objective functions employed in various projects, associate them with the adopted stakeholder's perspective and compare the resulted retrofit strategies.

It is acknowledged that the residential building retrofit process is a complex multifactorial task and the selection of the optimal strategies does not solely depend on the objective functions employed but on a large number of parameters, such as the climate conditions, the building type and the target or the constraint settings.

A strong correlation was observed among owners, as research stakeholders, and the objective functions set of LCC and OEn. Owners, being the retrofit investors, also employ purely financial objective functions to assess the financial viability of the venture.

The major finding is that, when ESMs are assessed under financial objective functions they are not among the cost-effective options. Under both financial and environmental objective functions, energy efficient heating systems are preferred from costly ESMs. Investigations employing the LCC objective function do not favour RES. Finally, natural and mechanical ventilation, heat recovery and smart control systems are among the optimal strategies under all various sets of objective functions discussed.

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Appendix B – Conference Paper #2

Comparison of Multi-objective Optimisation Tools for Building Performance Simulation with TRNSYS 18

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Abstract

Recent progress in computer science has led to applications of simulation-based optimisation methods for building design. This application-focused paper compares two generic optimisation tools: Multi-Objective Building Performance Optimisation (MOBO) and Design Analysis Kit for Optimisation and Terascale Applications (DAKOTA). The workflow and coupling of each tool with TRNSYS 18 software are presented.

Results show that computing times were comparable, and both tools display similar optimal solutions. MOBO, specifically developed for building performance optimisation, is a user-friendly software, whereas DAKOTA requires a steep learning curve for non-programmers. Conversely, DAKOTA provides flexibility in interfacing the simulation software and defining the optimisation settings.

Introduction

Buildings are responsible for a significant portion of anthropogenic greenhouse gas emissions. The design of low-carbon energy efficient buildings is complex, as many parameters affect their energy performance. Multi-objective optimisation is a decision-making method for selecting an appropriate set of design variables. In case of building design, a 'simulation-based optimisation' method is employed, because the optimisation routine calls the building simulation software to be executed. The computation process is most of the times automated, as a result of the iterative nature. The following sections of the introduction give an overview of the optimisation algorithms and tools being used in the building performance optimisation (BPO) process.

Optimisation algorithms and their performance

In general, BPO is the process of minimising/maximising objective function/s, by identifying a set of variables, under a number of constraints. Depending on the number of objective functions (single-objective or multi-objective optimisation), there is one global optimal solution or a set of non-dominated optimal solutions, called Pareto optimal (Pareto, 1896). A solution is non-dominated when there is no other solution that improves one objective function without deteriorating another one.

A BPO problem may have both continuous and discrete variables. Therefore, the objective function/s can be discontinuous (Banos et al., 2010). Discontinuities may also be attributed by the optimisation software, which applies iterative solution algorithms (Wetter & Wright, 2004). This behaviour poses a restriction to the selected optimisation algorithms to those that can handle discontinuities, such as derivative-free algorithms.

Another important characteristic of most BPO methods is that optimisation algorithms treat a simulation software as a 'black-box'. In that case, problem-depended optimisation methods, such as heuristic and gradient-based algorithms, that require information on the problem, cannot be implemented. If there is an analytical expression of the objective function, it can be solved numerically. For building energy performance simulations, this is the case when functions can be mathematically described.

Non-linear problems or optimisation software containing iterative solution algorithms can cause discontinuities in the objective functions. The evaluation of the objective function/s with the use of a building performance simulation program is a non-linear problem and requires the use of derivative-free algorithms (Machairas, Tsangrassoulis, & Axarli, 2014). Algorithms sensitive to those discontinuities or to multi-modal function, such as gradient-based algorithms and direct search algorithms, might fail on the convergence to the optimal solution (Wetter & Wright, 2003).

Evolutionary optimisation algorithms are the most popular among BPO. Being meta-heuristic, thus problem independent, they treat the optimisation problem as a 'black-box'. In order to identify the optimum solution/s, they generate a set of random numbers for the optimisation variables and use the principle of natural selection to evolve. However, their convergence to a global optimum or a set of optimal solutions cannot be guaranteed, especially for a small number of iterations. Genetic algorithms (GA) are very effective when used for non-linear, discontinuous problems with many local minima, however, they cannot ensure that the optimal solution/s will be found.

Optimisation software tools

The optimisation tools that have been applied for BPO can be classified in two major categories: dedicated optimisation tools for building design and generic optimisation packages. They can be further sub-classified based on their capability to deal with single-objective or multi-objective optimisation problems, to handle discrete and continuous variables and constraint functions and to allow parallel computing. This section provides a brief description of the commonly used tools, their capabilities and limitations. An extended literature review on optimisation tools used for BPO may be found in (Attia et al. 2013).

Some of the dedicated optimisation tools for building design are: Opt-E-Plus, GENE_ARCH, BEopt, MultiOpt2 and jEPlus+EA. Opt-E-Plus was developed by NREL (Ellis, Griffith, Long, Torcellini, & Crawley, 2006) for EnergyPlus building simulation software and it is a freeware. It is not designed for multi-objective optimisations and it is oriented towards the United States context. GENE_ARCH (Caldas, 2006) is also a freeware and able to handle multi-objective optimisations. It was developed to couple DOE-2.1 building simulation engine. BEopt was also developed by NREL (Christensen et al., 2005) to be coupled both with DOE-2.2 and TRNSYS (Solar Energy Laboratory, 2017) 'Type 56'. It was developed to explore design options for the envelope and the heating, ventilation, and air conditioning (HVAC) systems and calculate the energy savings. Once more, the software is tailored to the United States context. MultiOpt2 (Chantrelle, Lahmidi, Keilholz, Mankibi, & Michel, 2011) is a commercial multi-objective optimisation tool developed for TRNSYS. It uses the NSGA-II and has built-in financial and environmental databases. The combined software jEPlus+EA (Zhang, 2017) can be coupled with EnergyPlus , TRNSYS and DOE-2. It should be noted that for jEPlus+EA all variables are considered to be discrete during optimisation.

On the other hand, generic optimisation packages are more flexible but, most of the times, they require advanced programming skills. Some of the most commonly used software tools with user interface are GenOpt, DAKOTA, modeFRONTIER, and MOBO. Matlab, R and Python programming languages have optimisation toolboxes which can call the objective function routine. GenOpt is one of the most popular packages as it has been used for a large number of BPO investigations (Attia et al., 2013). It is a freeware, single-objective optimisation software that can be coupled with any simulation software that enables text-based input and output files. DAKOTA is also a freeware and its optimisation algorithms can handle both single-objective and multi-objective optimisation problems. Despite having a user's interface, programming knowledge is required. The modeFRONTIER (ESTECO, 2017) is a commercial product with a large number of capabilities, regarding multi-objective optimisation, sensitivity analysis and parallel computing. MOBO (Palonen, Hamdy, & Hasan, 2013) is probably one of the most user's friendly software for BPO problems as it is a freeware which has a graphical user interface (GUI). It can handle continuous and discrete variables, as well as derived functions. The user can define up to four function types, including objective functions, equality and inequality constraint functions. Up to two input files and two output files can also be defined. It allows multi-objective optimisation and has an integrated library of the most commonly used algorithms, such as NSGA-II, aNSGA-II, OMNI-optimiser, J-H, the hybrid coupling of GA and J-H, along with random search and brute force processes.

The programming languages Matlab (MathWorks, 2017), R (Venables & Smith, 1990) and Python (The Python Software Foundation, 2018) also provide optimisation capabilities via toolboxes or libraries, however, their use requires advanced programming knowledge. Matlab environment, a commercial platform, has been widely used in BPO investigations because of its flexibility in interfacing the simulation software and the extended capabilities to handle both single and multi-objective optimisation problems, discrete and continuous variables and parallel computing, while providing a variety of optimisation algorithms. Python language has been used for the automation of building energy simulation workflows by Miller et al. (2012) and for the design optimisation of the building envelope by Echenagucia et al. (2015). R language, despite the fact that it has packages for optimisation and sensitivity analysis, has not been implemented, to the best of the authors' knowledge, for BPO problems.

This application-focused investigation aims to compare two currently available generic optimisation tools: MOBO and DAKOTA. They were selected for the following reasons: they are freeware, they can handle multi-objective optimisation problems, they have a sufficient number of optimisation algorithms and are available for the variants of three operating systems: Windows, Linux and Mac OS.

Method

In this investigation a multi-residential building, located in Southern Europe, has been used as a case study. The annual electricity required for heating and cooling of the building for defined set points has been modelled in TRNSYS 18. Retrofit alternatives of the building envelope have been studied as for their performance in improving the annual electricity consumption for heating and cooling and minimising the net present value of life-cycle cost (NPV-LCC) of the retrofit.

The multi-objective genetic algorithm (MOGA) and the Non-dominated-and-crowding sorting genetic algorithm II (NSGA-II) (Deb et al. 2002) have been selected for this investigation. The reason is the limited number of GAs available in each software. The general workflow involves defining the objective functions and constraints, selecting an optimisation algorithm, executing pre-process parametric simulations, running simulations, executing post-process simulations, storing simulation parameters and evaluating results. While MOBO has the built-in capability to handle the whole process, DAKOTA is responsible only for the pre- and post-process for the optimisation routine. For simulations to be executed, a subroutine must be called. For the purpose of this investigation, a subroutine script has been created using the Python programming language to interface TRNSYS 18 with DAKOTA. Python has been selected as it is a high-level, interpreted and dynamically typed scripting language. In addition, Python has object-oriented programming capabilities which are used for the location and extraction of the simulation output files.

The specific workflow and coupling of each tool with TRNSYS 18 is presented in the following sections and illustrated in Figure 1 and Figure 2. The computing time, the results obtained and the user friendliness level of each tool were compared.

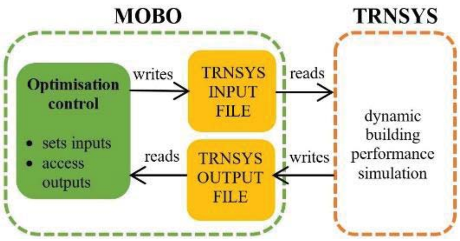

Figure 1: MOBO optimisation workflow

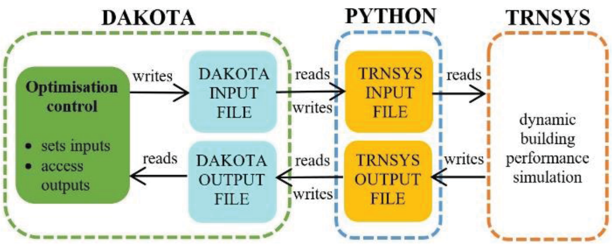

Figure 2: DAKOTA optimisation workflow

The case study

A building was selected out of the 'Intelligent Energy Europe' programme 'Typology Approach for Building Stock Energy Assessment' (IEE-TABULA) (TABULA, 2017), which is an EU funded programme for the development of a common database of the residential building stock typologies in 20 European countries. It is a multi-family house (MFHs) constructed prior to 1980 (the early 1960's), and is located in the Greek climate zone B. The building is shown in Figure 3. It should be noted that in 1980 the 'Hellenic Building Thermal Insulation Regulation' was introduced for the first time in Greece.

Figure 3: Baseline building: (a) street view and (b) simulation model

The selected building is a 6-storey multi-residential building with a basement, located in Athens, Greece. It has 27 apartments. The model geometry was created using SketchUp Make 2015 and TRNSYS3d plug-in. The file was saved as an '*.idf' format file and imported in TRNBuild 3.0, which creates '*.b18' file for TRNSYS 18 'Type 56'.

The building was modelled as 14 zones, 7 of them are conditioned and 7 non-conditioned communal areas. The information about building envelope, construction types, materials, properties and areas of the floor and the external surfaces was extracted from IEE-TABULA project data set (TABULA, 2017). IEE-TABULA project also provides information on the infiltration rate and the thermal bridge energy gains/losses of the building envelope. The minimum required ventilation rate, as well as the heat gains from people, lighting and equipment for residential buildings are provided by national technical instructions on the calculation of the energy performance of buildings (Technical Chamber of Greece, 2010).

The heating system operates in two modes. The daytime heating set-point temperature is 20 ^{o}C (Technical Chamber of Greece, 2010). The set-back temperature for nighttime and non-operation hours is 18 ^{o}C. Heating season begins on the 28th of October and finishes on the 15th of April in Athens. The set-point temperature for cooling is 26 ^{o}C (Technical Chamber of Greece, 2010). There is no set-back temperature for cooling as cooling system does not operate during non-occupied hours of the house. However, for simulation in TRNSYS 18, a set-back temperature of 50 ^{o}C has been used. This value was selected because the ambient air temperature in Athens never reaches 50 ^{o}C. Cooling season begins on the 1st of May and finishes on the 30th of September in Athens. A typical weekday and weekend schedule of the heating and cooling system operating hours are presented in Figure 4 and Figure 5, along with the selected set-point temperatures.

For building performance simulations, the weather data file used is a TMY2 format, created by using Meteonorm software. The data for Athens Observatory (WMO station ID 167140) located at latitude 37.97^{o} N & longitude 23.72^{o} E and 107 m above sea level was utilised. The selected time stamp for TMY2 weather file is solar time.

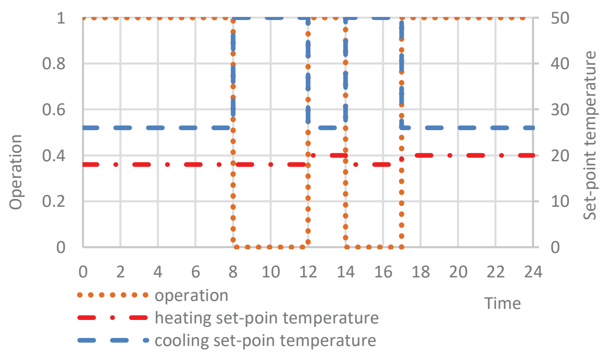

Figure 4: Weekday schedule: heating and cooling system operating hours (left) and set-point temperatures (right)

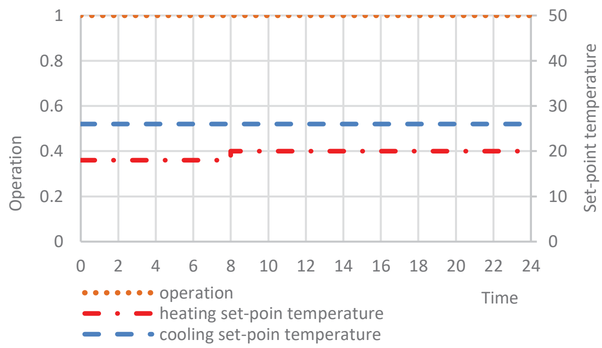

Figure 5: Weekend schedule: heating and cooling system operating hours (left) and set-point temperatures (right)

Objective functions and retrofit strategies

Two objective functions to be minimised were selected: the NPV-LCC of the retrofit and the annual electricity consumption for heating and cooling. The project life for the analysis was assumed to be 30 years. The functional unit is the square meter (m^2) of the floor area. The calculations of the objective functions were carried out using TRNSYS 18 equation tool. The NPV-LCC is given in Equation (1). The discount rate assumed for this investigation is the bank loan interest rate (5.01%) for energy retrofit projects in Greece (National Bank of Greece, 2017). The rate of increase for electricity price is 4.47%, estimated based on bi-annual data of electricity prices for household consumers (Eurostat, 2017).

$$NPV\text{-}LCC = IC + EC\sum_{j=1}^{N}\frac{(1+i)^{j-1}}{(1+d)^{j}} \quad (1)$$

Reverse circuit split air-conditioning (heat pump) units which enable both heating and cooling were assumed. The heat pump units are driven by electric motors. The characteristics of mini-split heat pump (Mitsubishi model FE12NA) has been used (NREL, 2011). The correlations between system coefficient of performance for heating and cooling (COP_H) (COP_C) and the temperature difference were developed by using the manufacturer's reported data and are provided in Equation (2) and (3). The annual electricity consumption for heating and cooling of the building (E) is calculated by Equation (4) (Aye, 2014).

$$COP_H = 0.0955(T_{OUT} - T_{IN}) + 5.1497 \quad (2)$$

$$COP_C = -0.0925(T_{OUT} - T_{IN}) + 4.5623 \quad (3)$$

$$E = \frac{Q_H}{COP_H} + \frac{Q_C}{COP_C} \quad (4)$$

A number of energy saving measures were considered as retrofit strategies. They are the additional external wall insulation thickness, above basement floor and external floor insulation thickness, external roof insulation thickness and window replacement types. The Expanded Polystyrene (EPS) panels were selected as the additional insulation material, due to their low thermal conductivity and low environmental impact (Densley Tingley, Hathway, & Davison, 2015). Because of their mechanical (compressive strength) and physical (moisture resistance) properties, (see Table 1), they can be used for the insulation of all external and internal building surfaces. Three parameters considered for the window replacement alternatives are: the thermal transmittance (U-value) of frame, U-value of glazing, and the solar heat gain co-efficient (SHGC) of glazing. All four variables are discrete and the values considered are listed in Table 2 and Table 3. The insulation thicknesses of the building envelope have a lower bound constraint, which is the maximum allowable heat transfer coefficient required by the current Greek building code (Technical Chamber of Greece, 2010). The calculation of the minimum thickness takes also into account the thermal transmittance properties of the existing construction types of the baseline building envelope, as provided by (TABULA, 2017).

Table 1: Properties of the EPS insulation material

Property	Value
Thermal conductivity (W $m^{-1}K^{-1}$)	0.036
Specific heat capacity (kJ kg^{-1} K^{-1})	1.5
Density (kg m^{-3})	15
Panel size (mm)	1000x600
Available panel thickness by 10 mm step (mm)	30-160

Table 2: Energy saving measures design variables and values for the insulations of the envelope

External wall insulation thickness (mm)	Roof insulation thickness (mm)	Floor above basement and external floor insulation thickness (mm)
1) 0 2) 50 3) 60 4) 70 5) 80 6) 90	1) 0 2) 70 3) 80 4) 90 5) 100 6) 110	1) 0 2) 50 3) 60 4) 70 5) 80 6) 90

Table 3: Window replacement design variables and values

Type description	Frame property	Glazing properties
1) no replacement	-	-
2) uPVC frame, argon filled double glazing (4x15x5mm)	U-value: 1.3 (W $m^{-2}K^{-1}$)	U-value: 1.1 (W $m^{-2}K^{-1}$) SHGC: 0.44
3) uPVC frame, lowE argon filled triple glazing (4LowEx15x5x15x5mm)	U-value: 0.9 (W $m^{-2}K^{-1}$)	U-value: 0.6 (W $m^{-2}K^{-1}$), SHGC: 0.44

Optimisation process

The optimisations were conducted by using MOBO and DAKOTA generic optimisation packages. Results were compared with those obtained by using the brute force process in MOBO.

Algorithm availability

As mentioned before, due to the nature of BPO problem, meta-heuristic algorithms, and more specifically GAs, have been used in order to identify the set of optimal solutions. Both MOBO and DAKOTA have a number of available algorithms that can potentially be applied. As for the GAs, MOBO has NSGA-II and aNSGA-II, while DAKOTA has single-objective genetic algorithm (SOGA) and MOGA.

Through MOBO's user interface there are four parameters that can be defined for NSGA-II: the population size, the number of generations, the mutation and crossover probability. A larger variety of algorithm options is provided by DAKOTA, such as fitness and replacement type, population size and initialisation type, crossover and mutation types, as well as termination conditions (maximum number of iterations, maximum number of function evaluations). Those options can be set either through the GUI or by changing DAKOTA's input file, using a text editor.

For the purpose of this investigation, common settings have been used for both MOBO and DAKOTA optimisations, as shown in Table 4. The population size and the number of generations were selected after some alternatives were assessed as for their result differences. Mutation and cross-over probability values have been selected based on the available literature and the suggestions of Eiben and Smith (2015).

Table 4: Optimisation settings

Variables	4
Representation	648
Population size	12
Generations	22
Mutation probability	0.2
Crossover probability	0.9

Graphical user interface

Each optimisation software tool has a GUI for setting up the problem specific optimisation parameters. MOBO enables the setting of all variables, functions, algorithm and their parameters via the GUI. Both continuous and discrete variables, as well as derived variables can be defined. Functions include the optimisation functions as well as the equality or inequality constraints.

DAKOTA GUI can also be used to define the computing environment settings, such as the output files, the variables type and value set, the objective functions to be optimised and the optimisation algorithm to be used. Constraints are being set under the method specifics. Listing 1 shows the part of the DAKOTA input file where algorithm parameters are defined.

Listing 1: DAKOTA input file – method

```
method
moga
    max_function_evaluations 264
    population_size 12
    initialization_type unique_random
    print_each_pop
```

DAKOTA also requires the interface type. This investigation uses 'the fork' interface to call an external program (TRNSYS 18) which calculates the values of the two objective functions for the input set of variables provided. Despite the fact that DAKOTA offers the option of creating a ready-made subroutine file which is called 'analysis driver', using Python scripting language, it requires extensive modifications. The subroutine script can also be created from scratch, using any programming language, such as C, C++, Java, Basic and Python.

Input/output files and simulation program call

The source input file that TRNSYS 18 uses is in American Standard Code for Information Interchange (ASCII) text. The input file needs to be parametrised with the use of delimiters, both for MOBO and DAKOTA. The user has to define those delimiters manually at the template input file, replacing the existing value with a text string. In case of MOBO, the name of the variable is surrounded by '%' character, as shown in Listing 2. MOBO automatically creates the new input file, replacing delimiters with the selected variable values. The number of input files is limited to two, which is sufficient for TRNSYS 18 Type 56 simulations. The simulation uses a pair of '*.dck' and '*.b18' files. MOBO cannot handle optimisations which require three or more input files.

*Listing 2: TRNSYS 18 *.d18 input file parametrisation*

```
CONSTRUCTION EXT_WALL_nonBEARING
 LAYERS   = Mortar Brick EPS80 Mortar
 THICKNESS= 0.02   0.09  0.09  %w%   0.02
 ABS-FRONT= 0.48  : ABS-BACK= 0.48
 EPS-FRONT= 0.9   : EPS-BACK= 0.9
 HFRONT   = 27.72 : HBACK= 90
```

The subroutine reads the values that the optimisation algorithm's pre-process has assigned to the variables, from the created file named 'params.in' (see Listing 3).

Listing 3: DAKOTA parameters file

```
                     4 variables
                     3 window
  1.100000000000000e-01 floor
  1.100000000000000e-01 roof
  9.000000000000000e-02 wall
                     2 functions
```

The equivalent DAKOTA delimiter used in the template input files is the variable name string, within curly brackets. In practice, any symbol can be used, as it is user-defined through the script. Listing 4 presents the delimiter replacing process and the creation of the new input files. Script variable 'vars' is a Python list that contains the values of the optimisation variables given by DAKOTA's 'params.in' file. DAKOTA does not limit on the number of input files however, the operating system does.

Calling TRNSYS 18 is similar for both optimisation software. In case of MOBO GUI, under the simulation tab, there is an input text box where the user can insert the command that runs the simulation program. In case of DAKOTA, the command has to be provided in the subroutine script, in a way that python can read it. For this investigation, the 'os.system()' library function was used.

Listing 4: Subroutine – delimiter replacement

```
# Create new input file 1
with open('templatedir\\mf-building.dck',
'r') as f1:
    text=f1.read()
text=text.replace('{w}', vars[0])
text=text.replace('{r}', vars[1])
text=text.replace('{f}', vars[2])
text=text.replace('{wd}', vars[3])

with open('workdir\\mf-building.dck', 'w')
as f2:
    f2.write(text)
```

The process of reading TRNSYS 18 output files, in order to get the calculated objective functions' value, is similar to the one used for the input files. In the case of MOBO, the delimiter is the string before the value of the objective function to be optimised, separated by space.

DAKOTA can deal with the output files in many ways. In this investigation, each output text file was copied to the Python dictionary. Once more, the string before the requested value was used as a delimiter. The value was copied to a temporary Python variable and then saved in a new file, traditionally named 'results.out'. The contents of the 'results.out' file are shown in Listing 5. The output file is a text file that can be read by the optimisation algorithm's post-process. MOBO can read up to two output files, whereas the maximum number of files for DAKOTA is only limited by the operating system.

Listing 5: Contents of DAKOTA simulation results file

```
+3.372044E+04 energy
+2.159625E+04 cost
```

Parallel simulation

Modern computer processors can divide the computing in multiple threads, which can run in parallel. The selected algorithms support multithreading. In MOBO, the user needs to create sub-folders inside the temporary folder as many as the number of available logical processors of the computer. DAKOTA enables users to select single thread or multi threads. All files are located inside the project's directory and subdirectories. The user has to modify the 'analysis driver' subroutine in order to locate each asynchronous evaluation's input and output files.

Results and discussion

Results obtained by MOBO and DAKOTA for the case study were compared with that of the brute force process. MOBO with NSGA-II, executed 264 iterations for objective functions evaluation, 11 of them formed the Pareto front. DAKOTA with MOGA, conducted 264 iterations, 12 of them formed the Pareto front. Brute force process executed 648 iterations, as many as the number of the available combinations of variables. The Pareto front consists of 12 non-dominated optimal solutions. Brute force, NSGA-II and MOGA results are shown in Figure 6, Figure 7 and Figure 8 respectively.

Both NSGA-II and MOGA, using the same settings, came close to the set of optimal solutions, executing less than half of the total number of iterations required by brute force process. In terms of calculation time, MOBO required 70 minutes to execute the optimisation process, while DAKOTA 67 minutes, which are the equivalent 35% and 33.5% of the time that brute force process required to be executed.

Optimisation results indicate that the electricity consumption for heating and cooling can be reduced from 34.36 kWh m^{-2} a^{-1} to 13.97 kWh m^{-2} a^{-1}, depending on the available retrofit budget. A number of selected Pareto front solutions is presented in Table 5.

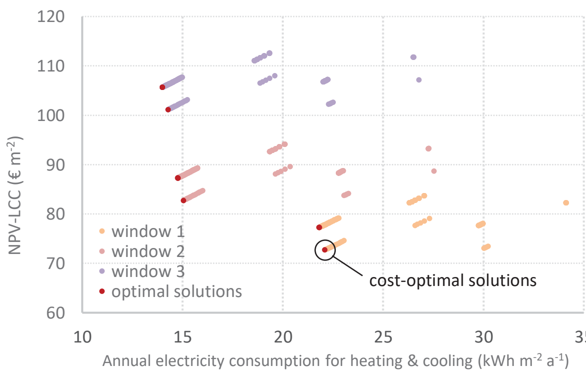

Figure 6: Brute force process results

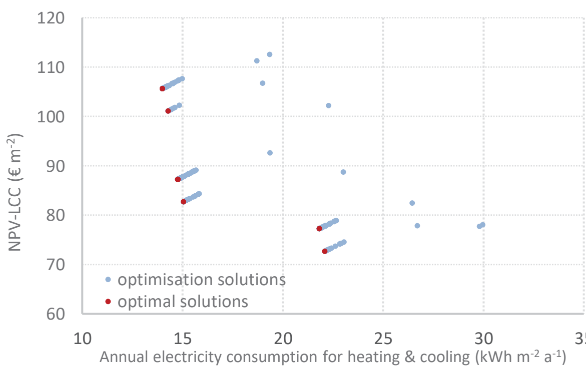

Figure 7: MOBO results, using NSGA-II

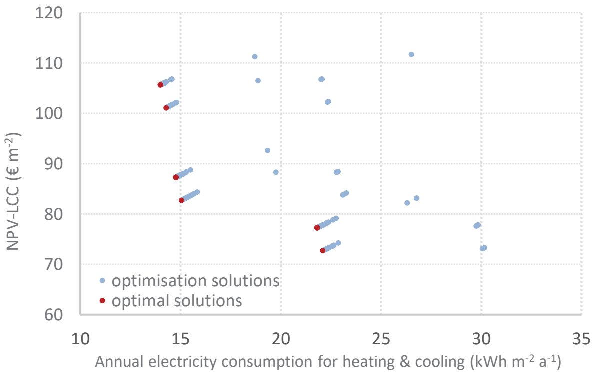

Figure 8: DAKOTA results, using MOGA

Further analysis shows that additional wall insulation retrofit has the higher reduction in annual electricity consumption, because the external walls' area is larger than that of roof and floor. The highest values of wall and roof insulation thicknesses have been selected as optimal solutions. A variety of floor over basement and external floor insulation thicknesses are part of the Pareto optimal solutions, including the non-insulation option. The same applies to window replacement options as all three window types are among the optimal solutions. However, window replacement Type 2 resulted in a higher ratio of annual electricity consumption to NPV-LCC, compared to Type 3.

Table 5: Optimisation settings

Solution	S1	S2	S3
Wall insulation thickness (mm)	90	90	90
Roof insulation thickness (mm)	110	110	110
Floor above basement and external floor insulation thickness (mm)	0	70	90
Window replacement type	1	2	3
Annual electricity consumption for heating and cooling (kWh m^{-2} a^{-1})	22.07	14.74	13.97
Retrofit cost (€ m^{-2})	72.72	87.30	105.70

Conclusions

The aim of this study is to compare two public domain software optimisation tools: MOBO and DAKOTA, in terms of computing time and user friendliness, for a BPO application. The selected objective functions to be minimised are the annual electricity consumption for heating and cooling of the building and the NPV-LCC of the retrofit. The annual electricity consumption for space heating and cooling was simulated using TRNSYS 18.

It was found that, the computing times are comparable, and both optimisation tools displayed similar Pareto front solutions. MOBO, specifically developed for building performance optimisation, is a user-friendly software that does not require programming skills. The most significant limitation of MOBO is the maximum number of input and output files to be handled for the simulations.

In comparison, DAKOTA, despite the fact that has a GUI, requires programming knowledge and a steep learning curve for non-programmers. Advanced programming knowledge on scripting language is required. Having been developed for research purposes, it lacks user-friendliness. Conversely, it provides flexibility in interfacing the simulation software and defining the optimisation settings.

Nomenclature

COP_C	coefficient of performance-cooling (-)
COP_H	coefficient of performance-heating (-)
d	real discount rate (-)
E	annual electricity consumption for heating and cooling (kWh a^{-1})
EC	annual energy cost for heating and cooling (€)
i	annual rate of increase for electricity price (-)
IC	initial cost (€)
j	year counter
N	project life for NPV-LCC analysis (a)
NPV-LCC	net present value of life-cycle cost (€)
Q_C	annual cooling load (kWh a^{-1})
Q_H	annual heating load (kWh a^{-1})
T_{IN}	supplied air temperature to the room (°C)
T_{OUT}	outdoor ambient air temperature (°C)

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Appendix C – Building audit

C.1 Building audit form

Building address: *5 Charalampi Sotiriou, Athens, 11472 Athens*

Audit date: *June 25th, 2019*

Building manager name: *Ms Lina Tsiara*

General Information

1.	What is the construction year of the building?	
	1961	
2.	How many apartments does the building have?	
	Dew to apartment being merged, the number of apartments has been changed	
3.	How many are the residents of the building?	
	Not Known	
4.	How many shops does the building have?	
	Two shops, not connected to the central heating system	
5.	Has the building been renovated since the construction year? If yes, what type of renovation (for example: external insulation, window replacement, boiler replacement) has been made and when (year)?	
	Year	Intervention type
	1966	*Boiler change from crude oil boiler to diesel oil boiler*
	2012	*Boiler change from diesel oil boiler to natural gas boiler*
	Not Known	*Few apartments have replaced the old single-grazed windows with double-glazed.*
	Not Known	*Few apartments have replaced the old cast iron (AKAN type) radiators with new (panel type)*

Heating System

1.	Is there a central heating system at the building?
	Yes
	If yes, what is the type of the central heating system?
	Hydronic system (non-condensing natural gas boiler)
	If yes, what is the system capacity?
	Boiler capacity: 200 kW, Burner capacity range: 160 – 340 kW
	If yes, where is the system located?
	At the basement level, inside the boiler room
2.	If there is a central heating system, what is the fuel used?
	Natural gas
	Is there a fuel central storage?
	No
	If yes, what is the storage capacity?
	Not Applicable

3.	If there is a central heating system, what is the distribution system type of the central heating system?
	Double-pipe distribution system and radiators
	Is the distribution system insulated?
	No
	Have you installed any type of heating autonomy?
	No
	If yes, what is the type of heating autonomy in place (flow meters, calorific meters etc)?
	Not Applicable
4.	If there is a central heating system, are the retail shops on the ground floor connected to it?
	No
5.	If there is a central heating system, are you operating it?
	Yes
	If yes, what is the operating schedule?
	Approximately from 12 pm – 3 pm and from 6 pm – 10 pm every day (from end of October till mid. April). The schedule is manually adjusted by the building manager.
6.	Is the building connected to the natural gas network?
	Yes
7.	If the building is connected to the natural gas network, are there apartments that they have autonomous heating systems?
	No
	If yes, how many apartments have autonomous heating systems?
	Not Applicable
	What type of system do they use (for example: wall-mounted condensing gas boilers with 'umbrella' type hydronic distribution system with radiators)?
	Not Applicable

Cooling System

1.	Is there any central cooling system at the building?
	No
	If yes, what type of central cooling system? What is the system capacity?
	Not Applicable
	If yes, where is the system located?
	Not Applicable
2.	Is there any autonomous cooling system installed and used at the apartments?
	Yes
	If yes, what is the cooling system type?
	Mini-split reverse circuit heat pumps
	What is the system average/approximate capacity?
	Not Known
	What is the energy used by the cooling system (for example: electricity)?
	Electricity

Hot Water System

1.	Is there a central hot water system at the building?
	No
	If yes, what is the system type?
	Not Applicable
	If yes, what is the system capacity?
	Not Applicable
	If yes, where is it located?
	Not Applicable
	If yes, is it connected with the central heating system?
	Not Applicable
2.	Are the apartments using autonomous hot water systems?
	Yes
	If yes, what is the system type (for example: electric water heater)?
	Electric water heater
	If yes, what is the energy source of the system (for example: electricity, natural gas)?
	Electricity
	If yes, what is the typical capacity of the water heating?
	Not Known
	If yes, what is the typical water storage tank used per apartment?
	Either 100L or 200L
	If yes, where is the storage tank located?
	In the bathroom
3.	Does any apartment have a solar water heating system installed?
	No
	Is yes, what is the type of the system (example: solar thermosyphon)?
	Not Applicable
	How many apartments have solar water heating systems?
	Not Applicable

Lighting

1.	What is the type of lamps used in the common areas of the building?
	There is a variety of lamp types
	What are the characteristics of a typical lamp (lumens/W)?
	Not Known
2.	Are there any controllers or sensors used by the lighting system of the building's common areas?
	Timer

Energy Consumption

1.	Annual energy consumption of the building or building areas (for example: common areas)				
	Year	2017-2018			
	Area				
	Electricity		Natural Gas	Other	Other
Month	kWh		kWh	kWh	kWh
January	*1,438*		*22,000*		
February			*14,000*		
March			*10,000*		
April			*2,500*		
May	*1,059*		*0*		
June			*0*		
July			*0*		
August			*0*		
September	*1,344*		*0*		
October			*0*		
November			*7,000*		
December			*17,000*		
Total	*3,841*		*73,000*		

Typical apartment

1.	List of apartment equipment.	
	Apartment floor	*4th floor*
	Number of residents	*2*
	Apartment area	*Approx. 80 m^2 after merging with nearby apartment*
Equipment		
Stove and oven		*Yes*
Fridge		*Yes*
Clothes washing machine		*Yes*
Dishwashing machine		*Yes*
Water heater		*Yes*
TV		*Yes*
Computer		*Yes*
Kettler		*Yes*
Toaster		*Yes*
Lights		*Yes*
Air-conditioner		*Yes*
Other		

The Building Inspector,

Maria Panagiotidou,

PhD Candidate,

Department of Infrastructure Engineering,

The University of Melbourne, Australia

C.2 Building pictures

Figure C.1. Natural gas boiler and main pipes of the distribution system (top left), burner plate (top right), circulation pump (bottom left) and hydronic distribution system (bottom right).

Figure C.2. External unit of mini-split heat pump (left) and rooftop staircase exit (right).

Appendix D – Distribution losses of the central heating system

D.1 Distribution losses of the central hydronic heating system

The case study building, located in Greek climate zone B, was modelled, using TRNSYS Type 56, as presented in Chapter 3. A high supply temperature of 80 °C was assumed, in order the maximum losses to be calculated. TRNSYS Type 700 was employed to simulate the boiler performance. The boiler was sized to the 80% of the peak load. The supply water temperature and water flow rate were assumed to be fixed; only the return water temperature varied, depending on the heating load. A cut-down load of 5% was also applied to the heating load of each zone. The water flow rate (kg h^{-1}) of each zone was calculated for a temperature difference of 15 ℃, based on Equation D.1:

$$\dot{m} = \frac{\dot{Q}_{heat}}{C_p \Delta T} \qquad \text{Eq. D.1}$$

Where $\dot{Q}_{heat}$ is the space heating load of the conditioned zone (kJ h^{-1}), C_p is the specific heat capacity of water (kJ kg^{-1} K^{-1}) and ΔT is the temperature difference between water supply and return temperature (K).

The circulation pipes of the central hydronic heating system are made of cast iron and are located inside the building, passing through both conditioned and non-conditioned building zones. The thermal conductivity of cast iron is 55 Wm^{-1} K^{-1}. For calculation purposes, all pipes located in the basement (non-conditioned zone) were assumed to be insulated with a 13 mm thickness elastomeric rubber insulation. The thermal conductivity of elastomeric rubber insulation is 0.045 W m^{-1} K^{-1}. Seven vertical pipes were assumed, serving two radiators at each level. The building has 6 conditioned zones (residential use); thus, the total number of radiators is 84.

The pipe size and pressure were calculated based on the Technical Chamber of Greece (2010c) guide. The pipe properties are presented in Table D.1. Pipes were sized to maintain a water flow velocity of less than 0.5 m s^{-1}. The main hot water pipes leaving the boiler and returning to the boiler were assumed to be 2 ½” and 1.5 m long. Leaving the main pipe, the hot water circulates inside smaller distribution pipes of 1”, which are located horizontally under the basement ceiling, each one at a distance of 5 m apart. The pipes turn vertical, climbing five floors of 3.1 m height each. The total height of each vertical pipe is 15.5 m. The maximum total pipe length is 25 m. For calculation purposes, an average of 12.5 m horizontal pipe length was assumed. The diameter of the vertical pipes was assumed to be 1" for the first level, 1 ¾" for the next 2 levels and ½" for the last level.

Table D.1: Properties of the cast iron hot water pipes (Technical Chamber of Greece 2010c).

Pipe size (DN)	Pipe size (inches)	External diameter (mm)	Thickness (mm)
DN 15	½	21.3	2.65
DN 20	¾	26.9	2.65
DN 25	1	33.7	3.25
DN 32	1 ¼	42.4	3.25
DN 40	1 ½	48.3	3.25
DN 50	2	60.3	3.65
DN 65	2 ½	76.1	3.65

Heat losses of the vertical pipes that pass by conditioned zones were not considered. The pipe heat loss rates were calculated based on Equation D.2:

$$\dot{Q} = \frac{2\pi L \Delta T}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_p} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_i}} \qquad \text{Eq. D.2}$$

Where L the pipe length (m), ΔT is the temperature difference of the fluid and the environment (℃), r_1 is the internal radius of the pipe (m), r_2 is the external radius of the pipe (m), r_3 is the radius of the insulation (m), k_p is the thermal conductivity of the pipe (W m^{-1} K^{-1}) and k_i is the thermal conductivity of the insulation (m).

Figure D.1 shows the correlation of the pipe heat losses and the heating load. The ratio of the annual heating losses of the pipes to the annual heating load is 5.5%. Results are in agreement with the minimum distribution system efficiency of 96% required by the regulations (Technical Chamber of Greece 2010c).

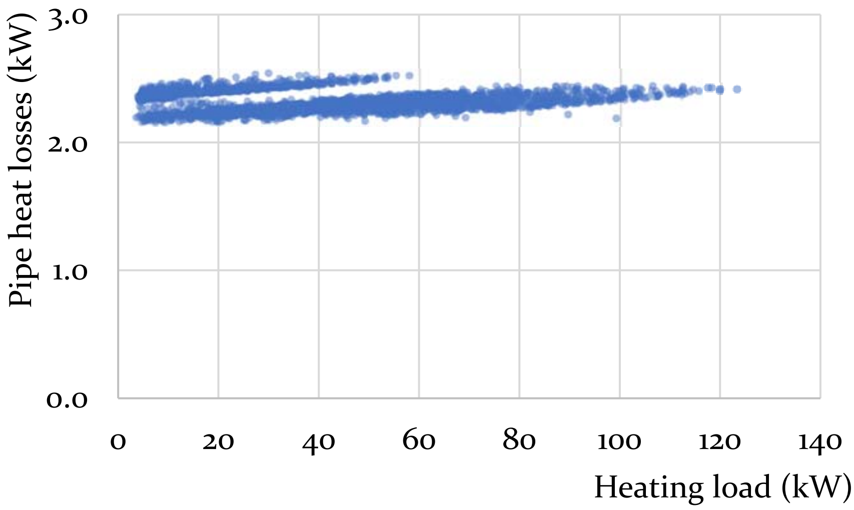

Figure D.1: Correlation chart of heating load and pipe heat losses.

D.2 Energy consumption of the circulation pump

The total pressure friction loss of the pipes was calculated based on the framework provided by the Technical Chamber of Greece (2010c). To calculate friction losses inside the pipes, the longer loop was considered, starting from the boiler and ending back to the boiler. Table D.2 shows the pressure drop and the velocity of the water inside the pipes. An additional 30% of the friction losses of the linear part was considered for the friction losses of pipe joints. The pressure-drop of the boiler ranges from 150 mm to 500 mm of head. The higher value was considered for the present calculation. Finally, the total amount was increased by 50% for safety reasons. The total friction pressure losses of the pipes were calculated equal to 2,760 mm of head.

Table D.2: Pressure drop and water velocity of cast iron hot water pipes (Technical Chamber of Greece 2010c).

Pipe size (inches)	Water flow rate (kg h^{-1})	Pressure drop (mm of head)	Velocity (m s^{-1})
½	163	9	0.26
½	302	27	0.48
¾	416	11.5	0.39
¾	530	18	0.48
1	662	8	0.38
1	760	10.1	0.43
2 ½	7,600	2.6	0.47

The installed circulation pump is a Wilo TOP S model. For calculation purposes, Wilo TOP S 40/1-4 was modelled, based on the properties of Figure D.2 (Wilo 2019). The power of the pump varies based on the water flow rate. The correlation is given in Figure D.3. The calculated annual energy consumption of the circulation pump is 2,934 kWh and the ratio of the annual energy consumption of the circulation pump to the annual heating load is just over 2%.

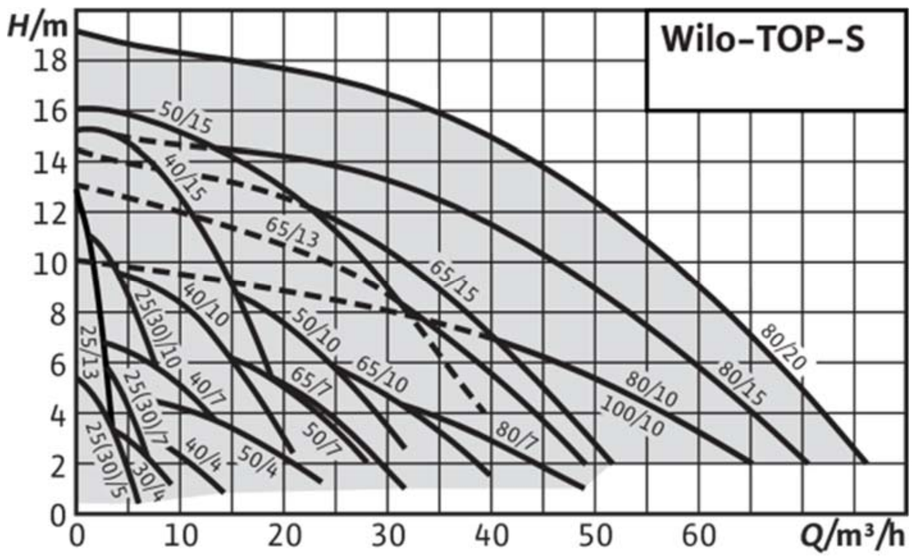

Figure D.2: Wilo TOP S series circulation model map (Wilo 2019).

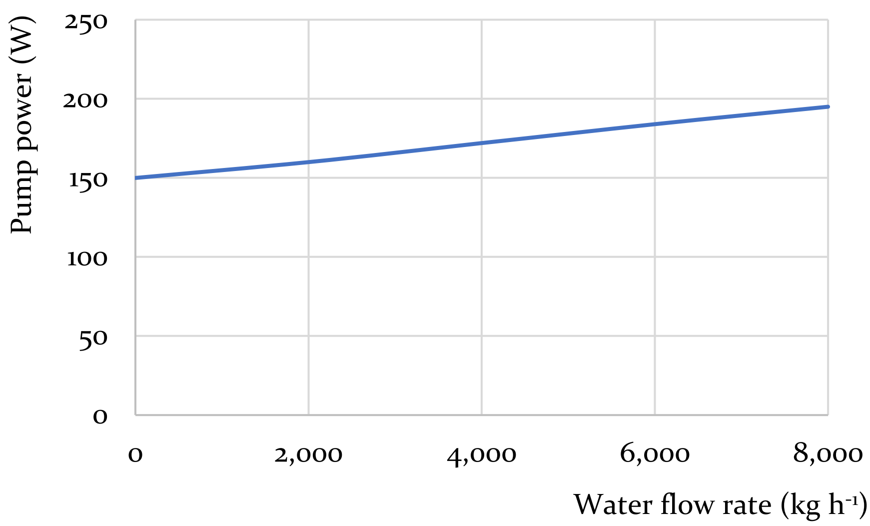

Figure D.3: Wilo TOP S 40/1-4 power graph (Wilo 2019).

D.3 References

Technical Chamber of Greece 2010a, ‘Greek Regulation for the Energy Efficiency of Buildings - T.O.T.E.E. 20701-1/2010 - Guidelines on the evaluation of the energy performance of buildings’,.

Technical Chamber of Greece 2010b, ‘Energy Performance of Buildings Directive - Technical Guidelines - T.O.T.E.E. 20701-4/2010 - Guidelines on the energy audit procedure and the energy performance certificate’,.

Technical Chamber of Greece 2010c, ‘Greek Regulation for the Energy Efficiency of Buildings- T.O.T.E.E. 20701-3/2010 - Guidelines on the Greek climatic data’,.

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Appendix E – Developed TRNSYS Types

E.1 Type 254: General boiler with a performance map

Type 254 models a general boiler, based on the heating load and the performance map. The rated heating capacity and electrical power are provided to the model as inputs. The Type calculates the return fluid temperature and the part-load ratio (PLR) which is used to retrieve the part-load factor (PLF). The fuel can be diesel oil, natural gas or biomass. The boiler can be either a conventional or a condensing boiler. The capacity control can be on/off or modulating. Figure E.1 illustrates the flowchart of the developed TRNSYS Type 254.

E.1.1 Parameter/Input/Output Reference

Parameters

1	Logical unit for boiler type	[-]	The logical unit assigned to the data file which contains the boiler performance data.
2	Number of dry-bulb temperatures	[-]	The number of outdoor ambient dry-bulb temperatures for which data is provided in the boiler performance data file.
3	Number of loads	[-]	The number of heating load for which data is provided in the boiler performance data file.
4	Rated capacity	[kJ hr^{-1}]	The rated heating capacity of the boiler.
5	Rated electrical power	[kJ hr^{-1}]	The rated electrical power of the boiler.
6	Fluid supply temperature	[°C]	The supply temperature of the fluid.
7	Mass flow rate	[kg hr^{-1}]	The mass flow rate of the fluid.
8	Specific heat capacity of fluid	[kJ kg^{-1} K^{-1}]	The specific heat capacity of the fluid.

Inputs

1	Heating load	[kJ hr^{-1}]	The heating load.

Outputs

1	Heating power	[kJ hr^{-1}]	The heat rate supplied by the boiler.
2	Heating efficiency	[-]	The operating heating efficiency of the boiler.
3	Fuel input rate	[kJ hr^{-1}]	The rate at which fuel is being consumed by the boiler to heat the fluid.
4	Electrical input rate	[kJ hr^{-1}]	The rate at which electricity is being consumed by the boiler to operate.

E.1.2 Nomenclature

Cp_{fluid}	[kJ kg^{-1} K^{-1}]	specific heat of the liquid stream
$\dot{Q}_{need}$	[kJ hr^{-1}]	heating load
$\dot{Q}_{fluid}$	[kJ hr^{-1}]	operating device capacity
$\dot{Q}_{fuel}$	[kJ hr^{-1}]	fuel energy consumption rate
$\dot{Q}_{RC}$	[kJ hr^{-1}]	rated device heating capacity
$\dot{P}_{RC}$	[kJ hr^{-1}]	rated device electrical consumption
$\dot{P}_{in}$	[kJ hr^{-1}]	device electrical input rate
PER	[-]	the device part electricity ratio.
$\dot{m}_{fluid}$	[kg hr^{-1}]	mass flow rate of liquid flowing through the boiler
T_s	[C]	supply fluid temperature
T_r	[C]	return fluid temperature
PLR	[-]	the device part-load ratio
η	[-]	operating device efficiency

E.1.3 Mathematical Description

If the load ($\dot{Q}_{need}$) is greater than the rated device capacity, then the operating device capacity ($\dot{Q}_{fluid}$) is set to rated device capacity ($\dot{Q}_{DC}$). The supply temperature is set equal to the setpoint temperature defined by the user and the return fluid temperature is calculated according to:

$$T_r = T_s - \frac{\dot{Q}_{fluid}}{\dot{m}_{fluid} Cp_{fluid}} \quad \text{Eq. E.1}$$

The part-load ratio is calculated according to:

$$PLR = \frac{\dot{Q}_{fluid}}{\dot{Q}_{RC}} \quad \text{Eq. E.2}$$

If the heating load is greater than zero, the model calls the TRNSYS data interpolation routine to determine the boiler's operating efficiency and electricity consumption ratio as a function of return fluid temperature and PLR. Performance data is read from the user-specified boiler performance file.

The Type calculates the boiler fuel energy and electrical energy input, according to:

$$\dot{Q}_{fuel} = \frac{\dot{Q}_{fluid}}{\eta} \quad \text{Eq E.3}$$

$$\dot{P}_{in} = \dot{P}_{RC} PER \qquad \text{Eq. E.4}$$

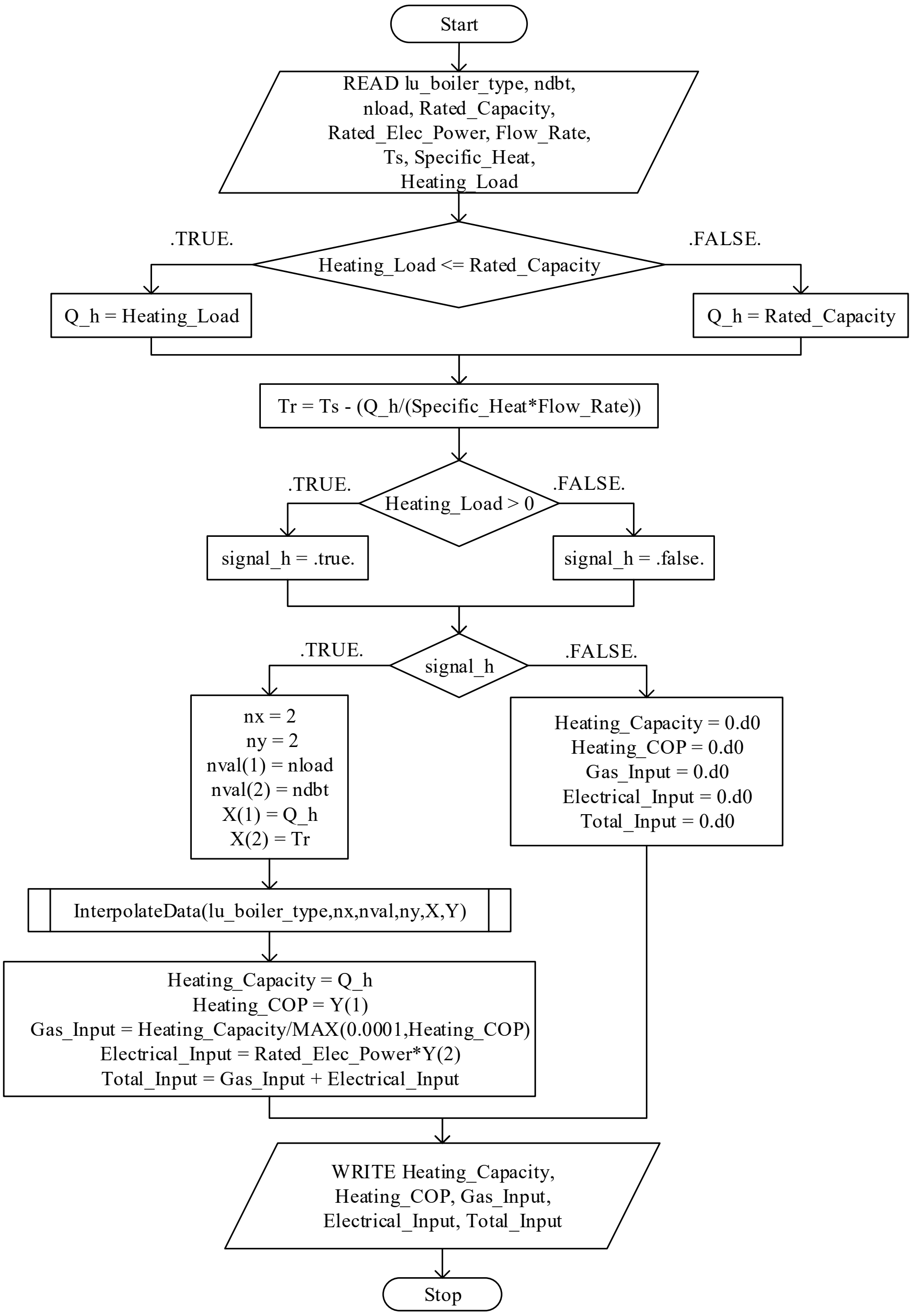

Figure E.1 Flowchart of TRNSYS Type 254 for the performance simulation of biomass, diesel oil and natural gas boilers.

E.2 Type 253: Gas absorption heat pump with normalised performance map

This Type has been developed to model one or more gas absorption heat pump(s) (GAHP) for space heating. In case one unit is selected it can operate in modulating capacity control. If more than one units are connected in parallel, they operate in on/off capacity control. The type reads the heating load, the rated device capacity, the rated gas utilisation efficiency (GUE), the number of units, the ambient dry-bulb temperature and the declared capacity at the dry-bulb temperature to calculate the gas and electrical energy input rate, based on the normalised performance map. Figure E.2 illustrates the flowchart of the developed TRNSYS Type 253.

E.2.1 Parameter/Input/Output Reference

Parameters

1	Logical unit for on/off capacity control	[-]	The logical unit assigned to the data file which contains the GAHP with on/off capacity control performance data.
2	Logical unit for modulating capacity control	[-]	The logical unit assigned to the data file which contains the GAHP with modulating capacity control performance data.
3	Number of dry-bulb temperatures for on/off capacity control	[-]	The number of outdoor ambient dry-bulb temperatures for which data is provided in the GAHP with on/off capacity control performance data file.
4	Number of dry-bulb temperatures for modulating capacity control	[-]	The number of outdoor ambient dry-bulb temperatures for which data is provided in the GAHP with modulating capacity control performance data file.
5	Number of loads for on/off capacity control	[-]	The number of heating load for which data is provided in the GAHP with on/off capacity control performance data file.
6	Number of load for modulating capacity control	[-]	The number of heating load for which data is provided in the GAHP with modulating capacity control performance data file.
7	Rated capacity	[kJ hr^{-1}]	The rated heating capacity of the GAHP unit.
8	Rated GUE	[-]	The rated GUE of the GAHP.
9	Rated electrical power	[kJ hr^{-1}]	The rated electrical power of the GAHP.
10	Number of units	[-]	The number of units connected in parallel. The number of units can be from 1 to 5.

Inputs

1	Heating load	[kJ hr^{-1}]	The heating load.
2	Ambient dry-bulb temperature	[℃]	The ambient dry-bulb temperature.
3	Declared capacity at ambient dry-bulb temperature	[℃]	The declared heating capacity of the GAHP unit at the dry-bulb temperature.

Outputs

1	Heating power	[kJ hr^{-1}]	The heat rate supplied by the GAHP system.
2	Heating GUE	[-]	The operating GUE of the GAHP system.
3	Gas input rate	[kJ hr^{-1}]	The rate at which gas is being consumed by the GAHP to heat the fluid.
4	Electrical input rate	[kJ hr^{-1}]	The rate at which electricity is being consumed by the GAHP to operate.

E.2.2 Nomenclature

$\dot{Q}_{need}$	[kJ hr^{-1}]	heating load
$\dot{Q}_{fluid}$	[kJ hr^{-1}]	operating system capacity at fluid supply temperature
$\dot{Q}_{gas}$	[kJ hr^{-1}]	fuel energy consumption rate
$\dot{Q}_{RC}$	[kJ hr^{-1}]	device rated capacity at fluid supply temperature
$\dot{Q}_{DC}$	[kJ hr^{-1}]	device declared capacity at ambient dry-bulb temperature at the fluid supply temperature
$\dot{P}_{RC}$	[kJ hr^{-1}]	device electrical consumption at rated conditions
$\dot{P}_{in}$	[kJ hr^{-1}]	device electrical input rate
PER	[-]	the device part electricity ratio.
N_{ou}	[-]	number of operating units at each timestep
PLR	[-]	the device part-load ratio
GUE_{RC}	[-]	gas utilisation efficiency
PLF	[-]	part-load factor is the ratio of operating GUE to declared GUE at fluid supply temperature

E.2.3 Mathematical Description

At the first step, the number of operating GAHP units needs to be specified, dividing the heating load to the declared heating capacity of the GAHP unit at each timestep. The integer part of the number is the number of units that operate at full load. An additional unit is operating at part-load conditions. If the load ($\dot{Q}_{need}$) is greater than the declared device capacity multiplied by the number of units, then the operating device capacity ($\dot{Q}_{fluid}$) is set to the declared device capacity ($\dot{Q}_{DC}$) multiplied by the number of units.

The part-load ratio of the units operating in full load is equal to 1. The part-load ratio of the unit operating in part-load conditions is calculated according to:

$$PLR = \frac{\dot{Q}_{fluid} - (N_{ou} - 1)\dot{Q}_{DC}}{\dot{Q}_{RC}} \qquad \text{Eq E.5}$$

If the heating load is greater than zero, the model calls TRNSYS data interpolation routine to determine the GAHP's operating GUE and electricity consumption ratio for every operating unit, as a function of the PLR of each unit and the ambient dry-bulb temperature. Performance data is obtained from the user-specified GAHP performance files.

The Type calculates the GAHP gas energy and electrical energy input for each unit, according to:

$$\dot{Q}_{gas} = \frac{PLR\dot{Q}_{RC}}{PLFGUE_{RC}} \qquad \text{Eq E.6}$$

$$\dot{P}_{in} = \dot{P}_{RC}PER \qquad \text{Eq. E.7}$$

The operating heating capacity, the gas energy input and the electrical energy input of the GAHP system is the sum of all operating units, while the operating GUE of the system is the average GUE of all operating units.

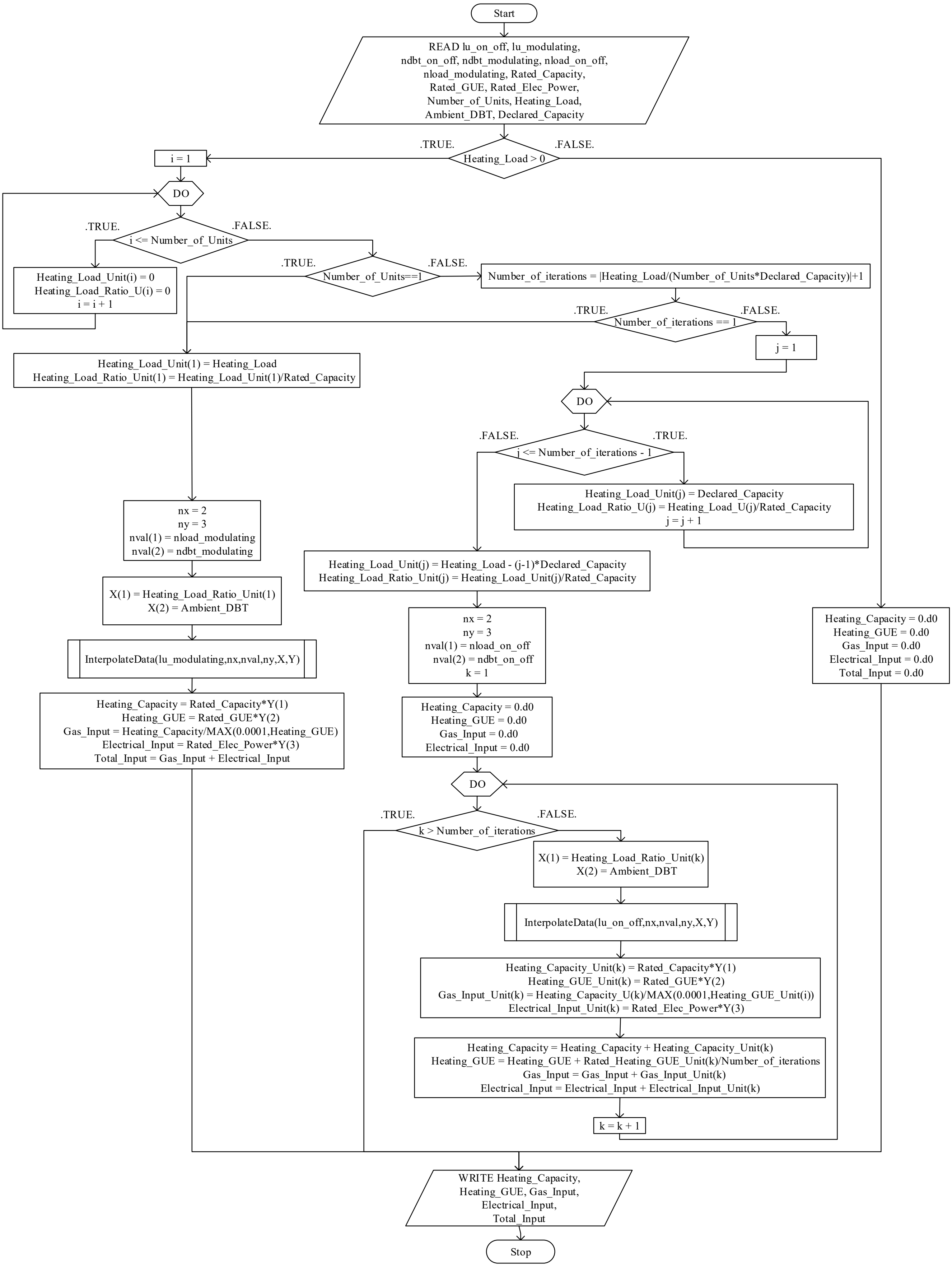

Figure E.2 Flowchart of TRNSYS Type 253 for the performance simulation of a GAHP.

E.3 Type 252: Air-to-air or air-to-water heat pump with a normalised performance map

This Type has been developed to model the performance of air-to-air or air-to-water reverse-circuit heat pump(s) (HP) for one or more conditioned zones. The type reads the heating and cooling load, the declared device heating and cooling capacity and declared heating and cooling COP, the number of conditioned zones and the ambient dry-bulb temperature to calculate the electrical energy input rate, based on the normalised performance maps. Figure E.3 illustrates the flowchart of the developed TRNSYS Type 252.

E.3.1 Parameter/Input/Output Reference

Parameters

1	Logical unit for cooling	[-]	The logical unit assigned to the data file which contains the cooling performance data of the HP.
2	Logical unit for heating	[-]	The logical unit assigned to the data file which contains the heating performance data of the HP.
3	Number of dry-bulb temperatures for cooling	[-]	The number of outdoor ambient dry-bulb temperatures for which data is provided in the cooling performance data of the HP.
4	Number of dry-bulb temperatures for heating	[-]	The number of outdoor ambient dry-bulb temperatures for which data is provided in the heating performance data of the HP.
5	Number of loads for cooling	[-]	The number of heating load for which data is provided in the cooling performance data of the HP.
6	Number of loads for heating	[-]	The number of heating load for which data is provided in the heating performance data of the HP.
7	Number of zones	[-]	The number of conditioned zones.
8	Rated cooling capacity	[kJ hr^{-1}]	For each conditioned zone, the rated cooling capacity of the HP.
9	Rated cooling COP	[-]	For each conditioned zone, the rated cooling COP of the HP.
10	Rated heating capacity	[kJ hr^{-1}]	For each conditioned zone, the rated heating capacity of the HP.
11	Rated heating COP	[-]	For each conditioned zone, the rated heating COP of the HP.

Inputs

1	Ambient dry-bulb temperature	[°C]	The ambient dry-bulb temperature.
2	Cooling load	[kJ hr^{-1}]	For each conditioned zone, the cooling load.
3	Heating load	[kJ hr^{-1}]	For each conditioned zone, the heating load.

Outputs

1	Cooling power	[kJ hr^{-1}]	For each conditioned zone, the heat rate removed by the HP.
2	Heating power	[kJ hr^{-1}]	For each conditioned zone, the heat rate supplied by the HP.
3	Cooling COP	[-]	For each conditioned zone, the operating cooling COP of the HP.
4	Heating COP	[-]	For each conditioned zone, the operating heating COP of the HP.
5	Cooling electrical input rate	[kJ hr^{-1}]	For each conditioned zone, the rate at which electricity is being consumed by the HP for space cooling.
6	Heating electrical input rate	[kJ hr^{-1}]	For each conditioned zone, the rate at which electricity is being consumed by the HP for space cooling.

E.3.2 Nomenclature

$\dot{Q}_{need}$	[kJ hr^{-1}]	cooling or heating load
$\dot{Q}_{fluid}$	[kJ hr^{-1}]	operating system capacity at supply temperature
$\dot{Q}_{el}$	[kJ hr^{-1}]	electrical energy consumption rate
$\dot{Q}_{RC}$	[kJ hr^{-1}]	rated HP capacity at supply temperature
COP_{RC}	[-]	rated HP COP
PLR	[-]	the HP part-load ratio
COP	[-]	coefficient of performance of cooling or heating
PLF	[-]	part-load factor is the ratio of operating COP to declared COP at supply temperature, for cooling or heating

E.3.3 Mathematical Description

For each conditioned zone, if the cooling or heating load ($\dot{Q}_{need}$) is greater than the declared HP cooling or heating capacity, then the operating device capacity ($\dot{Q}_{fluid}$) is set to the declared device capacity ($\dot{Q}_{RC}$). For each conditioned zone, the part-load ratio for heating or cooling is calculated according to:

$$PLR = \frac{\dot{Q}_{fluid}}{\dot{Q}_{RC}} \qquad \text{Eq. E.8}$$

For each conditioned zone, if the cooling or heating load is greater than zero, the model calls the TRNSYS data interpolation routine to determine the HP's operating PLF as a function of the return fluid temperature and PLR. Performance data is read from the user-specified HP performance file for cooling and heating. The Type calculates the HP's electrical energy input, according to:

$$\dot{Q}_{el} = \frac{PLR\dot{Q}_{RC}}{PLFCOP_{RC}} \quad \text{Eq. E.9}$$

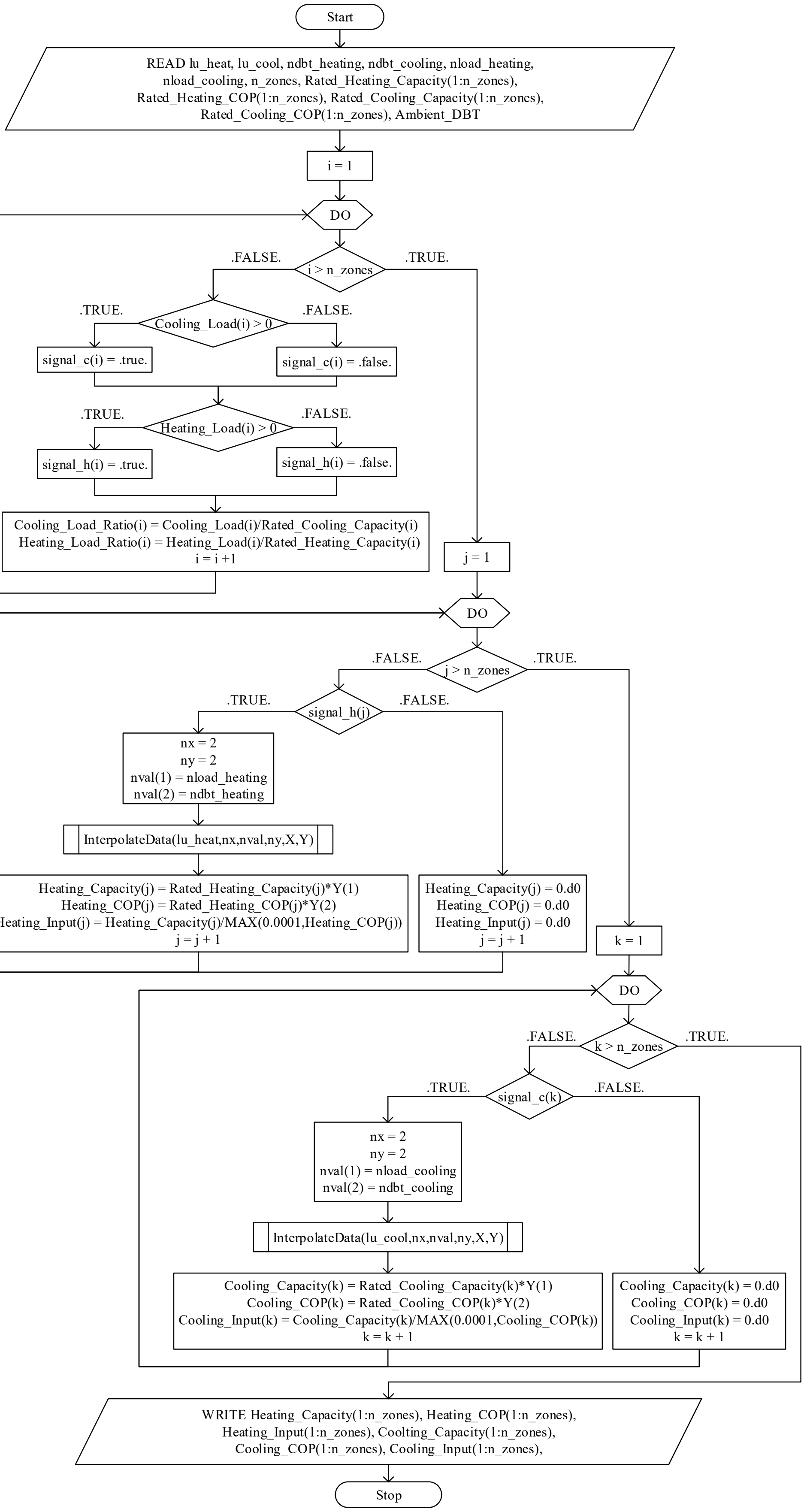

Figure E.3 Flowchart of TRNSYS Type 254 Type for the performance simulation of air-to-air and air-to-water heat pumps.

E.4 Type 255: Fan coil unit with normalised performance map

This Type has been developed to model the performance of fan coil (FC) unit(s), for one or more conditioned zones. The Type reads the cooling and heating load of each FC unit, the rated FC cooling and heating capacity, the rated electrical input rate and the number of conditioned zones to calculate the electrical energy input rate, based on a user-defined normalised performance map. Figure E.4 illustrates the flowchart of the developed TRNSYS Type 255.

E.4.1 Parameter/Input/Output Reference

Parameters

1	Logical unit for FC performance map	[-]	The logical unit assigned to the data file which contains the performance data of the FC unit.
2	Number of part-load ratio	[-]	The number of part-load ratio for which data is provided in the performance data of the FC unit.
3	Number of zones	[-]	The number of the conditioned zones.
4	Rated cooling capacity	[kJ hr^{-1}]	For each conditioned zone, the rated cooling capacity of the FC unit.
5	Rated heating capacity	[kJ hr^{-1}]	For each conditioned zone, the rated heating capacity of the FC unit.
6	Rated electrical power	[kJ hr^{-1}]	For each conditioned zone, the rated electrical input of the FC unit.

Inputs

1	Cooling load	[kJ hr^{-1}]	For each conditioned zone, the cooling load of the FC unit.
2	Heating load	[kJ hr^{-1}]	For each conditioned zone, the heating load of the FC unit.

Outputs

1	Cooling electrical input rate	[kJ hr^{-1}]	For each conditioned zone, the rate at which electricity is being consumed by the FC for space cooling.
2	Heating electrical input rate	[kJ hr^{-1}]	For each conditioned zone, the rate at which electricity is being consumed by the FC for space cooling.

E.4.2 Nomenclature

$\dot{Q}_{need}$	[kJ hr^{-1}]	cooling or heating load of the FC
$\dot{P}$	[kJ hr^{-1}]	electrical energy input rate
$\dot{P}_{RC}$	[kJ hr^{-1}]	rated electrical energy input rate
$\dot{Q}_{RC}$	[kJ hr^{-1}]	rated FC capacity for cooling or heating
PLR	[-]	the FC part-load ratio

E.4.3 Mathematical Description

For each conditioned zone, the part-load ratio of each FC unit for heating or cooling is calculated according to:

$$PLR = \frac{\dot{Q}_{need}}{\dot{Q}_{RC}} \qquad \text{Eq. E.10}$$

For each conditioned zone, if the cooling or heating load of each FC is greater than zero, the model calls the TRNSYS data interpolation routine to determine FC's operating PLF as a function of the PLR. Performance data is read from the user-specified FC performance file. The Type calculates FC's electrical energy input rate, according to:

$$\dot{P} = PLF\dot{P}_{RC} \qquad \text{Eq E.11}$$

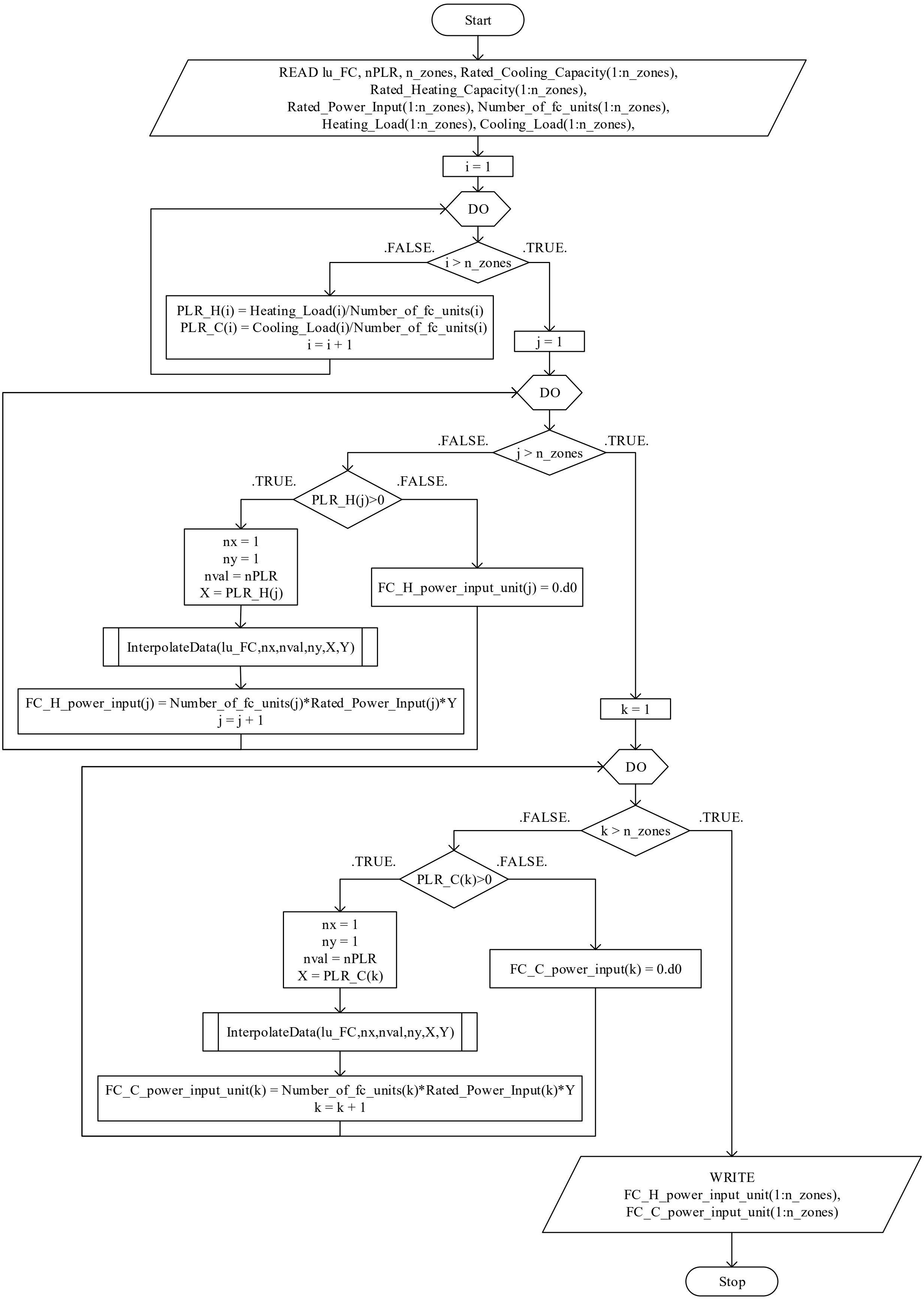

Figure E.4 Flowchart of TRNSYS Type 255 for the performance simulation of the FC units.

Appendix F – Declarations of a thesis with publications

F.1 Declaration for Publication #1

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Declaration for a thesis with publication

PhD and MPhil students may include a primary research publication in their thesis in lieu of a chapter if:

- The student contributed greater than 50% of the content in the publication and is the "primary author", ie. the student was responsible primarily for the planning, execution and preparation of the work for publication
- The student has approval to include the publication in their thesis from their Advisory Committee
- It is a primary publication that reports on original research conducted by the student during their enrolment
- The initial draft of the work was written by the student and any subsequent editing in response to co-authors and editors reviews was performed by the student
- The publication is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in the thesis

Students must submit this form, along with *Co-author authorisation forms* completed by each co-author, when the thesis is submitted to the Thesis Examination System: *https://tes.app.unimelb.edu.au/*. If you are including multiple publications in your thesis you will need to list each publication on this form. Further information on this policy is available at: *gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication*

A. STUDENT'S DECLARATION

I declare that:

- the information below is accurate
- the publication(s) below meets the requirements to be included in the thesis
- The advisory committee has met and agreed to the inclusion of the publication(s) in the student's thesis
- All co-authors of the publication(s) have reviewed the information below and have agreed to its veracity.

Co-Author Authorisation forms for each co-author are attached.

Student's name	Student's signature	Date *(dd/mm/yy)*
Maria Panagiotidou	[signature]	09/09/20

PRINCIPAL SUPERVISOR'S DECLARATION

Supervisor's name	Supervisor's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.09.09 18:41:03 +10'00'	09/09/20

B. PUBLICATION DETAILS *(to be completed by the student)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Alternative heating and cooling systems for the retrofit of medium-rise residential buildings in Greece		
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi		
Student's contribution (%)	75%	Volume/page numbers	Enter Volume/Page numbers here.
Journal or book name	Energy		
Status	☐Accepted and In-press ☐ Published ☒ In progress	Date accepted/ published	Enter Date

F.2 Co-author authorisation for Publication #1

Co-author authorisation form

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gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication

A. PUBLICATION DETAILS *(to be completed by the student)*		
Full title	Alternative heating and cooling systems for the retrofit of medium-rise residential buildings in Greece	
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi	
Student's contribution (%)	75%	
Journal or book name	Energy	
Volume/page numbers		
Status	☐ Accepted and In-press ☐ Published ☒ In progress	Date accepted/published

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Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.09.09 18:38:46 +10'00'	09/09/20

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Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi	
Student's contribution (%)	75%	
Journal or book name	Energy	
Volume/page numbers		
Status	☐ Accepted and In-press ☐ Published ☒ In progress	Date accepted/published

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Dr Behzad Rismanchi	Behzad Rismanchi Digitally signed by Behzad Rismanchi Date: 2020.09.09 14:03:22 +10'00'	09/09/20

F.3 Declaration for Publication #2

Declaration for a thesis with publication

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- It is a primary publication that reports on original research conducted by the student during their enrolment
- The initial draft of the work was written by the student and any subsequent editing in response to co-authors and editors reviews was performed by the student
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Student's name	Student's signature	Date *(dd/mm/yy)*
Maria Panagiotidou	[signature]	15/04/20

PRINCIPAL SUPERVISOR'S DECLARATION

Supervisor's name	Supervisor's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.04.15 14:07:32 +10'00'	15/04/20

B. PUBLICATION DETAILS *(to be completed by the student)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Solar driven water heating systems for medium-rise residential buildings in urban Mediterranean areas		
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi		
Student's contribution (%)	70%	Volume/page numbers	v. 147, p. 559-569
Journal or book name	Renewable Energy		
Status	☐Accepted and In-press ☒ Published ☐ In progress		Date accepted/ published 08/09/19

The University of Melbourne
CRICOS Provider Number: 00116K

Last Updated 6 December 2019

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Full title	Solar driven water heating systems for medium-rise residential buildings in urban Mediterranean areas	
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi	
Student's contribution (%)	70%	
Journal or book name	Renewable Energy	
Volume/page numbers	v. 147, p. 559-569	
Status	☐ Accepted and In-press ☒ Published ☐ In progress	Date accepted/published 08/09/19

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Student's contribution (%)	70%	
Journal or book name	Renewable Energy	
Volume/page numbers	v. 147, p. 559-569	
Status	☐ Accepted and In-press ■ Published ☐ In progress	Date accepted/published 08/09/19

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Dr Behzad Rismanchi	Behzad Rismanchi Digitally signed by Behzad Rismanchi Date: 2020.04.15 17:55:30 +10'00'	15/04/20

F.5 Declaration for Publication #3

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Student's name	Student's signature	Date *(dd/mm/yy)*
Maria Panagiotidou	[signature]	09/09/20

PRINCIPAL SUPERVISOR'S DECLARATION

Supervisor's name	Supervisor's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.09.09 18:49:17 +10'00'	09/09/20

B. PUBLICATION DETAILS *(to be completed by the student)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Energy retrofit optimisation for multi-residential buildings: A 'whole-building' approach		
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi		
Student's contribution (%)	75%	Volume/page numbers	Enter Volume/Page numbers here.
Journal or book name	Applied Energy		
Status	☐Accepted and In-press ☐ Published ☒ In progress	Date accepted/ published 8	

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Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi	
Student's contribution (%)	75%	
Journal or book name	Applied Energy	
Volume/page numbers		
Status	☐ Accepted and In-press ☐ Published ☒ In progress	Date accepted/published

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Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.09.09 18:44:02 +10'00'	09/09/20

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Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi	
Student's contribution (%)	75%	
Journal or book name	Applied Energy	
Volume/page numbers		
Status	☐ Accepted and In-press ☐ Published ■ In progress	Date accepted/published

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Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Dr Behzad Rismanchi	Behzad Rismanchi Digitally signed by Behzad Rismanchi Date: 2020.09.09 14:03:53 +10'00'	09/09/20

F.7 Declaration for Conference Paper #1

THE UNIVERSITY OF MELBOURNE

Declaration for a thesis with publication

PhD and MPhil students may include a primary research publication in their thesis in lieu of a chapter if:

- The student contributed greater than 50% of the content in the publication and is the "primary author", ie. the student was responsible primarily for the planning, execution and preparation of the work for publication
- The student has approval to include the publication in their thesis from their Advisory Committee
- It is a primary publication that reports on original research conducted by the student during their enrolment
- The initial draft of the work was written by the student and any subsequent editing in response to co-authors and editors reviews was performed by the student
- The publication is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in the thesis

Students must submit this form, along with *Co-author authorisation forms* completed by each co-author, when the thesis is submitted to the Thesis Examination System: *https://tes.app.unimelb.edu.au/*. If you are including multiple publications in your thesis you will need to list each publication on this form. Further information on this policy is available at: *gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication*

A. STUDENT'S DECLARATION

I declare that:

- the information below is accurate
- the publication(s) below meets the requirements to be included in the thesis
- The advisory committee has met and agreed to the inclusion of the publication(s) in the student's thesis
- All co-authors of the publication(s) have reviewed the information below and have agreed to its veracity.

Co-Author Authorisation forms for each co-author are attached.

Student's name	Student's signature	Date *(dd/mm/yy)*
Maria Panagiotidou	[signature]	15/04/20

PRINCIPAL SUPERVISOR'S DECLARATION

Supervisor's name	Supervisor's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.04.15 14:10:22 +10'00'	15/04/20

B. PUBLICATION DETAILS *(to be completed by the student)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Low energy building retrofit: A review of objectives and solutions		
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi		
Student's contribution (%)	75%	Volume/page numbers	Enter Volume/Page numbers here.
Journal or book name	ZEMCH 2018 International Conference Proceedings, Melbourne, Australia: 29 January-1 February		
Status	☐Accepted and In-press ☒ Published ☐ In progress		Date accepted/ published 01/02/18

The University of Melbourne
CRICOS Provider Number: 00116K

Last Updated 6 December 2019

F.8 Co-author authorisation for Conference Paper #1

Co-author authorisation form

THE UNIVERSITY OF MELBOURNE

All co-authors must complete this form. By signing below co-authors agree to the listed publication being included in the student's thesis and that the student contributed greater than 50% of the content of the publication and is the "primary author" ie. the student was responsible primarily for the planning, execution and preparation of the work for publication.

In cases where all members of a large consortium are listed as authors of a publication, only those that actively collaborated with the student on material contained within the thesis should complete this form. This form is to be used in conjunction with the *Declaration for a thesis with publication form*.

Students must submit this form, along with the *Declaration for thesis with publication form*, when the thesis is submitted to the Thesis Examination System: *https://tes.app.unimelb.edu.au/*

Further information on this policy and the requirements is available at:
gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication

A. PUBLICATION DETAILS *(to be completed by the student)*		
Full title	Low energy building retrofit: A review of objectives and solutions	
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi	
Student's contribution (%)	75%	
Journal or book name	ZEMCH 2018 International Conference Proceedings, Melbourne, Australia: 29 January-1 February	
Volume/page numbers		
Status	☐ Accepted and In-press ■ Published ☐ In progress	Date accepted/published 01/02/18

B. CO-AUTHOR'S DECLARATION *(to be completed by the collaborator)*

I authorise the inclusion of this publication in the student's thesis and certify that:

- the declaration made by the student on the *Declaration for a thesis with publication form* correctly reflects the extent of the student's contribution to this work;
- the student contributed greater than 50% of the content of the publication and is the "primary author" ie. the student was responsible primarily for the planning, execution and preparation of the work for publication.

Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.04.15 14:21:52 +10'00'	15/04/20

THE UNIVERSITY OF MELBOURNE

Co-author authorisation form

All co-authors must complete this form. By signing below co-authors agree to the listed publication being included in the student's thesis and that the student contributed greater than 50% of the content of the publication and is the "primary author" ie. the student was responsible primarily for the planning, execution and preparation of the work for publication.

In cases where all members of a large consortium are listed as authors of a publication, only those that actively collaborated with the student on material contained within the thesis should complete this form. This form is to be used in conjunction with the *Declaration for a thesis with publication form*.

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A. PUBLICATION DETAILS *(to be completed by the student)*

Full title	Low energy building retrofit: A review of objectives and solutions
Authors	Maria Panagiotidou, Lu Aye, Behzad Rismanchi
Student's contribution (%)	75%
Journal or book name	ZEMCH 2018 International Conference Proceedings, Melbourne, Australia: 29 January-1 February
Volume/page numbers	
Status	☐ Accepted and In-press ■ Published ☐ In progress — Date accepted/published: 01/02/18

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I authorise the inclusion of this publication in the student's thesis and certify that:

- the declaration made by the student on the *Declaration for a thesis with publication form* correctly reflects the extent of the student's contribution to this work;
- the student contributed greater than 50% of the content of the publication and is the "primary author" ie. the student was responsible primarily for the planning, execution and preparation of the work for publication.

Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Dr Behzad Rismanchi	Behzad Rismanchi Digitally signed by Behzad Rismanchi Date: 2020.04.15 17:54:50 +10'00'	15/04/20

F.9 Declaration for Conference Paper #2

Declaration for a thesis with publication

THE UNIVERSITY OF MELBOURNE

PhD and MPhil students may include a primary research publication in their thesis in lieu of a chapter if:

- The student contributed greater than 50% of the content in the publication and is the "primary author", ie. the student was responsible primarily for the planning, execution and preparation of the work for publication
- The student has approval to include the publication in their thesis from their Advisory Committee
- It is a primary publication that reports on original research conducted by the student during their enrolment
- The initial draft of the work was written by the student and any subsequent editing in response to co-authors and editors reviews was performed by the student
- The publication is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in the thesis

Students must submit this form, along with *Co-author authorisation forms* completed by each co-author, when the thesis is submitted to the Thesis Examination System: *https://tes.app.unimelb.edu.au/*. If you are including multiple publications in your thesis you will need to list each publication on this form. Further information on this policy is available at: *gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication*

A. STUDENT'S DECLARATION

I declare that:

- the information below is accurate
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- All co-authors of the publication(s) have reviewed the information below and have agreed to its veracity.

Co-Author Authorisation forms for each co-author are attached.

Student's name	Student's signature	Date *(dd/mm/yy)*
Maria Panagiotidou	[signature]	15/04/20

PRINCIPAL SUPERVISOR'S DECLARATION

Supervisor's name	Supervisor's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye — Digitally signed by Lu Aye Date: 2020.04.15 14:15:27 +10'00'	15/04/20

B. PUBLICATION DETAILS *(to be completed by the student)*

Click on this box and on the "+" button in the bottom right corner to enter multiple publications.

Full title	Comparison of Multi-Objective Optimisation Tools for Building Performance Simulation		
Authors	Maria Panagiotidou, Lu Aye		
Student's contribution (%)	75%	Volume/page numbers	Enter Volume/Page numbers here.
Journal or book name	Proceedings of BSO 2018: 4th Building Simulation and Optimisation Conference, Cambridge, UK: 11-12 September		
Status	☐ Accepted and In-press ☒ Published ☐ In progress		Date accepted/ published 12/09/18

F.10 Co-author authorisation for Conference Paper #2

THE UNIVERSITY OF MELBOURNE

Co-author authorisation form

All co-authors must complete this form. By signing below co-authors agree to the listed publication being included in the student's thesis and that the student contributed greater than 50% of the content of the publication and is the "primary author" ie. the student was responsible primarily for the planning, execution and preparation of the work for publication.

In cases where all members of a large consortium are listed as authors of a publication, only those that actively collaborated with the student on material contained within the thesis should complete this form. This form is to be used in conjunction with the *Declaration for a thesis with publication form*.

Students must submit this form, along with the *Declaration for thesis with publication form*, when the thesis is submitted to the Thesis Examination System: *https://tes.app.unimelb.edu.au/*

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gradresearch.unimelb.edu.au/preparing-my-thesis/thesis-with-publication

A. PUBLICATION DETAILS *(to be completed by the student)*

Full title	Comparison of Multi-Objective Optimisation Tools for Building Performance Simulation	
Authors	Maria Panagiotidou, Lu Aye	
Student's contribution (%)	75%	
Journal or book name	Proceedings of BSO 2018: 4th Building Simulation and Optimisation Conference, Cambridge, UK: 11-12 September	
Volume/page numbers		
Status	☐ Accepted and In-press ■ Published ☐ In progress	Date accepted/published 12/09/18

B. CO-AUTHOR'S DECLARATION *(to be completed by the collaborator)*

I authorise the inclusion of this publication in the student's thesis and certify that:

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- the student contributed greater than 50% of the content of the publication and is the "primary author" ie. the student was responsible primarily for the planning, execution and preparation of the work for publication.

Co-author's name	Co-author's signature	Date *(dd/mm/yy)*
Lu Aye	Lu Aye Digitally signed by Lu Aye Date: 2020.04.15 14:23:03 +10'00'	15/04/20

Appendix G – List of electronic files

G.1 List of Electronic Files

Journal Paper 1

Building Loads

- Heraklion_Heating_cooling_Load.xlsx
- Athens_Heating_cooling_Load.xlsx
- Thessaloniki_Heating_cooling_Load.xlsx
- Florina_Heating_cooling_Load.xlsx

Equipment and Performance

a-a-HP-Mitsubishi

- Mits-part load performance.xlsx
- Mitsubishi MUZ-FE12NA.pdf
- NREL-test-report-reverse-circuit-HP-52175.pdf

a-w-HP-Ariston

- Ariston_Nimbus S Plus.pdf
- Ariston_Pacman.pdf
- Ariston-part-load-performance.xlsx
- Pacman 3.2 complete technical data set.xlsx
- PSD 3.2 e secondo 11300.xlsx

Boilers

- Product_List_Ariston_Nimbus_GR.pdf
- Genus_Premium_Evo_HP.pdf
- Biomass_Boiler_Mavil_Premus.pdf
- De_Dietrich_GTU_C_220_330.pdf
- Boilers-PLF-PLR.xlsx

GAHP-Robur

- MP_B01_GAHP_A_EN.pdf
- GAHP_Robur_EN_14825_Cd.pdf
- CR and Cd coefficients in english.xlsx
- Robur-part load performance.xlsx

Results

Heraklion

        - Heraklion-annual-cost-ghg.xlsx
        - Heraklion-LCC.xlsx

    Athens

        - Athens-annual-cost-ghg.xlsx
        - Athens-LCC.xlsx

    Thessaloniki

        - Thessaloniki-annual-cost-ghg.xlsx
        - Thessaloniki-LCC.xlsx

    Florina

        - Florina-annual-cost-ghg.xlsx
        - Florina-LCC.xlsx

  TRNSYS files

    - Athens-S1.tpf
    - Athens-S2.tpf
    - Athens-S3.tpf
    - Athens-S4.tpf
    - load.dat
    - seven-zones.b18
    - seven-zones.shm

Journal Paper 2

  Equipment

    PV-Electric

        - Aquamax_VE_Electric.pdf
        - Inverter.pdf
        - PV_STP275.pdf

    Solar-Thermal-Electric

        - C&G Energy KLB 2.5.pdf

    PVT-Electric

        - DE-PVT-Serie_P.pdf

    PV_HPHW

        - Stiebel_Eltron_WWK302.pdf

Results

- Heraklion- cost-GHG.xlsx
- Heraklion-LCC.xlsx
- Athens-cost-GHG.xlsx
- Athens-LCC.xlsx
- Thessaloniki- cost-GHG.xlsx
- Thessaloniki-LCC.xlsx
- Florina- cost-GHG.xlsx
- Florina-LCC.xlsx

TRNSYS files

- electric.tpf
- PV-electric.tpf
- solar-thermal.tpf
- PVT-electric.tpf
- PV-HPHW.tpf

Journal Paper 3

Cost Data

- Offer-Roof-Insulation.pdf
- Offer-Wall-Insulation.pdf
- Offer-uPVC-double-glazing.pdf
- Offer-uPVC-triple-glazing.pdf
- PV-maintainance-cost.pdf

Optimisation Routine

excel-data

- DHWRES_Z1.csv
- DHWRES_Z2.csv
- DHWRES_Z3.csv
- DHWRES_Z4.csv
- HC_FC.csv
- HC_S3.csv
- HC_S4.csv

- HC_ZA_S1.csv
- HC_ZA_S2.csv
- HC_ZB_S1.csv
- HC_ZB_S2.csv

templatedir

- ZA_S1.dck
- ZA_S2.dck
- ZB_S1.dck
- ZB_S2.dck
- S3.dck
- S4.dck
- seven-zones.b18
- seven-zones.shm

Heraklion-optim

- calltrnsys.py
- DakotaHeraklion.in

Athens-optim

- calltrnsys.py
- DakotaAthens.in

Thessaloniki-optim

- calltrnsys.py
- DakotaThessaloniki.in

Florina-optim

- calltrnsys.py
- DakotaFlorina.in

Results

Heraklion

- Heraklion-sensitivity.xlsx
- Optim-results-Heraklion.xlsx

Athens

- Athens-sensitivity.xlsx

- Optim-results-Athens.xlsx

Thessaloniki

- Thessaloniki-sensitivity.xlsx
- Optim-results-Thessaloniki.xlsx

Florina

- Florina-sensitivity.xlsx
- Optim-results-Florina.xlsx