MULTI-OBJECTIVE GENETIC ALGORITHM OPTIMIZATION OF ENERGY EFFICIENCY MEASURES IN A SINGLE-FAMILY HOUSE BUILDING IN GREECE

Konstantinos Braimakis[1], Dimitrios Ioannidis[1], Panagiotis Rigopoulos[2], Platon Pallis[2], Sotirios Karellas[2]

[1]Laboratory of Refrigeration, Air-Conditioning & Solar Energy, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece
[2]Laboratory of Thermal Processes, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece

*Corresponding Author: mpraim@central.ntua.gr

ABSTRACT

The goal of the present work is to demonstrate the potential of Genetic Algorithm (GA) methods for energy efficiency and economic performance optimization of energy efficiency measures in a single-family house building in Greece. The energy efficiency measures include different heating/cooling systems (such as low-temperature and high-temperature heat pumps, natural gas boilers, split units), building envelope components for floor, walls, roof and windows of variable heat transfer coefficients, the installation of solar thermal collectors and PVs. The calculations of the building loads and the investment and operating and maintenance costs of the measures are based on the methodology defined in the Directive 2010/31/EU. The economic assumptions were based on the EN 15459-1 standard. Typically, multi-objective optimization of energy efficiency measures requires the simulation of very large numbers of cases involving all possible combinations (exhaustive search), resulting in intense computational load and requiring significant amount of time. The results of the study indicate that GA methods can be used as an alternative, valuable tool for reliably predicting the optimal measures which minimize primary energy consumption and life cycle cost of the building with greatly reduced computational requirements.

1 INTRODUCTION

Buildings are at the core of the EU's energy efficiency policies (European Commission, 2011), as they take up approximately 30-40% of the final energy consumption and for 36% of greenhouse gas emissions (Attia, 2018a; Eurostat European Commission, 2012). Directives 2010/31/EU (Energy Performance of Buildings Directive-EPBD) (The European Parliament and the Council of the European Union, 2010) and 2012/27/EU (Energy Efficiency Directive – EED) (The European Parliament and the Council of the European Union, 2012) introduced specific measures for improving the energy performance of the European building stock. Although the aforementioned Directives were recently amended by 2018/844 and 2018/2002 Directives, respectively (The European Parliament and the Council of the European Union, 2018), a major focus of the EPDB is nearly Zero-Energy Buildings (nZEBs) both for new buildings and renovations, as well as the long term renovation strategies through cost-effective approaches. According to Article 2 (The European Parliament and the Council of the European Union, 2010) of the EPBD, nZEB defines "a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". An important aspect of nZEB regards the notions of cost-effectiveness and cost-optimality. In fact, the minimization of the financial gap between cost-optimal and nZEB/NZEB solutions constitutes a prerequisite for the implementation of the EPBD through the progressive tightening of the minimum requirements of the national regulations. The determination of the cost-

https://doi.org/10.52202/077185-0161

optimal performance for nZEBs requires the development of a comparative framework methodology taking into account the economic and also energetic/environmental aspects of all possible designs based on multiple technologies and utilizing variable energy sources (Attia, 2018b).The gap between cost optimality and nZEBs was evaluated in terms of a) availability/technical feasibility of technologies needed and b) differences in life cycle (global) costs for different European countries in the Towards nZEB (European Commission, 2013) study. The aforementioned study reached two main conclusions. The first one is that it is technically feasible to reach nZEB energy consumption levels in buildings by the implementation of currently available technologies focusing on the reduction of the energy demand and improved conversion efficiencies combined with the utilization of renewable energy sources (RES). The second conclusion is that while capital expenditure reductions and improved performance of the involved components can universally promote the viability of nZEBs, the utilization of RES may be occasionally hindered due to temporal and geographical limitations as well as local market trends and policy frameworks.

Up to date, very few systematic studies have been carried out to outline the relationship between cost-optimality and energy efficiency of different energy efficiency measures in buildings considering a broad scope of technologies and climate conditions. In past studies, Pallis et al. investigated the cost-effectiveness and primary energy savings potential of intervention packages (IPs) consisting of single or multiple measures on existing single and multi-family house buildings erected in two climate zones (B and C) of Greece previous to 1980 and within 1980-2000 (Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, & Vourliotis, 2019) as well as in newly constructed residential buildings (Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, Vourliotis, et al., 2019) and office buildings (Pallis et al., 2021). In the case of residential buildings, the investigated IPs included upgrading of building envelope materials (BEMs) considering various final U-values, the installation of sunshades, different air conditioning heating, domestic hot water (DHW) production and cooling systems and automation systems, the installation of photovoltaic (PV) panels and the installation of solar assisted heating and DHW systems. In the case of office buildings, special focus was also given to lighting systems.

The calculations in the previous studies were based on the methodology defined in the Directive 2010/31/EU and Regulation 244/2012 (European Commission, 2012; The European Parliament and the Council of the European Union, 2010) on the energy performance of buildings, while economic evaluation assumptions were based on the EN 15459-1 standard (European Committee for Standardization, 2017). An exhaustive search (“brute force”) calculation approach was implemented, in which IPs consisting of all possible combinations of energy efficiency measures were considered and their resulting primary energy consumption (PEC) and life cycle cost (LCC) were determined. Because of the large number of investigated IPs, a vast number of calculations was necessary, which had a considerable computational load. Considering the above, the goal of the present study is to investigate the potential of using genetic algorithm (GA) optimization in order to identify the cost-optimal IPs for a single-family house (SFH) building for two climate zones in Greece in terms of accuracy and computational efficiency. The results obtained by the GA optimization are compared to the results that are calculated through an exhaustive search optimization.

2 METHODOLOGY

2.1 Computational Framework

In the present study, a numerical platform is developed integrating TEE KENAK software with Matlab software (Matlab, 2012). TEE KENAK is the official national building energy simulation program in Greece and is based on the monthly method of EN ISO 13790:2008 (European Committee for Standardization), developed by the Energy Efficiency Group of the Institute for Environmental Research and Sustainable Development of the National Observatory of Athens ("https://www.iersd.noa.gr/en/,") in collaboration with the Technical Chamber of Greece ("https://web.tee.gr/kenak/logismiko-tee-kenak/,"). The software is used for energy inspections which are a prerequisite for issuing Energy Performance Certificate in buildings. The main inputs to the software include climate data, building envelope geometrical and thermal specifications as well as technical specifications (size, efficiency parameters) of active heating, cooling and domestic hot water

https://doi.org/10.52202/077185-0161

(DHW) production or additional systems such as SWHs and photovoltaics (PVs). Based on these inputs, the software performs building energy simulations, ultimately computing the energy consumption of the building. In the present work, TEE KENAK software is linked with the genetic algorithm optimization toolbox of Matlab and more specifically the gamultiobj multi-objective optimization feature, as shown in Figure 1. The goal is to perform a multi-objective optimization of energy efficiency IPs for a building of given characteristics.

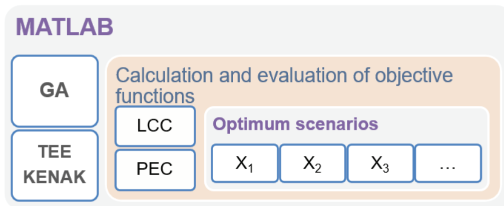


Figure 1: Integration of Matlab gamultiobj multi-objective optimization feature with TEE KENAK software

2.2 Definition of reference building

The first step of the methodology is the definition of the reference buildings to be considered in the evaluation (Greek Ministry of Environment and Energy, 2016a). A SFH building is considered for the analysis, which is illustrated in **Figure 2**. The building has a heated area of 80 m^2 and a cooled area of 40 m^2. The specifications of the building (building envelope U-values and heating, cooling, DHW system etc.) are considered assuming that it belongs to a construction period between 1945 and 1980. Therefore, the envelope has a relatively poor quality, while the energy systems are not efficient. Finally, the analysis is carried out considering climate zones B (Athens) and C (Thessaloniki), which are representative of mild and harsh winter climate conditions respectively and the combined population accounts for approximately 37%. The climate zones are defined according to National Greek Legislation regarding the approval and implementation of Technical Directives of the Technical Chamber of Greece (Energy, 2014).

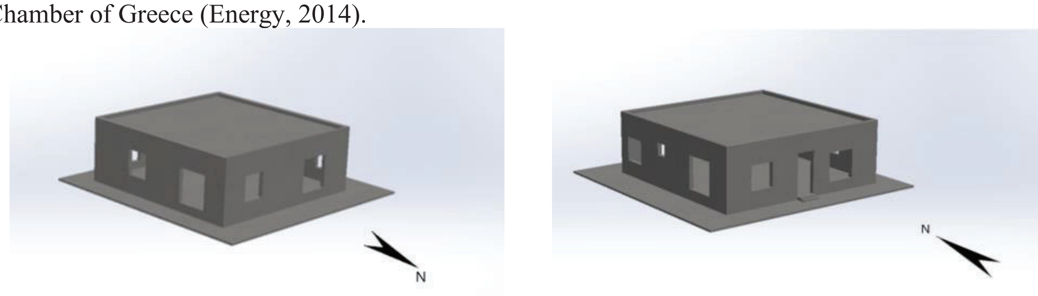


Figure 2: 3D depiction of SFH building that is considered for the analysis

The building envelope characteristics of the reference building are summarized in Table 1. The average specific heat capacity of the building envelope is 260 kJ/m^2K (Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, & Vourliotis, 2019).

Table 1 Envelope characteristics of the reference building

Building element	U-value (W/m^2K)	Area (m^2)
External walls	2.32	100.5
Roof	1.95	80
Floor	1.73	80
Windows	4.25	15.12

The characteristics of the heating, DHW and cooling systems of the reference building are summarized in Table 2. The building is heated with a non-condensing oil boiler (NCOB), while DHW is produced with an electric water heater. Moreover, cooling is produced by a conventional split unit (CSU).

https://doi.org/10.52202/077185-0161

Table 2 Reference building heating, DHW and cooling systems characteristics

Type of energy demand	System characteristics	Technical specifications
Heating	Non-condensing oil boiler	30 kW_{th}, η_{th}=67.64%
Cooling	Old split unit	15.25 kW_c, COP=1.7
DHW	Electric water heater	7.5 kW_{th}, η_{th}=100%

The automation category of the reference building is labeled “3”, according to the Technical Directive 20701-1/2010 of the Technical Chamber of Greece (Technical Chamber of Greece, 2017b) which is based on the European Standard EN 15232:2017 (European Committee for Standardization, 2007, 2017). Automation category “3” includes individual room automatic control by thermostatic valves or electronic controller and automated hydraulic or temperature adaptation of distribution circuit to heating/cooling loads.

2.3 Description of energy efficiency intervention packages

Multiple energy efficiency measures are available for reducing either the energy demand of the building (for example through building envelope upgrading) or the energy consumption through more efficient energy production systems. Following the methodology presented in previous studies by the authors (Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, & Vourliotis, 2019; Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, Vourliotis, et al., 2019) a wide range of measures are included in the present study as well, while also ensuring that reasonable combinations of different measures for the production of heating, cooling and domestic hot water (DHW) are selected, omitting mutually exclusive measures. The scope of the measures along with a brief description of each is presented in Table 3. Overall, these include upgrading of building envelope materials (BEMs), the installation of automation control systems as well as upgrades/retrofits of active energy systems (heating/cooling systems, PVs, solar water heaters (SHWs)).

Table 3 Overview of energy efficiency measures

1) Building envelope materials (BEMs) - 54 scenarios Different insulation levels of building envelope components corresponding to different final U-values including: a) external walls (**3 scenarios**): no upgrade (**Table 1**) & 2 upgrading scenarios (0.84 and 0.35 W/m^2K) b) roof (3 **scenarios**): no upgrade (**Table 1**) & 2 upgrading scenarios (0.75 and 0.35 W/m^2K) c) lower floor (2 **scenarios**): no upgrade (**Table 1**) & 1 upgrading scenarios (0.87 W/m^2K) d) windows (3 **scenarios**): no upgrade (**Table 1**) & 2 upgrading scenarios (1.81 and 1.20 W/m^2K)
2) Heating, cooling and DHW systems – 12 scenarios The systems are intended for: a) heating b) cooling and c) domestic hot water. Sizing of systems is carried according to national official simulation program entitled TEE-KENAK. The investigated system characteristics are illustrated in **Table 4** and the investigated combinations are shown in **Table 5**.
3) Automation systems-3 scenarios The achieved energy consumption for three different automation categories, numbered from 1 (sophisticated control) to 3 (less sophisticated controls) is calculated in accordance with the Technical Directive 20701-1/2010 of the Technical Chamber of Greece which is based on the European Standard EN 15232:2017.
4) Photovoltaic (PV) panels - 6 scenarios i) no PV installation ii) PV installation of south-facing polycrystalline panels of 4, 8, 16, 20 and 24 m^2 corresponding to peak power of about 0.84, 1.68, 3.36, 4.20 and 5.04 kW_p with nominal efficiency of $\eta_{PV,n}$=21% and solar utilization factor of 0.21
5) Solar water heater (SWH) - 4 scenarios i) no solar water heater ii) installation of 2, 3 and 4 m^2 of south-facing selective solar collector for DHW production

https://doi.org/10.52202/077185-0161

An upper limit of total coverage from solar systems has been also been taken into account, at 1/3 of total roof surface area. The technical specifications of the investigated heating, cooling and DHW systems categorized by both their energy source and climate zone are summarized in Table 4.

Table 4 Summary of heating and cooling systems (Greek Ministry of Environment and Energy, 2016b)

Energy source & Purpose	Abbr.	Heating and DHW	Abbr.	Cooling
Oil	**NCOB (existing)**	Non-condensing oil boiler, η_{th}=64.67%	-	-
Natural gas	**NGB**	Condensing natural gas boiler, η_{th}=105%	-	-
Electricity	**LTHP**	Low temperature (55 °C) heat pump & fan coil units, COP: 4.3 (B), 4 (C)	**LTHP**	Low-temperature heat pump & fan coil units, COP: 4 (B), 4.2 (C)
	GHPFC	Geothermal heat pump with fan coil units, COP: 5.3 (B), 5.1 (C)	**GHPFC**	Geothermal heat pump & fan coil units, COP: 5.1 (B), 5.3 (C)
	HTHP	High-temperature (75 °C) heat pump, COP: 3 (B), 2.75 (C)	**MSU**	Modern split units, COP=3.5
	GHP	Geothermal heat pump without fan coil units (heating only), COP: 5.3 (B), 5.1 (C)	**CSU (existing)**	Conventional split units, COP=1.7
Biomass	**BB**	Wood pellet boiler, η_{th}=82%	-	-

The investigated combinations of heating/cooling systems are showcased in **Table 5**. A total of 12 combinations of heating and cooling systems were considered.

Table 5 Investigated combinations of heating and cooling systems

Heating and DHW	**Cooling**			
	CSU (existing)	MSU	LTHP	GHP
NCOB (existing)	✓	✓	X	X
NGB	✓	✓	X	X
LTHP	X	X	✓	X
HTHP	✓	✓	X	X
GHPFC		X	X	✓
GHP	✓	✓	X	X
BB	✓	✓	X	X

Considering all combinations of interventions packages, their total number is equal to 3 (external walls) x 3 (roof insulation) x 2 (floor insulation) x 3 (window insulation) x 12 (heating and cooling systems) x 3 (automation category) x 22 (PV & solar water heater) = 42768 scenarios.

2.4 Energy simulations and cost-effectiveness assessment

2.4.1 Energy simulations and primary energy consumption calculation

Energy simulations are performed in order to estimate the heating, cooling and domestic hot water demands as well as the annual energy consumption. The meteorological data used in the calculations are based on weighted average values retrieved for the two considered cities based on the national legislation (Ministry of Environment and Energy, 2014), by taking into account the residential building stock in each region (at a Prefecture level), provided by the Hellenic Statistical Authority (Hellenic Statistical Authority).The main calculation parameters are summarized in Table 6.

https://doi.org/10.52202/077185-0161

Table 6 Basic parameters used by TEE-KENAK for residential use energy simulations (Technical Chamber of Greece, 2017a)

Parameter	Value
Hours of operation	18 hours per day
Days of operation	7 days per week
Months of operation	12 months
Heating period	November-April
Cooling period	June-September
Indoor temperature during heating period	20 °C
Indoor temperature during cooling period	26 °C
Relative humidity during heating period	40%
Relative humidity during cooling period	45%
Fresh air requirements	0.75 $m^3/h/m^2$
DHW requirements	27.38 m^3/bedroom/year
Discharged heat from building users	80 W/person
Non-synchronized discharged heat from building equipment/ devices	2 W/m^2

2.4.2 Life cycle cost calculation

The cost-effectiveness assessment is performed based on the standard EN 15459-1:2014 (European Committee for Standardization) by calculating the life cycle cost (LCC) expressed in €/m^2. Generally, the LCC is calculated by estimating the initial investment cost (C_{inv}), the final disposal cost (C_{disp}), the residual value (C_{val}) as well as the net annual operation and maintenance cost (Ca) deduced to the present for each j_{th} energy efficiency measure, according to the equation:

$$LCC = C_{fixed} + \sum_{j}\left[C_{inv,j} + \sum_{i}\left(C_{a,j}\left(\frac{1}{1+p}\right)^{i}\right) + C_{disp,j} - C_{val,j}\right] \tag{1}$$

Additionally, the disposal cost (C_{disp}) and the residual cost C_{val}, which is the remaining value associated with the implementation of a measure at the end of the techno-economic evaluation period, have been also taken into account. The calculations are carried out considering an interest rate of 7%, a lifetime of 30 years and an annual increase rate of energy prices of 2.8%.

2.4.3 Cost estimation data

In this section, the most important cost data that have been used in the calculations are presented. Data were retrieved from the Union of Hellenic Heating & Energy Enterprises ("Union of Hellenic Heating & Energy Enterprises, https://uhhe.gr/,"). The costs of building envelope upgrading and the energy systems are shown in Figure 3. The size (y-axis) refers to nominal heating/cooling capacity for dedicated heating and cooling systems, heating capacity for reversible heat pumps and peak electricity output for the PVs. The cost of solar thermal collectors is taken equal to 1170 € corresponding to a 2 m^2 solar collector including a 120 lt tank. Regarding the terminal units, their cost is taken equal to 65 €/m^2 for panels and 225 kW_{th} for fan coil units.

The annual cost of maintenance and replacement for all systems is taken equal to 5% of the investment cost with the exception of solar thermal collectors and PVs, for which it is taken equal to 3% and 5% of the initial investment cost, respectively.

https://doi.org/10.52202/077185-0161

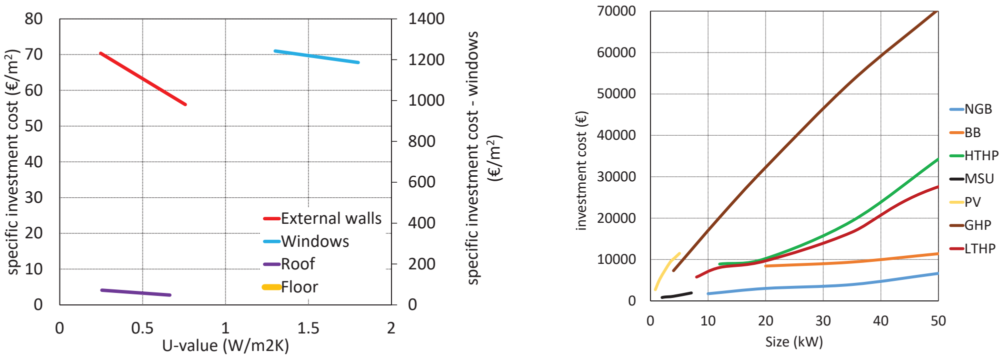


Figure 3: Investment cost data for building envelope upgrading (left) and active energy systems (right)

2.4.4 Energy cost and primary energy conversion factors

The energy costs and primary energy conversion factors used in the calculations are summarized in Table 7. Energy prices were retrieved from the study of the Laboratory of Steam Boilers and Thermal Plants and Laboratory of Thermal Processes on Comparison of cost of heating from different technologies ("Comparison of cost of heating for different technologies," 2023). PEC conversion factors were retrieved from the previous study by the authors. It must be highlighted that the used PEC conversion factors in the present work are not updated to 2023, therefore the reported PEC values are not representative of the current electricity mix in Greece.

Table 7 Energy/Emissions costs and primary energy conversion factors

Energy carrier	Unit cost (€/kWh)	Primary energy conversion factors	CO2 Emissions (kgCO2/kWh)	CO2 Costs per period (€/tn CO2)
Natural gas	0.186	1.05	0.196	86 (2023-25)
Heating oil	0.143	1.10	0.264	100 (2026-30)
Electricity	0.405	1.75	0.332 to 0.1 in 2030	182 (2031-50)

2.5 GA optimization

The first step of the GA optimization process is the initialization of the 1st generation of the population, which consists of IPs consisting of randomized energy efficiency measures. The LCC and PEC, as defined in the previous sections, are calculated for every individual of the 1st generation and their fitness is evaluated. From the simulations, it was found that an initial population of 200 individuals led to the best results in times of computational efficiency and accuracy of the results. Subsequently, 50% of the individuals are selected as parents of the next generation after recombination and adaptive mutation (by the introduction of randomized changes in the energy efficiency measures). In scattered crossovers, different genes are inherited from each parent as exchanges are made between more positions. The process is repeated for multiple pairs of parents until a sufficient number of descendants are generated for the next generation. The adaptive mutation option seems the most beneficial for the algorithm to converge efficiently, especially when the optimal IP involves varying degrees of freedom for the different variables as in this case. The next step of the method is the replacement of the population. In the present work, the steady state population replacement strategy was adopted, as suggested by the study of Goldberg et al. (Goldberg & Deb, 1991). A convergence tolerance is defined based on the change in population or pareto front in successive generations. In the context of such algorithms, function tolerance usually refers to a termination criterion used to stop the algorithm when the improvement in the objective function values becomes less than a certain threshold. A tolerance of 0.001 was chosen as the minimum convergence threshold. Such order criteria are popular and are defined in both single objective and two objective optimization problems. All GA optimization parameters are summarized in Table 8.

Table 8 GA optimization parameters

https://doi.org/10.52202/077185-0161

Parameter	**Value**
Number of variables	9
Population size	200
Maximum number of generations	50
Crossover function	crossoverscattered
Mutation function	mutationadaptfeasible (0.02)
Convergence tolerance	0.001
Maximum number of stable generations	5
Pareto fraction	0.5

3 RESULTS

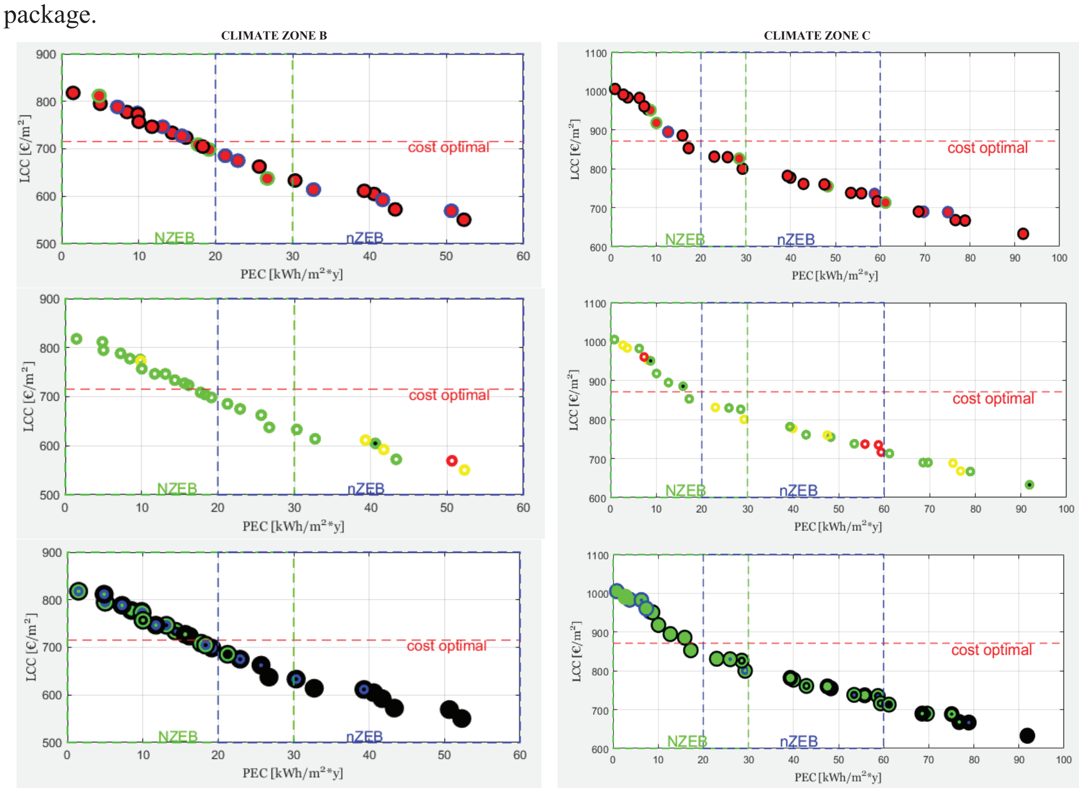
3.1 Detailed Analysis of the results

The Pareto front consisting of cost-optimal IPs as a function of the PEC values is illustrated in the diagrams of Figure 4. In these diagrams, the NZEB, nZEB and cost-optimality regions are depicted, enclosed in dashed-line rectangles, according to the values of **Table 9**:

Table 9 NZEB, nZEB and cost-optimal region boundaries

Parameter	**Value**
NZEB (kWh/m^2/y)	0-30
nZEB (kWh/m^2/y)	20-60
LCC (€/m^2)	$LCC_{thres} = LCC_{min} + 0.1 * (LCC_{max} - LCC_{min})$

On the left of **Figure 4**, IPs represent climate zone B (Athens), while on the right, IPs correspond to climate zone C (Thessaloniki). From top to bottom, the diagrams are grouped by active energy systems (heating, cooling and automation), DHW solar panels/photovoltaics, and lastly by type of building envelop materials (BEMs) upgrade. Each circular point corresponds to a cost-optimal intervention package.



https://doi.org/10.52202/077185-0161

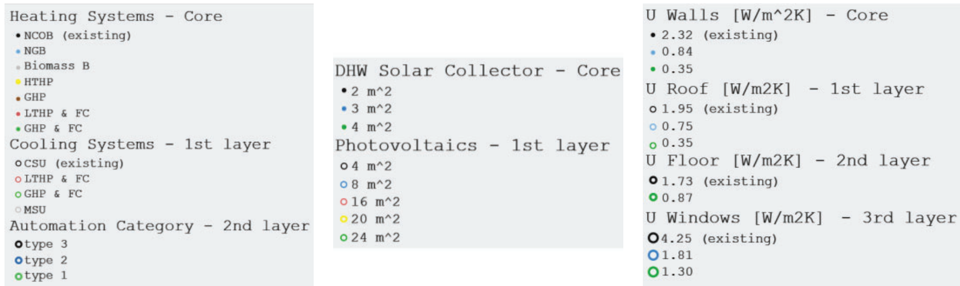


Figure 4 Pareto front of multi-objective optimization for LCC and PEC in climate zone B (left) and C (right)

In Climate Zone B, there are many cost-optimal IPs inside both NZEB/nZEB regions. The IPs which have the lowest PEC consist of the highest insulation upgrades for all BEMs. However, it is possible to attain NZEB PEC levels at significantly lower LCC without window or floor insulation as long as the external walls and roof are insulated. The IPs inside the NZEB region universally consist of LTHP&FCs, PVs and automation category upgrades but no SWHs. In the nZEB region, cost-optimal IPs have lower LCCs. The IPs feature insulation upgrade of external walls, roofs and floors (but no windows), while the dominant systems also include LTHP&FCs with PVs. Overall, the lowest LCCs are obtained by IPs which also have the maximum PEC involving only the installation of a LTHP&FCs, while significantly low LCCs but greatly lower PEC levels are obtained by IPs in which PVs are also installed.

In Climate Zone C, the rigorous environmental conditions necessitate increased heating demands, which correspondingly elevate the PEC levels. Despite these heightened PEC levels, numerous cost-optimal IPs exist within both the NZEB/nZEB regions. Within the nZEB region, the vast majority of cost-optimal IPs are characterized by the maximal insulation of external walls, roofs, and floors. This enhanced insulation is crucial for maintaining low PEC values. For scenarios aiming for very low PEC values, the upgrade of window insulation becomes necessary. Interestingly, similar to observations in Climate Zone B, while the most energy-efficient IPs (those with the lowest PEC values) require maximum window insulation, the IPs achieving the lowest LCCs within the nZEB region typically do not include window insulation upgrades. This suggests that while window insulation significantly contributes to reducing PEC, its impact on overall cost-effectiveness is less pronounced when considering long-term costs. Regarding active energy systems, SWHs are once again not part of cost-optimal solutions. In the nZEB region, cost-optimal IPs universally include LTHP&FCs and PVs, with some IPs also including automation category upgrades, similar to what was observed in Climate Zone B. Notably, the LCC of IPs in the nZEB region is considerably lower than the LCC cost-optimality threshold.

Cost-optimal IPs universally combine LTHP&FCs and PV systems which are essential to achieving the desired energy performance and cost-efficiency.

3.2 Evaluation of GA optimization approach

To evaluate the effectiveness of the GA optimization approach in identifying the cost optimal IPs corresponding to different PEC values, the Pareto fronts derived from the GA that were presented in the previous section are overlayed against the total collection of points corresponding to all possible IPs derived from an exhaustive search calculation. Furthermore, for each PEC value, the relative deviation between the LCC of the cost-optimal IPs identified by the GA and the LCC corresponding to the global minimum is calculated.

The aforementioned results are shown in **Figure 5** with left-side IPs representing climate zone B (Athens) and right-side IPs correspond to climate zone C (Thessaloniki). It can be observed that the Pareto front obtained by the GA captures with very high accuracy the global minimum Pareto front derived from the exhaustive search calculation.

Meanwhile, the relative deviation of the LCC is very low. For the vast majority of PEC values, the cost-optimal IPs identified by the GA coincide with the global cost-optimal IPs (relative deviation is null). The maximum relative deviation is less than 1% with a very low probability of occurrence.

https://doi.org/10.52202/077185-0161

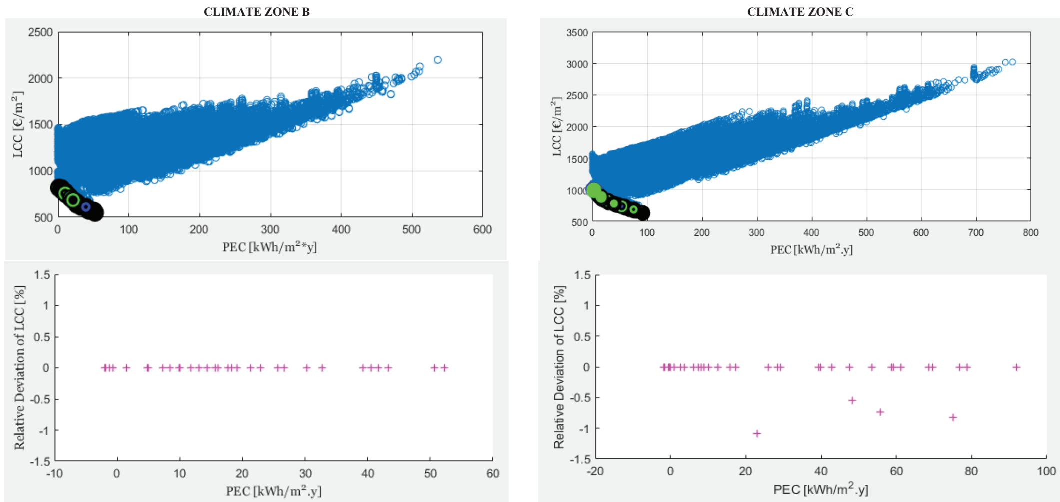


Figure 5 Comparison of the Pareto fronts obtained by the GA (multi-colored points) with the collection of all possible intervention packages (blue-colored points) and relative deviation of LCC for different PEC values in climate zone B (left) and C (right)

It must be highlighted that the calculations in the present work were performed in a computer featuring an AMD Ryzen 5 5000 CPU with a RAM of 8 GB. The calculation time needed for evaluating all possible IPs (42768 evaluations) is equal to about 18 hours. On the other hand, the GA requires considerably less time, equal to about 50 min for climate zone B and 35 min for climate zone C, while it can determine the cost-optimal IPs through 2000 (climate zone B) and 1800 (climate zone C) evaluations.

The above results demonstrate the GA method is a valuable tool for accurately and very efficiently identifying the cost-optimal Pareto front of cost-optimal IPs corresponding to different target PEC values by achieving a dramatic reduction of the computational effort by more than 97%.

4 CONCLUSIONS

The most important conclusion of the study is that the use of GA optimization is a valuable tool for the efficient evaluation of IPs consisting of multiple energy efficiency measures in buildings based on BEM and active energy systems upgrading. Although the study is limited to the evaluation of SFH buildings located in two climate zones in Greece, it is demonstrated that the application of GA optimization methodology can be effectively extended to different types of buildings (MFH buildings, offices, hospitals etc.) and locations of different climate characteristics.

The conclusions of the study with regard to the cost-optimality assessment of IPs are similar to those of past studies that have been carried by the authors (Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, & Vourliotis, 2019; Pallis, Gkonis, Varvagiannis, Braimakis, Karellas, Katsaros, Vourliotis, et al., 2019). Despite the differences in absolute LCC and PEC values because of the significant increase of energy prices and costs in the last years, the findings are similar from a qualitative point of view.

NOMENCLATURE

Abbreviations

BB	biomass boiler	LTHP	low-temperature air-source heat pump
BEM	building envelope material	MSU	modern split unit
COP	Coefficient of Performance	NGB	condensing natural gas boiler
DHW	domestic hot water	NOB	condensing oil boiler

https://doi.org/10.52202/077185-0161

EPBD	Energy Performance of Buildings Directive	nZEB	near Zero Energy Building
FC	fan coil unit	NZEB	net Zero Energy Building
GA	genetic algorithm	PEC	primary energy consumption
GHP	ground-source heat pump	PV	photovoltaic
HTHP	high-temperature air-source heat pump	RES	renewable energy sources
IP	intervention package	SFH	single-family house building
LCC	Life Cycle Cost	ZEB	Zero Energy Building

Subscript

th	thermal
e	electricity
p	peak
c	cooling

REFERENCES

Attia, S. (2018a). Chapter 1 - Introduction to NZEB and Market Accelerators. In S. Attia (Ed.), *Net Zero Energy Buildings (NZEB)* (pp. 1-20): Butterworth-Heinemann.

Attia, S. (2018b). Chapter 12 - Roadmap for NZEB Implementation. In S. Attia (Ed.), *Net Zero Energy Buildings (NZEB)* (pp. 343-369): Butterworth-Heinemann.

Comparison of cost of heating for different technologies. (2023). *Laboratory of Steam Boilers and Thermal Plants, Laboratory of Thermal Processes*.

Energy, M. o. E. a. (2014). Approval and implementation of Technical Directives of the Technical Chamber of Greece for the Energy Efficiency of Buildings. *Official Greek Government Gazette 2618/23.10.2014/ΦΕΚ 2945Β/2014*.

European Commission. (2011). Progress by Member States towards Nearly Zero-Energy Buildings *Report from the Commission to the European Parliament and the Council*.

European Commission. (2012). COMMISSION DELEGATED REGULATION (EU) No 244/2012. *https://eur-lex.europa.eu/eli/reg_del/2012/244/oj*.

European Commission. (2013). Towards nearly zero energy buildings: Definition of common principles under the EPBD. *https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_full_report.pdf*.

European Committee for Standardization. EN 13790:2008: Energy performance of buildings. Calculation of energy use for space heating and cooling. *https://www.cen.eu/Pages/default.aspx*.

European Committee for Standardization. (2007). EN 15459-1:2017: Energy performance of buildings. Impact of building automation, controls and building management. *BS EN 15232:2007*.

European Committee for Standardization. (2017). Energy Performance of Buildings. Impact of Building Automation, Controls and Building Management. Modules. *BS EN 15232-1:2017*.

Eurostat European Commission. (2012). Energy, transport and environment indicators.

Goldberg, D. E., & Deb, K. (1991). A Comparative Analysis of Selection Schemes Used in Genetic Algorithms. In G. J. E. Rawlins (Ed.), *Foundations of Genetic Algorithms* (Vol. 1, pp. 69-93): Elsevier.

Greek Ministry of Environment and Energy. (2016a). Report on the determination of cost optimal levels of minimum energy efficiency requirements for buildings and structural elements. *https://ec.europa.eu/energy/en/content/eu-countries-2013-cost-optimal-reports-part-1*.

Greek Ministry of Environment and Energy. (2016b). Report on the determination of cost optimal levels of minimum energy efficiency requirements for buildings and structural elements, https://ec.europa.eu/energy/en/content/eu-countries-2013-cost-optimal-reports-part-1.

Hellenic Statistical Authority. http://www.statistics.gr/.

https://web.tee.gr/kenak/logismiko-tee-kenak/.

https://www.iersd.noa.gr/en/.

Matlab, S. (2012). Matlab. *The MathWorks, Natick, MA*.

https://doi.org/10.52202/077185-0161

Ministry of Environment and Energy. (2014). Approval and implementation of Technical Directives of the Technical Chamber of Greece for the Energy Efficiency of Buildings. *Official Greek Government Gazette 2618/23.10.2014/ΦΕΚ 2945Β/2014*.

Pallis, P., Braimakis, K., Roumpedakis, T. C., Varvagiannis, E., Karellas, S., Doulos, L., . . . Vourliotis, P. (2021). Energy and economic performance assessment of efficiency measures in zero-energy office buildings in Greece. *Building and Environment, 206*, 108378. doi:https://doi.org/10.1016/j.buildenv.2021.108378

Pallis, P., Gkonis, N., Varvagiannis, E., Braimakis, K., Karellas, S., Katsaros, M., & Vourliotis, P. (2019). Cost effectiveness assessment and beyond: A study on energy efficiency interventions in Greek residential building stock. *Energy and Buildings, 182*, 1-18. doi:https://doi.org/10.1016/j.enbuild.2018.10.024

Pallis, P., Gkonis, N., Varvagiannis, E., Braimakis, K., Karellas, S., Katsaros, M., . . . Sarafianos, D. (2019). Towards NZEB in Greece: A comparative study between cost optimality and energy efficiency for newly constructed residential buildings. *Energy and Buildings, 198*, 115-137. doi:https://doi.org/10.1016/j.enbuild.2019.06.005

Technical Chamber of Greece. (2017a). Technical Directive: Analytical National Specifications of the parameters for the calculation of the building energy performance and issuing of energy certificates. *http://portal.tee.gr/portal/page/portal/tptee/totee/TOTEE-20701-1-Final-%D4%C5%C5-2nd.pdf*.

Technical Chamber of Greece. (2017b). Technical Directive: Analytical National Specifications of the parameters for the calculation of the building energy performance and issuing of energy certificates, 'http://portal.tee.gr/portal/page/portal/SCIENTIFIC_WORK/GR_ENERGEIAS/kenak/files/TOTEE_20701-1_2017_TEE_1st_Edition.pdf'.

The European Parliament and the Council of the European Union. (2010). Directive 2010/31/EU of the European Parliament and the Council on the energy performance of buildings (recast). *Official Journal of the European Union*.

The European Parliament and the Council of the European Union. (2012). Directive 2012/27/EU of the European Parliament and the Council on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives
2004/8/EC and 2006/32/EC. *Official Journal of the European Union*.

The European Parliament and the Council of the European Union. (2018). Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance). *Official Journal of the European Union*.

Union of Hellenic Heating & Energy Enterprises, https://uhhe.gr/.

https://doi.org/10.52202/077185-0161