Energy Hub Optimization on Residential Building Case

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Abstract. The growth of the energy consumed, have led to the need of upgrading and restructuring the operation of existing energy systems in the building sector. In context, goals of reducing the primary energy consumption based on fossil fuels and the limitation of carbon dioxide (CO_2) emissions to the atmosphere, were set, in order to enhance the provision of affordable and generally clean energy for the citizens. In addition, the European Union (EU) promotes the utilization of energy systems based on Renewable Energy Sources (RES). All above highlight the importance of the decision-making process during the design phase of a building. For these reasons, this paper deals with the optimization of multi energy systems, introducing the concept of the Energy Hub, in order to cover the thermal demands of a residential building located in Thessaloniki (Greece). The proposed methodology includes the calculation of the building energy demands on a monthly basis via the simulation program FineGREEN19. Afterwards, a Mathematical Programming model was constructed, in order to provide the optimization scheme of multi energy systems, considering different criteria. The criteria include the minimization of economic, energy and environmental aspects, considering the concept of Life Cycle Assessment (LCA). The General Algebraic Modeling System (GAMS) was used to model the optimization problem. The results of Single Criteria Optimization problem figure out the contradictory between the criteria, showing that the use of the optimization models can improve and facilitate the building design.

1 Introduction

The increase in energy consumption and environmental pollution worldwide, led the EU to focus on the energy sector by instituting measures for the normalization of this condition, as reflected in the official texts and directives [1, 2]. There are three main sectors possessing an important share of energy consumption, industry, transportation and buildings. The building sector contributes 40% of the energy used across the EU and it is responsible for 1/3 of Carbon Dioxide (CO_2) emissions, resulting in a considerably negative environmental impact [3]. The sustainability of the building sector is essential for providing social, economic and environmental benefits, considering the occupants thermal comfort too. The proper management of energy consumption can result in high energy efficiency, which is related to a combination of different factors, including construction materials, building orientation, heating and cooling systems etc. Such an energy managing, combined with the mitigation of greenhouse gas (GHG) emission, under the cost optimization, address a decision-making problem, which can be reached more easily during the design phase of a building [4].

The EU set ambitious environmental and energy goals in order to design low-carbon energy systems. Such goals include the reduction of GHG emissions by 55% by 2030, the upgrade of the renewable electricity share by 32%, and the improvement of energy efficiency by 32.5% [5]. In this context, the development of multi-energy systems could enhance environmental protection, as well as the creation of market-oriented energy services, while aiming at security, reliability, and resilience of the energy supply. Moreover, the installation of multi-energy systems in the building sector, combined with renewable energy systems, could turn the households from passive into active consumers, called prosumers, by generating energy for their own use or even sell it to the network [6]. In fact, a single-energy system cannot effectively deploy the potential benefits of a multi-energy one, where the energy uses, i.e., electricity, heating, cooling, can interact with each other at various levels, under an optimized decision-making methodology [7]. To deal with such a concern, it is important for the concept of the Energy Hub (EH) to be introduced, for analyzing multi-energy conversion from

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an input–output perspective [8]. An EH, or multi-carrier energy system, can provide energy in such a way, so that different energy carriers at the input of the hub can be converted into other types of energy carriers at the output, via converters (energy systems). So, the general concept of EH is the optimal coupling of different energy carriers, that can be converted, conditioned, stored, and finally consumed [9]. The implementation of multi-energy systems to the concept of the EH, could take advantage of the synergistic effects of interactions in order for the energy resources to be efficiently utilized, and the energy demands to be covered.

The optimal design and operation of the EH is a crucial aspect, where different optimization criteria could be examined throughout single or multi objective optimization techniques, as reflected in the relative literature of residential EHs. For instance, Fabrizio et al., modeled an EH for a residential building, including many energy systems like photovoltaics (PV), gas boilers (GB), heat pumps (HPs), photovoltaic thermal collectors (PVT), and electric chillers. Their objective was to determine the configuration that minimizes the investment costs, the use of non-renewable sources or the life-cycle costs, under the construction of a Mathematical Programming (MP) model [10]. Barmayoon et al., introduced a new approach in which the economic dispatch problem has been formulated as a non-linear programming optimization problem for a residential EH, including both electrical and heat storage systems [11]. Brahman et al., formulated an optimization problem of a residential EH, for scheduling household appliances, production and storage components, and which receives electricity, natural gas and solar radiation in order to supply required electrical, heating and cooling demands. The objectives were to minimize the total energy cost, considering preferences in terms of desired hot water and air temperature. A multi-objective optimization method was also proposed to include CO_2, NO_x and SO_x emissions [12].

In this paper, a decision-making methodology was developed for optimizing the operation of the energy systems installed in a typical building of 97 m^2 floor area. The multi-energy system was arranged in a generalized EH, which includes conventional and RES energy systems. Initially, the building energy demands were calculated on a monthly basis via the simulation program FineGREEN19, considering the climatic data of Thessaloniki and the geometric peculiarities of the building envelope. Afterwards, an optimization approach, based on the principles of MP, was constructed, in order to provide the optimization scheme of multi-energy systems, considering different criteria. The criteria include the minimization of economic, energy and environmental aspects, considering the concept of LCA. GAMS was used to model the optimization problem. The final decisions of the optimization problem consider the optimal participation rates (operation) of the participated energy systems for covering the monthly energy demands (heating, cooling, domestic hot water) of the examined building, as well as the appropriate thermal installation power. The general methodology is illustrated in the flowchart of Figure 1.

The rest of the paper is structured in three more sections. Section 2 introduces the proposed approach and the basic parameters of the examined case study, while Section 3 presents the results and findings. In Section 4, the basic conclusions were summarized, as well as the future research is highlighted.

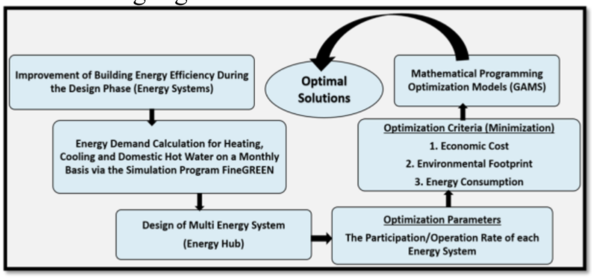

Fig. 1. The framework of the proposed methodology.

2 Materials and Methods

2.1 Basic Parameters

2.1.1 Building Envelope Characteristics

The examined building envelope has been sketched as a three dimensional (3D) drawing in the design environment of FineGREEN, which is an energy building simulation software program, constructed by the 4M corporation. FineGREEN is distinguished for its functionality and the user-friendly interface, incorporating the internationally recognized computing engine EnergyPlus (e+), which is used for all the calculations of the energy simulation [13]. The examined building is a typical apartment with a total surface area of 97 m^2, built in 2018 in the city of Thessaloniki, which belongs to Climatic Zone C, according to the Greek version of the EPBD [14,15]. The examined building can be considered as a newly constructed one, providing that it is thermally insulated adequately, as illustrated from the calculated average thermal transmittance coefficient (U_m = 0.62 W/m^2K). Table 1 presents the basic geometrical features of the building case study.

Table 1. Basic characteristics of the building envelope.

Building Envelope Characteristics	
Height (m)	3
Floor Surface (m^2)	96.7
Volume (m^3)	290.1
Windows Surface (m^2)	23.2
Peripheral Surface (m^2)	147

Considering the climatic data of Thessaloniki and the geometric features of the building envelope, the monthly energy demands for heating, cooling and hot water were calculated in FineGREEN. For Climatic Zone C, the heating period is considered from 15th October to 30th April, while the cooling period from 1st June to 31st August, from which May and September were excluded as neutral months. Figure 2 presents the monthly energy demands for the three examined energy uses. It is evident that the building requires a greater amount of energy for heating than cooling, due to the climatic conditions. The highest energy demands appear in December and January, because of the low temperatures emerged in Thessaloniki. It is important to mention that these two months account for 44% of the energy demand for the total period. Moreover, the domestic hot water demands are the lower ones, and their monthly values depend on the number of the building occupants (200 l/day), as well as the temperature of the supply water. Another crucial aspect is the identification of the demanding power values of the energy systems that are going to be installed. For this case study, the power for heating and cooling is 7.7 kW and 6.7 kW, respectively. The power for water heating is calculated considering the monthly energy demands and 5 hours daily operation (from 1 kW to 1.7 kW).

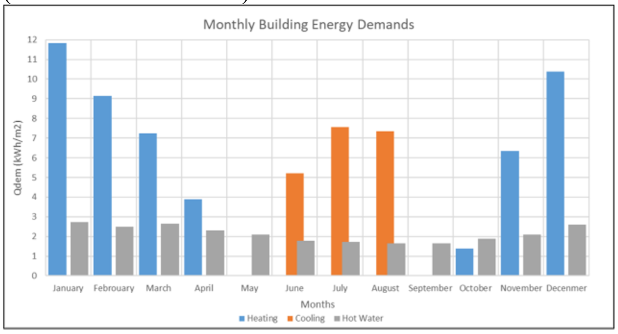

Fig. 2. Monthly energy demands for heating, cooling andhot water uses per building floor surface.

2.1.2 Multi-Energy System Characteristics

The examined multi-energy system includes the following systems: (a) biomass boiler (WD), (b) thermal oil boiler (OB), (c) natural gas condensation boiler (CB), (d) heat pump (HP), (e) electric water heater (EL), and (f) solar thermal collector (SC). In this section, the basic economic, environmental and energy data for each energy system and the available energy sources are presented. Firstly, Table 2 includes the purchasing economic cost of each energy resource, the amounts of GHG emitted from the consumption of each energy resource during the operation of the energy systems, and the primary energy coefficients, as illustrated in the Greek EPBD [14]. Also, in Table 3 the life cycle duration and the energy efficiency of each energy system are presented. The efficiency of the adopted energy systems could be considered as constant for all the systems, including the potential network heat losses. Especially for the solar thermal system, the respective efficiency is focused on the aspect of thermal losses, as the actual one is calculated on the basis of the Capacity Factor (CF). Moreover, for this case study, the economic cost includes the capital purchase and installation costs of the examined energy systems. Regarding the environmental footprint, CO_2 equivalent emissions, as well as the cumulative energy consumption were considered from literature [16,17], according to the LCA principles. The cumulative energy accounts for the total energy based on fossil fuels and renewable sources, which is consumed during the construction of a system or material. LCA is a useful approach to evaluate the environmental impacts of a product or process during its entire life cycle, including pre-use (product), construction and installation, use, and End-of-Life phases. In this study, the boundaries of the LCA methodology include the raw material extraction, the raw material processing, and the production of the final product. The functional unit (FU) is the size of the examined energy system (per kW or m^2). The Life Cycle Inventory was based on the Ecoinvent database [18] and the Environmental Product Declaration (EPD), while the environmental impacts were calculated according to CML 2 Baseline 2000 and Cumulative Energy Demand (CED) methods [19,20]. Table 3 presents the economic, environmental and energy data for the examined energy systems.

Table 2. Basic data of the examined energy sources.

Energy Sources	Economic Cost (€/kWh)	Primary Energy Coefficients (-)	GHG Emissions (kg CO_2/kWh)
Biomass (wd)	0.075	1	0
Thermal Oil (oil)	0.1	1.1	0.264
Natural Gas (ng)	0.078	1.05	0.196
Electric Energy (el)	0.19	2.9	0.989
Solar Energy (sol)	0	0	0

Table 3. Basic data of the examined energy systems (H: heating, C: cooling).

Energy Systems	WB	OB	CB	HP	SC	EL
Efficiency	0.75	0.85	0.92	3^H 2.6^C	0.4	0.98
Life Duration (years)	20	20	15	15	15	15
Installation Cost (€/kW)	250	115	115	225	400 €/m^2	100
Environmental Cost (kg CO_2/kW)	117	134	134	337	1890 kg/m^2	197
Energy Cost (kWh/kW)	23.5	27.2	27.2	142	103 kWh/m^2	15

2.2 Formulation of the Energy Hub Concept

Considering the aforementioned information for the building case study and the proposed multi-energy system, a concept of a residential EH is formulated (Figure 3). The aim of such an EH is to select the optimal operation of the energy systems in order to cover the energy demands for the different energy uses of the building (heating, cooling, hot water). The formulation of the EH includes the identification of input parameters, converters and the outputs. More specifically, in this analysis, the input parameters include the available energy resources that should be selected in order to meet the monthly energy demands for each energy use. These demands, as well as the demanding thermal power represent the output parameters of the EH, which were identified in the first phase of the study via the simulation program. Also, the part of converters in the EH concept is formed by the multi-energy system. In this context, the efficiency of the energy systems indicates the selection of energy resource, and the participation rate identifies the operation rate of the optimal selected energy system. The optimal selection of the participation rate formulates an optimization problem, considering different criteria, which are described in Section 2.3. In this case study, it is assumed that the cooling demands are fully covered by a heat pump, while for the space and water heating, there are available more than one energy systems. In particular, space heating demands could be met by biomass boiler or thermal oil boiler or natural gas condensation boiler or heat pump, while the domestic hot water demands by biomass boiler or natural gas condensation boiler or electric water heater or solar thermal collector, as illustrated in Figure 3.

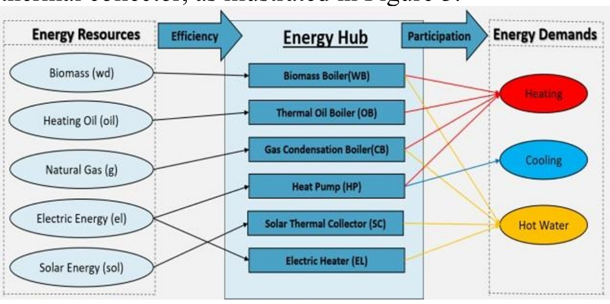

Fig. 3. The proposed concept of Energy Hub.

2.3 Formulation of the Optimization Problem

The proposed study is based on a previous work, where an EH was constructed for the optimal design of multi-energy systems for meeting the domestic hot water demands [21]. The present study focuses on the improvement of building energy performance, during the design phase, considering the optimal selection and operation of the energy systems via the concept of the EH, presented in Section 2.2. As a result, the formulation of mathematical models, which are based on the principles of MP, can lead to the development of a decision-making methodology, including the optimization of single or multi criteria. Such mathematical models include the following basic aspects:

1. Determination of decision variables.
2. Definition of constraints.
3. Definition of objective functions, i.e., optimization criteria.
4. Determination of mathematical techniques solving the problem.

More specifically, the goal of this study is to determine the optimal choice of the appropriate energy systems, considering both their operation and installation under the minimization of the total economic, energy and environmental costs on a monthly basis. The participation/operation rate for each energy system constitutes the decision variables to the optimization problem. For these decision variables, some feasible mathematical constraints should be defined, in order for the MP model to be properly formulated. Moreover, the optimum decisions were made considering three criteria; economic, energy and environmental, which construct the objective functions. The economic criterion aims at the minimization of operation (energy source cost) and installation costs, while the energy and the environmental ones focus on the minimization of the GHG emissions and the primary energy, respectively, where LCA estimations were included. Certainly, these criteria include the cumulative energy consumption and the total CO_2 emitted during the construction of the energy systems. The formulation and resolution of the proposed optimization problem developed through coding in GAMS environment, which is specialized in the formulation, analysis and solution of optimization problems, according to the principles of MP. The problem is characterized as a Linear Programming problem, due to the linear relationships developed between the decision variables in the objective functions and the constraints. The CPLEX solver was used, in order to find the optimal solutions.

2.3.1 Design Variables

As mentioned above, the decision of selecting the optimal participation rate of the energy systems included in the EH is done by a free design variable for each energy use and month. Such design variables indicate the operation rate of each energy system, as well as the size of the system in the base of thermal power. So, for the proposed EH, the following design variables should be introduced:

$$e_{j_H}^{H,wm}, e_{HPC}^{C,sm}, e_{j_{HW}}^{HW,wm} \quad (1)$$

where,

- H, C, HW represent the energy uses for Heating, Cooling and Hot Water, respectively.
- j_H represents the number of energy systems proposed to meet space heating demands (j_H = WB, OB, CB, HPH).
- j_{HW} represents the number of energy systems proposed to meet space heating demands (j_{HW} = WB, CB, EL, SC).
- wm represents the winter months, i.e., October-April.
- sm represents the summer months, i.e., June-August.
- ym represents all year months, including May and September.

Here, it is important to mention that there is no relation between the design variables of each month.

2.3.2 Constraints

It is necessary to develop some physical constraints for the design variables, included in the concept of EH. The formula and interpretation of each constraint are described below.

- Non negativity constraints and upper bounds of 100% participation/operation of each energy system (design variables) for each month and energy use:

$$0 \le e_{j_H}^{H,wm} \le 1, for\ each\ wm \tag{2}$$

$$0 \le e_{HPC}^{C,sm} \le 1, for\ each\ sm \tag{3}$$

$$0 \le e_{j_{HW}}^{HW,wm} \le 1, for\ each\ ym \tag{4}$$

• Constraint of full meeting the monthly energy demands for each energy use by the proposed energy systems:

$$\sum_{j_H} e_{j_H}^{H,wm} = 1, for\ each\ wm \tag{5}$$

$$e_{HPC}^{C,sm} = 1, for\ each\ sm \tag{6}$$

$$\sum_{j_{HW}} e_{j_{HW}}^{HW,ym} = 1, for\ each\ ym \tag{7}$$

2.3.3 Objective Functions

The aim of the proposed model is to select the optimal participation/operation rate of the energy systems, as well as their sizing, for fully covering the thermal energy demands on a monthly basis. Such optimal selection is determined by the design variables, considering three different criteria: economic, energy and environmental ones. In this context, three objective functions were formulated for each month, considering the examined energy uses for heating, cooling and water heating, according to Equation 8. The energy systems that are available to meet the energy needs of each energy use were indicated in the formulation of the proposed EH (Section 2.1). Although Equation 8 remains the same for every month, the terms of space heating and cooling were deleted when a summer or a winter month is examined, respectively. These terms were also excluded from this equation when a neutral month (May and September) was examined.

$$Min \begin{bmatrix} Cost \\ En \\ Env \end{bmatrix} = \sum_{i_H, j_H} \left(\begin{bmatrix} Cost_{i_H} \\ En_{i_H} \\ Env_{i_H} \end{bmatrix} \cdot \frac{Q_{dem}^H}{\eta_{j_H}} \cdot e_{j_H}^H + \begin{bmatrix} Inst_{j_H} \\ CEn_{j_H} \\ GHG_{j_H} \end{bmatrix} \cdot \frac{P_{dem}^H}{LD_{j_H}} \cdot e_{j_H}^H \right) + \left(\begin{bmatrix} Cost_{el} \\ En_{el} \\ Env_{el} \end{bmatrix} \cdot \frac{Q_{dem}^C}{COP_{HPC}} \cdot e_{HPC}^C + \begin{bmatrix} Inst_{HPC} \\ CEn_{HPC} \\ GHG_{HPC} \end{bmatrix} \cdot \frac{P_{dem}^C}{LD_{HPC}} \cdot e_{HPC}^C \right) + \sum_{i_{HW}, j_{HW}} \left(\begin{bmatrix} Cost_{i_{HW}} \\ En_{i_{HW}} \\ Env_{i_{HW}} \end{bmatrix} \cdot \frac{Q_{dem}^{HW}}{\eta_{j_{HW}}} \cdot e_{j_{HW}}^{HW} + \begin{bmatrix} Inst_{j_{HW}} \\ CEn_{j_{HW}} \\ GHG_{j_{HW}} \end{bmatrix} \cdot \frac{P_{dem}^{HW}}{LD_{j_{HW}}} \cdot e_{j_{HW}}^{HW} \right) \tag{8}$$

where,

• i_H: number of the energy sources that could be used for space heating (i_H = wd, oil, ng, el).
• j_H: number of the energy systems proposed to meet space heating demands (j_H =WB, OB, CB, HPH).
• i_{HW}: number of the energy sources that could be used for water heating (i_{HW} =wd, ng, el, sol).
• j_{HW}: number of the energy systems proposed to meet space heating demands (j_{HW} = WB, CB, EL, SC).
• Cost (€), En (kWh), Env (kg CO_2): represent the objective function parameters of the examined criteria, i.e., the minimization of economic, energy and environmental costs, respectively.
• Q^H_{dem}, Q^C_{dem}, Q^{HW}_{dem} (kWh): monthly energy demands for space heating, cooling and hot water, respectively.
• P^H_{dem}, P^C_{dem} P^{HW}_{dem} (kW): the demanding power values for each energy use.
• $Cost_{iH}$, $Cost_{el}$, $Cost_{iHW}$ (€/kWh): the economic costs of the energy sources that could be used for space heating, cooling, and hot water, respectively (Table 2).
• En_{iH}, En_{el}, En_{iHW} (-): the primary energy coefficients of the energy sources that could be used for space heating, cooling, and hot water, respectively (Table 2).
• Env_{iH}, Env_{el}, Env_{iHW} (kg CO_2/kWh): the GHG emissions of the energy sources that could be used for space heating, cooling, and hot water, respectively (Table 2).
• $Inst_{jH}$, $Inst_{HPC}$, $Inst_{jHW}$ (€/kW): the installation costs of the energy systems proposed to meet energy demands for space heating, cooling, and hot water, respectively (Table 3).
• CEn_{jH}, CEn_{HPC}, CEn_{jHW} (kWh/kW): the cumulative energy consumed during the construction (energy costs) of the energy systems, which are proposed to meet the energy demands for space heating, cooling, and hot water, respectively (Table 3).
• GHG_{jH}, GHG_{HPC}, GHG_{jHW} (kg CO_2/kW): the GHG emitted during the construction (environmental costs) of the energy systems, which are proposed to meet the energy demands for space heating, cooling, and hot water, respectively (Table 3).
• LD_{jH}, LD_{HPC}, LD_{jHW} (years): the life duration of the energy systems proposed to meet energy demands for space heating, cooling, and hot water, respectively (Table 3).
• n_{jH}, COP_{HPC}, n_{jHW} (years): the efficiency (or Coefficient of Performance for the heat pumps) of the energy systems proposed to meet energy demands for space heating, cooling, and hot water, respectively (Table 3).

Here, it is important to mention that the P^{HW}_{dem} (kW) value represents the collecting area for the solar thermal system A^{HW}_{sol} (m^2).

3 Energy Hub Optimization Results

3.1 Optimal Results for Heating and Cooling

Table 4 presents the optimal energy system selection for meeting the heating and cooling monthly demands, considering the three examined criteria, i.e., the minimization of the total economic, energy and environmental costs. The operation rate is 100% for each month, showing that only one energy system is going to cover the thermal demands of each month. More specifically, Table 4 shows that the heat pump (HPH, HPC) is preferable for both economic and energy criteria for meeting the heating demands, which is due to their high efficiency (COP) that decreases the monthly energy consumption, compared to the other energy systems, even if the economic and the energy data are lower in some of them. In the economic criterion and for covering the space heating demands, the annual fraction of the heat pump and the natural gas boiler is 71.5% and

28.5%, respectively. The results for minimizing the environmental footprint differ from the other two criteria, because the biomass boiler is considered as the environmentally friendlier energy system, with a 100% participation rate for meeting the heating demands. This is due to the zero primary energy coefficient and the minimum environmental cost.

Focusing on the economic criterion, the natural gas boiler is preferable to be installed in April and October, because of their minimum heating demands, compared to the other winter months. The replacement of the heat pump in these months is related to the low installation cost of the natural gas boiler, too. However, this replacement is not taking place in the energy criterion, because the primary energy consumption of the heat pump is lower than for the other systems, due to the heat pump's high efficiency, even if its primary energy coefficient and its cumulative energy cost are the higher ones.

Table 4. Optimal energy system selection for heating and cooling demands for each month and criterion.

	Optimization Criteria for Heating and Cooling		
Months	**Economic**	**Energy**	**Environmental**
January	HPH	HPH	WB
February	HPH	HPH	WB
March	HPH	HPH	WB
April	CB	HPH	WB
May	-	-	-
June	HPC	HPC	HPC
July	HPC	HPC	HPC
August	HPC	HPC	HPC
September	-	-	-
October	CB	HPH	WB
November	HPH	HPH	WB
December	HPH	HPH	WB

In Figure 4, the economic values for space heating and cooling, separating the operational and the installation ones, for each month and criterion were presented. It is obvious that the total costs are the highest in the environmental criterion for the winter months, due to the dominance of the biomass boiler. The costs in the economic criterion are similar to the energy ones, excluding May and October, because of the natural gas boiler participation, as described above. In the summer months, the total economic costs are equal for all the examined criteria, as the cooling heat pump was set from the formulation of the EH, to fully cover the cooling demands. It is also clear that the operational costs are higher than the monthly installation ones, for almost all months and criteria. An exception to this can be seen in October for the energy and the environmental criteria, where the heat pump and the biomass boiler were selected.

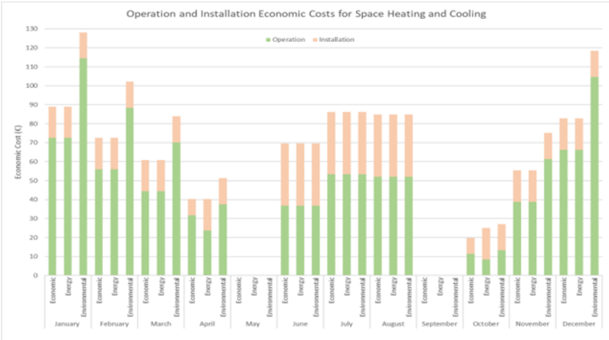

Fig. 4. Economic values for space heating and cooling for each month and criterion.

3.2 Optimal Results for Hot Water Use

As for the hot water demands, Table 5 presents the optimal energy system selection for each month and for the three examined optimization criteria. The solar thermal collector, which can be considered as RES system, is favoured for all year months in the energy criterion, while it is preferable for the summer months in the economic criterion. The annual participation of the solar thermal collector for water heating in the economic criterion is about 2/3, with a maximum solar surface of $6m^2$ in March. The maximum solar surface for the energy criterion ($14m^2$) is bigger than for the economic one, as the solar thermal system is preferable to meet the hot water demands even in winter months. The minimization of the environmental footprint was succeeded by a biomass boiler for water heating. Focusing on the economic criterion, the natural gas boiler is preferable to be installed in the winter months (November-February), because of the lower available solar radiation, compared to the other months, as well as the low installation cost of the natural gas boiler. In winter months, a bigger solar thermal collector surface is required to meet the hot water demands, which leads to a higher installation cost. However, this replacement is not taking place in the energy criterion, because of the primary energy consumed during the operation of the natural gas boiler, even if the cumulative energy cost during the construction of the solar system is higher.

Table 5. Optimal energy system selection for hot water demands for each month and criterion.

	Optimization Criteria for Hot Water		
Months	**Economic**	**Energy**	**Environmental**
January	CB	SC	WB
February	CB	SC	WB
March	SC	SC	WB
April	SC	SC	WB
May	SC	SC	WB
June	SC	SC	WB
July	SC	SC	WB
August	SC	SC	WB
September	SC	SC	WB
October	SC	SC	WB
November	CB	SC	WB
December	CB	SC	WB

Figure 5 presents the economic values of the energy system operation and installation for each month and criterion. The total economic costs in the economic criterion are equal to the ones of the energy criterion, except for the winter months, where the natural gas boiler is used, minimizing the costs. Moreover, the costs in the environmental criterion are higher compared to the ones in the other two criteria, due to the exclusive participation of the biomass boiler, whose operational economic cost is high. The only exception to this is illustrated in December, where the solar thermal collector installation cost of the energy criterion is higher than the ones of the environmental criterion. This is due to the low levels of solar irradiation of this month, requiring greater solar surface. It is also obvious that the operational costs are higher than the monthly installation ones in all months for the economic and energy criteria, when the solar thermal collector is excluded. Last but not least, the total economic costs are lower in the summer months, which is due to the fact that the demanding hot water energy is decreased, as well as the requires solar thermal surface is smaller, because of the higher levels of solar irradiation.

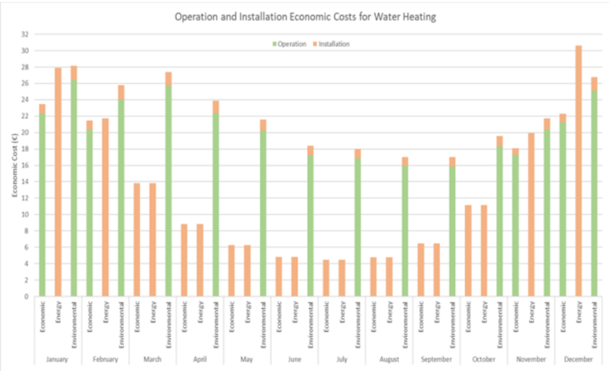

Fig. 5. Economic values for water heating for each month and criterion.

3.3 Annual Results

In Figure 6, the results on annual basis are presented, considering all the examined energy uses. The annual values derive from the monthly EH optimization, without any compromised decisions. It is clear that the economic criterion conforms with the energy one, even if the latter has a lower environmental footprint, due to the exclusive participation of the solar thermal collectors and heat pumps. The annual economic values are similar for the economic and energy criteria, noting a minor differentiation of the proper energy systems participation. However, these two criteria are conflicting to the environmental one, where the biomass boiler dominates, as the total cost and energy increase by 60% and 66% respectively, compared to the minimized values.

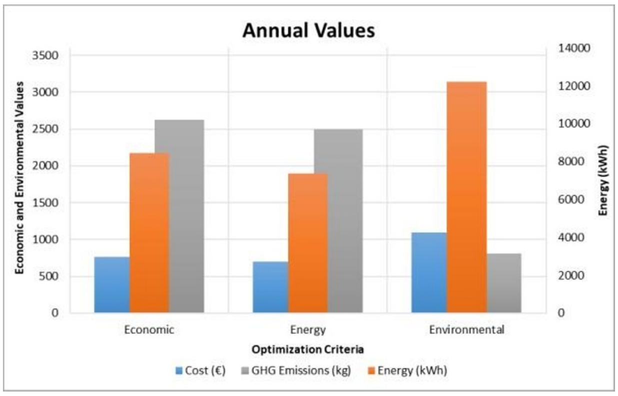

Fig. 6. Annual values for each optimization criterion.

3.4 Sensitivity Analysis

In this section, a short sensitivity analysis is taking place, considering the economic criterion. More specifically, the sensitivity analysis shows the differentiation in the optimal selection of the energy systems considering several values for the cost of electricity (€/kWh). The marginal cost values were presented in Figure 7, for meeting the space and water heating demands.

For the space heating, it is obvious that the natural gas boiler would be economically preferable in case the electricity cost overcame the value of 0.23 €/kWh for all year months. Only in October this marginal value is apparently low (0.073 €/kWh), due to its low heating demands. As for water heating, the electricity cost should reach the value of 0.083 €/kWh, in order for the electric heater to replace the natural gas boiler for the winter months. However, this value should be extremely lower in the summer months for the replacement of the thermal solar collector.

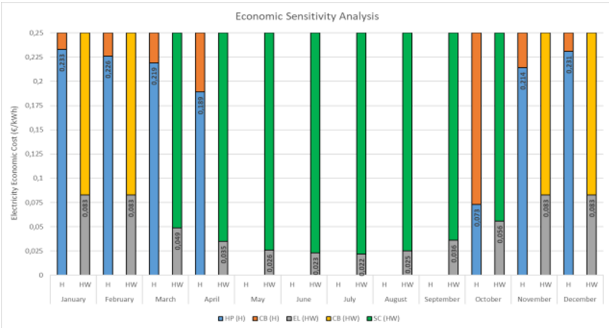

Fig. 7. Economic sensitivity analysis for the electricity cost.

4 Conclusions

The application of optimization algorithms in the design of multi energy systems highlights the in-depth analysis of the economic, energy and environmental parameters, as well as it provides the possibility of evaluating the results and including constrains regarding the limitation of conventional energy sources. The formulation of Mathematical Programming models for multi energy systems optimization, under the concept of the Energy Hub, was the goal of this study, in order to result in optimal solutions, considering the energy system rates of participation. In this context, a decision-making methodology is implemented in the thermal energy

demands of a residential building, so as to select the optimal energy system operation, considering economic, energy and environmental criteria. All in all, the use of the optimization models can improve and facilitate the building design process by analyzing the advantages and drawbacks of the various technologies and allowing the comparative evaluation of the considered alternatives.
According to the present case study, in terms of the economic and energy criteria, the optimal energy system is the heat pump for covering the heating and cooling energy demands, due to its high efficiency. the participation of the natural gas boiler is optimal for months with low energy demands, because of its low installation and operation cost. While the biomass boiler dominates in the environmental criterion, considering zero GHG during system's operation, for all the examined energy uses. Also, for meeting hot water demands, solar thermal collectors are preferable for the economic and energy criteria, in order for the available solar irradiation to be utilized. A short sensitivity analysis was conducted by alternating the cost of electricity, resulting that the natural gas boiler would replace the heat pump only in high electricity costs. All in all, the annual results show that the environmental criterion is conflicting to the other two, highlighting the problem of multi-criteria optimization, which is for future research extensions. In addition to this, further research may focus on utilizing a shorter time step for the optimization problem, investigating in depth the techno-economical and environmental parameters of the energy systems. Also, the sensitivity analysis could be expanded, considering the economic costs of several energy sources, as well as the installation costs of the energy systems, resulting in useful findings. In any case, the proposed tool is suitable for examining different case scenarios, in a relatively fast way.

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