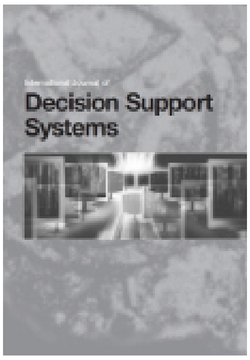

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A decision-making approach based on the TOPSIS method for supporting energy efficiency financing in buildings

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A decision-making approach based on the TOPSIS method for supporting energy efficiency financing in buildings

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Abstract: The European Commission considers energy efficiency (EE) in buildings as one of the key pillars to meet Europe's climate goals. To promote sustainable investments in buildings, decision analysis can be utilised to detect the most attractive and profitable EE solutions. The scope of this paper is the selection and application of the most appropriate multi-criteria approach using important evaluation criteria from investors' viewpoint, to assist financing bodies in assessing potential energy renovation projects. The technique for order of preference by similarity to ideal solution (TOPSIS) method is selected as the most suitable since it can be easily modelled to handle large amounts of alternatives. The proposed methodology is applied to a dataset of 48 EE projects in Greece. Results reveal that specific categories of renovation measures, such as upgrades of heating systems, might be more attractive for investors compared to other actions.

Keywords: sustainable investments; building renovation; multi-criteria analysis; energy transition; energy efficiency projects; energy retrofitting.

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1 Introduction

The building sector in the European Union (EU) accounts for a large percentage of energy consumption (around 40%), as well as CO_2 emissions (over 1/3 of total greenhouse gas emissions) (Energy Efficiency Directive, 2023). The European Commission (EC) considers energy efficiency as one of the key pillars to meet EU's climate goals, to reduce dependence on fossil fuels and increase security of supply. The 'energy efficiency first' (EE1st), a principle that complements EU objectives, especially in the areas of sustainability, climate neutrality and green growth, can be defined as taking utmost account of cost-efficient energy efficiency measures in shaping energy policy and making relevant investment decisions (Energy Efficiency First Principle, 2018). EU policy makers have recognised the severe environmental consequences of excessive energy consumption in buildings, therefore, the improvement of the energy performance of the building stock has become an important pillar towards achieving the energy transition and accomplishing carbon neutrality (Mexis et al., 2021a, 2021b; Papapostolou et al., 2020a).

The targets set by the EU are also highlighted in relevant directives, such as the Energy Efficiency Directive (EU/2023/1791) (EED) (Energy Efficiency Directive, 2023) and the Energy Performance of Buildings Directive (EU/2010/31) (EPBD) (Energy Performance of Buildings Directive, 2023). In addition, the Renovation Wave initiative, part of the EU Green Deal, aims to optimise building renovation across the EU encouraging investment and financing by addressing current low decarbonisation and renovation rates of around 1% across EU and by aiming to tackle underlying barriers for improving EE of the EU building stock (Communication on the European Green Deal, 2019; Renovation Wave, 2020). The low renovation rates are a result of various barriers: these include technical, behavioural, financial and social aspects, among other factors. The problem is intense when it comes to deep renovation, which is defined as refurbishment that decreases both the delivered and the final energy consumption of a building by a noteworthy percentage in comparison with the pre-renovation levels, resulting in a very enhanced energy performance. This is likely due to the fact that deep renovation has often been regarded as challenging from a technical point of view (D'Oca et al., 2018).

To decrease energy consumption in buildings, it is necessary to leverage the most suitable EE measures, to ensure enhanced energy performance and guarantee energy savings while maintaining comfort (Karakosta and Corovessi, 2023). Several measures can improve the building in terms of energy performance, including insulation of walls, roofs and floors (Sarihi et al., 2021), installation of less energy consuming heating and cooling systems (Akgüç and Yılmaz, 2022), more energy efficient lighting (Dubois et al., 2015), local generation of renewable energy, for example through solar panels (Liu et al., 2013), as well as installation of automated systems (O'Grady et al., 2021), to improve energy management (Ardente et al., 2011; Fenz et al., 2023). However, renovation rates in Europe continue to be too low and the EE potential of the European building stock remains untapped (Karakosta et al., 2023b; Sarmas et al., 2022a, 2022b).

Various barriers and challenges hinder the successful implementation of EE projects in buildings in Greece, as well as the whole Europe (Karakosta and Papapostolou, 2023). For instance, it is important to estimate energy savings resulted from the examined EE measures, but the estimations and predictions are not always accurate (Papapostolou et al., 2020a). This is referred to as the 'energy performance gap' in relevant literature, highlighting the fact that the actual energy savings achieved thanks to the applied renovation measures do not correspond to the originally expected savings as they have been calculated in the design phase of the EE projects (Cuerda et al., 2020; Turner et al., 2008). Furthermore, there is a chance that after installation of new systems, proper maintenance is neglected leading to inefficient operation, compromising the overall reduction of energy consumption and CO_2 emissions (Papapostolou et al., 2020b; Yeatts et al., 2017).

Besides technical aspects, the EE of a renovated building might be negatively influenced by behavioural issues in Greece (Karakosta et al., 2021). For example, due to behavioural bias, consumers might change their energy usage habits after the renovation, thus consuming more energy than expected and reducing the environmental benefits of the applied EE measures (Papapostolou et al., 2020; Sweatman and Managan, 2010). Lack of awareness regarding the benefits of EE interventions in buildings also negatively affects renovation rates (Alam et al., 2016; Baek and Park, 2012; van Oorschot et al., 2016; Vogel et al., 2015).

Although the aforementioned technical and behavioural issues are of vital importance, the financial barriers of renovation projects in the building sector are admittedly the most significant (Albrecht and Hamels, 2021; Mexis et al., 2021a, 2021b). Incompatible priorities among building owners, who primarily make the decisions about EE interventions, and tenants, who are the actual energy consumers, can also create problems when considering retrofitting projects in buildings. This is referred to as the problem of 'split incentives' in relevant literature (Bertone et al., 2016; Kleanthis et al., 2022; Melvin, 2018). High upfront cost might discourage building owners or managers from improving the energy performance of an asset through renovation. They might even favour cheaper measures over more effective solutions because of this (Bertone et al., 2016; Koutsandreas et al., 2022; van Oorschot et al., 2016). Therefore, unavailability of financial resources and lack of access to finance severely decrease willingness to apply EE interventions in buildings in Greece as well as the whole Europe (Bertone et al., 2016; Karakosta and Mylona, 2022; Karakosta et al., 2023a). Besides high initial costs, insufficient knowledge about available financial mechanisms for renovation projects, repayment uncertainty and inaccessibility to private capital inhibit the implementation of retrofitting actions in buildings (Bertone et al., 2016; Karakosta et al., 2021).

Based on all of the above, it becomes apparent that the pressure to increase the rate and depth of renovations in existing buildings and the need to face the aforementioned challenges deriving by the combination of technical, engineering, administrative and legal knowledge is of great importance. On top of that, a smooth collaboration between project developers and funding institutions is needed.

In order to encourage the application of EE measures in buildings and upscale renovation rates, investors, financing bodies and financial stakeholders in general, need to be motivated to financially support retrofitting projects. However, financial stakeholders willing to engage in such projects are often overwhelmed by the various criteria that need to be taken into account, rendering the decision-making process complex and challenging.

The scope of the paper is to propose an appropriate methodology to assist financial stakeholders in the decision-making procedure, by helping them evaluate potential energy related building renovation projects, so that they can find the most attractive investment according to their preferences. The proposed methodology is applied to a dataset of 48 EE projects in Greece and was based on multi-criteria analysis (MCDA). The projects are an indicative set of private office buildings in Greece, located mainly in the region of Attica, representing a broad range of EE measures, including heating, cooling, automation, lighting, and renewable energy sources installation.

Multi-criteria analysis is proven as the appropriate means to merge and analyse all of the perspectives associated with the decision-making process (Aspinall and Hill, 2007). It represents a sound methodology applied internationally during the last decades in several problems of strategic environmental and energy planning (Kurt, 2014; Mourmouris and

Potolias, 2013; Papapostolou et al., 2014). The use of multi-criteria analysis has many times supported the decisions in the energy sector and energy planning, as its methods are capable to solve very complex energy management problems (Arsenopoulos et al., 2020; Bortoluzzi et al., 2021; Neofytou et al., 2020a, 2020b; Papapostolou et al., 2022; Vallecha et al., 2021).

In order to exploit the disparate preferences of the investors that play the role of the decision makers, as well as to manage the uncertainty that arises when solving the decision problem, a methodological assessment is developed, using the multi-criteria technique for order of preference by similarity to ideal solution (TOPSIS) method.

The outputs provide a clear picture of the preferred options and their interactions with the evaluation criteria, while the conclusions focus on the categories of EE investments that might be more attractive for financiers, based on the factors that have been designated as crucial through consultation with stakeholders involved in sustainable and EE financing.

Apart from this introductory section, the remaining paper is structured as follows:

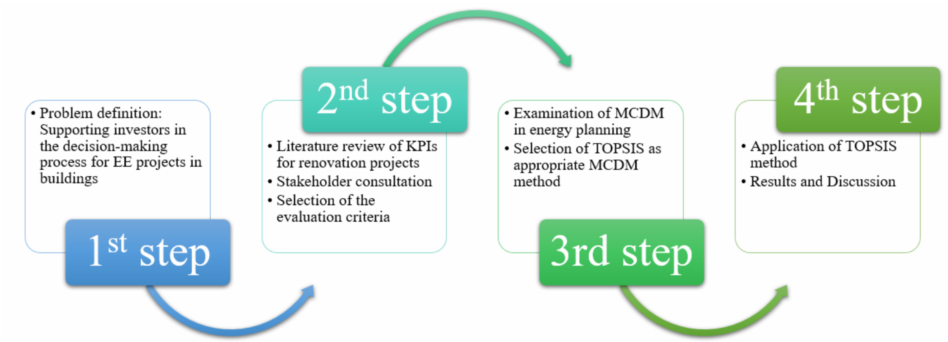
- in Section 2, the steps of the approach followed to result in a suitable methodology are described
- in Section 3, the decision-making problem is defined and formulated by detecting the criteria, as well as the alternatives that are going to be evaluated based on them
- in Section 4, the use of the TOPSIS method in energy planning and EE in general as conducted in previous research is examined, and the steps of the methodology are shown
- in Section 5, the methodology is applied and the results extracted from it are presented
- in Section 6, the results are discussed and analysed
- in Section 7, conclusions are drawn and potential areas of future research are proposed.

2 Overview of the methodological approach

An overview of the steps followed to apply the proposed methodology is illustrated in Figure 1.

The first step consists of the definition of the problem, which is the need to support investors in evaluating EE projects in buildings, thus facilitating the decision-making process. As a second step, the evaluation criteria need to be specified. To achieve this relevant literature is examined and the main key performance indicators (KPIs) of energy renovation projects in buildings are listed and categorised. Through stakeholder consultation, the KPIs that matter the most to investors and financing bodies are determined and, therefore, become the evaluation criteria of the decision-making problem. Subsequently, as a third step, the most appropriate MCDA method was selected, after examination of the most common methods used in energy planning and after taking into account the specific characteristics of the decision-making problem. This MCDA method (TOPSIS) was applied to assess, compare, and rank the alternatives from the most to the least attractive. The alternatives consist of 48 EE investments in buildings. More specifically, the selected projects for the application of TOPSIS in this paper are an indicative set of private office buildings in Greece, located mainly in the region of Attica (thus, they are in the same climate zone) representing a broad range of EE measures, including heating, cooling, automation, lighting, and renewable energy sources installation. Finally, the resulting rankings were analysed providing valuable insight regarding sustainability investments in the building sector.

Figure 1 Steps of the methodological approach (see online version for colours)



3 Problem formulation

In this section, the decision-making problem is formulated, starting from the specification and selection of the evaluation criteria, and proceeding with the selection of the most appropriate MCDM method.

To specify the evaluation criteria of the decision-making problem, the most important KPIs for the evaluation of EE projects are examined.

3.1 Key performance indicators review

When considering numerous EE investments, financial stakeholders are likely to prioritise renovation projects according to various evaluation criteria. These criteria could include heterogeneous KPIs, for instance energy related indicators, financial aspects, environmental factors, or even social parameters. KPIs are of vital importance when assessing the expected utility of different renovation measures, while monitoring them could lead to increased chances of achieving the established EE targets (Alwaer and Clements-Croome, 2010).

The first step towards specifying the most important KPIs for EE projects is examining relevant literature (Alwaer and Clements-Croome, 2010; Balaras et al., 2014; Bertone et al., 2016; Campos-Carriedo et al., 2023; Al Dakheel et al., 2020; Dunphy et al., 2012; Feifer, 2011; Ho et al., 2021; Kylili et al., 2016; Li et al., 2017, 2020; Martinaitis et al., 2007; McGinley et al., 2022; Ngacho and Das, 2014; Panicker et al., 2022; Pippi et al., 2020; Ugwu and Haupt, 2007; Walasek and Barszcz, 2017; de Wilde and Tian, 2010; Zachariadis et al., 2018). Based on the literature review conducted, some of the most important indicators are presented in the following sub sections.

3.1.1 Energy-related and environmental KPIs

- *Energy consumption after renovation:* perhaps one of the most substantial KPIs, since it reflects how effective the applied measures were towards increasing the energy performance of the building. It should be highlighted that one should not only focus on the consumption without considering changes in the environment or climate (for instance, if heating degree days are too high, increased consumption is expected, but this does not necessarily indicate that the applied EE measures were not effective enough). As a consequence, it is important to compare energy consumption after renovation with baseline energy consumption while also taking into account available data relevant to the climate and weather conditions. Alternatively, energy savings can be considered as a KPI, instead of energy consumption (Balaras et al., 2014).
- *Estimated energy performance certification (EPC) after renovation:* the EPC level is a very useful KPI, which represents the energy performance of a building. It is fairly easy to understand and, therefore, stakeholders without expertise in EE or energy related topics in general can also easily understand it (McGinley et al., 2022).
- *Greenhouse gas emissions after renovation:* similarly, to energy consumption, greenhouse gas emissions represent the direct impact of the renovation measures in the environment, and can also be expressed as the avoided emissions (CO_2 abatement) (Li et al., 2017).
- *Renewable energy sources integration:* sustainable technologies in buildings which can reduce their negative environmental impact, or even turn the asset into a net zero building, include renewable energy generating systems. These are usually photovoltaic panels turning solar energy into electrical energy, but they can also be small-scaled wind turbines. In any case, production of renewable energy at a local level is a very important and positive indicator when considering EE investments in buildings.
- *Peak energy demand reduction:* indicates the reduction of peak load for building operations as a result of retrofitting actions (Ho et al., 2021).
- *Water consumption:* besides electricity consumption, consumption of other resources, such as water, could also be taken into account in case they are influenced by the applied renovation measures (Ugwu and Haupt, 2007).

3.1.2 Economic and financial KPIs

- *Return on investment (ROI):* ROI is a measure of the financial return on investment in the renovation project. It is calculated by dividing the net benefits of the project by the total cost of the project. A high return on investment indicates that the project is economically attractive (Walasek and Barszcz, 2017).
- *Net present value (NPV):* NPV is a measure of the net economic benefit of the project over its lifetime. It is calculated by subtracting the present value of project costs from the present value of project benefits. A positive NPV indicates that the project is economically viable and provides a net economic benefit (Chan and Chan, 2004).

- *Internal rate of return (IRR):* it measures the annual rate of return of the project over its lifetime. A high IRR indicates that the project is financially attractive (Pippi et al., 2020).
- *Payback period:* this KPI measures the time it takes the project to recoup its initial investment through the savings generated by the project. A shorter payback period indicates that the project provides a faster return on investment (McGinley et al., 2022).
- *Cost effectiveness:* it is used to determine whether a project's benefits exceed its costs, indicating the relationship between the investment needed for an EE measure and the profit it is expected to deliver (Bertone et al., 2016).
- *O&M cost reduction:* O&M refers to the operational and maintenance cost, which is likely to be reduced as a result of renovation measures, therefore it should be considered as an additional KPI if applicable (Bertone et al., 2016).
- *Life cycle cost:* this KPI is a measure of the total cost of the project throughout its life cycle, including initial investment, operation and maintenance costs and end-of-life disposal costs. A low LCC indicates that the project provides long-term cost savings (McGinley et al., 2022).
- *Avoidance cost:* it expresses the average cost of an intervention for each kWh of energy saved over the life of the measure. Avoidance costs are a benchmarking indicator that can be used to classify the overall cost efficiency of different energy saving interventions, taking into account their expected lifetime savings (Zachariadis et al., 2018).
    - *Capital expenditure (CAPEX):* CAPEX expresses the total investment made in EE projects in a building. This is one of the most important KPIs, since evaluating resource allocation helps organisations monitor the effectiveness of their investments in achieving EE goals (Papapostolou et al., 2020a).

3.1.3 Sociological KPIs

- *Comfort level:* when applying EE interventions to a building, it is important to attempt to reduce energy savings without affecting the comfort level of the people using the building. This is of utmost importance in workspace environments, because comfort levels might affect productivity (Chan and Chan, 2004).
- *Health and safety:* lower frequency of issues, accidents, minor incidents related to the health and safety of the occupants using the building indicate that the renovation also benefited the building in this aspect (McGinley et al., 2022).
- *Accessibility:* accessibility is a vital social KPI, since it showcases that the building is accessible and functional for everyone, regardless of disabilities (Kylili et al., 2016).
- *Occupants' satisfaction:* the attitude of the building owners and/or tenants towards potential renovation measure and their satisfaction after the measure has been applied should not be neglected (McGinley et al., 2022).

- *Indoor environmental quality:* it is important to consider the impact of the renovation on the quality of the air, as well as the indoor environmental conditions such as temperature and humidity (McGinley et al., 2022).

The KPIs are summarised in Table 1.

An additional aspect that could be considered, that does not fall under the above-mentioned categories, is the digitalisation aspect (Höjer and Mjörnell, 2018). More specifically, the existence of metering infrastructure is important, especially when the financing scheme is performance-based, that is to say, the repayment depends on the energy savings resulted from the EE project (Bertoldi et al., 2021). In this case, digitalisation enables better monitoring and validation of the energy consumption as well as innovative approaches of financing such as pay-for-performance schemes (Tzani et al., 2022). Thus, the implementation of the International Performance Measurement and Verification Protocol is improved (IPMVP, 2022). Another important KPI when EE measures are considered is the Smart Readiness Indicator (SRI), which is a score indicating the readiness of a building to adapt operations to the needs of occupants by minimising energy use (Vigna et al., 2020).

3.2 Selection of the evaluation criteria

With the aim of detecting the most important KPIs to include them as criteria in the MCDA method, a consultation procedure took place. More specifically, financial stakeholders were asked to point out which of the aforementioned KPIs they would consider when selecting among different EE investment packages.

The stakeholder consultation procedure was conducted in the context of the LIFE EU-funded project Energy Efficiency Aggregation platform for Sustainable Investments (ENERGATE) (https://energate-project.eu/). ENERGATE aims to develop an information communication technology (ICT) platform which will function as a marketplace for EE projects in buildings. The platform will bring diverse stakeholders involved in such projects, constituting a user-friendly and intuitive interface which will ensure optimal communication and interaction between different market actors, so as to encourage investments in renovation projects and increase renovation rates. The different platform users are divided in two categories, the supply side, including building stakeholders aiming to apply EE projects for which they seek financial support, and the demand side, including financial stakeholders interested in investing in EE projects for which they are able to provide funds. The two sides are represented by five pilot organisations, whose role in the project is to assist in the platform's development, by providing initial data, testing, and validating the marketplace functionalities.

More specifically within the framework of a training workshop entitled 'Energy Efficiency in Buildings, from Financing to Implementation' which was organised in Madrid in September 2023, stakeholders from financing and energy sectors were engaged in order to extract important information on the most important KPIs that they are taking into account when it comes to assess building renovation projects (Energy Efficiency in Buildings, from Financing to Implementation: Survey Insights from the ENERGATE Workshop, 2023).

Table 1 KPIs summarised

Category	*KPIs*	*Sources*
Energy-related and environmental KPIs	Energy consumption after renovation	Balaras et al. (2014) and Zhang et al. (2021)
	Estimated energy performance certification (EPC) after renovation	McGinley et al. (2022) and Coyne and Denny (2021)
	Greenhouse gas emissions after renovation	Li et al. (2017) and Zhang et al. (2021)
	Renewable energy sources integration	Ahmed et al. (2022)
	Peak energy demand reduction	Ho et al. (2021) and Ciancio et al. (2020)
	Water consumption	Ugwu and Haupt (2007) and Rose et al. (2021)
Economic and financial KPIs	ROI	Walasek and Barszcz (2017) and Mustafaraj et al. (2023)
	NPV	Chan and Chan (2004) and Rockstuhl et al. (2021)
	IRR	Pippi et al. (2020) and Chen et al. (2020)
	Payback period	McGinley et al. (2022) and Zhang et al. (2021)
	Cost effectiveness	Bertone et al. (2016) and Economidou et al. (2020)
	O&M cost reduction	Bertone et al. (2016) and Chen et al. (2020
	Life cycle cost	McGinley et al. (2022) and Toosi et al. (2020)
	Avoidance cost	Zachariadis et al. (2018)
	CAPEX	Papapostolou et al. (2020a)
Sociological KPIs	Comfort level	Chan and Chan (2004) and López-Bernabé et al. (2021)
	Health and safety	McGinley et al. (2022) and Wen et al. (2022)
	Accessibility	Kylili et al. (2016) and Ivanova and Middlemiss (2021)
	Occupants' satisfaction	McGinley et al. (2022) and Yang et al. (2020)
	Indoor environmental quality	McGinley et al. (2022) and Yang et al. (2020)

Through the consultation process, it became evident that financial stakeholders mainly focus on financial KPIs, as expected. However, they are also interested in the impact of their investment on energy consumption of buildings, so as to simultaneously assess the EE potential and environmental impact of the examined renovation projects. More specifically, the projects can be evaluated based on the following criteria:

- energy savings (%)
- avoidance cost (€/kWh)
- payback time (years)
- internal rate of return (%)
- CAPEX (€).

4 Selection of MCDA method

MCDA methods have been used in problems relevant to energy planning and EE, as it has been proven that they can successfully support decision making in a variety of situations and circumstances (Mardani et al., 2017). Some of the most important MCDA methods used in such problems are mentioned below:

- Analytical hierarchy process (AHP): AHP is a widely used method, utilised to prioritise criteria and alternative solutions based on pairwise comparisons (Saaty, 1980; Chourabi et al., 2019).
- Elimination and choice translating reality (ELECTRE): ELECTRE is a family of methods that focus on ranking and sorting alternatives based on concordance and discordance (Mary and Suganya, 2016; Govindan and Jepsen, 2016).
- Preference ranking organisation method for enrichment evaluations (PROMETHEE): in PROMETHEE, alternatives are compared based on preference functions (Liao and Xu, 2014).
- Technique for order of preference by similarity to ideal solution (TOPSIS): TOPSIS prioritises alternatives based on their distance from an ideal and anti-ideal solution (Roszkowska, 2011).

4.1 Applications of the TOPSIS method in the energy sector

TOPSIS method was initially presented by Hwang and Yoon (1981) and its basic idea originates from the concept of a displaced ideal point from which the compromise solution has the shortest distance (Yue, 2011).

Based on the literature, it becomes apparent that the TOPSIS method is quite a useful one when it comes to applications relevant to EE, primarily thanks to its simplicity and its ability to easily incorporate large amounts of alternatives and prioritise solutions considering both quantitative and qualitative criteria (Papapostolou et al., 2020b). TOPSIS is a widely accepted multi-attribute decision-making technique owing to its simultaneous consideration of the ideal and the anti-ideal solutions, and easily programmable computation procedure. Its basic principle has to do with the fact that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS), compared to the others. Nevertheless, existing TOPSIS based procedures tend to ignore the common issue of multicollinearity trap which could result in misleading decisions (Wang et al., 2017). Many variations of the method have been emerged, e.g., for group decision making

(Chen, 2000), but the fuzzy TOPSIS is the most commonly used (Cavallaro, 2010; Karakosta and Psarras, 2012; Papapostolou et al., 2017, 2020b; Şengül et al., 2015).

TOPSIS and its variations have been used to evaluate the viability of renewable energy projects (Cavallaro, 2010; Doukas et al., 2010; Şengül et al., 2015; Yan et al., 2011), for the selection of a suitable location for the installation of power, energy plants, solar PVs (Hassan et al., 2023; Kaur and Majumder, 2022; Kaur et al., 2022), for the environmental assessment of energy suppliers (Awasthi et al., 2010; Wang et al., 2009), as well as for the selection of the optimum green energy sources for sustainable planning (Bhowmik et al., 2020; Dhiman and Sen, 2022), among other publications (Doukas et al., 2009; Sarmas et al., 2022a; Papapostolou et al., 2016, 2017a, 2017b).

More particularly, when it comes to EE projects TOPSIS has been utilised to promote the implementation of retrofitting actions and also the promotion of investments. Fonseca et al. (2019), for instance, classified projects of EE in order to be used in the decision-making process within the industry for resource allocation. Data from 97 EE projects implemented in 32 companies in the USA available on the Department of Energy website were used, which were ranked by the TOPSIS multi criteria decision making methodology using financial and sustainability indicators as criteria, varying the criteria weights in nine scenarios. The final rankings obtained resulted that maintenance projects for leakage, purge traps and insulation should be the starting point independently of the weights assigned to the criteria. Another example is the research of Abdulsalam et al. (2018), who proposed a fuzzy-TOPSIS approach for techno-economic viability of lighting EE measure in public building projects. Furthermore, Marzouk et al. (2023) presented a framework that combines techno-economic requirements as a means for evaluating the important retrofitting criteria and suitable lighting retrofit technologies for building projects. The analysis of the lighting technology selection was performed from technical, economic and techno-economic perspectives using TOPSIS method. On the other hand, Sarmas et al. (2022b) compare with respective data from past EE actions on buildings, exploiting the TOPSIS method in EE projects in building based in Latvia, which was applied based on four criteria: energy reduction per cost, energy reduction percentage per cost, building age and building consumption per heating area. The projects were classified into one of five categories according to their performance on the MCDA methodology. Moreover, Sun and Yu (2021) proposed an improved data-driven-based building energy performance evaluating and ranking approach for office building in city scale using the simple-normalisation, entropy-based TOPSIS and K-means method. Last but not least, Wang et al. (2017) benchmark energy performance through variable clustering-based compromise TOPSIS with objective entropy weighting.

In terms of EE in buildings, MCDA has also been used in order to identify key performance criteria and the alternative retrofitting solutions either during the design stage or upon the project completion. TOPSIS has been applied in papers providing stakeholders with a structured approach to perform the decision-making process of selecting renovation solutions in the context of residential renovation projects. In terms of selecting renovation solutions for residential buildings, TOPSIS proved to assist in overcoming the challenges due to the participation of multiple stakeholders, lack of clear decision-making procedures, and diverse effects resulting from the renovation alternatives (Amorocho and Hartmann, 2022, Liu et al., 2021, Marzouk et al., 2023).

4.2 TOPSIS method steps

As mentioned, TOPSIS is widely used in problems of evaluation and classification of possible alternative strategies into a multicriteria decision problem. The method is based on the existence of a decision maker or a group of decision makers, who evaluate the alternatives based on specific criteria.

Generally, the decision maker evaluates alternative j, R_j (j = 1, 2, 3, …, n) with respect to criterion i, C_i (i = 1, 2, 3, …, m). However, especially when considering quantitative criteria, it is possible to calculate the performance $x = (x_{ij}$, i = 1, 2, 3, …, m, j = 1, 2, 3, …, n) of each alternative to each criterion without the involvement of the decision maker. This is very useful when examining numerous alternatives, as it facilitates the decision making process. Naturally, the decision maker can still influence the result of the process by assigning weights to each criterion, thus indicating the importance of one criterion over another. The weights of m criteria are symbolised as $W = w_i$, (i = 1, 2, 3, …, m) [equation (1)]. The evaluation matrix for the alternatives is shown in equation (2).

$$W = \begin{pmatrix} w_1 & w_2 & \cdots & w_m \end{pmatrix} \tag{1}$$

$$A = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} = \left[A_{ij} \right]_{m \times n}, \qquad i = 1, 2, 3, \ldots, m;\ j = 1, 2, 3, \ldots, n \tag{2}$$

Each column of matrix A represents the different alternatives (j = 1, 2, 3, …, n), whereas the rows of the matrix represent the evaluation criteria (i = 1, 2, 3, …, m). $\tilde{X}_{ij}$ is the performance of each criterion i for each alternative j.

The normalised decision matrix is then calculated, symbolised as R. Each matrix element is calculated as follows:

$$r = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{3}$$

where r_{ij} symbolises the normalised performance of alternative A_i for criterion C_j.

The following step is the calculation of the weighted normalised decision matrix P, by multiplying the normalised matrix R with the weights of the criteria. The vector of the weights $W = (w_1\ w_2\ \ldots\ w_m)$ can be calculated through various methods. In any case, they should add up to 1, as shown in equation (4).

$$\sum_{j=1}^{j=n} W_j = 1 \tag{4}$$

Thus, the elements of matrix P can be calculated as shown in equation (5).

$$p_{ij} = W_j \times r_{ij} \tag{5}$$

After calculating the weighted normalised decision matrix, the vectors representing the hypothetical positive ideal solution P^+ (positive effect criterion) and the hypothetical negative ideal solution (or anti-ideal solution) P^- (negative effect criterion) are determined, as demonstrated in equations (6) and (7).

$$P^+ = \left(p_1^+, p_2^+, \ldots, p_n^+\right) \tag{6}$$

$$P^- = \left(p_1^-, p_2^-, \ldots, p_n^-\right) \tag{7}$$

This results in the positive and negative ideal solutions for each criterion:

$$p_i^+ = \left\{\left(\max p_{ij}, j \in J\right) or \left(\min p_{ij}, j \in J'\right)\right\} \tag{8}$$

$$p_i^- = \left\{\left(\min p_{ij}, j \in J\right) or \left(\max p_{ij}, j \in J'\right)\right\} \tag{9}$$

where J represents positive impact (beneficial) criteria and J' represents negative impact (cost or non-beneficial) criteria.

The distance of each alternative is calculated both from the positive ideal solution:

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(p_{ij} - p_j^+\right)^2} \tag{10}$$

And from the negative ideal solution:

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(p_{ij} - p_j^-\right)^2} \tag{11}$$

Finally, the relative proximity D_i to the positive ideal solution for each alternative A_i is calculated:

$$D_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{12}$$

which determines the final ranking and order of importance of alternative solutions.

5 Application and results

Based on the above-mentioned steps for the proposed methodology was applied for the evaluation of 48 EE projects in Greece that are presented in Table 2. The data relevant to the potential EE projects considered as alternatives in the decision-making problem have been collected in the context of the EU funded LIFE project ENERGATE from the ENERGATE pilot organisations. The pilot organisations are the first to test the ENERGATE platform and to provide feedback on its functionalities and services so as to ensure that the ENERGATE marketplace reflects the needs of the market. The purpose of the data collection is the initial identification of the pilot typologies, as well as the population of the ENERGATE database. The ENERGATE database will be useful since machine learning techniques will be applied so that when a new building is inserted, the ENERGATE platform will detect similarities with buildings in the database and showcase the most similar buildings to the users. Furthermore, estimations could be made regarding the energy and emission savings emerging from specific EE measures.

Therefore, the users will be able to detect best practices of renovation projects, and this will help them make decisions with regards to the renovation strategy they could follow to upgrade their building.

Table 2 Alternatives for TOPSIS application

Alternatives: energy efficiency projects in Greece	
Identifier	*Energy efficiency project*
P1	Upgrade of the central building management system (BMS)
P2	Replacement of lamps with more energy efficient (LED) lamps in offices and/or parking areas
P3	Lighting automation in offices and parking areas
P4	Insulation of air conditioning system networks
P5	Replacement of cooling towers with dry coolers
P6	Upgrade of the central building management system (BMS)
P7	Development and implementation of energy management system
P8	Insulation of air conditioning system networks
P9	Replacement of lamps with more energy efficient lamps (LED)
P10	Replacement of air conditioners with new ones with heat recovery
P11	Development and implementation of energy management system
P12	Lighting automation for indoor and outdoor lighting
P13	Replacement of light bulbs with more energy efficient ones (LED)
P14	Insulation of hot water networks of the boiler house
P15	Installation of photovoltaic systems for self-production
P16	Energy management system
P17	Variable speed transmission (VSD) system in the CCMs
P18	Adiabatic pre-cooling system
P19	Sensor installation on escalators
P20	Installation of PV system for self-production
P21	Installation of a system for recording and monitoring energy consumption
P22	Lighting automation in office areas
P23	Replacement of old VRVs with new ones of higher efficiency
P24	Replacement of old chillers with new higher efficiency VRV heat pumps
P25	Adiabatic pre-cooling system in chillers
P26	Development and implementation of energy management system
P27	Installation of temperature control system in offices
P28	Installation of temperature control system in data room
P29	Lighting automation in office areas and underground parking areas
P30	Replacement of light bulbs with more energy-efficient ones (LED)
P31	Upgrade of the central building management system (BMS)
P32	Insulation of air conditioning system networks
P33	Adiabatic pre-cooling system

Table 2 Alternatives for TOPSIS application (continued)

Alternatives: energy efficiency projects in Greece	
Identifier	*Energy efficiency project*
P34	Replacement of lamps with more energy efficient lamps (LED)
P35	Installation of photovoltaic system
P36	Installation of consumption meters in the air conditioning units of the data centre
P37	Replacement of units in data centre cage 1 with new ones equipped with EC fans and inverter compressors
P38	Installation of PVC curtains in data centre cage 1 to change the Set Points with parallel fan automation
P39	Development and implementation of energy management system
P40	Replacement of lamps with more energy efficient lamps (LED)
P41	Lighting automation in office areas
P42	Lighting automation in underground car parks
P43	Magnetic contacts in window frames to control air conditioning operation
P44	Installation of a system for recording and monitoring energy consumption
P45	Development and implementation of energy management system
P46	Replacement of light bulbs with more energy efficient ones (LED)
P47	Lighting automation in ancillary areas
P48	Installation of a temperature control system in the data room

Table 3 Values of criteria for examined alternatives

Alternatives	*Criteria*				
	C1. Energy savings (%) (beneficial)	*C2. Avoidance cost (€/kWh) (non-beneficial)*	*C3. Payback period (years) (non-beneficial)*	*C4. IRR (%) (beneficial)*	*C5. CAPEX (€) (non-beneficial)*
P1	0.020892	0.629213	6.2	0.138	16,800
P2	0.001017	0.473077	3	0.33	615
P3	0.025196	0.767081	7.5	0.102	24,700
P4	0.049765	0.150943	1.5	0.667	9,600
P5	0.049139	1.387261	5.4	0.152	87,120
P6	0.06931	0.453297	4.5	0.209	16,500
P7	0.010663	0.446429	5.3	0.172	2,500
P8	0.015614	0.190488	1.8	0.569	1,562
P9	0.028752	0.316556	2.4	0.407	4,780
P10	0.005332	2.510357	19	0	7,029
P11	0.009988	0.321285	3	0.329	8,000
P12	0.021941	0.559415	5.1	0.178	30,600
P13	0.059446	0.544669	4.1	0.231	80,720
P14	0.028279	0.070922	0.8	1.237	5,000
P15	0.073967	0.688178	8	0.091	126,900

Table 3 Values of criteria for examined alternatives (continued)

Alternatives	*Criteria*				
	C1. Energy savings (%) (beneficial)	*C2. Avoidance cost (€/kWh) (non-beneficial)*	*C3. Payback period (years) (non-beneficial)*	*C4. IRR (%) (beneficial)*	*C5. CAPEX (€) (non-beneficial)*
P16	0.009415	0.57764	5.2	0.176	9,300
P17	0.005789	0.909091	6.6	0.127	9,000
P18	0.024094	0.38835	3.5	0.28	16,000
P19	0.020585	0.238636	2.1	0.464	8,400
P20	0.007018	0.413167	5.1	0.181	4,958
P21	0.030045	1.756272	7.1	0.111	49,000
P22	0.012707	1.983051	8.1	0.09	23,400
P23	0.12675	1.784197	5.9	0.146	210,000
P24	0.092182	2.336449	7.4	0.105	200,000
P25	0.00708	0.524181	2.4	0.42	33,600
P26	0.02	0.307692	3.1	0.32	4,000
P27	0.004615	0.666667	6.6	0.126	2,000
P28	0.011231	0.191781	1.9	0.523	1,400
P29	0.021692	0.457447	4.6	0.206	6,450
P30	0.075077	0.513811	3.8	0.258	25,074
P31	0.004443	1.970149	2.3	0.432	13,200
P32	0.003316	2	2.8	0.347	10,000
P33	0.021883	0.735636	5.7	0.156	24,276
P34	0.07374	0.594721	3.2	0.308	66,133
P35	0.031764	0.561795	5.5	0.162	26,910
P36	0.030387	0.581818	3.2	0.304	6,400
P37	0.140746	1.747237	9.7	0.06	89,021.74
P38	0.040138	0.385409	2.1	0.466	5,600
P39	0.022474	0.359221	3.4	0.284	10,000
P40	0.047935	0.288662	2	0.505	17,140
P41	0.004094	0.650805	6	0.146	3,300
P42	0.003115	0.518319	4.7	0.196	2,000
P43	0.008527	0.53962	4.9	0.187	5,700
P44	0.029951	0.833248	5	0.183	3,300
P45	0.014975	0.757498	4.6	0.205	1,500
P46	0.113241	0.4791	3.2	0.309	7,174
P47	0.013463	0.348278	2.1	0.474	620
P48	0.00367	0.515199	3.1	0.3159	250
Weights of criteria	0.20	0.20	0.20	0.20	0.20

Table 4 Distance from ideal and anti-ideal solution

Alternatives	*Distance from*	
	Ideal solution	*Anti-ideal solution*
P1	0.161636	0.089452
P2	0.162936	0.107132
P3	0.161257	0.082457
P4	0.131587	0.132004
P5	0.134491	0.097421
P6	0.144579	0.108314
P7	0.167015	0.095766
P8	0.148459	0.123502
P9	0.149058	0.115349
P10	0.21065	0.004556
P11	0.15695	0.10994
P12	0.153479	0.096655
P13	0.122851	0.114597
P14	0.131421	0.159424
P15	0.121482	0.11447
P16	0.165002	0.093855
P17	0.170798	0.081495
P18	0.151927	0.106866
P19	0.147765	0.118742
P20	0.166642	0.097212
P21	0.157783	0.074282
P22	0.174794	0.061545
P23	0.108341	0.156304
P24	0.125189	0.136984
P25	0.145102	0.112472
P26	0.155719	0.110029
P27	0.172759	0.085731
P28	0.151489	0.12148
P29	0.160279	0.099521
P30	0.137355	0.11258
P31	0.162528	0.096488
P32	0.167539	0.091324
P33	0.157798	0.090337
P34	0.119529	0.118837
P35	0.153015	0.095554
P36	0.153077	0.105473
P37	0.136678	0.113445

Table 4 Distance from ideal and anti-ideal solution (continued)

Alternatives	*Distance from*	
	Ideal solution	*Anti-ideal solution*
P38	0.14327	0.118076
P39	0.154399	0.107384
P40	0.134594	0.122787
P41	0.170941	0.088831
P42	0.168247	0.0968
P43	0.165796	0.095637
P44	0.161698	0.091743
P45	0.164993	0.093872
P46	0.136775	0.127075
P47	0.152973	0.116714
P48	0.162886	0.105672

In Table 3, the values of each criterion in correlation to each alternative are demonstrated. Thus, Table 3 represents the evaluation matrix of the decision-making problem. To apply the methodology, all criteria are assumed to be equally important for the investor, thus, equal weights will be assigned to them. Criteria are also divided into 'beneficial' and 'non-beneficial' criteria, depending on whether they need to be maximised or minimised.

To proceed with the calculations, the values need to be normalised and each value is also multiplied with the respective weight of the criterion. As mentioned, the weights are equal in our case. Through the normalised weighted decision matrix, the ideal and anti-ideal solutions are extracted. Having specified the ideal and anti-ideal solutions, their distance from each alternative can be calculated. The results are shown in Table 4.

Calculating the distances from the ideal and anti-ideal solution leads to the calculation of the relative proximity, and therefore, the final ranking and order of importance of the examined alternatives (Table 5).

Table 5 Calculation of relative proximity

Alternatives	*Relative proximity*	*Ranking*	*Order of importance*
P1	0.356257	9	40
P2	0.396686	23	26
P3	0.338336	6	43
P4	0.500791	45	4
P5	0.420077	29	20
P6	0.428299	30	19
P7	0.364433	14	35
P8	0.454117	39	10
P9	0.436254	32	17
P10	0.021171	1	48
P11	0.411929	26	23
P12	0.386412	21	28

Table 5 Calculation of relative proximity (continued)

Alternatives	*Relative proximity*	*Ranking*	*Order of importance*
P13	0.48262	42	7
P14	0.54814	47	2
P15	0.485141	43	6
P16	0.362574	11	38
P17	0.323018	4	45
P18	0.412941	27	22
P19	0.44555	35	14
P20	0.368432	17	32
P21	0.320092	3	46
P22	0.26041	2	47
P23	0.590617	48	1
P24	0.522495	46	3
P25	0.43666	33	16
P26	0.414035	28	21
P27	0.33166	5	44
P28	0.445032	34	15
P29	0.383067	19	30
P30	0.450438	36	13
P31	0.372518	18	31
P32	0.352789	8	41
P33	0.364064	13	36
P34	0.498549	44	5
P35	0.384416	20	29
P36	0.407941	24	25
P37	0.453556	38	11
P38	0.451799	37	12
P39	0.410202	25	24
P40	0.477064	40	9
P41	0.341957	7	42
P42	0.365218	15	34
P43	0.365818	16	33
P44	0.36199	10	39
P45	0.362629	12	37
P46	0.481617	41	8
P47	0.432775	31	18
P48	0.39348	22	27

By following the procedure described above, the analysis ended up with a ranked list of the potential EE projects. The projects were also categorised so as to be able to extract more informed conclusions.

Table 6 Results and categorisation

Ranking	*Identifier*	*Description*	*Project category*
1	P23	Replacement of old VRVs with new ones of higher efficiency	Heating systems – heating generation
2	P14	Insulation of hot water networks of the boiler house	Heating systems – distribution improvements
3	P24	Replacement of old chillers with new higher efficiency VRV heat pumps	Cooling systems – cooling generation
4	P4	Insulation of air conditioning system networks	Cooling system – distribution improvement
5	P34	Replacement of lamps with more energy efficient lamps (LED)	Lighting – LED
6	P15	Installation of photovoltaic systems for self-production	RES – PV systems
7	P13	Replacement of light bulbs with more energy efficient ones (LED)	Lighting – LED
8	P46	Replacement of light bulbs with more energy efficient ones (LED)	Lighting – LED
9	P40	Replacement of lamps with more energy efficient lamps (LED)	Lighting – LED
10	P8	Insulation of air conditioning system networks	Cooling system – distribution improvement
11	P37	Replacement of units in data centre cage 1 with new ones equipped with EC fans and inverter compressors	Cooling system – cooling generation
12	P38	Installation of PVC curtains in data centre cage 1 to change the set points with parallel fan automation	Automation
13	P30	Replacement of light bulbs with more energy-efficient ones (LED)	Lighting – LED
14	P19	Sensor installation on escalators	Automation – sensors
15	P28	Installation of temperature control system in data room	Automation – temperature control
16	P25	Adiabatic pre-cooling system in chillers	Cooling system – cooling generation
17	P9	Replacement of lamps with more energy efficient lamps (LED)	Lighting – LED
18	P47	Lighting automation in ancillary areas	Lighting – lighting automation
19	P6	Upgrade of the central building management system (BMS)	Automation – BMS
20	P5	Replacement of cooling towers with dry coolers	Cooling system – cooling generation

Table 6 Results and categorisation (continued)

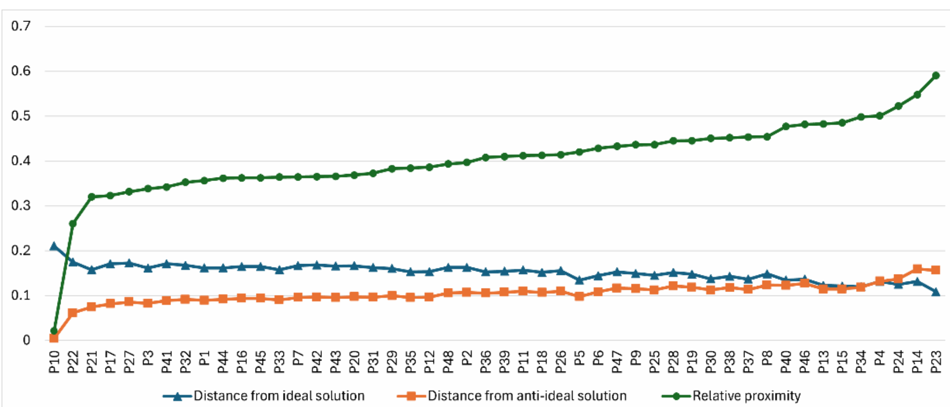
Ranking	*Identifier*	*Description*	*Project category*
21	P26	Development and implementation of energy management system	Automation – BMS
22	P18	Adiabatic pre-cooling system	Cooling system – cooling generation
23	P11	Development and implementation of energy management system	Automation – BMS
24	P39	Development and implementation of energy management system	Automation – BMS
25	P36	Installation of consumption meters in the air conditioning units of the data centre	Automation – energy meters
26	P2	Replacement of lamps with more energy efficient (LED) lamps in offices and/or parking areas	Lighting – LED
27	P48	Installation of a temperature control system in the data room	Automation – temperature control
28	P12	Lighting automation for indoor and outdoor lighting automation	Lighting – Lighting automation
29	P35	Installation of photovoltaic system	RES – PV systems
30	P29	Lighting automation in office areas and underground parking areas	Lighting – lighting automation
31	P31	Upgrade of the central building management system (BMS)	Automation – BMS
32	P20	Installation of PV system for self-production	RES – PV systems
33	P43	Magnetic contacts in window frames to control air conditioning operation	Automation – cooling
34	P42	Lighting automation in underground car parks	Lighting – lighting automation
35	P7	Development and implementation of energy management system	Automation – BMS
36	P33	Adiabatic pre-cooling system	Cooling system – cooling generation
37	P45	Development and implementation of energy management system	Automation – BMS
38	P16	Energy management system	Automation – BMS
39	P44	Installation of a system for recording and monitoring energy consumption	Automation – BMS
40	P1	Upgrade of the central building management system (BMS)	Automation – BMS
41	P32	Insulation of air conditioning system networks	Cooling system – distribution improvement
42	P41	Lighting automation in office areas	Lighting – lighting automation
43	P3	Lighting automation in offices and parking areas	Lighting – lighting automation

Table 6 Results and categorisation (continued)

Ranking	*Identifier*	*Description*	*Project category*
44	P27	Installation of temperature control system in offices	Automation – temperature control
45	P17	Variable speed transmission (VSD) system in the CCMs	Cooling system – cooling generation
46	P21	Installation of a system for recording and monitoring energy consumption	Automation – BMS
47	P22	Lighting automation in office areas	Lighting – lighting automation
48	P10	Replacement of air conditioners with new ones with heat recovery	Cooling system – cooling generation

The results are also summarised in Figure 2, where the distances from the ideal and anti-ideal solutions, as well as the relative proximity, are observed. On the horizontal axis, the alternatives are shown, starting from the worst performing (lower relative proximity, on the left) and leading up to the best performing (higher relative proximity, on the right).

Figure 2 Distances from ideal and anti-ideal solutions and relevant proximity (see online version for colours)



6 Discussion

To analyse and evaluate the results of the research, it is necessary to investigate the key takeaways of previous studies and examine their alignment with our research results. It is also beneficial to compare the results not only with studies relevant to Greece's building sector, but also with research conducted in other countries, to highlight the potential relationships and patterns and their correlation with geographical locations. Firstly, according to a different MCDA approach examining the Greek building stock based on PROMETHEE and SIMOS methods that was conducted to assist policy makers in designing EE policies through the choice of the most effective measures towards supporting sustainable development, in the non-residential sector, interventions regarding combined heat and power systems, heat pumps and gas boilers are measures of high priority (Neofytou et al., 2020b). It has been observed that to adopt EE measures with smart features (thus belonging to the 'automation' category according to the classification of our study) in Greece, the familiarity with information and communication technologies (ICT) is an important precondition (Spyridaki et al., 2020). This is not a unique observation in the Greek building sector. For instance, when investigating EE in the industrial and commercial sectors in Switzerland, Cooremans and Schönenberger observed indecisiveness as regards to EE investments, in particular when it comes to energy management systems. However, the lack of monitoring and control equipment and tools itself has a significant impact, since it makes the evaluation of the results of EE measures more difficult. Therefore, installing BEMS could be considered a strategic investment, and it has been concluded that when a project or investment is considered to be strategic, there is increased flexibility in terms of financial criteria (Cooremans and Schönenberger, 2019). Methods to encourage such strategic investments should therefore be explored, especially in the context of formulating appropriate policies.

The potential impact of policies in the uptake of EE investments has been studied in previous research. More specifically, the need to adapt policies by promoting appropriate financial schemes and suitable action plans in Greece to increase EE investment has been discussed in relevant research for many years (Patlitzianas, 2011; Markaki et al., 2013; Forouli et al., 2019; Karakosta and Papapostolou, 2023). The uptake of EE investments is a key driver of Greece's recovery plan, especially after the implications of the COVID-19 pandemic (Karakosta and Papapostolou, 2023). Researchers in other countries have also focused on the impact of policies on EE investments and have extracted valuable results and useful insights. For example, García-Quevedo and Jové-Llopis have studied the impact of regulation, taxes, subsidies, and tax credits as policy measures, in the EE of the Spanish industry. The results show that it is necessary to assess the influence of several policy instruments because their effects may vary significantly. In the case of Spain, subsidies as a policy instrument seem to be the most effective in promoting EE investments. On the contrary, the evidence was not sufficient to confirm a favourable relationship between environmental taxes, tax credits and regulation, and EE investments (García-Quevedo and Jové-Llopis, 2021).

When it comes to the results of our application, based on the implementation of the TOPSIS method presented above, conclusions were drawn about the effectiveness of EE projects in buildings and, most importantly, the determination of how attractive these projects might be for potential investors. Initially, it was observed that EE projects relevant to HVAC upgrades are prioritised. More specifically, upgrades of heating systems demonstrate the best overall performance according to the applied methodology. This is very much aligned with the results of the study conducted by Neofytou et al., described in the first paragraph of this section that also examined the EE of the Greek building stock (Neofytou et al., 2020b). The most attractive projects, both in the 'heating system' and 'cooling system' category, regard replacement of existing infrastructure (for heating and cooling generation, respectively) with new, more energy efficient equipment, followed by improvements of the distribution network (e.g., pipe insulation).

Besides HVAC systems, replacement of lighting equipment with more energy efficient lamps (usually LED) are also an effective measure, whereas installation of renewable energy generation systems also ranks quite high (it is, however, worth mentioning that such projects were only represented by a small percentage in the examined dataset).

Finally, it was observed that projects related to automation, aiming at controlling and harnessing excessive energy consumption, are generally not prioritised as much as other measures. It has to be noted that many projects under the ‘lighting’ category also considered automated lighting. More specifically, the examined projects related to automation include:

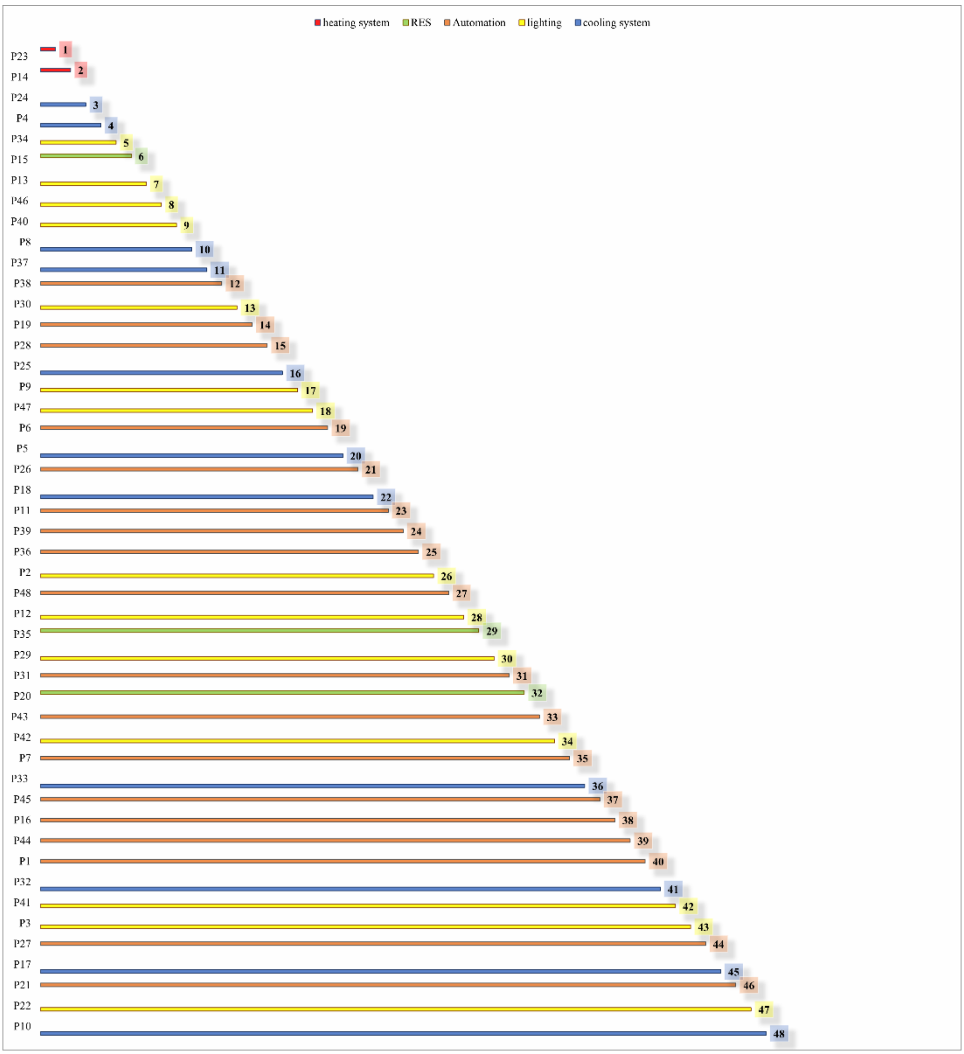
- automated lighting in buildings with various uses (such as offices, parking spaces and so on)
- building energy management systems recording and monitoring energy consumption
- systems to control temperature
- upgrades in existing systems for energy management
- instalment of energy meters, for instance in cooling systems
- instalment of sensors.

This observation is aligned with the research results of Cooremans and Schönenberger analysed in the first paragraph of this section. More specifically, it is observed that investments in automation are not prioritised. Nonetheless, an EE project in this category can be considered strategic, particularly when it comes to BEMS (Cooremans and Schönenberger, 2019). The overall ranking of the EE investments could also confirm the results of the study conducted by Pallis et al. on the energy and economic performance assessment of EE measures in zero-energy office buildings in Greece, according to which heat pumps are the most cost-effective heating/cooling system while also presenting the lowest primary energy consumption levels, followed by LED lighting systems with lighting controls and automation systems. The installation of PVs is also considered vital for reaching the nZEB threshold (Pallis et al., 2021). The high compatibility of these results with our results may be an indication of the high correlation between the EE measures’ impact and the typology of the building, since in both cases office buildings are examined. The usefulness of our research is also strengthened by the fact that each intervention is considered as a separate investment. Avelin et al., exploring the effect and investment costs of renovation actions in Sweden, have highlighted the challenge of assessing the impact of different retrofitting actions when those are implemented simultaneously (Avelin et al., 2017).

By installing automation systems, unnecessary consumption is prevented, leading to high levels of EE. Thus, the instalment of automation systems leads to indirect energy savings, as opposed to the rest of the examined measures that influence energy consumption directly. This could be one of the reasons why automation systems do not rank as high, since their effect on energy consumption could be underestimated. Furthermore, to apply the TOPSIS method, the criterion ‘CAPEX’ was considered as a non-beneficial criterion, meaning that it should be minimised, since lower price indicates a cost-effective measure. Thus, if the examined measures related to automation require relatively high expenditure, the results of the methodology are also significantly influenced. Nonetheless, different investors might be interested in different CAPEX ranges and therefore minimising the CAPEX is not desired for all financing bodies. In fact, some might prefer a greater investment size over a smaller one, which is why different renovation measures could be combined to create a financeable package (either in one building as a deep retrofit or across different buildings of similar typology). High costs of installation in combination with underestimated energy savings also result in lower performance for the ‘avoidance cost’ criterion.

The results, in correlation with the categories of measures examined, are also illustrated in Figure 3. The colours represent the different categories of EE measures. The alternatives are presented from the top to the bottom as a ranked list (the list that ensued from the application of TOPSIS). The number corresponding to each alternative showcases its position in the ranked list.

Figure 3 Ranked alternatives and EE project types (see online version for colours)



The fact that BEMS can have a very good impact in the energy consumption – although less direct compared to other measures – must not be neglected when formulating policies relevant to the adoption of EE measures in buildings. Automation systems including smart metering infrastructure can improve the implementation of the Energy Efficiency Directive and the Energy Performance of Buildings Directive, and improve the monitoring of energy savings, in line with the International Performance Measurement and Verification Protocol (IPMVP) (Energy Efficiency Directive, 2023; Energy Performance of Buildings Directive, 2023; IPMVP, 2022). Therefore, a policy recommendation for Greece, as well as other EU member states, could be the reinforcement of existing programmes (such as the 'EXOIKONOMO' programme and subsidy programmes in general) to promote the adoption of EE measures related to automation (EXOIKONOMO, 2023).

Another important aspect that should be considered is the correlation between the type of investment and financing scheme, and the EE measures applied. For instance, energy savings are of vital importance when it comes to performance-based schemes such as energy performance contracts. On the other hand, in more traditional financing schemes, for which the repayment in not tied to the results of the EE measure, the environmental impact of the project might be less important. In addition, different schemes have different flexibility in terms of payback period. The situation might be significantly different depending on the circumstances, for instance, when the investment is provided along subsidies, or when alternative and innovative financing schemes are considered, such as crowdfunding (Economidou et al., 2019; Bertoldi et al., 2021).

7 Conclusions

In this paper, multicriteria decision analysis is utilised to create a methodological approach with the aim of supporting financial stakeholders in selecting the most attractive EE investments in buildings. The methodology is based on the TOPSIS method and is applied to a dataset of 48 potential EE projects in Greece, while the evaluation criteria are selected based on extensive review of relevant literature and stakeholder consultation. The research conducted could be very useful for stakeholders involved in EE financing for renovation projects. More specifically, market actors involved in such initiatives can explore the various KPIs that might be interesting to them. Those are not limited to financial indicators, instead, energy-related, environmental and social factors are also considered. Furthermore, financiers can use the proposed methodology to evaluate several alternatives and prioritise them, since the method is easily exploitable and can be replicated effectively thanks to its simplicity.

Assisting investors in the decision-making process is of vital importance, because methodologies such as the one presented in this paper could encourage them to select the best alternatives among numerous potential projects. This could enable them to avoid lengthy procedures of EE project evaluation, as the assessment process is standardised and simplified, which is very beneficial especially when dealing with overwhelming datasets of potential investment packages. Since financial barriers, such as high upfront costs and limited access to finance, are the main issues hindering the uptake of renovation rates, prompting financial institutions to consider sustainable investments in buildings and facilitating them in decision-making is of utmost importance.

Through the application of the methodology, useful insights are extracted indicating which EE project types might be more interesting for financiers, especially in Greece. More specifically, it appears that upgrade of HVAC equipment – particularly improvement of heating systems through replacement of existing infrastructure – is quite an attractive investment category. This is also true for cooling systems (e. g. installation of heat pumps), while improving the distribution system is also cost efficient. The above mentioned are followed by measures such as installing of renewable energy generating systems, or enhancement of the energy efficiency of lighting infrastructure. Instalment of automated systems, however, seems to be less attractive as an investment opportunity according to the results of the methodology and as far as the examined alternatives are concerned. This paves the way for relevant policy recommendations, that could incentivise investors to not neglect the instalment of BEMS and metering infrastructure as important measures that can not only reduce energy consumption but also contribute to the effective monitoring of energy savings and the improved implementation of performance-based financing schemes.

The paper at hand paves the way for future research: first of all, within the application, TOPSIS was implemented assigning equal weights to all criteria. Nonetheless, designating certain criteria as more important by assigning different weights to them could lead to different conclusions as to which EE projects are more attractive for financiers. Furthermore, the methodology could be adapted so as to reflect the needs of different stakeholders belonging to the EE financing sector. For instance, a private financing institution, such as a bank, could consider different factors as essential when evaluating an EE investment, compared to a public financing body. In general, an important limitation of the study is the fact that it focuses on a specific building type and only in the private sector. Therefore, future research could focus on expanding the assessment and examining public buildings separately. Another aspect of further research could be the incorporation of risk factors in the evaluation of the EE investments, since risk assessment is an inherent part of investment decisions. Moreover, sensitivity analysis could be implemented, for instance, by applying different weights for each category. In addition, the proposed methodology could be applied to greater numbers of EE projects, or to a greater variety of such projects, to furtherly enhance the conclusions and gain better insights on the preferences of the financiers. Finally, the methodology could be automated and turned into a web tool, allowing users to quickly and effectively evaluate and rank EE projects in a user-friendly manner.

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References

Abdulsalam, K., Ighravwe, D. and Babatunde, M. (2018) 'A fuzzy-TOPSIS approach for techno-economic viability of lighting energy efficiency measure in public building projects', *Journal of Project Management*, Vol. 3, No. 4, pp.197–206.

Ahmed, A., Ge, T., Peng, J., Yan, W.C., Tee, B.T. and You, S. (2022) 'Assessment of the renewable energy generation towards net-zero energy buildings: a review', *Energy and Buildings*, Vol. 256, p.111755.

Akgüç, A. and Yılmaz, A.Z. (2022) 'Determining HVAC system retrofit measures to improve cost-optimum energy efficiency level of high-rise residential buildings', *Journal of Building Engineering*, Vol. 54, p.104631.

Al Dakheel, J., Del Pero, C., Aste, N. and Leonforte, F. (2020) 'Smart buildings features and key performance indicators: a review', *Sustainable Cities and Society*, Vol. 61, No. 1, p.102328.

Alam, M., Zou, P.X.W., Sanjayan, J.G., Stewart, R.A., Edoardo, B. and Wilson, J.L. (2016) Guidelines for building energy efficiency retrofitting', *Sustainability in Public Works Conference*.

Albrecht, J. and Hamels, S. (2021) 'The financial barrier for renovation investments towards a carbon neutral building stock – an assessment for the Flemish region in Belgium', *Energy and Buildings*, Vol. 248, p.111177.

Alwaer, H. and Clements-Croome, D.J. (2010) 'Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings', *Building and Environment*, Vol. 45, No. 4, pp.799–807.

Amorocho, J.A.P. and Hartmann, T. (2022) 'A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods', *Journal of Building Engineering*, Vol. 53, p.104596.

Ardente, F., Beccali, M., Cellura, M. and Mistretta, M. (2011) 'Energy and environmental benefits in public buildings as a result of retrofit actions', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 1, pp.460–470.

Arsenopoulos, A., Marinakis, V., Koasidis, K., Stavrakaki, A. and Psarras, J. (2020) 'Assessing resilience to energy poverty in Europe through a multi-criteria analysis framework', *Sustainability*, Vol. 12, No. 12, p.4899.

Aspinall, R.J. and Hill, M.J. (2007) *Land Use Change: Science, Policy and Management*, CRC Press, Boca Baton, Florida, USA.

Avelin, A., Dahlquist, E. and Wallin, F. (2017) 'Effect of different renovation actions, their investment cost and future potential', *Energy Procedia*, Vol. 143, pp.73–79.

Awasthi, A., Chauhan, S.S and Goyal, S.K. (2010) 'A fuzzy multicriteria approach for evaluating environmental performance of suppliers', *Int. J. Prod. Econ.*, Vol. 126, pp.370–378.

Baek, C. and Park, S. (2012) 'Policy measures to overcome barriers to energy renovation of existing buildings', *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 6, pp.3939–3947.

Balaras, C.A., Dascalaki, E.G., Droutsa, K.G., Kontoyiannidis, S., Guruz, R. and Gudnason, G. (2014) 'Energy and other key performance indicators for buildings – examples for Hellenic buildings', *Global Journal of Energy Technology Research Updates*, Vol. 1, No. 2, pp.71–89.

Bertoldi, P., Economidou, M., Palermo, V., Boza-Kiss, B. and Todeschi, V. (2021) 'How to finance energy renovation of residential buildings: review of current and emerging financing instruments in the EU', *Wiley Interdisciplinary Reviews: Energy and Environment*, Vol. 10, No. 1, p.e384.

Bertone, E., Sahin, O., Stewart, R.A., Zou, P., Alam, M. and Blair, E. (2016) 'State-of-the-art review revealing a roadmap for public building water and energy efficiency retrofit projects', *International Journal of Sustainable Built Environment*, Vol. 5, No. 2, pp.526–548.

Bhowmik, C., Kaviani, M.A., Ray, A. and Ocampo, L. (2020) 'An integrated entropy-TOPSIS methodology for evaluating green energy sources', *International Journal of Business Analytics (IJBAN)*, Vol. 7, No. 3, pp.44–70.

Bortoluzzi, M., de Souza, C.C. and Furlan, M. (2021) 'Bibliometric analysis of renewable energy types using key performance indicators and multicriteria decision models', *Renewable and Sustainable Energy Reviews*, Vol. 143, p.110958.

Campos-Carriedo, F., Bargiacchi, E., Dufour, J. and Iribarren, D. (2023) 'How can the European Ecodesign Directive guide the deployment of hydrogen-related products for mobility?', *Sustainable Energy & Fuels*, Vol. 7, No. 6, pp.1382–1394.

Cavallaro, F. (2010) 'Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems', *Appl. Energ.*, Vol. 87, No. 2, pp.496–503.

Chan, A.P. and Chan, A.P. (2004) 'Key performance indicators for measuring construction success', *Benchmarking: An International Journal*, Vol. 11, No. 2, pp.203–221.

Chen, C.T. (2000) 'Extensions of the TOPSIS for group decision-making under fuzzy environment', *Fuzzy Sets Syst.*, Vol. 114, No. 1, pp.1–9.

Chen, S., Zhang, G., Xia, X., Setunge, S. and Shi, L. (2020) 'A review of internal and external influencing factors on energy efficiency design of buildings', *Energy and Buildings*, Vol. 216, p.109944.

Chourabi, Z., Khedher, F., Babay, A. and Cheikhrouhou, M. (2019) 'Multi-criteria decision making in workforce choice using AHP, WSM and WPM', *The Journal of the Textile Institute*, Vol. 110, No. 7, pp.1092–1101.

Ciancio, V., Salata, F., Falasca, S., Curci, G., Golasi, I., de Wilde, P. (2020) 'Energy demands of buildings in the framework of climate change: an investigation across Europe', *Sustainable Cities and Society*, Vol. 60, p.102213.

Communication on the European Green Deal (2019) [online] https://commission.europa.eu/publications/communication-european-green-deal_en (accessed 28 November 2023).

Cooremans, C. and Schönenberger, A. (2019) 'Energy management: a key driver of energy-efficiency investment?', *Journal of Cleaner Production*, Vol. 230, pp.264–275.

Coyne, B. and Denny, E. (2021) 'Mind the energy performance gap: testing the accuracy of building energy performance certificates in Ireland', *Energy Efficiency*, Vol. 14, No. 6, p.57.

Cuerda, E., Guerra-Santin, O., Sendra, J.J. and Neila, F.J. (2020) 'Understanding the performance gap in energy retrofitting: measured input data for adjusting building simulation models', *Energy and Buildings*, Vol. 209, p.109688.

D'Oca, S., Ferrante, A., Ferrer, C., Pernetti, R., Gralka, A., Sebastian, R. and Veld, P. (2018) 'Technical, financial, and social barriers and challenges in deep building renovation: integration of lessons learned from the H2020 cluster projects', *Buildings*, Vol. 8, No. 12, p.174.

de Wilde, P. and Tian, W. (2010) 'Predicting the performance of an office under climate change: a study of metrics, sensitivity and zonal resolution', *Energy and Buildings*, Vol. 42, No. 10, pp.1674–1684.

Dhiman, H.S. and Sen, S. (2022) 'Data envelopment analysis based fuzzy TOPSIS and fuzzy COPRAS techniques for selection of solar energy projects', *Infrastructure Development – Theory, Practice and Policy: Sustainability and Resilience*, Vol. 118, p.11.

Doukas, H., Karakosta, C. and Psarras, J. (2009) 'A linguistic TOPSIS model to evaluate the sustainability of renewable energy options', *International Journal of Global Energy Issues*, Vol. 32, Nos. 1–2, pp.102–118.

Doukas, H., Karakosta, C. and Psarras, J. (2010) 'Computing with words to assess the sustainability of renewable energy options', *Expert Syst. Appl.*, Vol. 37, No. 7, pp.5491–5497.

Dubois, M-C. et al. (2015) 'Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: a literature review', *Energy Research Journal*, Vol. 6, No. 1, pp.25–41.

Dunphy, N., Little, J. and van der Krogt, R. (2012) 'Model for retrofit configuration selection using multiple decision diagrams', *Building Simulation and Optimization Conference*, Loughborough.

Economidou, M., Todeschi, V. and Bertoldi, P. (2019) *Accelerating Energy Renovation Investments in Buildings: Financial and Fiscal Instruments across the EU*, JRC Science for Policy Report, European Commission [online] https://www.smafin.eu/wp-content/uploads/2021/12/accelerating_energy_renovation_investments_in_buildings.pdf (accessed 30 April 2024).

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P. and Castellazzi, L. (2020) 'Review of 50 years of EU energy efficiency policies for buildings', *Energy and Buildings*, Vol. 225, p.110322.

Energate (2023) *Homepage* [online] https://energate-project.eu/ (accessed 20 November 2023).

Energy Efficiency Directive (2023) [online] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en (accessed 30 April 2024).

Energy Efficiency First Principle (2018) [online] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-first-principle_en (Accessed 28 November 2023).

Energy Efficiency in Buildings, from Financing to Implementation: Survey Insights from the ENERGATE Workshop, Energate [online] https://energate-project.eu/Energy_Efficiency_in_Buildings (accessed 20 November 2023).

Energy Performance of Buildings Directive (2023) [online] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed 30 April 2024).

EXOIKONOMO (2023) [online] https://exoikonomo2023.gov.gr/el (accessed 30 April 2024).

Feifer, L. (2011) 'Sustainability indicators in buildings. Identifying key performance indicators', *27th International Conference on Passive and Low Energy Architecture. Architecture and Sustainable Development*.

Fenz, S., Giannakis, G., Bergmayr, J. and Iousef, S. (2023) 'RenoDSS – a BIM-based building renovation decision support system', *Energy and Buildings*, Vol. 288, p.112999.

Fonseca, M.A.G., Soares, L., de Faria and Lourenço, S.R. (2019) 'Selection of energy efficiency projects using TOPSIS method', *International Journal of Development Research*, Vol. 9, No. 3, pp.26719–26724, ISSN: 2230-9926.

Forouli, A., Gkonis, N., Nikas, A., Siskos, E., Doukas, H. and Tourkolias, C. (2019) 'Energy efficiency promotion in Greece in light of risk: evaluating policies as portfolio assets', *Energy*, Vol. 170, pp.818–831.

García-Quevedo, J. and Jové-Llopis, E. (2021) 'Environmental policies and energy efficiency investments. An industry-level analysis', *Energy Policy*, Vol. 156, p.112461.

Govindan, K. and Jepsen, M.B. (2016) 'ELECTRE: a comprehensive literature review on methodologies and applications', *European Journal of Operational Research*, Vol. 250, No. 1, pp.1–29.

Hassan, I., Alhamrouni, I. and Azhan, N.H. (2023) 'A CRITIC-TOPSIS multi-criteria decision-making approach for optimum site selection for solar PV farm', *Energies*, Vol. 16, No. 10, p.4245.

Ho, A.M., Lai, J.H. and Chiu, B.W. (2021) 'Key performance indicators for holistic evaluation of building retrofits: systematic literature review and focus group study', *Journal of Building Engineering*, Vol. 43, p.102926.

Höjer, M. and Mjörnell, K. (2018) 'Measures and steps for more efficient use of buildings', *Sustainability*, Vol. 10, No. 6, p.1949.

Hwang, C.L. and Yoon, K. (1981) *Multiple Attribute Decision Making: Methods and Applications*, Springer-Verlag, New York.

International Performance Measurement and Verification Protocol (IPMVP) (2022) [online] https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp (accessed 30 April 2024).

Ivanova, D. and Middlemiss, L. (2021) 'Characterizing the energy use of disabled people in the European Union towards inclusion in the energy transition', *Nature Energy*, Vol. 6, No. 12, pp.1188–1197.

Karakosta, C. and Corovessi, A. (2023) 'Analysis of benefits and challenges of one-stop shops solution for residential building energy renovation', *9th International Scientific-Business Conference: Leadership, Innovation, Management and Economics: Integrated Politics of Research – LIMEN 2023*, 7 December, Graz, Austria.

Karakosta, C. and Mylona, Z. (2022) 'A methodological framework enhancing energy efficiency investments in buildings', *8th International Scientific-Business Conference: Leadership, Innovation, Management and Economics: Integrated Politics of Research – LIMEN 2022 (Hybrid)*, 1 December, Budapest, Hungary.

Karakosta, C. and Papapostolou, A. (2023) 'Energy efficiency trends in the Greek building sector: a participatory approach', *Euro-Mediterranean Journal for Environmental Integration*, Vol. 8, No. 1, pp.3–13, Invited paper.

Karakosta, C. and Psarras, J. (2012) 'Fuzzy TOPSIS approach for understanding a country's development priorities within the scope of climate technology transfer', in Acosta, M.J. (Ed.): *Advances in Energy Research*, pp.123–149, Nova Science Publishers, New York.

Karakosta, C., Mexis, F.D., Papapostolou, A. and Psarras, J. (2023a) 'On the stimulus of energy efficiency investments: the development of integrated online supporting tools and database', *International Journal of Decision Support Systems*, in press.

Karakosta, C., Mylona, Z., Papathanasiou, J. and Psarras, J. (2023b) 'Integrating existing knowledge to accelerate buildings renovation rates in Europe', in *Proceedings of the International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL 2023)*, Springer, pp.145–159.

Karakosta, C., Papapostolou, A., Mexis, F.D. and Doukas, H. (2022) 'A multidimensional approach for benchmarking energy efficiency projects', *32nd European Conference on Operational Research – EURO 2022*, 3–6 July, Espoo, Finland, ISBN 978-951-95254-1-9.

Kaur, G. and Majumder, A. (2022) 'A Comparative study and efficiency analysis between Sanchez and fuzzy TOPSIS methods in a multi-criteria decision-making problem for energy plant instalment', *Journal of Physics: Conference Series*, Vol. 2267, No. 1, p.012082, IOP Publishing.

Kaur, G., Majumder, A. and Yadav, R. (2022) 'An efficient generalized fuzzy TOPSIS algorithm for the selection of the hybrid energy resources: a comparative study between single and hybrid energy plant installation in Turkey', *RAIRO-Operations Research*, Vol. 56, No. 3, pp.1877–899.

Kleanthis, N., Koutsandreas, D., Karakosta, C., Doukas, H. and Flamos, A. (2022) 'Bridging the transparency gap in energy efficiency financing by co-designing an integrated assessment framework with involved actors', *Energy Reports*, Vol. 8, pp.9686–9699, ISSN: 2352-4847, https://doi.org/10.1016/j.egyr.2022.07.066.

Koutsandreas, D., Kleanthis, N., Flamos, A., Karakosta, C. and Doukas, H. (2022) 'Risks and mitigation strategies in energy efficiency financing: a systematic literature review', *Energy Reports*, Vol. 8, pp.1789–1802, ISSN 2352-4847.

Kurt, Ü. (2014) 'The fuzzy TOPSIS and generalized Choquet fuzzy integral algorithm for nuclear power plant site selection – a case study from Turkey', *Journal of Nuclear Science and Technology*, Vol. 51, No. 9, pp.1241–1255.

Kylili, A., Fokaides, P.A. and Jimenez, P.A.L. (2016) 'Key performance indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: a review', *Renewable and Sustainable Energy Reviews*, Vol. 56, pp.906–915.

Li, H., et al. (2020) 'System-level key performance indicators for building performance evaluation', *Energy and Buildings*, Vol. 209, p.109703.

Li, Y., O'Donnell, J., García-Castro, R. and Vega-Sánchez, S. (2017) 'Identifying stakeholders and key performance indicators for district and building energy performance analysis', *Energy and Buildings*, Vol. 155, pp.1–15.

Liao, H. and Xu, Z. (2014) 'Multi-criteria decision making with intuitionistic fuzzy PROMETHEE', *Journal of Intelligent & Fuzzy Systems*, Vol. 27, No. 4, pp.1703–1717.

Liu, S-Y., Perng, Y-H. and Ho, Y-F. (2013) 'The effect of renewable energy application on Taiwan buildings: what are the challenges and strategies for solar energy exploitation?', *Renewable and Sustainable Energy Reviews*, Vol. 28, pp.92–106.

Liu, Y., Chen, H. and Wang, X.J. (2021) 'Research on green renovations of existing public buildings based on a cloud model-TOPSIS method', *Journal of Building Engineering*, Vol. 34, p.101930.

López-Bernabé, E., Foudi, S., Linares, P. and Galarraga, I. (2021) 'Factors affecting energy-efficiency investment in the hotel industry: survey results from Spain', *Energy Efficiency*, Vol. 14, No. 4, p.41.

Mardani, A., Zavadskas, E.K., Khalifah, Z., Zakuan, N., Jusoh, A., Nor, K.M. and Khoshnoudi, M. (2017) 'A review of multi-criteria decision-making applications to solve energy management problems: two decades from 1995 to 2015', *Renewable and Sustainable Energy Reviews*, Vol. 71, pp.216–256.

Markaki, M., Belegri-Roboli, A., Michaelides, P., Mirasgedis, S. and Lalas, D.P. (2013) 'The impact of clean energy investments on the Greek economy: an input-output analysis (2010–2020)', *Energy Policy*, Vol. 57, pp.263–275.

Martinaitis, V., Kazakevičius, E. and Vitkauskas, A. (2007) 'A two-factor method for appraising building renovation and energy efficiency improvement projects', *Energy Policy*, Vol. 35, No. 1, pp.192–201.

Mary, S.S.A. and Suganya, G. (2016) 'Multi-criteria decision making using ELECTRE', *Circuits and Systems*, Vol. 7, No. 6, pp.1008–1020.

Marzouk, M., El-Maraghy, M. and Metawie, M. (2023) 'Assessing retrofit strategies for mosque buildings using TOPSIS', *Energy Reports*, Vol. 9, pp.1397–1414.

McGinley, O., Moran, P. and Goggins, J. (2022) 'An assessment of the key performance indicators (KPIs) of energy efficient retrofits to existing residential buildings', *Energies*, Vol. 15, No. 1, p.334.

Melvin, J. (2018) 'The split incentives energy efficiency problem: evidence of underinvestment by landlords', *Energy Policy*, Vol. 115, pp.342–352.

Mexis, F.D., Papapostolou, A., Karakosta, C. and Psarras, J. (2021a) 'Financing sustainable energy efficiency projects: the triple-A case', *Environmental Sciences Proceedings*, Vol. 11, No. 1, p.22.

Mexis, F.D., Papapostolou, A., Karakosta, C., Sarmas, E., Koutsandreas, D. and Doukas, H. (2021b) 'Leveraging energy efficiency investments: an innovative web-based benchmarking tool', *Adv. Sci. Technol. Eng. Syst. J.*, Vol. 6, No. 5, pp.237–248.

Mourmouris, J.C. and Potolias, C. (2013) 'A multi-criteria methodology for energy planning and developing renewable energy sources at a regional level: a case study Thassos, Greece', *Energy Policy*, Vol. 52, pp.522–530.

Mustafaraj, G., Markja, I. and Dhoska, K. (2023) 'Analysis of different energy efficiency technologies based on cost and return of investment', *Innovations*, Vol. 11, No. 1, pp.12–13.

Neofytou, H., Nikas, A. and Doukas, H. (2020a) 'Sustainable energy transition readiness: a multicriteria assessment index', *Renewable and Sustainable Energy Reviews*, Vol. 131, p.109988.

Neofytou, H., Sarafidis, Y., Gkonis, N., Mirasgedis, S. and Askounis, D. (2020b) 'Energy efficiency contribution to sustainable development: a multi-criteria approach in Greece', *Energy Sources, Part B: Economics, Planning, and Policy*, Vol. 15, Nos. 10–12, pp.572–604.

Ngacho, C. and Das, D. (2014) 'A performance evaluation framework of development projects: an empirical study of Constituency Development Fund (CDF) construction projects in Kenya', *International Journal of Project Management*, Vol. 32, No. 3, pp.492–507.

O'Grady, T., Chong, H-Y. and Morrison, G.M. (2021) 'A systematic review and metaanalysis of building automation systems', *Building and Environment*, Vol. 195, p.107770.

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*, Vol. 206, p.108378.

Panicker, K., Anand, P. and George, A. (2022) 'Assessment of building energy performance integrated with solar PV: towards a net zero energy residential campus in India', *Energy and Buildings*, Vol. 281, p.112736.

Papapostolou, A., Karakosta C., Marinakis V., Psarras J. (2014) 'Country risk evaluation methodology to support bilateral cooperation in the field of electricity generation from renewable sources', *3rd International Symposium and 25th National Conference on Operational Research*, 26–28 June, Volos, Greece, ISBN: 978-618-80361-3-0.

Papapostolou, A., Karakosta, C. and Doukas, H. (2017a) 'Analysis of policy scenarios for achieving renewable energy sources targets: a fuzzy TOPSIS approach', *Energy Environ.*, Vol. 28, Nos. 1–2, pp.88–109.

Papapostolou, A., Karakosta, C., Marinakis, V. and Flamos, A. (2016) 'Assessment of RES cooperation framework between the EU and North Africa: a multicriteria approach based on UTASTAR', *International Journal of Energy Sector Management*, Vol. 10, No. 3, pp.402–426.

Papapostolou, A., Karakosta, C., Nikas, A. and Psarras, J. (2017b) 'Exploring opportunities and risks for RES-E deployment under cooperation mechanisms between EU and Western Balkans: a multi-criteria assessment', *Renewable and Sustainable Energy Reviews*, Vol. 80, pp.519–530.

Papapostolou, A., Mexis, F.D., Sarmas, E., Karakosta, C. and Psarras, J. (2020a) 'Web-based application for screening energy efficiency investments: a MCDA approach', *2020 11th International Conference on Information, Intelligence, Systems and Applications (IISA)*, IEEE, pp.1–7.

Papapostolou, A., Karakosta. C., Apostolidis. G., Doukas. H. (2020b) An AHP-SWOT-fuzzy TOPSIS approach for achieving a cross-border RES cooperation', *Sustainability*, Vol. 12, No. 7, p.2886.

Papapostolou, A., Karakosta. C., Doukas., H. (2017) 'Analysis of policy scenarios for achieving renewable energy sources targets: a fuzzy TOPSIS approach', *Energy & Environment*, Vol. 28, Nos. 1–2, pp.88–109.

Papapostolou, A., Mexis, F.D., Karakosta, C. and Psarras, J. (2022) 'A multicriteria tool to support decision-making in the early stages of energy efficiency investments', *International Conference on Decision Support System Technology*, Springer International Publishing, Cham, pp.190–202.

Patlitzianas, K.D. (2011) 'An analysis of energy efficiency investments' environment in Greece – the potential role of JESSICA instrument', *Energy conversion and management*, Vol. 52, No. 1, pp.366–373.

Pippi, K.D., Papadopoulos, T.A. and Kryonidis, G.C. (2020) 'Viability assessment of PV systems in university campuses under the net-metering policy', *2020 55th International Universities Power Engineering Conference (UPEC)*, IEEE, pp.1–6.

Renovation Wave (2020) [online] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en (accessed 28 November 2023).

Rockstuhl, S., Wenninger, S., Wiethe, C. and Häckel, B. (2021) 'Understanding the risk perception of energy efficiency investments: investment perspective vs. energy bill perspective', *Energy Policy*, Vol. 159, p.112616.

Rose, J., Thomsen, K.E., Domingo-Irigoyen, S., Bolliger, R., Venus, D., Konstantinou, T., … Hidalgo-Betanzos, J.M. (2021) 'Building renovation at district level – lessons learned from international case studies', *Sustainable Cities and Society*, Vol. 72, p.103037.

Roszkowska, E. (2011) 'Multi-criteria decision making models by applying the TOPSIS method to crisp and interval data', *Multiple Criteria Decision Making/University of Economics in Katowice*, Vol. 6, No. 1, pp.200–230.

Saaty, T.L. (1980) *The Analytic Hierarchy Process*, McGraw Hill, New York.

Sarihi, S., Saradj, F.M. and Faizi, M. (2021) 'A critical review of façade retrofit measures for minimizing heating and cooling demand in existing buildings', *Sustainable Cities and Society*, Vol. 64, p.102525.

Sarmas, E., Marinakis, V. and Doukas, H. (2022a) 'A data-driven multicriteria decision making tool for assessing investments in energy efficiency', *Operational Research*, Vol. 22, No. 5, pp.5597–5616.

Sarmas, E., Spiliotis, E., Marinakis, V., Koutselis, T. and Doukas, H. (2022b) A meta-learning classification model for supporting decisions on energy efficiency investments', *Energy Build*, Vol. 258, p.111836.

Şengül, Ü., Eren, M., Shiraz, S.E., Gezder, V. and Şengül, A.B. (2015) 'Fuzzy TOPSIS method for ranking renewable energy supply systems in Turkey', *Renew. Energ.*, Vol. 75, pp.617–625.

Spyridaki, N.A., Stavrakas, V., Dendramis, Y. and Flamos, A. (2020) 'Understanding technology ownership to reveal adoption trends for energy efficiency measures in the Greek residential sector', *Energy Policy*, Vol. 140, p.111413.

Sun, F. and Yu, J. (2021) 'Improved energy performance evaluating and ranking approach for office buildings using Simple-normalization, Entropy-based TOPSIS and K-means method', *Energy Reports*, Vol. 7, pp.1560–1570, ISSN: 2352-4847.

Sweatman, P. and Managan, K. (2010) 'Financing energy efficiency building retrofits', *International Policy and Business Model Review and Regulatory Alternatives for Spain*, Climate & Strategy Partners, Madrid.

Toosi, H.A., Lavagna, M., Leonforte, F., Del Pero, C. and Aste, N. (2020) 'Life cycle sustainability assessment in building energy retrofitting: a review', *Sustainable Cities and Society*, Vol. 60, p.102248.

Turner, C., Frankel, M., U.G.B. Council (2008) 'Energy performance of LEED for new construction buildings', *New Buildings Institute*, Vol. 4, No. 4, pp.1–42.

Tzani, D., Stavrakas, V., Santini, M., Thomas, S., Rosenow, J. and Flamos, A. (2022) 'Pioneering a performance-based future for energy efficiency: lessons learnt from a comparative review analysis of pay-for-performance programmes', *Renewable and Sustainable Energy Reviews*, Vol. 158, p.112162.

Ugwu, O.O. and Haupt, T.C. (2007) 'Key performance indicators and assessment methods for infrastructure sustainability – a South African construction industry perspective', *Building and Environment*, Vol. 42, No. 2, pp.665–680.

Vallecha, H., Bhattacharjee, D., Osiri, J.K. and Bhola, P. (2021) 'Evaluation of barriers and enablers through integrative multicriteria decision mapping: developing sustainable community energy in Indian context', *Renewable and Sustainable Energy Reviews*, Vol. 138, p.110565.

van Oorschot, J.A.W.H., Hofman, E. and Halman, J.I.M. (2016) 'Upscaling large scale deep renovation in the Dutch residential sector: a case study', *Energy Procedia*, Vol. 96, pp.386–403.

Vigna, I., Pernetti, R., Pernigotto, G. and Gasparella, A. (2020) 'Analysis of the building smart readiness indicator calculation: a comparative case-study with two panels of experts', *Energies*, Vol. 13, No. 11, p.2796.

Vogel, J.A., Lundqvist, P. and Arias, J. (2015) 'Categorising barriers to energy efficiency in buildings', *Energy Procedia*, Vol. 75, pp.2839–2845.

Walasek, D. and Barszcz, A. (2017) 'Analysis of the adoption rate of building information modeling [BIM] and its return on investment [ROI]', *Procedia Engineering*, Vol. 172, pp.1227–1234.

Wang, E., Alp, N., Shi, J., Wang, C., Zhang, X. and Chen, H. (2017) 'Multi-criteria building energy performance benchmarking through variable clustering based compromise TOPSIS with objective entropy weighting', *Energy*, Vol. 125, pp.197–210.

Wang, J.W., Cheng, C.H. and Kun-Cheng, H. (2009) 'Fuzzy hierarchical TOPSIS for supplier selection', *Appl. Soft Computer*, Vol. 9, pp.377–386.

Wen, J., Okolo, C.V., Ugwuoke, I.C. and Kolani, K. (2022) 'Research on influencing factors of renewable energy, energy efficiency, on technological innovation. Does trade, investment and human capital development matter?', *Energy Policy*, Vol. 160, p.112718.

Yan, G., Ling, Z. and Dequn, Z. (2011) 'Performance evaluation of coal enterprises energy conservation and reduction of pollutant emissions base on GRD-TOPSIS', *Energy Proced.*, Vol. 5, pp.535–539.

Yang, S., Pernot, J.G., Jörin, C.H., Niculita-Hirzel, H., Perret, V. and Licina, D. (2020) 'Energy, indoor air quality, occupant behavior, self-reported symptoms and satisfaction in energy-efficient dwellings in Switzerland', *Building and Environment*, Vol. 171, p.106618.

Yeatts, D.E., Auden, D., Cooksey, C. and Chen, C.F. (2017) 'A systematic review of strategies for overcoming the barriers to energy-efficient technologies in buildings', *Energy Res. Soc. Sci.*, Vol. 32, pp.76–85.

Yue, Z. (2011) 'An extended TOPSIS for determining weights of decision makers with interval numbers', *Knowledge-Based Systems*, Vol. 24, No. 1, pp.146–153.

Zachariadis, T., Michopoulos, A., Vougiouklakis, Y., Piripitsi, K., Ellinopoulos, C. and Struss, B. (2018) 'Determination of cost-effective energy efficiency measures in buildings with the aid of multiple indices', *Energies*, Vol. 11, No. 1, p.191.

Zhang, C., Hu, M., Laclau, B., Garnesson, T., Yang, X. and Tukker, A. (2021) 'Energy-carbon-investment payback analysis of prefabricated envelope-cladding system for building energy renovation: cases in Spain, the Netherlands, and Sweden', *Renewable and Sustainable Energy Reviews*, Vol. 145, p.111077.