

Article

An AHP-Based Multicriteria Framework for Evaluating Renewable Energy Service Proposals in Public Healthcare Infrastructure: A Case Study of an Italian Hospital

Cristina Ventura ¹, Ferdinando Chiacchio ¹, Diego D'Urso ¹, Giuseppe Marco Tina ¹,
Gabino Jiménez Castillo ² and Ludovica Maria Oliveri ^{1,*}

¹ Dipartimento di Ingegneria Elettrica, Elettronica ed Informatica (D.I.E.E.I.), University of Catania, Via Santa Sofia 64, 95123 Catania, Italy; cristina.ventura@unict.it (C.V.); ferdinando.chiacchio@unict.it (F.C.); diego.durso@unict.it (D.D.); giuseppe.tina@unict.it (G.M.T.)

² Departamento de Ingeniería Eléctrica, Universidad de Jaén, Edificio A3, dependencia 231, Campus Las Lagunillas s/n., 23071 Jaén, Spain; gjimenez@ujaen.es

* Correspondence: ludovica.oliveri@phd.unict.it

Abstract

Public healthcare infrastructure is among the most energy-intensive of public facilities; therefore, it needs to become more environmentally and economically sustainable by increasing energy efficiency and improving service reliability. Achieving these goals requires modernizing hospital energy systems with renewable energy sources (RESs). This process often involves Energy Service Companies (ESCOs), which propose integrated RES technologies with tailored contractual schemes. However, comparing ESCO offers is challenging due to their heterogeneous technologies, contractual structures, and long-term performance commitments, which make simple cost-based assessments inadequate. This study develops a structured Multi-Criteria Decision-Making (MCDM) methodology to evaluate energy projects in public healthcare facilities. The framework, based on the Analytic Hierarchy Process (AHP), combines both quantitative (net present value, stochastic simulations of energy cost savings, and CO₂ emission reductions) with qualitative assessments (redundancy, flexibility, elasticity, and stakeholder image). It addresses the lack of standardized tools for ranking real-world ESCO proposals in public procurement. The approach, applied to a case study, involves three ESCO proposals for a large hospital in Southern Italy. The results show that integrating photovoltaic generation with trigeneration achieves the highest overall score. The proposed framework provides a transparent, replicable tool to support evidence-based energy investment decisions, extendable to other public-sector infrastructures.

Keywords: healthcare infrastructures; renewable energy resources; multi-criteria decision-making; analytic hierarchy process; energy service company



Academic Editor: Álvaro Gutiérrez

Received: 8 August 2025

Revised: 29 August 2025

Accepted: 1 September 2025

Published: 3 September 2025

Citation: Ventura, C.; Chiacchio, F.; D'Urso, D.; Tina, G.M.; Castillo, G.J.; Oliveri, L.M. An AHP-Based Multicriteria Framework for Evaluating Renewable Energy Service Proposals in Public Healthcare Infrastructure: A Case Study of an Italian Hospital. *Energies* **2025**, *18*, 4680. <https://doi.org/10.3390/en18174680>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Improving energy performance and sustainability in public healthcare infrastructure has become a strategic priority for governments and local authorities worldwide [1,2]. Hospitals, in particular, are among the most energy-intensive public buildings due to their continuous operational requirements, complex systems, and critical functions, such as intensive care and diagnostic technologies. In Southern Europe, aging hospital infrastructures and rising energy costs further emphasize the need for targeted energy investments that ensure both environmental responsibility and operational resilience [3].

The healthcare sector is highly energy-intensive, accounting for 5% of global greenhouse gas emissions, with a carbon footprint equivalent to 514 coal-fired power plants. Over half of these emissions come from electricity, gas, steam, and air conditioning use, while the remainder is linked to agriculture, pharmaceuticals and chemicals, transport, and waste treatment [4]. In this context, the decarbonization of the healthcare sector can no longer be postponed.

Several scientific studies analyze energy efficiency in the healthcare sector and the integration of RES [5–8]. The integration of RES in public buildings, such as hospitals, generally requires energy modernization to optimize demand profiles and maximize self-consumption. A study on hospitals in southwestern Europe [9] demonstrated that, through photovoltaic (PV) self-consumption systems, facilities can directly use over 90% of the generated energy, with only 30% of the roof area exploited, due to the alignment of daytime operations with solar production. To enable and finance such modernization efforts, public-private partnerships (PPPs) and ESCOs are increasingly employed in the public sector.

Nevertheless, when public infrastructures, and in particular hospitals, are challenged with multiple technical and financial proposals from ESCOs, as is often the case in public tenders, they need a robust, objective, and transparent decision-making process. The complex nature of these proposals, which often involve different technologies, contract durations, operating strategies, and performance guarantees, makes simple cost-based comparisons insufficient and potentially misleading. Despite the growing interest in sustainable healthcare and energy contracts, the literature is still scarce in providing structured methods to evaluate and rank real-world ESCO offerings comprehensively. While energy audits and retrofit strategies are widely discussed, few studies have focused on ex ante decision support tools applicable for the evaluation of public tenders, and even fewer address how to systematically integrate economic, technical, environmental, and reputational dimensions, together with stakeholder preferences, into a unified evaluation framework.

In this context, MCDM methods, such as the AHP, offer a structured approach to comparing complex ESCO proposals by combining quantitative and qualitative criteria, supporting transparent and evidence-based investment decisions.

In general, AHP is widely used to support complex decisions in healthcare infrastructure, from the location of new facilities to sustainable management and project selection, often integrated with other decision-making tools and GIS. In particular, there are three fundamental issues where AHP is used in the context of hospital facilities:

1. Location of new facilities: AHP is often integrated with GIS or fuzzy methods to assess multiple criteria (accessibility, cost, environmental impact) when selecting sites for hospitals or clinics [10–12].
2. Sustainability and asset management: AHP helps weigh environmental, economic, and social factors for hospital sustainability and infrastructural asset management [13,14].
3. Project selection and prioritization: AHP models support public and private entities in choosing between project alternatives, optimizing resource allocation [15–17].

The third issue is the one that comes closest to the purpose of the paper presented here. In particular, the study [16] developed an AHP-based MCDM framework to prioritize health infrastructure projects in Algeria, considering seven main criteria and eighteen sub-criteria, including political, sociodemographic, epidemiological, technical, economic-financial, and environmental factors. Through expert surveys and pairwise comparisons, the authors used ExpertChoice software (version 11) to compute criteria weights, evaluate three candidate projects (a polyclinic, an anti-cancer center, and a 60-bed hospital), and perform sensitivity analyses. The results indicated that the polyclinic project achieved the highest priority (46.7%), followed by the hospital (42.3%), and the cancer center (11%), with sociodemographic and epidemiological criteria being most influential. This work

focused on ex ante selection of healthcare infrastructure projects rather than energy service contracting. The paper [16] applied AHP to strategic facility planning, using primarily qualitative and demographic criteria, and it did not specifically address sustainable energy solutions and public procurement decision-making for operational hospitals.

The paper [17] analyzed the implementation of Industry 4.0 in healthcare supply chains using a hybrid fuzzy AHP and fuzzy DEMATEL approach. It identified eight main factors and 33 subfactors affecting smart HCSC adoption, prioritized them through fuzzy AHP, and mapped their causal relationships using fuzzy DEMATEL. The results showed that healthcare logistics management is the most critical factor, while integrated HCSC and logistics management act as key causal drivers for improving operational performance. This study focused on strategic supply chain transformation and operational performance rather than energy service contracting or economic–environmental multi-criteria evaluation.

In [15], a hybrid MCDM model integrating the AHP with the Combinative Distance-Based Assessment (CODAS) method was proposed to prioritize and select Six Sigma projects in the healthcare industry. Ten potential projects were evaluated using four main criteria groups: financial, operational, patient-centric, and organizational. AHP was used to determine the criteria weights, while CODAS ranked the projects by measuring Euclidean and Taxicab distances from the negative ideal solution. The paper focused on Six Sigma project prioritization in healthcare management rather than energy contracting. Its criteria were mainly operational and organizational (financial, patient-centric, and managerial), and the decision-making process used AHP–CODAS to rank internal improvement projects.

A methodology similar to the approach presented here was introduced in [18], where the AHP was used to rank candidate configurations of a hybrid PV–wind–battery system, selecting the optimal solution from Pareto-optimal alternatives generated through NSGA-II. Four candidate configurations were ranked using five criteria combining economic and technical aspects, and a sensitivity analysis highlighted the impact of decision-makers' preferences. Unlike this study, it focused on residential hybrid system design rather than public procurement and operational hospital energy solutions.

Paper [19] proposed an MCDC framework for selecting energy-efficient renovation strategies in hospital wards, integrating energy performance, economic feasibility, and thermal comfort as the main evaluation dimensions. The paper focused exclusively on internal retrofit options for a single building without public procurement considerations.

In [20], a multi-platform analysis for accelerating the deployment of distributed renewable energy systems for the electrification of healthcare facilities in low-income regions is presented. The study focused on off-grid solar PV planning in resource-constrained clinics.

Study [21] developed an AHP-based MCDM model to prioritize sustainable energy resources in Afghanistan, considering technological, environmental, economic, and social criteria, with 15 sub-criteria. The analysis ranked solar energy first, followed by hydro, wind, biomass, and geothermal, emphasizing the high potential of solar energy due to its cost-effectiveness, environmental benefits, and social acceptance. The study focused on national-level RES prioritization rather than site-specific energy service solutions.

Summarizing, previous studies have focused on internal retrofits, off-grid electrification, or national-level RES prioritization. To the best of the authors' knowledge, this study fills a critical gap by providing a structured MCDM framework for the evaluation and ranking of real ESCO proposals in operational, grid-connected public healthcare facilities, integrating economic, technical, environmental, and reputational dimensions within the public procurement process. Compared to closely related MCDM studies in the healthcare energy domain, the originality of this work lies in its explicit focus on real ESCO proposals, submitted within a public procurement process. Prior studies have typically concentrated on internal retrofits and energy-efficient renovation strategies [19], the electrification of

off-grid clinics [20], or national-level prioritization of renewable resources [21]. Other AHP-based hospital applications have emphasized infrastructure planning or demographic and epidemiological drivers [16] rather than energy contracting. Unlike these contributions, our framework integrates deterministic, discounted cash flow, and stochastic simulations with six technical, economic, and reputational criteria, providing a structured decision-support tool directly applicable to hospital tenders. This gap between conceptual MCDM models and practical procurement decisions in grid-connected healthcare infrastructures is precisely what this study addresses.

The methodology here proposed integrates six carefully selected criteria and applies the AHP with weights derived from a structured stakeholder survey, ensuring that internal decision-makers' perspectives are directly embedded into the evaluation.

A further innovation of this study lies in the hybrid economic assessment, which combines three distinct approaches:

- A deterministic cost comparison;
- A discounted cash flow analysis (NPV);
- A probabilistic simulation based on historical energy price volatility.

This triple-method approach enhances robustness and accounts for uncertainty in long-term scenarios. Moreover, the framework also includes both technical system assessments (such as redundancy, flexibility, and elasticity) and intangible value dimensions, such as stakeholder image and institutional compatibility.

The resulting evaluation model is not only thorough and technically sound but also applicable in many distinct types of public infrastructure, such as schools, city buildings, transportation hubs, and other facilities that use a lot of energy. This work adds a new decision-support tool that can help improve public procurement practices during the energy transition by combining openness, stakeholder involvement, and sound methods.

The rest of the paper is organized as follows: Section 2 details the methodology, including the criteria definition, scoring rubrics, and AHP weighting process; Section 3 presents the case study, including the hospital profile and the three ESCO proposals; Section 4 provides the results of the multi-criteria evaluation, including normalized scores and final ranking; Section 5 concludes the paper, discusses the main findings, implications, and limitations, and suggests future research directions.

2. Methodology

This section presents the methodological framework developed to evaluate and compare alternative energy solutions in complex decision-making contexts. In this study, this framework is applied to assess three RES proposals for a public hospital in the south of Italy. The analysis is based on a MCDM approach [22], aimed at capturing the multidimensional trade-offs inherent in energy planning for healthcare infrastructures [20]. The methodology consists of four key phases: the definition of evaluation criteria, the performance assessment of the proposed solutions, prioritization through the AHP, and stakeholder engagement through survey design.

In practice, as shown in Figure 1, the first phase involves identifying the criteria, based on the specific needs of the healthcare infrastructure and supported by a preliminary review of the relevant literature, which will guide the assessment of each proposed solution and the AHP. In the second phase, a performance score is assigned to each solution with respect to every criterion. These scores are then integrated with the weights derived from the AHP analysis, which allows us to assign a different level of importance to each criterion and compute a final overall score for each alternative.

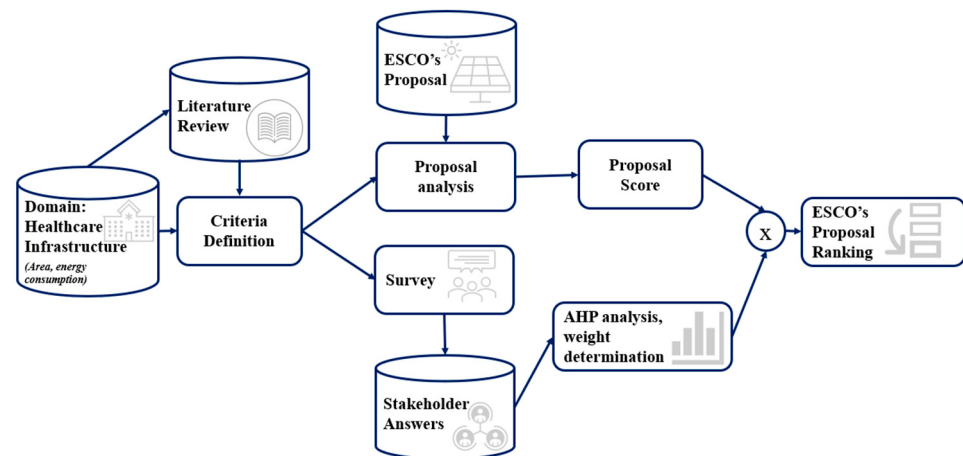


Figure 1. Block diagram of the methodological framework used to evaluate and rank energy service proposals for public healthcare infrastructure. The process integrates the technical analysis of ESCO proposals and stakeholder-informed AHP weighting.

2.1. Definition of Criteria

Evaluating energy service proposals in a healthcare setting demands a multidimensional approach that accounts for economic viability, technical reliability, environmental sustainability, and public accountability.

This phase of the methodology is aimed at identifying the evaluation criteria that will be used first to assign a performance score to each solution with respect to each criterion and subsequently to support the MCDM process. The criteria employed in this study were identified through an iterative process that integrated expert judgment with established approaches commonly adopted in energy-related MCDM research. This process led to the selection of six key criteria, reflecting economic, technical, environmental, and social/institutional dimensions frequently used to evaluate energy systems, especially in the context of healthcare and other public infrastructures [19,21,23].

- **Economic feasibility:** This criterion reflects stakeholders' preferences regarding the overall affordability of an energy solution. It encompasses both initial investment costs (CAPEX) and ongoing operational expenses (OPEX). The respondents were asked to express whether they favored solutions that minimize installation and maintenance costs, thus supporting financial sustainability over the system's lifetime.
- **System redundancy:** Redundancy measures the capacity of the proposed energy solutions to ensure uninterrupted supply, including during critical events and after the expiration of contractual agreements. It assesses the system's robustness under stress conditions and its ability to maintain core functions independently.
- **Environmental performance:** This criterion expresses stakeholders' concerns regarding the environmental sustainability of each energy alternative. It includes perceptions of ecological responsibility, alignment with decarbonization goals, and the solution's overall environmental footprint in the context of public infrastructure.
- **Flexibility:** Flexibility is defined as the system's ability to adjust output and operating conditions in response to fluctuating energy demands or external constraints. It reflects the degree of operational adaptability to diverse clinical and infrastructural needs. In addition, in the context of evolving energy markets, flexibility also includes the ability to participate in ancillary service markets such as dispatching services, thereby enabling the hospital to provide grid support through demand response or the modulation of local generation, as encouraged in smart grid-integrated systems.
- **Elasticity:** Elasticity refers to the energy system's capacity for scalability and future-readiness. It captures the system's ability to seamlessly accommodate technological

advancements, anticipated load growth, and potential integration with emerging energy sources, ensuring long-term adaptability and resilience.

- **Institutional image:** This criterion captures the symbolic and reputational impact of the energy solution on external stakeholders, including patients, staff, and the public. It reflects alignment with institutional values such as innovation, environmental responsibility, and modernization.

The criteria identified in this paper represent a minimum core set suitable for evaluating energy solutions in public infrastructure. Additional criteria may be incorporated to reflect the specific characteristics or priorities of the infrastructure under analysis.

2.2. Performance Assessment of the Proposed Solutions

This paragraph provides a detailed assessment of each engineering solution with respect to the six decision criteria defined above, serving as the basis for the subsequent integration with the AHP-derived weights. To ensure consistency and comparability, a qualitative scoring framework was adopted, whereby each alternative received a performance score ranging from 1 (very poor performance) to 9 (excellent performance) under each criterion.

The evaluation combined quantitative indicators (e.g., net present value and emission estimates) with qualitative reasoning, particularly for criteria where direct measurements were not available, or a purely quantitative assessment was not feasible. In such cases, scores were assigned based on predefined scenarios and logical inference, ensuring transparency and replicability in the scoring process.

The specific evaluation logic, data sources, and assumptions for each criterion are described in Sections 2.2.1–2.2.6.

2.2.1. Economic Feasibility

To enable a consistent and robust economic comparison of the three energy service proposals, a multi-scenario analysis was conducted based on the hospital's historical energy consumption and contract conditions specified by each supplier. The analysis covers a 25-year horizon—15 years under concession and 10 years of post-contract system operation. All scenarios assume the following: energy prices indexed to market (year 2023), identical boundary conditions for irradiance (uniform irradiance conditions based on the MeteoNorm dataset), system degradation (0.5% per year), and a conservative nominal escalation of prices (energy: 0.5%; feed-in tariff for surplus PV energy under the Ritiro Dedicato (RID) scheme [24]: 0.6%). These two rates are linked because RID revenues ultimately follow wholesale electricity dynamics. In the sensitivity analysis, we therefore vary a joint nominal growth g for energy prices and set $g_{\text{RID}} = g + 0.1\%$ to reflect the small baseline differential (0.5% vs. 0.6%), while keeping RID a minor component relative to avoided purchase costs. All cash flows are modelled in nominal terms. The NPV discount rate is set to 6% nominal (per annum), consistent with the EU guidance for public CBA—3–4% [24] real social discount rate for euro-area projects—combined with the ECB's 2% medium-term inflation objective ($\approx 3.9\%$ real), and within typical WACC ranges for PV/ESCO investments. Plant ownership and operational responsibility are transferred to the hospital post-concession.

Three complementary approaches were adopted:

- *Direct Method*
This approach estimates the cumulative economic benefit by applying current unit prices of electricity and natural gas to the forecasted energy balances. It calculates cost savings relative to a “business-as-usual” baseline (i.e., no investment in new systems) [25,26]. The analysis assumes that, after year 15, the hospital assumes full

operational responsibility for the energy infrastructure, as all contractors plan to relinquish system management at the end of the concession period. From that point onward, the hospital is expected to bear the operational costs (e.g., maintenance), while continuing to benefit from reduced energy expenditures and revenues from the sale of surplus electricity to the grid.

- *Net Present Value (NPV) Method*

The direct method results are further processed through a financial model to obtain the net present value (NPV) of each scenario [27]. The NPV reflects the discounted sum of annual net profits over 25 years, using a fixed discount rate. This allows for time-consistent comparisons between upfront investment costs and long-term savings. To validate the economic comparison among the ESCOs, we conducted sensitivity analyses on (i) the discount rate $r \in [3\%, 9\%]$ nominal and (ii) the nominal growth of energy $g \in [0.3\%, 1.0\%]$ with $g_{\text{GRID}} = g + 0.1\%$. The results are reported in Appendix A.

- *Mathematical Expectation Method (Stochastic Simulation)*

To capture market volatility and uncertainty in future energy prices, a probabilistic approach was applied. A Monte Carlo simulation was run over 100 scenarios, each varying electricity and gas prices within plausible bounds [28]. The scenarios were weighted using a Gaussian probability distribution centered on historical average prices. The correlation between electricity and gas price trends was incorporated to reflect real-world dynamics. This method provides an expected economic value based on a distribution of outcomes, accounting for risk and uncertainty rather than relying on a single fixed-price assumption. It is particularly useful for long-term investments under market volatility, where the true economic performance depends heavily on external variables [29]. Cost savings relating to a “business-as-usual” baseline are calculated.

Each of these methods provides complementary insights: the direct method reflects current market conditions, the NPV method introduces the time value of money, and the stochastic method incorporates future uncertainty. Together, they form a comprehensive economic assessment framework for evaluating complex energy service proposals in the hospital setting.

To translate raw total economic saving of proposal i into a qualitative 1–9 score compatible with the AHP framework, each value was normalized with respect to the total maximum value among all R_i :

$$\text{Normalized } R_i = \frac{R_i}{R_{\max}} \quad (1)$$

Normalized R_i was then linearly rescaled to a 1–9 performance scale using the formula

$$\text{Score}_i = 1 + 8 \left(\frac{R_i}{R_{\max}} \right) \quad (2)$$

This transformation preserves proportional differences while aligning the results with the AHP-compatible qualitative scoring framework.

2.2.2. System Redundancy

The criterion system redundancy refers to the ability of an energy solution to ensure continuity of supply in critical conditions, including emergencies and post-contractual scenarios. In the hospital context, redundancy is particularly relevant due to the presence of life-supporting equipment and sensitive services that cannot tolerate outages [30,31].

An energy system was considered to exhibit redundancy if it fulfilled most or all of the following operational characteristics:

- Autonomous operation in case of grid failure (e.g., islanding mode or embedded smart grid);
- Multiple backup options to ensure coverage of essential loads (e.g., surgery rooms, ICUs);
- Reduced dependency on external energy providers, especially after the end of the concession period;
- Clear provisions for continuity of supply in emergencies or post-contract scenarios.

Scores were assigned based on a qualitative rubric (Table 1), which classifies each solution according to the number and nature of redundancy attributes fulfilled. A maximum score of 9 indicates full operational redundancy across all four dimensions; intermediate values reflect partial fulfilment [32].

Table 1. Scoring rubric for the “System Redundancy” criterion.

Score (1–9)	Description
9	Full redundancy: all four conditions met—autonomous operation, backup systems for critical loads, low external dependency, and post-contract continuity ensured.
7	High redundancy: three conditions met, including autonomous operation and at least one backup system for critical loads.
5	Moderate redundancy: two conditions met, typically partial coverage of critical loads and some provisions for post-contract operation.
3	Low redundancy: only one condition met, with limited backup or unclear post-contract operability.
1	No redundancy: no backup capability, full dependency on grid and external supply, no continuity beyond contractual term.

2.2.3. Environmental Performance

The environmental performance criterion quantifies the reduction in greenhouse gas emissions associated with each proposed energy solution. Specifically, the analysis focuses on the amount of CO₂ avoided per year compared to a business-as-usual scenario, in which the hospital continues to rely entirely on grid-supplied electricity [33].

The calculation of CO₂ savings was based on the following:

- The estimated annual self-production of electricity from RES and high-efficiency cogeneration;
- The application of the national electricity emission factor, set at approximately 256.6 g CO₂/kWh in 2023, according to official ISPRA data [34].

For each alternative i , the environmental performance was expressed as follows:

$$Score_i = 9 \left(\frac{CO_{2avoided_i}}{CO_{2avoided_{max}}} \right) \quad (3)$$

This proportional scaling ensures that the alternative with the highest annual CO₂ reduction receives a score of 9, while the others are ranked accordingly. This method maintains both interpretability and alignment with the AHP framework.

2.2.4. Flexibility

The flexibility criterion assesses the capability of an energy system to adjust its operational profile in response to short-term variations in energy demand, generation capacity, or external market signals. Within the broader context of grid flexibility, this objective can be achieved through several strategies, including the reinforcement of energy storage systems, the deployment of smart grids capable of dynamically managing distributed energy resources, and the increased use of dispatchable generation from low-emission fuels, such as natural gas,

instead of coal. This latter option represents a promising approach to supporting grid stability while simultaneously contributing to the decarbonization of the power system.

Moreover, system flexibility not only enhances resilience but also enables the provision of flexibility services, which consist of the upward or downward modulation of the power exchanged with the grid by a connected entity. Through these services, the system achieves both economic optimization and seamless integration with evolving grid dynamics. High flexibility also allows participation in ancillary service markets, such as fast reserves and voltage/frequency regulation, ultimately transforming the facility into a value-added grid flexibility provider and improving its operational performance and economic returns [35].

Operational flexibility is assessed based on two primary dimensions:

- **Energetic adaptability:** the system's capability to modulate production and consumption in real time, including load-following capabilities and response to peak or fluctuating demand [36–38];
- **Market integration potential:** The extent to which a system can participate in electricity dispatching and balancing markets, including reserve services and intraday trading, enabled by its capability to modulate power exchange with the grid in near real-time. Participation can occur either directly or through aggregation mechanisms, such as Virtual Power Plants (VPPs) [39–43].

Technologies such as high-efficiency cogeneration units, dynamic load control systems, and energy storage play a key role in enhancing flexibility. Systems capable of being actively managed, by ramping up or down, providing ancillary services, or reducing imbalance costs, receive higher scores.

To increase transparency and replicability, a weighted attribute-based scoring framework was developed, assigning a total of 9 points distributed across five key indicators (Table 2). Each attribute contributes a fixed weight to the total flexibility score, based on its relevance in grid-interactive energy systems:

Table 2. Scoring rubric for the “Flexibility” criterion.

Attribute	Score (1–9)	Description
Programmable generation units (e.g., storage systems, combined heat and power (CHP)/trigeneration)	3	Capability to modulate production based on demand or scheduling
Eligibility for dispatch and reserve markets	2	Formal technical requirements to participate in Terna balancing services
Smart control systems (EMS, VPP-ready, forecast-based)	2	Digital optimization and real-time energy management
Presence of energy storage (electrical or thermal)	1	Enables peak shaving, time-shifting, and enhanced self-consumption
Bidirectional energy exchange (import/export capacity)	1	Infrastructure supports dynamic interaction with the grid
Total Score (1–9)	9	Final flexibility score is the sum of active attributes

Each proposed solution was evaluated against the five attributes; the resulting partial scores were aggregated into a total value between 0 and 9, subsequently used as the AHP input for the flexibility criterion.

2.2.5. Elasticity

The elasticity criterion assesses the long-term adaptability of an energy system to evolving technological, infrastructural, and regulatory conditions. In the context of hospital infrastructures, where energy needs, technologies, and policies evolve over multi-decade timelines, elasticity represents a key driver of sustainable investment.

This criterion encompasses four main dimensions:

- Scalability: the potential to expand system capacity (e.g., additional PV panels, co-generation, or CHP units). Strategic energy management and capacity planning are essential to accommodate future growth and changing hospital needs [44].
- Technological upgradability: ease of integrating newer technologies such as high-efficiency modules or energy storage. The adoption of distributed generation, renewable energy, and advanced control systems supports ongoing technological upgrades and efficiency improvements [45].
- Post-concession flexibility: contractual or technical readiness for continued operation and upgrade after the end of service agreements. Sustainable energy management guidelines emphasize the importance of long-term planning and adaptability beyond initial contracts [46].
- Readiness for future integration: compatibility with emerging solutions, such as hydrogen, EV charging stations, smart grid technologies, and VPPs. The literature highlights the need for hospital energy systems to be designed with flexibility for future integration of innovative technologies and participation in evolving energy markets [3].

Each proposed system was evaluated across these attributes using a weighted scoring matrix, where weights reflect each sub-dimension's contribution to long-term adaptability. A total of 9 points was distributed proportionally (Table 3), and partial scores were aggregated to determine the AHP input score.

Table 3. Scoring rubric for the “Elasticity” criterion.

Attribute	Score (1–9)	Description
Future scalability of installed capacity	3	Design reserve, layout modularity, headroom for expansion
Technological upgradability (PV, storage, etc.)	2	Ease of retrofit, component modularity, monitoring systems
Flexibility after contract expiration	2	Concession terms, asset ownership, reusability
Integration readiness for emerging technologies	2	Smart systems, VPP integration, hydrogen/EV charging compatibility

By evaluating elasticity across these four pillars, the methodology captures both technical foresight and contractual flexibility, elements increasingly essential for ensuring hospital energy systems remain robust, efficient, and upgradable over time.

2.2.6. Stakeholder Image

The stakeholder image criterion captures the symbolic and reputational impact that each energy solution may exert on external stakeholders [47], including local communities, institutional partners, regulatory authorities, and the general public [48,49]. In healthcare infrastructure, particularly publicly owned hospitals, investments in sustainability are increasingly scrutinized not only for technical performance, but also for their alignment with broader values such as environmental responsibility, social commitment, and transparency [50].

From a methodological standpoint, this criterion was assessed through qualitative judgment, based on the following:

- Visibility of technology (e.g., rooftop solar PV vs. underground pipelines);
- Symbolic value (e.g., RES vs. fossil fuels);
- Alignment with stakeholder expectations regarding environmental responsibility and innovation;
- A 9-point scoring rubric was applied, as shown in Table 4. Technologies are ranked based on their perceived sustainability, innovation value, and symbolic visibility to external stakeholders.

Table 4. Scoring rubric for the “Stakeholder Image” criterion.

Technology/Solution	Score (1–9)	Description
PV Systems	9	High symbolic value and visibility; strong association with sustainability
Sustainable Biomass	8	Promotes RES use and circular economy principles
Waste Heat Recovery	7–8	Perceived as energy-efficient and environmentally conscious
Heat Pumps (Green Energy Source)	7–8	Innovative, emission-reducing, moderate visibility
High-Efficiency Trigeneration	5–7	Technically valuable, but less public-facing; fossil-based fuel mix
Natural Gas	3–4	Considered transitional; limited positive symbolic impact
Diesel-Based Systems	1–2	Perceived as polluting and outdated

This qualitative scoring aimed to reflect the perceptual, communicative, and strategic value of energy investments in strengthening the hospital’s identity as a socially responsible and forward-looking institution.

2.3. Analytic Hierarchy Process (AHP)

The AHP is a robust tool within MCDM that addresses complex decision-making problems by structuring them hierarchically. The AHP enables decision-makers to break down problems into a hierarchy of goals, criteria, sub-criteria, and alternatives, simplifying the decision-making process. The methodology relies on pairwise comparisons between criteria and alternatives, resulting in priority weights that reflect the relative importance of each element to the overall decision [51].

One of the key strengths of the AHP is its ability to integrate both qualitative and quantitative factors into decision-making. By providing a structured approach to decompose complex problems into simpler comparisons, the AHP enables decision-makers to systematically evaluate trade-offs between competing criteria [52]. Over the years, the AHP has been applied in various decision-making contexts and remains one of the most powerful tools in MCDM. It has been extensively used in supply chain management, environmental decision-making, and healthcare.

For instance, in supply chain management, the AHP has proven effective for supplier selection, enabling decision-makers to balance factors such as cost, quality, and delivery performance. In a study by [53], the AHP was combined with other MCDM techniques to enhance supplier selection in healthcare, demonstrating its flexibility and adaptability in complex decision-making environments.

In environmental management, the AHP has been employed to evaluate sustainability projects by incorporating economic, environmental, and social criteria. This application is particularly relevant in contexts where trade-offs must be made between long-term ecological benefits and short-term economic costs. For instance, in a study on selecting the best RES projects, the AHP enabled the integration of technical and environmental performance criteria, leading to more sustainable decision-making processes [54,55]. Similarly, healthcare applications of the AHP are prevalent, particularly in hospital site selection and healthcare supplier evaluation. For example, [56] applied the AHP combined with fuzzy logic to assess potential hospital locations, considering factors such as accessibility, environmental impact, and patient satisfaction.

Despite its widespread adoption, the AHP has faced some criticism. Researchers such as [57] pointed out limitations in the pairwise comparison process, particularly as the number of criteria increases. They argue that maintaining consistency becomes difficult as the complexity of the decision increases. Additionally, there is the potential for decision-makers to manipulate the consistency ratio to achieve the desired outcomes, which could undermine the objectivity of the process.

At the core of AHP is a well-defined methodology that involves the following steps:

- Problem structuring: the decision problem is structured hierarchically, with the goal at the top, followed by criteria and sub-criteria, and finally the alternatives at the lowest level.
- Pairwise comparisons: Decision-makers compare pairs of elements (criteria or alternatives) against a specific criterion, using Saaty's scale, which ranges from 1 (equal importance) to 9 (extreme importance of one element over another). This process allows for a systematic and quantifiable assessment of subjective judgments.
- Priority weight calculation: the pairwise comparisons are synthesized to compute the priority weights of the alternatives with respect to each criterion.
- Consistency check: A consistency ratio (CR) is calculated to ensure the pairwise comparisons are logically consistent. If the CR is higher than the acceptable threshold (usually 0.1), the decision-maker must review the comparisons to improve consistency.
- Synthesis of results: the priority weights for each criterion and alternative are aggregated to produce a final ranking of alternatives [57,58].

The AHP is grounded in a rigorous mathematical framework that systematically breaks down complex decision-making problems. This methodology revolves around pairwise comparisons of criteria and alternatives to determine their relative priorities or weights. In Appendix B are the core mathematical concepts that underlie the AHP and explain the connection between subjective criteria and the evaluation of consistency in judgments.

2.4. Stakeholder Engagement Through Survey Design

In the AHP, the elicitation of expert judgments is a critical step in constructing the pairwise comparison matrix. The process typically involves the use of a structured questionnaire, where decision-makers or domain experts are asked to compare elements (criteria, sub-criteria, or alternatives) in pairs using a standardized 1–9 scale developed by Saaty [51]. This scale captures the intensity of preference of one element over another, ranging from equal importance (1) to extreme importance (9).

To ensure methodological rigor, the selection of experts should follow transparent criteria, targeting individuals with relevant experience or decision-making responsibility in the domain of interest. The number of experts can vary, but the literature suggests that group judgments are often more robust than individual ones [59–61], particularly when consensus or diversity of views is critical.

The survey can be administered in person, via structured interviews, or through online tools, depending on the complexity of the model and the geographical distribution of the participants. The questions are typically arranged in matrix format, allowing for efficient pairwise comparisons across all elements at a given hierarchy level.

Once collected, expert judgments are commonly aggregated using the arithmetic mean (for ordinal scale interpretations) or the geometric mean (particularly when preserving reciprocal properties is essential). This aggregated matrix is then used to compute the priority vector and assess consistency, as described in previous sections. In cases where the CR exceeds acceptable thresholds (typically 0.10), it is standard practice to revise or reconcile judgments, often through facilitated group discussion or iterative rounds of evaluation.

3. Case Study: The Hospital

This section presents the case study of this paper and introduces the main motivations which have driven to the adoption of the AHP analysis.

The public hospital under investigation is one of the most advanced medical facilities in the south of Italy. In recent years, the administration of the hospital has increasingly acknowledged the importance of integrating sustainable practices into its daily operations. This strategic shift aims to effectively respond to the dual challenges of climate change and rising economic pressures on the healthcare system. Consequently, the hospital has com-

mitted to exploring innovative energy production solutions. These solutions are designed not only to reduce operational costs but also to align with contemporary ecological principles.

As shown in Figure 2 and Table 5, the hospital complex includes several buildings and open areas.



Figure 2. Schematic aerial representation of the hospital and its surrounding areas, segmented into functional zones for energy analysis. The image has been digitally modified to ensure the anonymity of the facility, in compliance with data protection and publication consent requirements. The red line indicates the boundary of the hospital premises considered in this study.

Table 5. Areas into which the hospital and its surrounding premises have been divided, including the surface extension and characteristics.

Area	Size [m ²]	Characteristics
Building A	19,700.00	Flat roof
Building B	20,500.00	Flat roof
Building C	41,000.00	Flat roof
Building D	5500.00	Flat roof
Car Parking #1	19,000.00	Solar canopy
Car Parking #2	24,800.00	Solar canopy
Elevated Car Parking	1500.00	Flat roof
Employees Car Parking	10,000.00	Solar canopy
Green Area #1	19,000.00	Terrain to be levelled
Green Area #2	7000.00	Terrain to be levelled
Green Area #3	11,000.00	Terrain to be levelled
Green Area #4	5500.00	Terrain to be levelled
Green Area #5	4287.00	Terrain to be levelled

Based on the documents (bills and contracts) provided by the hospital administration, in the next subsections, the energy needs of the medical center examined in this study are presented. First, the electrical energy consumption will be analyzed; afterward, the thermal energy profile will be examined.

3.1. Hospital Profile and Energy Needs

At the time of this study, the electricity used by the hospital was entirely supplied from the public distribution network at an average voltage of 20 kV, with a contractual power of 7000 kW. The analysis of the power bills shows the electricity consumption over the years from 2020 to 2022. Table 6 and Figure 3 show the average of the electrical energy consumption (2020–2022) grouped per month and consumption time slot. As for the latter, in the context of Italian electricity bills, F1, F2, and F3 refer to different time slots for measuring electricity consumption, each with a different rate. Specifically:

- F1: corresponds to the peak hours, during the times of highest consumption. It includes work hours and late afternoon activities on weekdays (8 a.m.–6 p.m.).
- F2: is the intermediate time slot covering hours of moderate consumption, usually early in the morning and late in the evening on weekdays (7 a.m.–8 a.m., 6 p.m.–11 p.m.).
- F3: represents the off-peak hours, which include all nighttime hours and the entire day on weekends and public holidays (11 p.m.–7 a.m. working days; h24 weekend and holidays).

Table 6. Average of the electrical energy consumption (2020–2022) grouped by month and consumption time slot.

Month	Interval F1 [kWh]	Interval F2 [kWh]	Interval F3 [kWh]	Total [kWh]	Max Power Request [kW]
January	436,320.00	311,220.00	650,813.00	1,398,353.00	2186.00
February	450,996.00	329,333.00	545,563.00	1,325,892.00	2394.00
March	488,857.00	331,613.00	540,304.00	1,360,774.00	2350.00
April	413,782.00	334,608.00	603,632.00	1,352,022.00	2449.00
May	589,341.00	403,949.00	712,318.00	1,705,608.00	2946.00
June	690,483.00	478,926.00	859,991.00	2,029,400.00	3638.00
July	755,810.00	590,736.00	1,002,379.00	2,348,925.00	3647.00
August	796,123.00	548,265.00	994,629.00	2,339,017.00	3723.00
September	739,223.00	522,786.00	864,727.00	2,126,735.00	3621.00
October	585,887.00	456,165.00	756,565.00	1,798,618.00	3229.00
November	535,758.00	374,786.00	654,934.00	1,565,478.00	3045.00
December	453,738.00	329,927.00	677,311.00	1,460,976.00	2523.00
Total	6,936,319.00	5,012,313.00	8,863,166.00	20,811,798.00	3723.00

As far as the economic aspect is concerned, the following information could be inferred:

- 2020: 23,498,593 kWh, with a total bill of EUR 4,566,507 (0.1943 EUR per kWh);
- 2021: 20,092,928 kWh with a total bill of EUR 4,422,789 (0.2201 EUR per kWh);
- 2022: 18,843,873 kWh with a total bill of EUR 3,068,998 (0.1629 EUR per kWh).

This data allowed for an estimation of the average annual electricity consumption over the last three years of approximately 20,811,798 kWh, with an average cost of 0.1931 EUR per kWh. In this last evaluation, it is important to note that the electricity costs in 2022 were reduced due to a government subsidy that lowered the system charges.

Another important analysis of the historical time-series data for 2022 (Figure 4) revealed that the peak power demand from the network was 3371 kW (on August 10th at 2:00 pm), while the minimum was 807 kW (on April 30th at 9:00 pm). This information is crucial for determining the optimal solution, as knowledge of the peak demand is a key factor that must be considered.

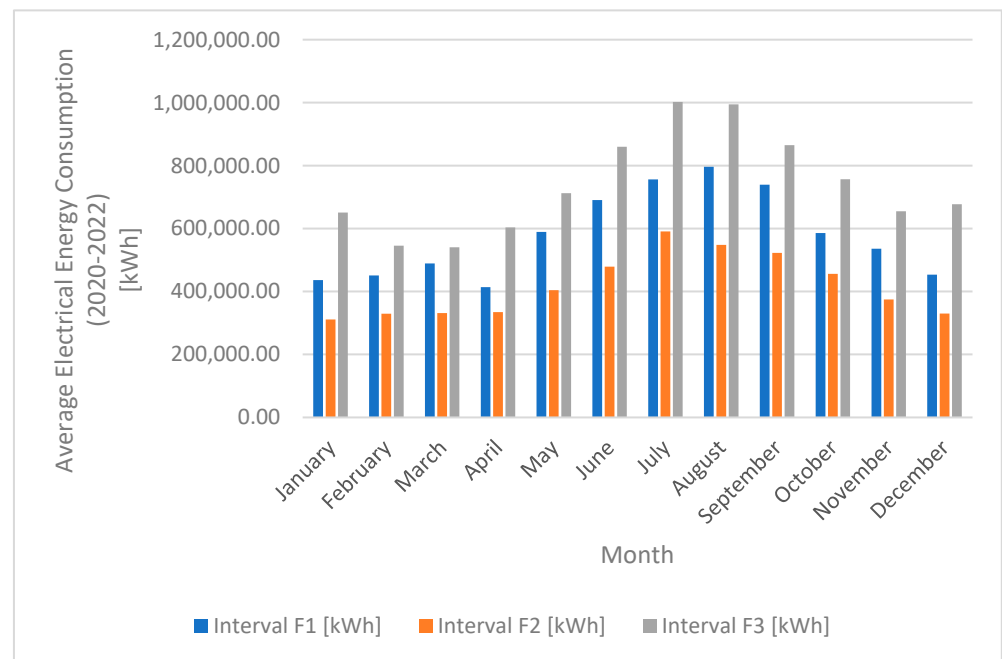


Figure 3. Average of electrical energy consumption (2020–2022) grouped per month and consumption time slot.



Figure 4. Historical time-series data for 2022 showing the hospital's electricity demand profile. The plot also highlights the minimum and maximum power demand recorded during the year: a minimum of 807 kW (on April 30th at 9:00 p.m.) and a maximum of 3371 kW (on August 10th at 2:00 p.m.).

The hospital's thermal energy is currently generated by the following systems:

- Two bi-fuel boilers, utilizing methane and diesel oil, primarily powered by methane. Each boiler has a thermal output of 6000 kWt, contributing to a total of 11,000 kWt. This capacity is used to produce hot water at 80 °C for winter air conditioning, domestic hot water (DHW) production, and supplying post-heating coils in all-air systems.
- Two additional bi-fuel boilers, also operating on methane and diesel oil, primarily use methane to produce saturated steam at 12 bar, with each boiler providing a thermal output of 1000 kW, for a combined total of 2000 kWt. Although the sterilizers are currently electrically powered, steam production is primarily used for heating, DHW production, and post-heating purposes.

The methane consumption and corresponding thermal energy production data for the years 2020, 2021, and 2022 are shown in Figures 5 and 6. The calculation of thermal energy from methane consumption was based on a conventional calorific value of methane of 9.56 kWh/m³ and a production efficiency of 85%.

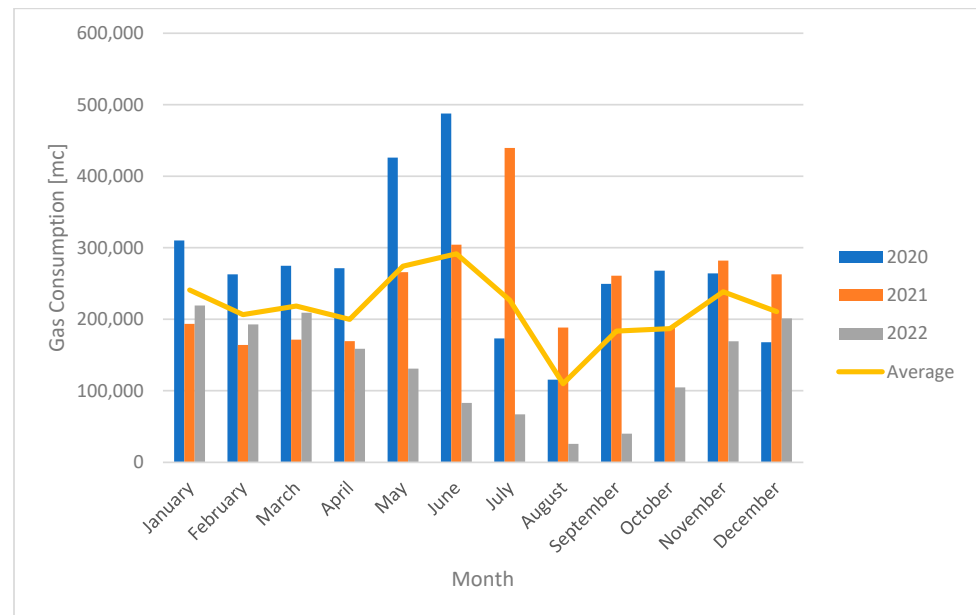


Figure 5. Methane consumption data for the years 2020, 2021, and 2022. The yellow line represents the average annual consumption across the three years.

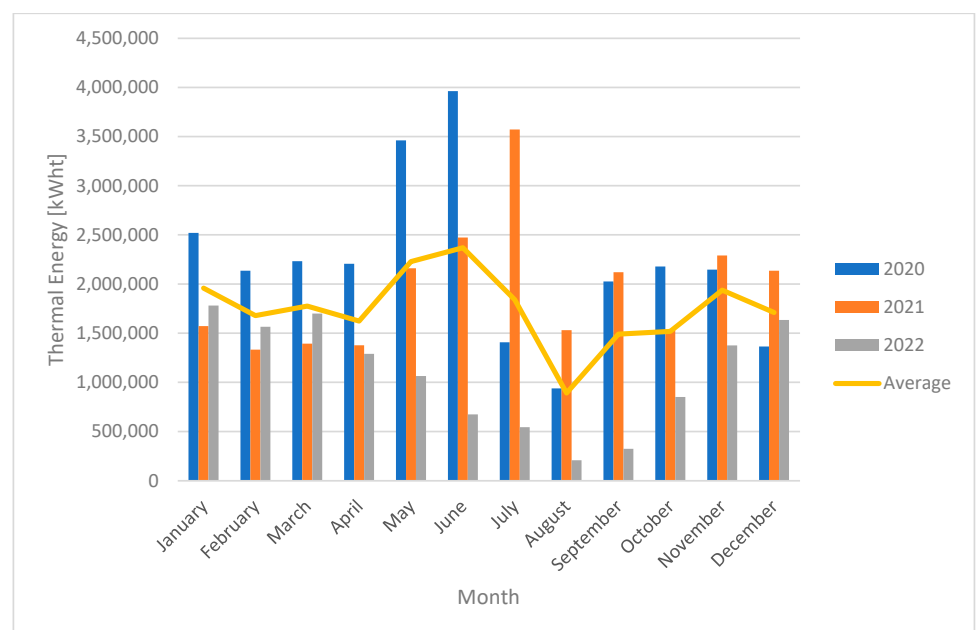


Figure 6. Thermal energy production data for the years 2020, 2021, and 2022. The yellow line represents the average annual consumption across the three years.

The total consumption of methane for the years under analysis is listed below:

- 2020: 3,270,533 m³/y, corresponding to 26,576,512 kWh;
- 2021: 2,890,121 m³/y, corresponding to 23,485,124 kWh/y;
- 2022: 1,601,121 m³/y, corresponding to 13,010,685 kWh/y.

It can be observed that from 2020 to 2022, the hospital successfully reduced its methane consumption by approximately 50% due to a more rational management of needs dur-

ing the warmer months of the year. For 2022, the average cost per unit of methane was determined to be 1.571 EUR per cubic meter, corresponding to an energy cost of 0.1932 EUR per kWh of thermal energy.

Therefore, for the year 2022, we could consolidate data on electrical and thermal energy consumption to create a comprehensive energy needs diagram. This diagram is shown in Figure 7, and it summarizes the current energy consumptions of the hospital.

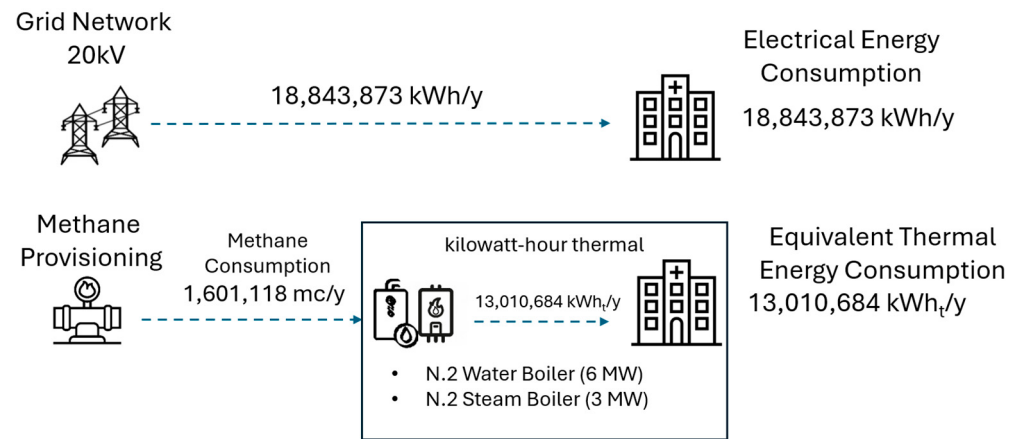


Figure 7. Current energy status of the hospital. The diagram consolidates both electrical and thermal energy consumption for 2022, highlighting the relative contribution of electricity (≈ 18.84 GWh) and methane-derived thermal energy (≈ 13.01 GWh). Cooling demand is included within electricity consumption.

To summarize, from an energy standpoint, the hospital exhibits a complex and continuous demand profile, driven by 24/7 operations and critical service requirements. In 2022, electricity consumption reached approximately 18.84 GWh, with a contracted power capacity of 7 MW. The monthly energy expenditure for electricity ranged from approximately EUR 200,000 to over EUR 350,000, depending on the season and market conditions. Thermal energy needs were equally substantial, with natural gas consumption exceeding 1.6 million cubic meters in 2022, equal to EUR 1,392,000. Gas usage supports space heating, domestic hot water production, and various medical and sterilization processes. The hospital's energy infrastructure, high consumption levels, and critical mission profile underscore the strategic importance of integrating RES and resilient energy systems.

One more last point to note is that, at the time of this study, cooling demand was not separately metered and was fully supplied by electric chillers, and is therefore included in baseline electricity purchases.

3.2. Overview of the Three Technical Proposals

This chapter presents the technical solutions proposed by the three ESCOs for enhancing the hospital's energy system. Each proposal combines different technologies and contractual models, tailored to meet the facility's energy needs over a 15-year concession period. The following subsections provide a detailed description of the proposed systems. It is important to highlight that the hospital was already equipped with a trigeneration plant, capable of simultaneously producing electricity, heating, and cooling; however, only the third proposal (ESCO3) includes its commissioning as part of the project.

3.2.1. Overview of Proposal 1

ESCO1's proposal centers on the implementation of a large-scale PV system with a total installed capacity of 8.537 MWp, to be distributed across the hospital's three main buildings. Based on the hospital's architectural layout, this installation would fully occupy

the available rooftop surfaces of these buildings. The project is structured as a 15-year concession: the first two years are dedicated to installation and commissioning, followed by thirteen years of operational management and service delivery.

According to the service contract, the self-generated electricity from the PV system will be supplied to the hospital at a fixed tariff of 87.00 EUR/MWh. Additionally, a guaranteed 10% discount will be applied to the remaining electricity purchased from the national grid.

ESCO1 will also manage all operational, maintenance, and reporting activities via a dedicated technical coordination service. This includes monitoring platforms, periodic reporting, system performance verification, and emergency support.

Figure 8 illustrates the energy flow configuration resulting from the implementation of ESCO1's solution. In this scenario, the methane supply remains unchanged compared to the current baseline. The system enables approximately 7236 MWh/year of self-consumed electricity, leading to a reduction in grid-supplied energy of around 11.6 MWh/year. A distinctive feature of this proposal is the significant amount of electricity exported to the grid under the RID scheme. According to the contractual terms proposed by ESCO1, revenues from energy sold to the grid during the 15-year concession period will accrue entirely to the ESCO, while any financial returns from feed-in sales will be transferred to the hospital only after the contract's expiration.

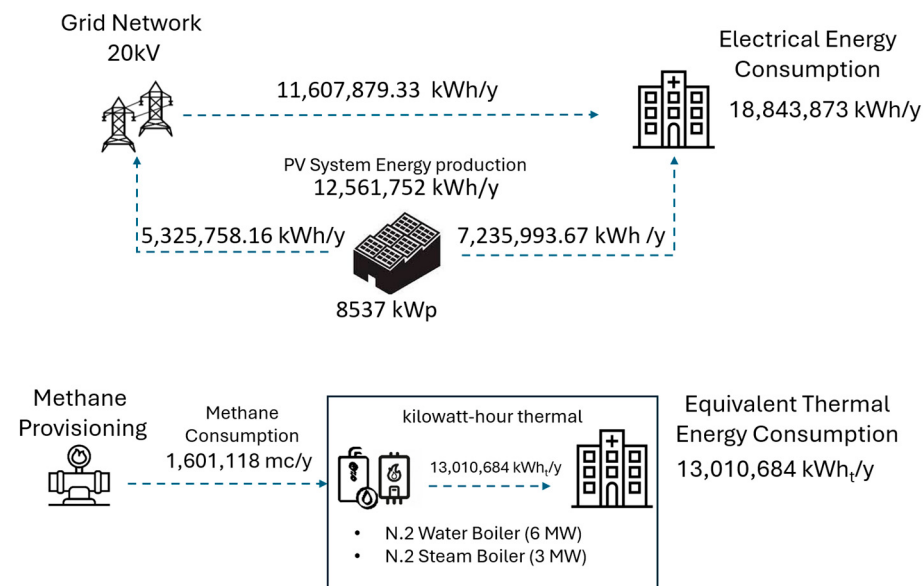


Figure 8. Energy flow configuration under ESCO1's proposal. The scheme illustrates the contribution of the 8.5 MWp PV system, highlighting the share of self-consumed electricity (≈ 7236 MWh/year) and the significant portion of surplus energy exported to the grid through the RID scheme. Methane consumption remains unchanged compared to the baseline scenario.

The contractual structure of the ESCO1 proposal outlines distinct cost components across the concession period, including PV energy supply, grid electricity provision, and maintenance services. These are summarized in Table 7.

All fees are subject to adjustment mechanisms based on energy price variations and inflation indexes, except for the PV energy fee, which remains fixed over the contract duration.

The economic implications of ESCO1's proposal have been assessed using the comparative methodology detailed in Section 2.2.1. This includes direct cost calculations, discounted cash flow analysis, and a probabilistic simulation based on stochastic energy price trends. The evaluation adopts a 25-year investment horizon and harmonized assumptions across all alternatives (e.g., energy demand, PV degradation, inflation, ownership transfer). The results are summarized in Table 8, including net savings compared to the business-as-usual

scenario. Notably, the analysis also accounts for revenues from surplus PV energy sold under the dedicated feed-in tariff scheme (“Ritiro Dedicato”, RID) of 0.10 EUR/kWh.

Table 7. Contractual breakdown for ESCO1 over the concession period.

Period	Fee Component	Annual Amount [EUR/y]	Notes
Years 1–2	Total Annual Fee	4,628,000	Covers full energy needs from the grid
Years 3–15	PV Energy Fee	638,000	Fixed price: 87.00 EUR/MWh
	Grid Electricity Fee	2,824,000	After 10% discount
	Maintenance Fee	211,347	Includes remote monitoring, upkeep
	Total Annual Fee	3,673,347	

Table 8. Total economic performance summary for ESCO1 after a 25-year horizon, including direct costs, discounted present value, and expected savings under stochastic simulation.

	Direct Method [M EUR]	NPV Method [M EUR]	Stochastic Simulation [M EUR]	Stochastic Simulation Discounted [M EUR]
ESCO1	110.8	58.5	127.6	67.7
Business-as-usual	150.2	75.7	176	88.7
Total economic saving (Benefit for the Hospital)	39.4	17.2	48.4	21

3.2.2. Overview of the Proposal 2

ESCO2 proposes the installation of a 3.304 MWp photovoltaic (PV) system under a 15-year concession agreement. The project is solely dedicated to the generation of renewable electricity from solar energy, without the integration of backup systems or energy storage technologies. The design strategy focuses exclusively on utilizing the car parking areas for solar canopies, deliberately preserving all other available spaces for potential future developments.

The proposal includes the following:

- Supply and installation of the PV system across multiple buildings and open areas;
- Energy self-production priced at 157.00 EUR/MWh for auto-consumed electricity;
- No discount applied on electricity purchased from the grid;
- Zero maintenance cost charged to the hospital throughout the duration of the concession.

Table 9 presents the contractual fees associated with this proposal, including capital and service charges.

Table 9. Contractual breakdown for ESCO2 over the concession period.

Period	Annual Fee [EUR/y]	Notes
Year 1	116,987	Initial setup phase
Year 2	779,915	Start of operational phase
Years 3–15	779,915 decreasing by 0.6% annually	Fixed price adjusted yearly (no inflation indexation)
Maintenance (Years 2–15)	0	Entirely included in the energy price

A detailed economic analysis of ESCO2’s offers was performed following the standardized framework outlined in Section 2.2.1. The evaluation covers direct expenditures, present value calculations, and stochastic simulations reflecting price uncertainties.

The 25-year assessment adopts uniform conditions across all scenarios, including energy usage, inflation, and post-concession plant operation by the hospital.

Table 10 presents the total costs and savings associated with ESCO2 compared to the status quo, incorporating potential income from excess PV energy sold at the RID rate of 0.10 EUR/kWh.

Table 10. Total economic performance summary for ESCO2 over a 25-year horizon, including direct costs, discounted present value, and expected savings under stochastic simulation.

	Direct Method [M EUR]	NPV Method [M EUR]	Stochastic Simulation [M EUR]	Stochastic Simulation Discounted [M EUR]
ESCO2	132.20	68	153	78.51
Business-as-usual	150.20	75.70	176	88.70
Total economic saving (benefit for the hospital)	18	7.70	23	10.19

Figure 9 illustrates the energy flow configuration following the implementation of ESCO2's proposal. In this scenario, the methane supply remains unchanged relative to the current baseline. The system enables approximately 4709 MWh/year of self-consumed electricity, leading to a reduction in grid-supplied energy of approximately 14,134 MWh/year. As shown in the figure, the amount of electricity exported to the grid is minimal, accounting for only about 152 MWh/year.

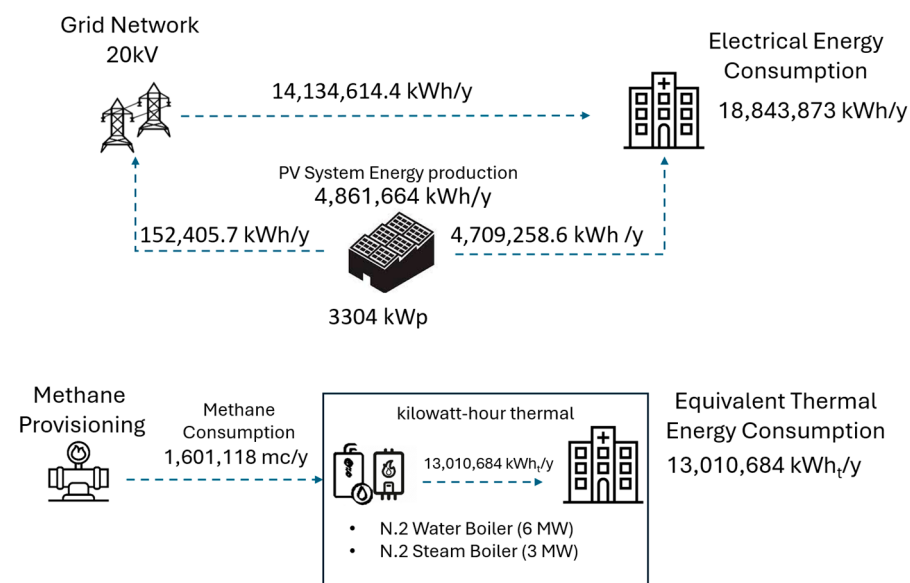


Figure 9. Energy flow configuration under ESCO2's proposal. The figure shows the 3.3 MWp PV system installed on parking canopies, with approximately 4709 MWh/year of self-consumed electricity and minimal surplus exported to the grid (≈ 152 MWh/year). As in the baseline, methane consumption is not affected.

3.2.3. Overview of Proposal 3

The third proposal, submitted by ESCO3, examines the options of coupling the grid-connected PV power plant with a cogeneration unit, aiming to provide a more robust energy system capable of delivering electricity, heating, and cooling. This approach could be particularly valuable for its potential to serve as an alternative and reliable energy source during peak demand times or when solar production is limited.

The project entails the installation of a 5.3 MWp PV system, to be deployed on Buildings B and C, along with the commissioning and full operational management of the hospital's existing trigeneration plant. The integrated system is designed to dynamically track the hospital's energy demand profile and is optimized for high levels of self-consumption.

According to the proposed agreement, the electricity generated by the PV system will be provided at a 20% discounted rate, while the energy supplied by the cogeneration unit will benefit from a 7.96% discount—corresponding to a gas-to-electricity price ratio ($P_{\text{gas}}/P_{\text{el}}$) in the range of 3.5 to 4.

The contractual framework is based on a 15-year concession, featuring zero annual fixed fees in the first year. Remuneration is performance-based and incorporates a tiered discount mechanism linked to the $P_{\text{gas}}/P_{\text{el}}$ ratio, which affects both PV- and cogeneration-sourced energy tariffs, as detailed in Table 11.

Table 11. Tariff discount structure based on gas-to-electricity price ratio.

$P_{\text{gas}}/P_{\text{el}}$ Ratio	Discount on PV Tariff (K1)	Discount on Cogeneration Tariff (K2)
>5	15%	0% (cogeneration off)
$4.5 < x \leq 5$	20%	1.00%
$4 < x \leq 4.5$	20%	0.76%
$3.5 < x \leq 4$ (Base Case)	20%	7.96%
$3 < x \leq 3.5$	20%	15.66%
$2.5 < x \leq 3$	20%	23.91%
$2 < x \leq 2.5$	20%	31.48%
$1.5 < x \leq 2$	20%	39.64%
≤ 1.5	20%	48.44%

Unlike the previous two solutions, the third proposal includes a contractual agreement for the supply of both electricity and methane. As a result, the energy flow configuration changes significantly, as illustrated in Figure 10. In this scenario, the strategy favors an increased use of methane to maximize the operation of the cogeneration system, thereby prioritizing the on-site production of both electricity and thermal energy.

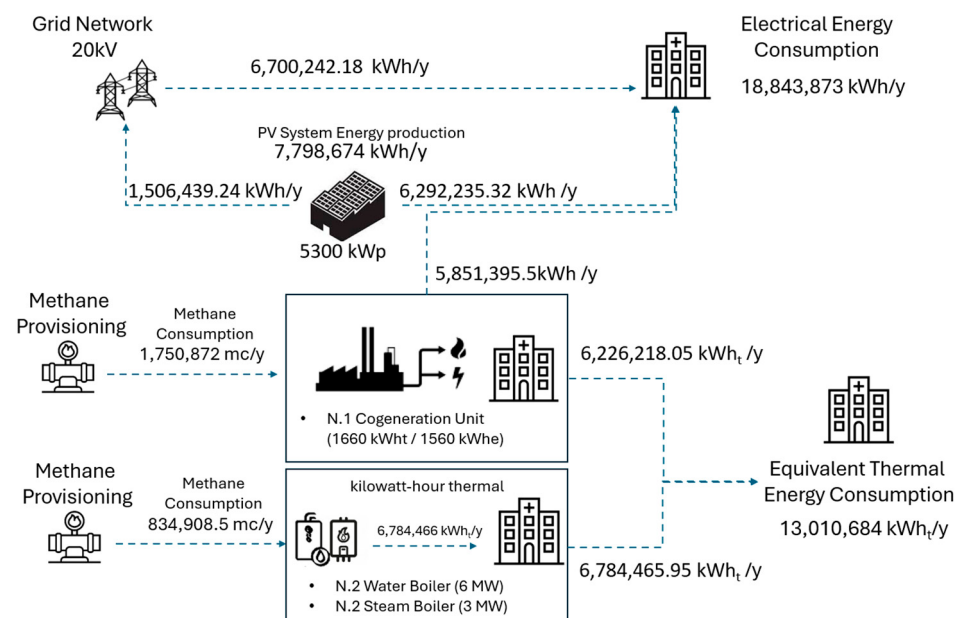


Figure 10. Energy flow configuration under ESCO3's proposal. The scheme represents the integrated operation of a 5.3 MWp PV system with the existing trigeneration plant, enabling simultaneous production of electricity, heating, and cooling. This configuration allows higher self-consumption and system redundancy, while increasing methane use to maximize cogeneration benefits.

The financial performance of ESCO3's integrated solution was evaluated using the multi-method approach in Section 2.2.1. This includes deterministic and stochastic methods

to capture both fixed and variable cost scenarios over a 25-year period. All analyses were conducted under consistent technical and economic assumptions, enabling a fair comparison between suppliers.

The results shown in Table 12 report total expenditures and economic savings compared to the baseline case, including the revenue derived from PV surplus under the dedicated feed-in tariff (RID) of 0.10 EUR/kWh applied after the concession phase.

Table 12. Total economic performance summary for ESCO3 over a 25-year horizon, including direct costs, discounted present value, and expected savings under stochastic simulation.

	Direct Method [M EUR]	NPV Method [M EUR]	Stochastic Simulation [M EUR]	Stochastic Simulation Discounted [M EUR]
ESCO3	117.2	62.3	137.1	73
Business-as-usual	150.2	75.7	176	88.7
Total economic saving	33	13.4	38.9	15.7

4. Results and Discussion

4.1. Evaluation of Each Alternative Based on the Six Criteria

This section presents the results of the multi-criteria evaluation and discusses their implications, highlighting the strengths and weaknesses of each ESCO proposal with respect to the six decision criteria.

The technical proposals submitted by the three ESCOs were assessed using the structured multi-criteria framework described in Section 2.2. The evaluation was based on the six proposed key decision criteria: economic feasibility, system redundancy, environmental performance, flexibility, elasticity, and stakeholder image (Figure 11).

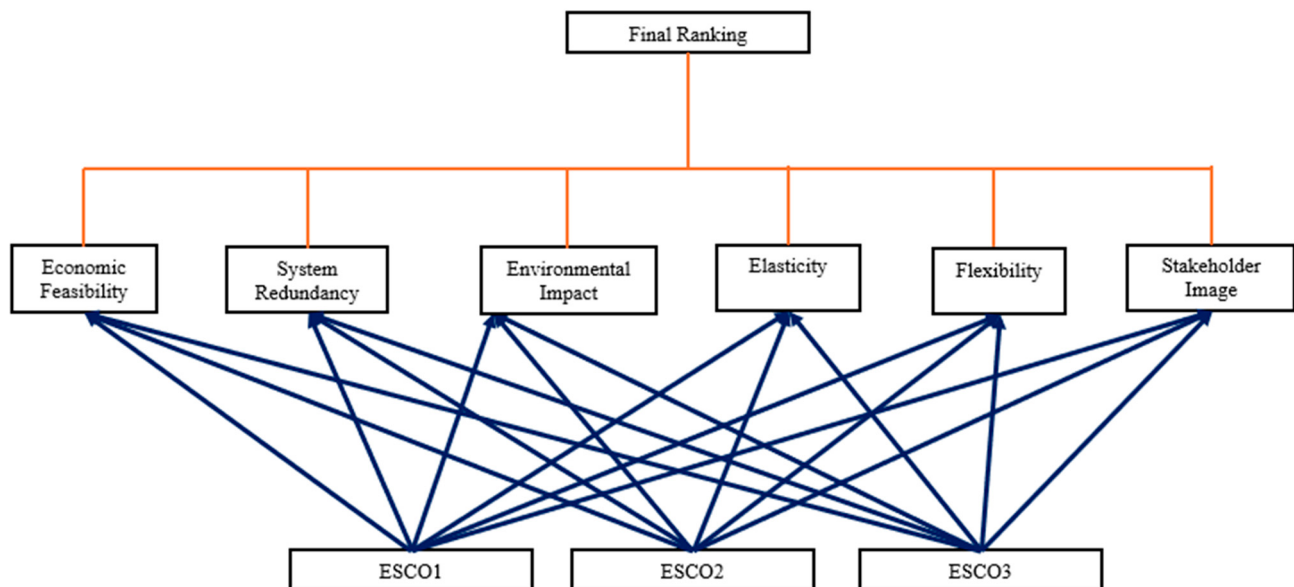


Figure 11. AHP hierarchical structure used for evaluating the ESCOs' proposals.

Each criterion was assigned a score on a normalized 1–9 scale, derived through a combination of quantitative calculations (e.g., total economic saving, CO₂ emissions avoided, and PV self-consumption) and qualitative judgments based on the documentation submitted. With regard to the flexibility criterion, it should be specified that systems based solely on PV were assigned lower scores due to their limited capability to modulate power output, whereas configurations integrating PV with combined CHP units achieved higher

scores, as their dispatchable generation enhances both operational flexibility and market integration potential.

The following tables (Tables 13–15) present the comparative evaluation matrices for each ESCO. Each matrix includes the criterion-wise scores, along with explanatory notes to justify the evaluations, ensuring transparency and traceability of the scoring process.

Table 13. Comparative evaluation matrix for ESCO1 across the six decision criteria.

Criterion	Score (1–9)	Explanation
Economic Feasibility	9	Estimated 20.5% cost savings over historical baseline in operational phase; significant investment (EUR 11.1 M) and 8.5 MWp installed capacity enhance value proposition.
System Redundancy	3	No storage, no mention of islanding or post-concession continuity. Backup systems and critical load coverage are not addressed.
Environmental Performance	5	High emissions savings: 2354 tCO ₂ /year avoided (0.4 tCO ₂ /MWh), covering ~40% of total hospital demand.
Flexibility	3	Limited interaction with dispatch markets or grid services; no smart control or VPP integration.
Elasticity	5	Medium score due to modular layout and moderate expansion potential; lacks detailed provisions for future tech integration.
Stakeholder Image	4	Positive for renewables but lacks CSR strategy or visibility actions that enhance symbolic value to external stakeholders.

Table 14. Comparative evaluation matrix for ESCO2 across the six decision criteria.

Criterion	Score (1–9)	Explanation
Economic Feasibility	5	Estimated 20.8% cost reduction over 15 years, moderate CAPEX, strong ROI
System Redundancy	3	No backup systems, no island-mode capability, and the system is not autonomous beyond grid dependency
Environmental Performance	3	Avoids ~1493 tCO ₂ /year via PV production (~6.7 GWh/year), aligns with ISPRA factors
Flexibility	4	Limited to smart monitoring and passive grid injection, no active dispatchability
Elasticity	8	Modular design and future expansion supported, good tech upgrade potential
Stakeholder Image	7	Visible rooftop PV and parking shelters, aligns with sustainability branding, but no CSR strategy

Table 15. Comparative evaluation matrix for ESCO3 across the six decision criteria.

Criterion	Score (1–9)	Explanation
Economic Feasibility	7	Strong integrated solution with trigeneration + PV; full-risk O&M; solid financials, with long-term guarantees.
System Redundancy	7	Presence of trigeneration and advanced design implies system robustness; backup and islanding unclear.
Environmental Performance	9	High environmental benefit from combined heat and power + PV; intelligent system use enhances efficiency; avoids ~3899 tCO ₂ /year.
Flexibility	7	Technologically flexible system, though not explicitly integrated with dispatch/market participation.
Elasticity	6	Good design elasticity with tech upgradeability; however, a highly saturated PV system reduces the margin for future scaling.
Stakeholder Image	7	Includes energy efficiency as institutional goal, limited explicit CSR/public engagement elements.

4.2. Results of the AHP Methodology

In this study, the AHP framework was employed to support the evaluation and prioritization of RES solutions for a public hospital in the south of Italy. The goal was to integrate technical and institutional factors into a structured decision model that supports transparent and consistent judgments.

4.2.1. Pairwise Comparisons and Weight Calculations

To derive the relative weights among the six criteria presented in Section 2.1, a structured survey was prepared. The questionnaire was administered through an online platform during September–October 2024. The survey involved 22 respondents, including two energy specialists (9%) and 20 participants (91%) who occupied managerial, administrative, or related professional roles. This composition was intentional, as the evaluation of energy projects in public healthcare requires not only technical expertise but also the perspectives of non-specialist stakeholders involved in decision-making. Figure 12 provides an overview of respondents' profiles. Most participants were affiliated with organizations known to the authors, spanning both the private and public sectors. Although not all respondents were directly employed in energy companies, all were familiar with large-scale infrastructure or energy-related decision-making contexts. For analytical clarity, respondents' companies were categorized by size according to the European Commission classification: large enterprises (more than 250 employees or financial thresholds above EUR 50 M in turnover or balance sheet total of EUR 43 M), medium (up to 250 employees and EUR 50 M turnover), small (up to 50 employees and EUR 10 M turnover), and micro (up to 10 employees and EUR 2 M turnover) (Figure 12a).

- Regarding professional roles (Figure 12b), the original free-text responses were grouped into three macro-categories to reflect functional areas:
- Leadership and management, including CEOs, directors, and company owners;
- Technical and specialist roles, such as consultants, energy managers, and data scientists;
- Administrative and office roles, encompassing administrative staff, marketing, legal, and public-sector professionals with non-managerial tasks.

Another piece of data collected concerns the respondents' seniority (Figure 12c). Additional data collected included the respondents' tenure in their respective organizations (Figure 12c).

This classification ensures a clearer interpretation of the respondent pool while preserving the diversity of perspectives captured in the survey.

Each respondent was asked to perform all 15 pairwise comparisons among the six criteria using Saaty's standard 1–9 scale. The survey was designed to elicit expert judgment in a consistent and replicable manner, although several participants noted that the comparison task was technically demanding. Their insights were aggregated by computing the arithmetic mean of each pairwise comparison across all respondents. The pairwise comparison judgments were aggregated using the arithmetic mean across all respondents to construct a group comparison matrix. Considering this matrix, normalized weights were derived using the row normalization method, as per the standard AHP procedure. The full pairwise comparison matrix is reported in Table 16.

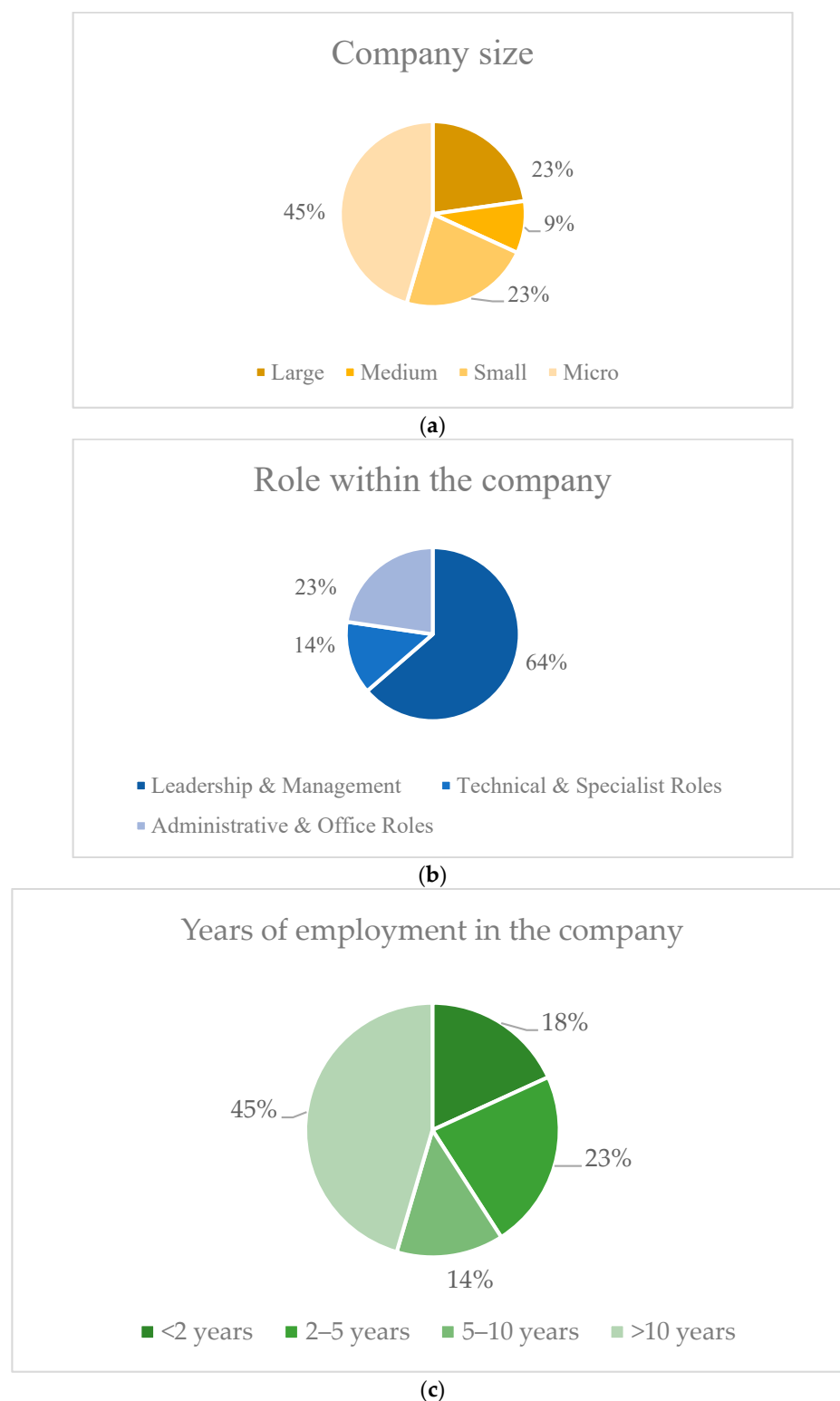


Figure 12. Profiles of the survey respondents involved in the AHP analysis. Panel (a) shows the distribution of company size according to the European Commission classification (micro, small, medium, large enterprises). Panel (b) illustrates the respondents' professional roles, grouped into leadership/management, technical/specialist, and administrative/office categories. Panel (c) reports the respondents' seniority in their respective organizations.

Table 16. The resulting pairwise comparison matrix.

i/j	Economic Feasibility	Environmental Performance	System Redundancy	Elasticity	Flexibility	Stakeholder Image
Economic Feasibility	1.00	2.51	2.58	2.10	1.84	2.01
Environmental Performance	0.40	1.00	3.26	2.72	2.14	3.07
System Redundancy	0.39	0.31	1.00	2.03	1.11	2.66
Elasticity	0.48	0.37	0.49	1.00	1.26	2.60
Flexibility	0.54	0.47	0.90	0.79	1.00	2.68
Institutional Image	0.50	0.33	0.38	0.38	0.37	1.00

The computed weights for each criterion are reported in Table 17 below.

Table 17. Weight for each criterion for AHP.

Criterion	Weight	Rating
Environmental Performance	0.2642	26%
Economic Feasibility	0.2524	25%
System Redundancy	0.1572	16%
Elasticity	0.1301	13%
Flexibility	0.1340	13%
Stakeholder Image	0.0621	6%
Total	1.000	100%

These results reflect a slight preference toward environmental and economic criteria, which is consistent with current policy priorities in sustainable energy planning for healthcare infrastructure.

4.2.2. Consistency Check

To validate the logical coherence of the expert judgments, the consistency of the pairwise comparison matrix was assessed using the *CI* (Equation (A3)) and *CR* (Equation (A4)). The maximum eigenvalue of the matrix was computed as $\lambda_{\max} = 6.483$, yielding a *CI* = 0.097. Given the *RI* = 1.24 for a 6×6 matrix [51], the resulting *CR* was 0.078. Since this value is below the commonly accepted threshold of 0.10, the matrix is considered consistent, and the derived weights are deemed reliable.

4.3. Final Scoring and Ranking of Alternatives

To synthesize the comparative evaluation, a weighted scoring model was applied to each technical proposal. This approach combines the raw performance scores (Tables 13–15) with the relative importance of each criterion, as determined through the AHP method (Table 17). Table 18 summarizes the performance of each ESCO with respect to the six criteria defined in Section 2.2. In particular, each ESCO's final score is the sum of the products between criterion scores and weights. The resulting composite scores, presented in Table 18, enable a transparent and quantitative ranking of alternatives, providing decision-makers with a robust basis for selecting the most suitable energy service configuration for the hospital.

Table 18. ESCO's final score.

	Total Score	Environmental Performance	Economic Feasibility	System Redundancy	Elasticity	Flexibility	Stakeholder Image
ESCO1	5.36	1.32	2.27	0.47	0.65	0.40	0.25
ESCO2	4.54	0.79	1.26	0.47	1.04	0.54	0.43
ESCO3	7.40	2.38	1.77	1.10	0.78	0.94	0.43

The results, summarized in Table 18 and in Figure 13, show that ESCO3 achieved the highest total score (7.39), followed by ESCO1 (5.36) and ESCO2 (4.54).

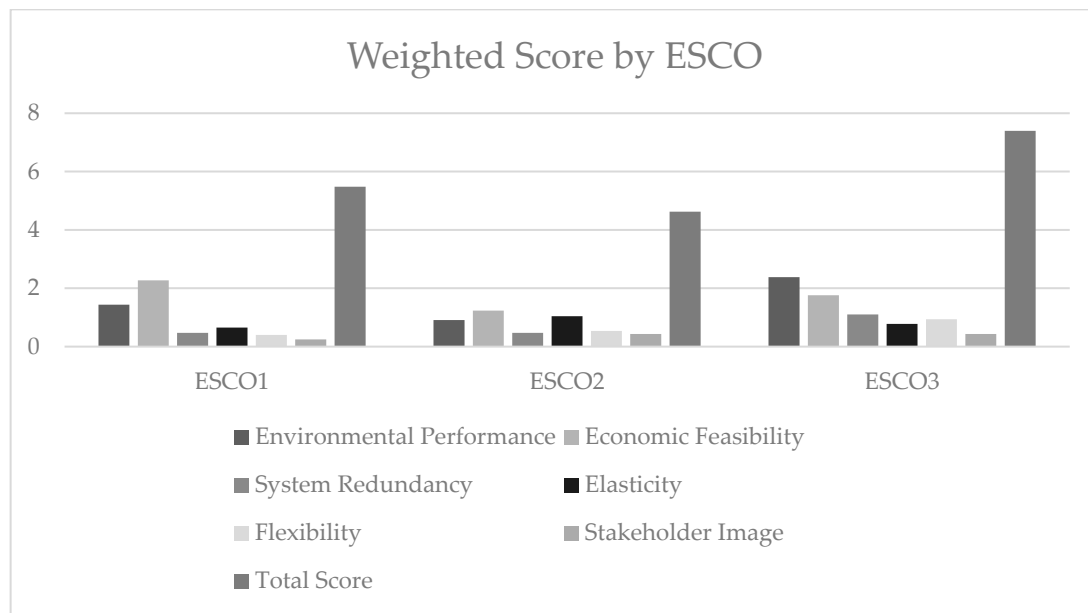


Figure 13. Comparative scores of the ESCO proposals after AHP weighting.

ESCO3's leading position stems from consistently strong performance across all six criteria, particularly in redundancy, flexibility, and environmental performance, owing to the integration of a trigeneration system with PV, robust system design, and long-term financial guarantees.

While ESCO1 achieved the highest score in the economic criterion, its overall performance was penalized by limited flexibility and the absence of backup provisions. As a result, despite its economic advantage, ESCO1 ranked lower in the final integrated assessment compared to solutions offering a more balanced profile across all criteria. ESCO2 scored well on elasticity and stakeholder image, but its overall ranking was penalized by lower scores in environmental and economic dimensions, which are the criteria with the highest weights.

While the purely economic evaluation would have favored ESCO1, the hospital decision-makers emphasized the importance of environmental performance, system reliability, and long-term adaptability. Considering the AHP-derived ranking, which integrates these broader dimensions, ESCO3 was identified as the most suitable option, as it offered a more balanced and sustainable solution, in line with the hospital's strategic goals.

5. Conclusions

This study presents a structured and replicable decision-making framework for evaluating energy service proposals in large public healthcare facilities. Through the integration of technical assessments, stakeholder-informed weighting via AHP, and a multi-scenario economic simulation, the model provides a transparent and holistic tool for guiding investment choices in complex public infrastructure contexts.

The comparative analysis of three competing ESCO proposals demonstrated significant variability across criteria, especially in economic performance and technical flexibility. The economic criterion, weighed most heavily by surveyed stakeholders, proved decisive, with one proposal achieving markedly higher expected savings over a 25-year horizon. The evaluation method ensured alignment with stakeholder priorities and allowed a quantitative, evidence-based ranking of alternatives.

The six criteria adopted in this study represent a core set of fundamental dimensions, including economic, technical, environmental, and social, that are most commonly employed in energy evaluations. However, additional criteria can be incorporated depending on the specific objectives of the decision-making process, ensuring that the framework remains adaptable to the unique priorities of different institutions or public tenders.

This approach holds broader applicability beyond hospitals, offering a generalizable model for energy-related decisions in public-sector buildings such as universities, municipal campuses, and transportation hubs. By emphasizing replicability, stakeholder engagement, and scenario robustness, the framework supports public administrations in navigating complex energy transitions with confidence. In the present study, the framework was applied to a case study in Southern Italy, where high solar irradiance favors PV-based solutions. Nevertheless, the framework is also generalizable to regions with lower solar irradiance. In such contexts, PV-based options would provide lower economic returns, which the economic feasibility criterion would capture, while alternative technologies might become more competitive.

Some limitations of this study should be acknowledged. First, while the economic and environmental evaluations relied on objective and quantifiable models, stochastic simulation, and CO₂-based metrics, respectively, the remaining four criteria (flexibility, redundancy, elasticity, and stakeholder image) were assessed using expert-derived scoring grids. Although these grids were designed to enhance transparency and consistency, a residual level of subjectivity in assigning scores based on proposal content remains, albeit minimized through structured judgment by domain experts. Second, the model focused on a single case study; future applications could enrich the methodology by including sensitivity analyses, broader stakeholder categories, real-time market data, and advanced statistical tools, such as panel regression or causality analysis, to further validate the relationships among criteria and strengthen the robustness of the decision-making framework.

Despite these limitations, the proposed framework represents a substantial contribution toward standardized, reproducible decision-making in public energy infrastructure planning. As a direction for future development, the inclusion of “Self-Consumption” as an additional criterion could further enhance the decision framework. Maximizing self-consumption can increase economic benefits by reducing dependency on grid electricity, mitigating exposure to market volatility, and improving local energy autonomy.

Author Contributions: Conceptualization, F.C., D.D. and G.M.T.; methodology, F.C., D.D., L.M.O. and C.V.; software, F.C. and D.D.; validation, F.C., L.M.O. and C.V.; formal analysis, F.C., D.D. and G.M.T.; investigation, F.C., L.M.O. and C.V.; resources, F.C. and D.D.; data curation, L.M.O. and C.V.; writing—original draft preparation, L.M.O. and C.V.; writing—review and editing, F.C., L.M.O., C.V. and G.J.C.; visualization, L.M.O. and G.J.C.; supervision, G.J.C., D.D. and G.M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Sensitivity Analysis

This appendix reports the results of the two-way sensitivity analysis on the financial drivers used in the economic comparison. We vary the nominal discount rate $r \in \{3\%, 4\%, \dots, 9\%\}$ and the growth of energy and RID $g \in \{0.3\%, 0.4\%, \dots, 1.0\%\}$ with $g_{\text{RID}} = g + 0.1\%$ to reflect the baseline differential. For each r , a bar chart shows the total economic saving (NPV method) versus g for the three proposals. The figure for $r = 6\%$ is shown first, as it matches the

baseline used in the main text, followed by the remaining six charts to document robustness. Full 56-cell matrices (one per ESCO) are also provided.

Key findings. Across the entire grid, savings increase monotonically with g and decrease as r rises, as expected from growing-annuity cash flows. The ranking remains stable in all cases for the economic comparison: ESCO-1 > ESCO-3 > ESCO-2, with roughly parallel shifts in levels as r and g change. The discount rate is the dominant driver of variability (larger vertical spread across the seven charts), while the effect of g within each chart is comparatively moderate; this reflects the fact that all scenarios are evaluated in nominal terms, and that RID remains a minor component relative to avoided electricity purchases. Overall, no cross-over of the proposals is observed within the tested ranges, confirming that our conclusions are robust to plausible changes in discounting and price escalation.



Figure A1. Savings versus g at discount rate of 6%.



Figure A2. Savings versus g at discount rate of 9%.

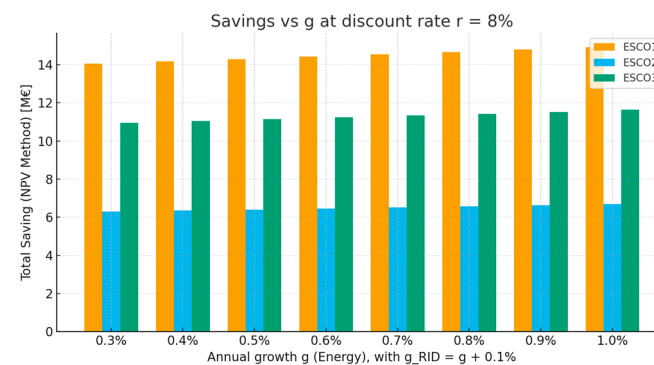


Figure A3. Savings versus g at discount rate of 8%.

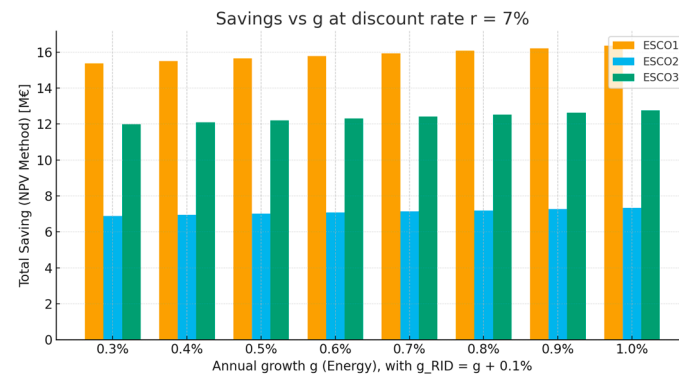


Figure A4. Savings versus g at discount rate of 7%.

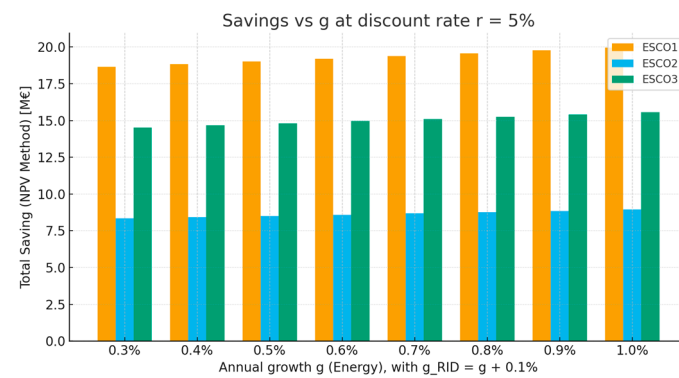


Figure A5. Savings versus g at discount rate of 5%.

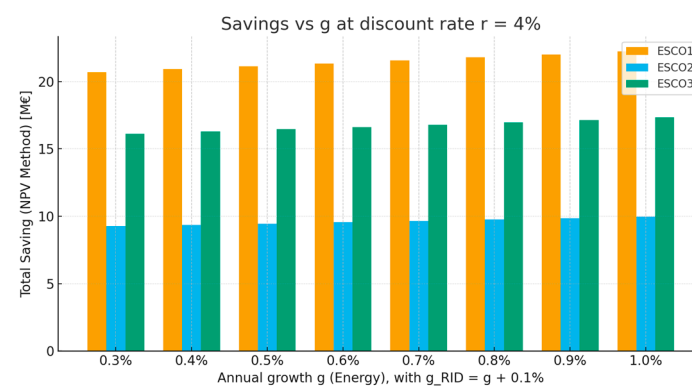


Figure A6. Savings versus g at discount rate of 4%.



Figure A7. Savings versus g at discount rate of 3%.

Appendix B. Analytic Hierarchy Process (AHP)

This appendix reports the core mathematical concepts that underline the AHP method and explain the connection between subjective criteria and the evaluation of consistency in judgments.

Decision-makers compare criteria (or alternatives) two at a time and assign numerical values based on Saaty's scale (from 1 to 9). For n criteria, the pairwise comparison matrix A is an $n \times n$ matrix, where each element a_{ij} represents the relative importance of the i th criterion over the j th, as shown in Equation (A1):

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \dots & 1 \end{bmatrix} \quad (\text{A1})$$

Once the pairwise comparison matrix is defined, the priority vector w (the eigenvector of A) represents the relative weights of the criteria. Solving for w involves the following equation, where λ_{max} is the maximum eigenvalue of matrix A :

$$A \cdot w = \lambda_{max} \cdot w \quad (\text{A2})$$

As it can be understood, matrix A is built upon a prior step that involves the inquiry of experts who express their opinions by comparing the criteria. This activity can involve stakeholders from different fields, depending on the nature of the decision-making process. As decision-making problems grow in complexity with more criteria and alternatives, maintaining consistency in pairwise comparisons becomes increasingly challenging. Techniques such as sensitivity analysis or involving multiple experts in the decision process help mitigate these issues. Therefore, a key feature of AHP is its ability to check for consistency in the decision-maker's judgments. A perfectly consistent matrix would have $\lambda_{max} = n$ (where n is the number of criteria). However, because subjective judgments may introduce inconsistency, the Consistency Index (CI) is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (\text{A3})$$

The CI measures how consistent the pairwise comparisons are. A higher CI suggests that the judgments are inconsistent and need to be revised. This index is then compared with another element, the Random Consistency Index (RI), which is derived from randomly generated pairwise comparison matrices [51]. At this point, it is possible to evaluate the Consistency Ratio (CR), as shown in Equation (A4). If $CR \leq 0.1$, the judgments are considered consistent. If the CR exceeds this threshold, the decision-maker is advised to revise the pairwise comparisons to improve consistency. The acceptable consistency level is crucial in maintaining the reliability of the priority weights derived from the comparisons.

$$CR = \frac{CI}{RI} \quad (\text{A4})$$

Once the priority vectors are calculated for all levels of the hierarchy (e.g., criteria and sub-criteria), the last step is to synthesize these priorities to rank the alternatives. The alternatives are scored based on their weighted performance on each criterion, and the overall scores determine their final ranking. Mathematically, the alternative ranking R is

computed by multiplying the priority vectors of the criteria by the alternatives' performance scores, as shown in Equation (A5):

$$R = \sum_i (w_i \cdot S_i) \quad (\text{A5})$$

where w_i is the weight of criterion i , and S_i is the score of alternatives with respect to the i th criterion.

References

1. Baglivo, C.; Congedo, P.M.; Malatesta, N.A. Building Envelope Resilience to Climate Change under Italian Energy Policies. *J. Clean. Prod.* **2023**, *411*, 137345. [\[CrossRef\]](#)
2. Direttiva 2012/27/UE del Parlamento Europeo e del Consiglio, del 25 Ottobre 2012, Sull'efficienza Energetica, che Modifica le Direttive 2009/125/CE e 2010/30/UE e Abroga le Direttive 2004/8/CE e 2006/32/CE Testo Rilevante ai Fini del SEE; European Union: Brussels, Belgium, 2012.
3. Psillaki, M.; Apostolopoulos, N.; Makris, I.; Liargovas, P.; Apostolopoulos, S.; Dimitrakopoulos, P.; Sklias, G. Hospitals' Energy Efficiency in the Perspective of Saving Resources and Providing Quality Services through Technological Options: A Systematic Literature Review. *Energies* **2023**, *16*, 755. [\[CrossRef\]](#)
4. Lee, Y.; Lee, H. Greenhouse Gas Emissions and Climate Change in Healthcare: A Global Scoping Review of Infrastructure, Financial Burdens, and Policy. *Asia-Pac. J. Conver. Res. Interchange* **2025**, *11*, 607–621. [\[CrossRef\]](#)
5. Burch, H.; Anstey, M.H.; McGain, F. Renewable Energy Use in Australian Public Hospitals. *Med. J. Aust.* **2021**, *215*, 160. [\[CrossRef\]](#)
6. Prada, M.; Prada, I.F.; Cristea, M.; Popescu, D.E.; Bungău, C.; Aleya, L.; Bungău, C.C. New Solutions to Reduce Greenhouse Gas Emissions through Energy Efficiency of Buildings of Special Importance—Hospitals. *Sci. Total Environ.* **2020**, *718*, 137446. [\[CrossRef\]](#)
7. Vourdoubas, J. Review of Sustainable Energy Technologies and Financial Tools for Achieving Net-Zero Emission Hospitals. *J. Environ. Ecol.* **2022**, *13*, 18. [\[CrossRef\]](#)
8. Schwab, R.; Schiestl, L.J.; Hasenburg, A. Greening the Future of Healthcare: Implementation of Sustainability Strategies in German Hospitals and beyond—A Review. *Front. Public Health* **2025**, *13*, 1559132. [\[CrossRef\]](#)
9. Montero, I.; Miranda, M.T.; Barrena, F.; Sepúlveda, F.J.; Arranz, J.I. Analysis of Photovoltaic Self-Consumption Systems for Hospitals in Southwestern Europe. *Energy Build.* **2022**, *269*, 112254. [\[CrossRef\]](#)
10. Tripathi, A.K.; Agrawal, S.; Gupta, R.D. Comparison of GIS-Based AHP and Fuzzy AHP Methods for Hospital Site Selection: A Case Study for Prayagraj City, India. *Geojournal* **2022**, *87*, 3507–3528. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Caprioli, C.; Bottero, M. Addressing Complex Challenges in Transformations and Planning: A Fuzzy Spatial Multicriteria Analysis for Identifying Suitable Locations for Urban Infrastructures. *Land Use Policy* **2021**, *102*, 105147. [\[CrossRef\]](#)
12. Chowdhury, A.A.; Irshad, A.S.; Banerjee, S. Analysis of Government Healthcare Infrastructure for the District of West Bengal: A Case of Purulia and Bankura. *Int. J. Sci. Res.* **2023**, *12*, 648–657. [\[CrossRef\]](#)
13. Salem, D.; Elwakil, E. Asset Condition Assessment Model for Healthcare Facilities. *Int. J. Constr. Manag.* **2023**, *23*, 182–203. [\[CrossRef\]](#)
14. Gupta, H.; Garg, S.; Gupta, U. Development of Sustainable Healthcare Model for the Hospitals in Northern India. *J. Adm. Kesehat. Indones.* **2023**, *11*, 131–144. [\[CrossRef\]](#)
15. Can, G.F.; Toktaş, P.; Pakdil, F. Six Sigma Project Prioritization and Selection Using AHP–CODAS Integration: A Case Study in Healthcare Industry. *IEEE Trans. Eng. Manag.* **2023**, *70*, 3587–3600. [\[CrossRef\]](#)
16. Akhruf, M.; Derghoum, M. Use of a Multi-Criteria Decision Support Model Based on the Ahp Method for the Selection of Health Infrastructure Projects. *Int. J. Anal. Hierarchy Process* **2023**, *15*. [\[CrossRef\]](#)
17. Hossain, M.K.; Thakur, V. Benchmarking Health-Care Supply Chain by Implementing Industry 4.0: A Fuzzy-AHP-DEMATEL Approach. *Benchmarking Int. J.* **2020**, *28*, 556–581. [\[CrossRef\]](#)
18. Tomczewski, A.; Mikulski, S.; Szymenderski, J. Application of the Analytic Hierarchy Process Method to Select the Final Solution for Multi-Criteria Optimization of the Structure of a Hybrid Generation System with Energy Storage. *Energies* **2024**, *17*, 6435. [\[CrossRef\]](#)
19. Shi, Y.; Wang, R.; Chen, P. Multi-Criteria Decision-Making Approach for Energy-Efficient Renovation Strategies in Hospital Wards: Balancing Energy, Economic, and Thermal Comfort. *Energy Build.* **2023**, *298*, 113575. [\[CrossRef\]](#)
20. Pakravan, M.H.; Johnson, A.C. Electrification Planning for Healthcare Facilities in Low-Income Countries, Application of a Portfolio-Level, Multi Criteria Decision-Making Approach. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 750. [\[CrossRef\]](#)
21. Zaheb, H.; Obaidi, O.; Mukhtar, S.; Shirani, H.; Ahmadi, M.; Yona, A. Comprehensive Analysis and Prioritization of Sustainable Energy Resources Using Analytical Hierarchy Process. *Sustainability* **2024**, *16*, 4873. [\[CrossRef\]](#)

22. Witt, T.; Dumeier, M.; Geldermann, J. Combining Scenario Planning, Energy System Analysis, and Multi-Criteria Analysis to Develop and Evaluate Energy Scenarios. *J. Clean. Prod.* **2020**, *242*, 118414. [\[CrossRef\]](#)
23. Bohra, S.S.; Anvari-Moghaddam, A. A Comprehensive Review on Applications of Multicriteria Decision-making Methods in Power and Energy Systems. *Int. J. Energy Res.* **2022**, *46*, 4088–4118. [\[CrossRef\]](#)
24. European Commission. Directorate General for Regional and Urban Policy. In *Economic Appraisal Vademecum 2021–2027: General Principles and Sector Applications*; Publications Office: Luxembourg, 2022.
25. Dranka, G.G.; Ferreira, P.; Vaz, A.I.F. Co-Benefits between Energy Efficiency and Demand-Response on Renewable-Based Energy Systems. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112936. [\[CrossRef\]](#)
26. Slabe-Erker, R.; Dominko, M.; Bayar, A.; Majcen, B.; Primc, K. Energy Efficiency in Residential and Non-Residential Buildings: Short-Term Macroeconomic Implications. *Build. Environ.* **2022**, *222*, 109364. [\[CrossRef\]](#)
27. Saddari, N.; Derkyi, N.S.A.; Peprah, F. Technical and Economic Analysis of Solar PV Electricity Generation under the Net Metering Scheme at Sunyani Teaching Hospital (STH), Ghana. *Renew. Sustain. Energy Transit.* **2025**, *6*, 100097. [\[CrossRef\]](#)
28. De Souza, M.F.Z.; Canizares, C.A.; Bhattacharya, K. Self-Scheduling Models of a CAES Facility Under Uncertainties. *IEEE Trans. Power Syst.* **2021**, *36*, 3607–3617. [\[CrossRef\]](#)
29. Pritchard, G.; Zakeri, G.; Philpott, A. A Single-Settlement, Energy-Only Electric Power Market for Unpredictable and Intermittent Participants. *Oper. Res.* **2010**, *58*, 1210–1219. [\[CrossRef\]](#)
30. Rodrigues, L.; Gonçalves, I.; Fé, I.; Endo, P.T.; Silva, F.A. Performance and Availability Evaluation of an Smart Hospital Architecture. *Computing* **2021**, *103*, 2401–2435. [\[CrossRef\]](#)
31. Silva, F.A.; Brito, C.; Araújo, G.; Fé, I.; Tyan, M.; Lee, J.-W.; Nguyen, T.A.; Maciel, P.R.M. Model-Driven Impact Quantification of Energy Resource Redundancy and Server Rejuvenation on the Dependability of Medical Sensor Networks in Smart Hospitals. *Sensors* **2022**, *22*, 1595. [\[CrossRef\]](#)
32. Stawowy, M.; Rosiński, A.; Paś, J.; Klimczak, T. Method of Estimating Uncertainty as a Way to Evaluate Continuity Quality of Power Supply in Hospital Devices. *Energies* **2021**, *14*, 486. [\[CrossRef\]](#)
33. García-Sanz-Calcedo, J.; Al-Kassir, A.; Yusaf, T. Economic and Environmental Impact of Energy Saving in Healthcare Buildings. *Appl. Sci.* **2018**, *8*, 440. [\[CrossRef\]](#)
34. ISPRA. Efficienza Energetica e Decarbonizzazione, «Rapporto 404/2024». Available online: https://emissioni.sina.isprambiente.it/wp-content/uploads/2024/10/Rapp-404-2024_-Energy-and-Decarbonization_2024.pdf (accessed on 1 August 2025).
35. Mustafa, M.B.; Keatley, P.; Huang, Y.; Agbonaye, O.; Ademulegun, O.O.; Hewitt, N. Evaluation of a Battery Energy Storage System in Hospitals for Arbitrage and Ancillary Services. *J. Energy Storage* **2021**, *43*, 103183. [\[CrossRef\]](#)
36. Junker, R.G.; Azar, A.G.; Lopes, R.A.; Lindberg, K.B.; Reynders, G.; Relan, R.; Madsen, H. Characterizing the Energy Flexibility of Buildings and Districts. *Appl. Energy* **2018**, *225*, 175–182. [\[CrossRef\]](#)
37. Impram, S.; Nese, S.V.; Oral, B. Challenges of Renewable Energy Penetration on Power System Flexibility: A Survey. *Energy Strategy Rev.* **2020**, *31*, 100539. [\[CrossRef\]](#)
38. Wagner, L.P.; Reinpold, L.M.; Kilthau, M.; Fay, A. A Systematic Review of Modeling Approaches for Flexible Energy Resources. *Renew. Sustain. Energy Rev.* **2023**, *184*, 113541. [\[CrossRef\]](#)
39. Khalili, S.; Lopez, G.; Breyer, C. Role and Trends of Flexibility Options in 100% Renewable Energy System Analyses towards the Power-to-X Economy. *Renew. Sustain. Energy Rev.* **2025**, *212*, 115383. [\[CrossRef\]](#)
40. Shahzad, S.; Jasińska, E. Renewable Revolution: A Review of Strategic Flexibility in Future Power Systems. *Sustainability* **2024**, *16*, 5454. [\[CrossRef\]](#)
41. Yasmin, R.; Amin, B.M.R.; Shah, R.; Barton, A. A Survey of Commercial and Industrial Demand Response Flexibility with Energy Storage Systems and Renewable Energy. *Sustainability* **2024**, *16*, 731. [\[CrossRef\]](#)
42. Koltsaklis, N.; Knápek, J. The Role of Flexibility Resources in the Energy Transition. *Acta Polytech. Hung.* **2023**, *20*, 137–158. [\[CrossRef\]](#)
43. Entec Digitalisation of Energy Flexibility. Available online: https://energy.ec.europa.eu/system/files/2022-02/Report_Digitalisation%20of%20Energy%20Flexibility%20_Final.pdf (accessed on 31 July 2025).
44. Chen-Xu, J.; Moutinho, V. Drivers of Energy Consumption in Portuguese Hospitals—A Panel Analysis. *Eur. J. Public Health* **2022**, *32*, iii478–iii479. [\[CrossRef\]](#)
45. Vourdoubas, J. Applications of Distributed Electricity Generation Systems in Hospitals. *Adv. Image Video Process.* **2021**, *9*, 10–20. [\[CrossRef\]](#)
46. de Oliveira, B.K.; Dos Santos, E.F.; Neto, A.F.; De Mello Santos, V.H.; De Oliveira, O.J. Guidelines for Efficient and Sustainable Energy Management in Hospital Buildings. *J. Clean. Prod.* **2021**, *329*, 129644. [\[CrossRef\]](#)
47. Cvijović, J.; Obradović, V.; Todorović, M. Stakeholder Management and Project Sustainability—A Throw of the Dice. *Sustainability* **2021**, *13*, 9513. [\[CrossRef\]](#)
48. Hyatt, D.G.; Berente, N. Substantive or Symbolic Environmental Strategies? Effects of External and Internal Normative Stakeholder Pressures. *Bus. Strategy Environ.* **2017**, *26*, 1212–1234. [\[CrossRef\]](#)

49. Chan, A.P.C.; Oppong, G.D. Managing the Expectations of External Stakeholders in Construction Projects. *Eng. Constr. Archit. Manag.* **2017**, *24*, 736–756. [\[CrossRef\]](#)
50. Maqbool, R.; Rashid, Y.; Ashfaq, S. Renewable Energy Project Success: Internal versus External Stakeholders' Satisfaction and Influences of Power-interest Matrix. *Sustain. Dev.* **2022**, *30*, 1542–1561. [\[CrossRef\]](#)
51. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [\[CrossRef\]](#)
52. Gawlik, R. Methodological Aspects of Qualitative-Quantitative Analysis of Decision-Making Processes. *Manag. Prod. Eng. Rev.* **2016**, *7*, 3–11. [\[CrossRef\]](#)
53. Akcan, S.; Güldeş, M. Integrated Multicriteria Decision-Making Methods to Solve Supplier Selection Problem: A Case Study in a Hospital. *J. Healthc. Eng.* **2019**, *2019*, 1–10. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Zopounidis, C.; Doumpos, M. Multicriteria Classification and Sorting Methods: A Literature Review. *Eur. J. Oper. Res.* **2002**, *138*, 229–246. [\[CrossRef\]](#)
55. Hmamed, H.; Benghabrit, A.; Cherrafi, A.; Hamani, N. Achieving a Sustainable Transportation System via Economic, Environmental, and Social Optimization: A Comprehensive AHP-DEA Approach from the Waste Transportation Sector. *Sustainability* **2023**, *15*, 15372. [\[CrossRef\]](#)
56. Al Mohamed, A.A.; Al Mohamed, S.; Zino, M. Application of Fuzzy Multicriteria Decision-Making Model in Selecting Pandemic Hospital Site. *Future Bus. J.* **2023**, *9*, 14. [\[CrossRef\]](#)
57. Asadabadi, M.R.; Chang, E.; Saberi, M. Are MCDM Methods Useful? A Critical Review of Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP). *Cogent Eng.* **2019**, *6*, 1623153. [\[CrossRef\]](#)
58. Saaty, T.L. Fundamentals of the Analytic Hierarchy Process. In *The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making*; Schmoldt, D.L., Kangas, J., Mendoza, G.A., Pesonen, M., Eds.; Springer: Dordrecht, The Netherlands, 2001; pp. 15–35, ISBN 978-94-015-9799-9.
59. Snizek, J.A.; Henry, R.A. Accuracy and Confidence in Group Judgment. *Organ. Behav. Hum. Decis. Process.* **1989**, *43*, 1–28. [\[CrossRef\]](#)
60. Dong, Y.; Zhang, G.; Hong, W.-C.; Xu, Y. Consensus Models for AHP Group Decision Making under Row Geometric Mean Prioritization Method. *Decis. Support Syst.* **2010**, *49*, 281–289. [\[CrossRef\]](#)
61. Forman, E.; Peniwati, K. Aggregating Individual Judgments and Priorities with the Analytic Hierarchy Process. *Eur. J. Oper. Res.* **1998**, *108*, 165–169. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.