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Improving the Energy Performance of Public Buildings in the Mediterranean Climate via a Decision Support Tool

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Abstract: Addressing Europe's decarbonisation challenge involves widespread deployment of nearly zero-energy buildings, deep energy renovations and renewable energy integration in the building sector. Enhancing energy efficiency in public buildings necessitates tailored solutions and strategic planning involving Local Public Administration. This work focuses on advancing insights into the application of the PrioritEE Decision Support Tool in Portuguese public buildings, highlighting the energy and financial savings and carbon dioxide emission reduction potential. Using detailed building characterisation data from energy performance certificates, we applied the tool across 22 public buildings of diverse typologies in three distinct regions of Portugal, representing various public entities. Results demonstrate the tool's adaptability, enabling a comprehensive assessment of energy performance and facilitating the exploration of customised energy efficiency and renewable energy solutions. The research emphasises the critical role of user-friendly tools in aiding policymakers and local administration technicians in meeting national renovation targets and contributing to the broader energy transition objectives.

Keywords: public buildings; energy efficiency; buildings renovation; decision support tools; Mediterranean area; Portugal

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1. Introduction

The decarbonisation of the building sector is a significant challenge that Europe faces, and the large-scale adoption of nearly zero-energy buildings (nZEBs) is seen as one solution. The recast Energy Performance of Buildings Directive EPBD 2010/31/EU required all buildings to become nZEBs by the end of 2020. However, to attain climate neutrality in Europe by 2050, additional commitments beyond the nZEBs level are required. Consequently, in December 2021, the European Commission (EU) aligned the energy performance requirements of buildings with the European Green Deal and set out the decarbonisation of the EU's building stock by 2050 in the context of the newly revised directive, EPBD 2021/0426 (awaiting Parliament's position on 1st reading).

Efficiency in energy use and the high integration of renewable energy are the main pillars of deep decarbonisation pathways and the urgent energy transition. Concerning integration within buildings, they continue to be the main drivers towards achieving the medium- and long-term building stock decarbonisation strategies for 2030 and 2050. Among the estimated 24 billion m^2 of floor area in the EU, residential buildings account for 75%, whereas non-residential buildings constitute only 25%. However, it is important to note that the latter includes a more complex and heterogeneous sector [1,2].

Buildings account for about 40% of the final energy consumption in the European Union (EU) and about 30% in the case of Portugal, and these values can be reduced by half with the application of energy efficiency measures [3]. In addition, especially in countries that use fossil fuels heavily for air conditioning, buildings also emit significant amounts of greenhouse gases (GHGs), mainly in the form of CO_2, contributing to climate change [1]. While substantial attention and efforts have been devoted to the housing sector, acknowledging its predominant representation in the building stock, non-residential buildings have been somewhat overlooked. This critical research gap in focus is noteworthy, considering that the public sector constitutes a significant portion of the overall non-residential building stock, which stands out as a pivotal and multifaceted domain essential for effectively disseminating and implementing energy-related measures and innovations. Notably, targeted energy efficiency measures within this sector have the potential to yield a substantial reduction of up to 28% in energy consumption [4,5]. Acknowledging and addressing this research gap is fundamental for advancing comprehensive strategies towards sustainable energy usage and achieving broader decarbonisation goals.

1.1. Policies and Strategic Plans

Adopting energy efficiency (EE) solutions in buildings has been a longstanding concern among the scientific community, practitioners and policymakers. Over the past few years, EE solutions have mainly been adopted through deep energy renovation as a key action towards improving energy efficiency and comfort. With the adoption of the nearly zero-energy buildings (nZEB) performance, since 2010, special attention has been paid to deep renovation of existing buildings in all end-use sectors—residential, commercial and public [6]. To that aim, calculations to support the derivation of cost-optimal levels of minimum energy performance requirements for buildings and building elements were performed by Member States (MS) to support the implementation of the EPBD recast at the national level [7,8]. In Portugal, the national programme of the Building Energy Certification System (SCE) [9] maintains a database that provides essential energy assessment details for the energy exploitation conditions of buildings [8]. The Long-Term Strategy for the Renovation of Buildings (LTRS) [10] is another priority programme in line with the European Energy Performance of Buildings Directive (EPBD) and Green Deal commitment, which imposes strict criteria for energy efficiency or support for the construction of new buildings with primary energy demand towards nZEB requirements.

The National Low Carbon Roadmap (RNBC) [11], published in 2012, and the Roadmap for Carbon Neutrality 2050 (RNC2050), published in 2019 [12], are key plans driving the country's overall decarbonisation agenda in the last decade. In 2019, the Government presented the National Energy and Climate Plan (NECP2030) [13] with the primary objective of achieving carbon neutrality by 2050 through the decarbonisation of the economy and energy transition in the period 2021–2030. Accordingly, achieving significant emissions reduction within the buildings sector is a pivotal measure, alongside the transport sector, with targeted reductions of 35% and 40% by 2030 compared to 2005. Simultaneously, ambitious targets have been established for the uptake of renewable energy in Portugal's gross final energy consumption, aiming for a 47% uptake by 2030. NECP 2030 specifically aims for urban renovation, promoting energy efficiency and integrating renewable energy into buildings to reduce dependence on fossil fuels, setting the nation's economy on a trajectory towards carbon neutrality. A strategy of European policies for urban renovation has been put in place to promote energy performance and renovation goals in buildings, as implemented by the European Energy Directive.

Buildings' role in cutting emissions, reducing energy consumption and, consequently, energy imports is a recognised important step for climate transition and moving towards nearly zero-carbon-emission buildings [14]. In addition, most public authorities should strengthen their institutional and technical capacity in energy efficiency (EE) and Renewable Energy Sources (RES) to contribute to the Energy Efficiency Directives and Energy Performance of Buildings, promoting renovation solutions and measures tailored to local contexts. Housing stock has received more attention with multiple analyses due to its potential for improvement and the related costs for retrofitting and renovation [15–19]. This is justified by the barriers that public buildings face, such as the lack of financial resources and necessary technical expertise on the part of local decision makers to promote and demonstrate the profits obtained in energy efficiency investment in public buildings [20].

As part of the Recovery and Resilience Plan (PRR) in response to the COVID-19 crisis, Portugal has allocated 38% of its total funds to measures supporting climate objectives [21]. This includes financing for a large-scale renovation programme aimed at enhancing the energy efficiency of buildings, known as the Sustainable Buildings Program (SBP). The SBP encompasses a diverse array of initiatives and sub-programmes, including renovating central government buildings (TC-C13-i02), funded with 200 million euros. The Recovery and Resilience Plan (RRP) [21] programme supports the renovation of buildings and infrastructures, with an exceptional implementation period lasting until 2026 for investments in health, housing, social responses, and qualifications and skills.

1.2. Nearly Zero-Energy Buildings Performance and Design

Several authors have addressed the topic of nZEB design [22,23], and there is a consensus that the best approach is, to begin with, passive sustainable design. This type of design is achieved by following two basic steps: reducing the energy demand of the building and harnessing renewable energy sources (RES) to generate electricity or other energy carriers. By doing this, it is possible to obtain sufficient credits to achieve the desired energy balance. This approach is seen as the most effective way to reach the nZEB performance level. Notably, the focus on passive sustainable design not only addresses energy efficiency but also plays a critical role in reducing carbon dioxide (CO_2) emissions, contributing to broader environmental sustainability goals. It is crucial to address nZEB design using passive sustainable approaches and solutions because they directly impact the mechanical, electrical and heating loads placed on buildings and, indirectly, the effort to generate renewable energy. The sustainable integration of renewable energy is not always straightforward and consensual between architects and engineers. Still, it should ensure the balance between the architectural and structural aspects of the buildings, and the efficiency of the systems.

There are few studies related to promoting the renovation of public buildings towards high energy performance. Aelenei et al. [7,8] published the results of a European project, RePublic_ZEB [23], which primarily aimed to target the modernisation of the public building infrastructure in 11 south-east European countries. The focus was on achieving nZEB in accordance with the Energy Performance of Building Directive of the European Union. The project's fundamental goal was to assist the participant nations in formulating and endorsing a specific set of technical measures for renovating their public building infrastructure towards nZEB, to promote these solutions in the market. In their publications, Aelenei et al. [7] address the characterisation of the public building stock and the challenges of these buildings in 11 countries. Another publication [8] discusses the implementation of cost-optimality methodology towards nZEB and the energy-efficient packages resulting from energy-efficient measures selected in 11 countries. In Portugal, public buildings were already a focus of the analysis by Reis [24]. The author assessed 1190 energy performance certificates (EPC), split the study into representative building typologies, and identified the primary energy efficiency measures proposed on the EPC by category of intervention and typology (Figure 1).

Mungia et al. [25] explore the role of energy efficiency in public buildings for the UN 2030 sustainable development. The authors explain how energy audits are relevant for energy efficiency in residential, commercial and public buildings. A case study of a small public building in Mexico is presented, examining the potential of energy audits to define a baseline to identify opportunities for energy efficiency measures in public buildings. It is concluded that the occupants' behaviour was the primary source of energy waste and that, through the energy audit developed, an energy awareness programme was essential for the reduction of this waste.

Figure 1. Public building categorisation according to EUROSTAT [4].

In a study that examined opportunities for improving public buildings' energy efficiency, four public healthcare buildings were improved by retrofitting external walls and roof spaces, and modernising heating systems. From the energy modelling of the buildings during the survey period, Terziev et al. [26] conclude that the measures led to 37.9% energy savings and increased profitability of the energy efficiency measures.

A comprehensive investigation was conducted into the advantages of energy efficiency measures by analysing the outcomes of energy efficiency projects in public buildings in Serbia and Croatia. The study evaluated the impact of these measures on energy conservation, reduction in greenhouse gas emissions, and the socio-economic benefits achieved. The study findings were documented in [14]. Three types of public buildings with different non-energy efficiency investment benefits were explored. It was possible to observe that although financially not viable, energy efficiency measures can sometimes be advantageous for society. For instance, emergency healthcare centres' most significant benefits resulting from energy efficiency measures would be the benefits associated with the enhancement of education and quality improvement of the healthcare services. Finally, the study reinforces the importance of investment project prioritisation tools for public buildings of other building stock.

1.3. Energy Performance Evaluation and Support Tools

The evaluation of buildings' energy performance can be performed by experimental means and measurements (existing buildings scenario), but more often through dedicated simulation tools as they permit the characterisation of the building and study optimisation scenarios.

Many tools and information sources are available on various platforms and directories tackling energy-related topics, e.g., energy planning and energy efficiency. A review of tools related to energy efficiency in buildings has been previously conducted by SENTECH [27], which only focused on energy audits. The study categorised the tools into five types: web-based calculators; prioritised lists of measures, checklists or survey instruments; asset rating tools; operational rating; and audit tools. Another study by NREL [28] visually represented 43 tools to assist cities in implementing data-driven energy action plans. The tools are categorised by sector and city-planning phase, ranging from gathering baseline data to measuring and managing results. Although these tools are designed for cities, they do not specifically focus on buildings' energy efficiency.

In contrast, Becqué et al. [29] provided an overview of technical assessment tools applicable to building efficiency policies and projects, which municipal policymakers can utilise to establish objectives, develop programmes and evaluate performance. The tools were classified into two groups: policy tools and project tools. Expanding on this research, Petrichenko et al. [30] analysed 50 publicly available tools for energy efficiency in buildings, characterising them based on their approach, scope, stage of policy development cycle and city focus. The SISMA SET Model [31] is an output of the Interreg MED project SISMA PLUS for the energy and techno-economic analysis of energy-saving measures. This specific decision support tool gives the most appropriate mechanism for retrofitting public buildings. The model is composed of an Excel file that aims to support the public authorities in better applying their resources to renovate public buildings. It is common practice to use tools that perform analysis on buildings' energy needs (e.g., Energy Plus, TRNSYS), evaluate the impacts, or provide ranking analysis of prioritisation of measures, to increase energy efficiency and the adoption of renewable energy sources in a specific building, building archetype or given group of buildings. On the other hand, there is a need for simplified models to be used for strategic planning, as decision support tools help local and regional authorities calculate and prioritise investments and implement measures that capture the greatest energy and financial savings.

The absence of consistent utilisation of analytical tools and indicators to design and implement local energy-efficiency policies is a prevalent issue. To address this, there is a pressing need to provide local decision makers with suitable (yet straightforward) tools to establish benchmarking scenarios, assess the effectiveness of policies and measures, and meticulously plan local investments. The comparison of alternatives based on various performance indicators is necessary to ensure informed decision making. Furthermore, analytical tools are essential to support capacity building in non-expert personnel working in technical departments, who often need to outsource specialised work for energy-efficiency decision support. Another example of such a tool was developed in the context of the projects PrioritEE and PrioritEE PLUS as the primary output, and it is used in this work.

1.4. PrioritEE PLUS Project

The PrioritEE PLUS project [32] was funded under the Interreg MED programme with the primary goal of capitalising on the main output and experience of a previous project, PrioritEE: "Prioritize energy efficiency measures in public buildings: a decision support tool for regional and local public authorities". It aimed to develop a comprehensive and generally applicable set of tools (PrioritEE toolbox) for professionals and experts from different levels, to foster energy efficiency and renewable energies, and prioritise various energy interventions [20,33,34]. In addition to transnational cooperation, local policies on sustainable energy use can also be strengthened, as well as the capacity of public authorities and stakeholders to evaluate, define and adopt analytical tools for improving the energy efficiency of public buildings. Training and transferring activities were carried out using the Decision Support Tool 1.0 (DSTool) in the territories of the partners in the MED area (Croatia, Italy, Greece, Portugal and Spain). In Europe, the majority of public authorities need to strengthen their institutional capacity for energy efficiency (EE) and Renewable Energy Sources (RES) to contribute to high building energy performance (nearly zero-energy buildings) and to fulfil the requirements of European directives like EPBD, Energy Efficiency Directives, developing solutions tailored to regional needs.

This paper focuses on the results of the use of an energy-efficiency decision support tool in Portugal, which is used to analyse and improve building energy performance by assessing different energy efficiency solutions together with the integration of renewable energy technologies. It was tested in three pilot areas/entities in Portugal (LNEG, ARE-ANATejo region and Arruda dos Vinhos Municipality). The main objective of this paper is to present the methodological approach used and the results obtained by applying the

DSTool to different locations in Portugal and several building typologies (e.g., offices, schools and swimming pools).

Our research novelty is fundamentally centred around showcasing the practical application of this tailor-made PrioritEE DSTool 2.0 in Portugal. The core emphasis is on its utility for local authorities, offering a systematic approach to assess a diverse portfolio of buildings and possible energy renovation measures. The DSTool facilitates the prioritisation of energy efficiency measures, encompassing a spectrum from insulation measures to window replacement and equipment upgrades. This strategic prioritisation is instrumental in addressing public buildings' specific energy efficiency needs and aligns with the overarching goal of fostering sustainable practices in the building sector.

The paper is structured into four sections. Section 1 is followed by the methodological approach, including a short description of the public entities presenting their buildings, a brief characterisation of the 22 building regional cases under study, and a description of the tool. This is followed by Section 3, where the main identified parameters (the savings in energy and the reduction in CO_2 emissions and costs) are presented for all case studies. Section 4 presents a discussion of the results. The paper ends with the final section (Section 5) of the conclusion, where a critical discussion of the research is presented, along with the major findings.

2. Materials and Methods

This study aims to use an advanced toolbox, DSTool, dedicated to proficiently managing energy consumption and advancing energy efficiency, integrating renewable energy utilisation within MPBs. The DSTool accommodates a diverse audience, including professionals, experts, and local administrators, presenting a range of specialised components to cater to their distinctive requirements.

Throughout the lifespan of the PrioritEE project work, the DSTool underwent meticulous development and refinement. This process was informed by a comprehensive testing phase involving five localised pilot studies within the Mediterranean region, aimed at creating a transparent and standardised methodological platform. This platform is designed to formulate local action plans, explicitly targeting the enhancement of energy efficiency within public buildings. Moreover, this research is dedicated to supporting public authorities in efficiently renovating public buildings by effectively employing the DSTool. This effort is situated within the broader context of the PrioritEE PLUS project, with participating countries—Spain, Italy and Portugal—identifying and proposing specific case study regions. Notably, these include the Municipality of Narni in Italy, the Aragonese Federation of Municipalities, Counties, and Provinces (FAMCP) in Spain and Portugal, entities such as the National Laboratory of Energy and Geology (LNEG), the Municipality of Arruda dos Vinhos, and the Energy and Environmental Agency of North Alentejo and Tejo (AREANATejo). Within this research, particular focus is placed on the processes and outcomes observed during the study conducted within the Portuguese regions. At the same time, some work has already been developed for other countries and regions (e.g., Teruel, Spain) [35].

The Decision Support Tool (DST) is a pivotal component of the toolkit, aiding in the assessment of cost-effectiveness for predetermined energy efficiency (EE) and renewable energy source (RES) measures. Key indicators integrated within the DST enable comparison of various intervention scenarios and their proposed effects. The development of the DST was guided by specific requisites outlined by city governments and stakeholders. They sought a user-friendly interface, multilingual online availability, focus on building project evaluation, flexibility in data input, and ranking of EE and RES measures based on key performance indicators [20].

The DST also underwent thorough research and customisation, drawing from an existing spreadsheet tool. As described in [33], the tool was further refined for inclusivity and adaptability for the Mediterranean and multiple countries context to include national-specific information (e.g., on climate, energy prices and taxes), to consider electricity and

LPG use for space heating, and to address space cooling, solar thermal hot water, solar PV and three different levels of insulation thickness (low, medium and high).

Its transition to a web-based application ensured widespread accessibility and ease of use, with tailored features for different countries. The DST's structured input layers facilitated efficient data entry, empowering users to customise assumptions and quantify technical and financial parameters for their buildings. Calculation options could be fine-tuned, allowing users to influence the results based on their inputs. The DST computed the impacts of selected EE and RES interventions in MPBs, calculating energy savings and costs for various interventions. It also facilitated results analysis, presenting indicators for informed prioritisation of interventions within each MPB and the broader building stock [33].

Overall, the planning objectives of the local governments and public institutions where the PrioritEE DSTool was tested included the renovation of public buildings, adoption of renovation packages comprising energy efficiency measures and renewable energy integration, promotion of passive and bioclimatic solutions, and integration of renewable sources towards nearly zero-energy buildings (nZEB). The use of simplified tools for rapidly achieving the best renovation solutions in public buildings, capacity building and communication with public administration technicians for effective building renovation was also prioritised.

The expected outcomes of these objectives were identified as improving energy efficiency in public buildings, increasing the use of renewable sources, enhancing thermal comfort, reducing energy consumption-related expenditures, disseminating good practices, reducing the time taken for building renovation solution calculation through simplified tools, and providing technical support to non-skilled public authorities on energy efficiency decisions. Table 1 provides an overview, categorised by building typology, of the public buildings targeted by the PrioritEE DSTool and portrayed on each building energy performance certificate (EPC).

Table 1. LNEG buildings' main features.

Build. ID	Typology	Energy Class	Net Conditioned Area [m^2]	Annual Gas and Other Fuels Consumption [MWh/Year]	Annual Electricity Consumption [MWh/Year]	Date of the EPC
LEG1	Office	C	8445	143.1	555.1	2017
LEG2	Office	B	301	-	21.3	2020
LEG3	Office	D	4120	-	319.4	2018

2.1. Portuguese Regional Case Studies

The PrioritEE DSTool was tested through three local pilots, which served as a testbed for its development and usage. These pilots were selected to be diverse in size, number of inhabitants, climate, type of buildings, energy consumption patterns and levels. Such diversity enabled a significant level of testing to assess the adaptability and potential transferability of the DSTool to other regions and countries in the future. The geographical distribution of the building clusters considered in Portugal is illustrated in Figure 2, and a brief description of the cases and their geographical locations is presented after, with a detailed overview of key building characteristics that enable further evaluation of their energy efficiency renovation potential. It is relevant to pinpoint that the selected buildings were also chosen due to the existence of detailed information provided on their energy performance certificates issued between 2015 and 2020. This way, the PrioritEE DST could be fully explored with the appropriate level of detail for each studied building.

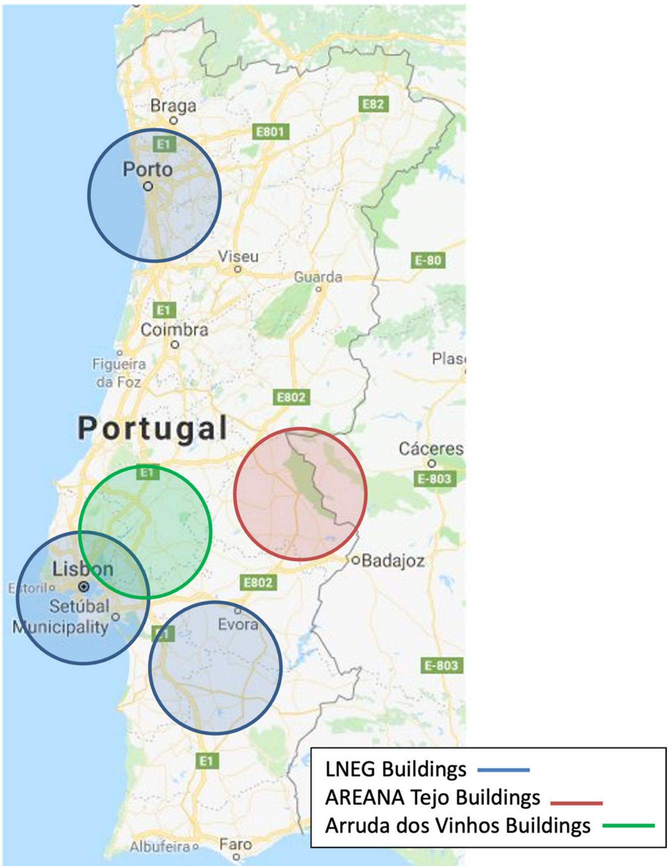

Figure 2. Regions where the different buildings of the Portuguese case studies are located.

2.1.1. The National Laboratory for Energy and Geology (LNEG)

LNEG is a state laboratory for energy and geology under the Ministry of Environment and Climate Action, dedicated to conducting research and development that caters to the needs of society and businesses. LNEG has four poles located across the country, from north to south, and four other office buildings (Figure 3) situated in São Mamede de Infesta (North of Portugal, council Matosinhos), Lumiar and Alfragide (Lisbon, Center of Portugal), and Aljustrel (Alentejo, South of Portugal).

LEG1 LEG2 LEG3

Figure 3. LNEG buildings case studies.

The building characteristics belonging to LNEG offices are presented in Table 1, where the main indicators of the energy performance before renovation are presented. The energy class classification ranges from A+ (most efficient) to F (least efficient), and the net conditioned area is the total area being climatised by HVAC systems. This is followed by information on energy consumption (natural gas and electricity) and the relevant data source, which in all cases is the energy performance certificate of each of the buildings.

The characteristics of the construction components of the buildings and existing equipment are presented in Table 2. The table details the external walls, roofs and windows' thermal transmittance (U-value)—the better insulated a structure is, the lower the U-value will be. It also depicts the presence of relevant energy-consuming systems such as lighting, HVAC systems and renewable energy technologies. Similar information is detailed in the tables of the other two regional case study buildings for comparative purposes.

Table 2. LNEG building components' characteristics.

Build. ID	Ext. Walls U-Value [W/m^{2}K]	Roof U-Value [W/m^{2}K]	Windows U-Value [W/m^{2}K]	Lighting	H&C Systems [Y/N]	Mech. Vent. [Y/N]	RES Tech. [Y/N]
LEG1	0.60	0.67	6.5	Fluorescent lamps	Y	N	N
LEG2	0.48	0.77	3.7	Fluorescent lamps + LED	Y	N	Y
LEG3	1.50	2.60	6.5	Fluorescent lamps	Y	N	N

2.1.2. Municipality of Arruda Dos Vinhos

Arruda dos Vinhos is a municipality in the Lisbon district of Portugal, covering an area of approximately 77.7 km^2. The municipality falls under the NUTS 3 classification, West of the Region of Lisbon and Vale do Tejo. As per the 2010 land occupation chart, less than 8% of the municipality area comprises artificialised territories, amounting to around 616 ha out of its 2636 ha of gross area. This study focuses on seven buildings, as illustrated in Figure 4, with their typologies in Table 3. The main characteristics of the buildings belonging to Arruda dos Vinhos are presented in Table 3, where the main indicators of the energy performance before renovation are presented based on the information from energy performance certificates.

Figure 4. Arruda dos Vinhos case study buildings.

Table 3. Arruda dos Vinhos buildings' main features.

Build. ID	Typology	Energy Class	Net Conditioned Area [m^2]	Annual Gas and Other Fuels Consumption [MWh/Year]	Annual Electricity Consumption [MWh/Year]	Date of the EPC
AV1	Office	B-	398	-	35.6	2015
AV2	Education	B	907	11.5	99.0	2015
AV3	Office	C	997	-	74.8	2018
AV4	Social	C	167	-	16.6	2020
AV5	Sport	C	432	-	48.0	2020
AV6	Cultural	C	1104	-	66.9	2018
AV7	Office	C	1104	-	114.6	n.a.

The main characteristics of the construction components and existing equipment are presented in Table 4.

Table 4. Arruda dos Vinhos building components' characteristics.

Build. ID	Ext. Walls U-Value [W/m^{2}K]	Roof U-Value [W/m^{2}K]	Windows U-Value [W/m^{2}K]	Lighting	H&C Systems [Y/N]	Mech. Vent. [Y/N]	RES Tech. [Y/N]
AV1	1.10	2.60	3.50	Fluorescent lamps	Y	Y	N
AV2	0.29	0.47	3.30	Fluorescent lamps	Y	Y	Y
AV3	1.75	3.40	4.64	Fluorescent lamps	N	N	N
AV4	1.80	3.80	5.10	Fluorescent lamps	Y	Y	N
AV5	1.10	2.60	4.89	Fluorescent lamps	N	N	N
AV6	1.50	3.80	5.10	Fluorescent lamps	Y	N	Y
AV7	0.54	0.60	4.30	Fluorescent lamps	Y	N	Y

2.1.3. AREANATejo

In this study, PrioritEE PLUS Portugal also focused on buildings located in Alentejo, a predominantly rural area with a strong agricultural sector as well as industrial and services. The buildings are located in the northern region of Alentejo and experience a warm and temperate climate with higher rainfall in the winter than in the summer. The Regional Agency for Energy and Environment of North Alentejo and Tagus (AREANATejo), an associated project partner, aims to promote sustainable local development by adopting best practices for energy efficiency in buildings. The agency seeks to contribute to the development of new projects and methods and to achieve greater energy efficiency and better environmental performance in the municipalities it serves. Twelve representative buildings (Figure 5) with different typologies (Table 5) were considered for this study. The main features of the buildings belonging to Arruda dos Vinhos are presented in Table 5, where the main indicators of the energy performance before renovation are given based on the information from buildings' energy performance certificates.

Table 5. AREANA Tejo Arruda dos Vinhos buildings' main features.

Build. ID	Typology	Energy Class	Net Conditioned Area [m^2]	Annual Gas and Other Fuels Consumption [MWh/Year]	Annual Electricity Consumption [MWh/Year]	Date of the EPC
AR1	Sport	B-	924	59.8	44.1	n.a.
AR2	Office	B-	1127	-	76.4	2017
AR3	Sport	A	1049	-	70.3	n.a.
AR4	Cultural	C	1815	-	65.0	2015
AR5	Cultural	D	712	-	29.4	2017
AR6	Sport	-	3058	-	-	-

Table 5. *Cont.*

Build. ID	Typology	Energy Class	Net Conditioned Area [m^2]	Annual Gas and Other Fuels Consumption [MWh/Year]	Annual Electricity Consumption [MWh/Year]	Date of the EPC
AR7	Edu.	C	238	5.7	18.0	n.a.
AR8	Office	D	937	-	127.3	2020
AR9	Office	B	5208	543.4	393.9	2015
AR10	Sport	C	774	68.7	120.2	2021
AR11	Sport	C	2887	520.3	315.3	2016
AR12	Office	B-	1456	-	97.0	2019

Figure 5. AREANA Tejo case studies.

The main characteristics of the construction components and main existing energy-consuming equipment are shown in Table 6.

Table 6. AREANA Tejo building components' characteristics.

Build. ID	Ext. Walls U-Value [W/m^{2}K]	Roof U-Value [W/m^2 K]	Windows U-Value [W/m^{2}K]	Lighting	H&C Systems [Y/N]	Mech. Vent. [Y/N]	RES Tech. [Y/N]
AR1	1.6	2.6	3.50	Fluorescent lamps	Y	Y	Y
AR2	0.96	2.25	3.40	Fluorescent lamps	Y	Y	N
AR3	1.10	0.67	3.90	Fluorescent lamps	Y	Y	Y
AR4	0.95	2.25	3.90	Fluorescent lamps	Y	Y	N
AR5	1.10	3.40	4.30	Fluorescent lamps	Y	Y	N
AR6	1.10	0.42	4.98	Fluorescent lamps	Y	Y	Y
AR7	1.76	2.25	3.90	Fluorescent lamps	Y	N	N
AR8	0.96	2.60	4.20	Fluorescent lamps	Y	Y	N
AR9	0.51	0.32	2.90	Fluorescent lamps	Y	Y	Y
AR10	0.96	2.60	6.10	Fluorescent lamps	Y	N	N
AR11	0.47	2.60	4.10	Fluorescent lamps	Y	Y	N
AR12	0.55	0.97	3.90	Fluorescent lamps	Y	Y	N

2.2. PrioritEE DSTool Description

The PrioritEE DSTool, which can be accessed online [32], enables local and regional authorities to evaluate the potential energy and financial savings achievable by implementing various measures to enhance the energy efficiency of individual public buildings and the entire building stock. The DSTool is currently being utilised by local administrations in the Mediterranean (MED) region, in Italy [34] and Spain [35], among others, to assess buildings' energy consumption and the cost-effectiveness of predefined measures, and to prioritise renovation actions and investments. The Decision Support Tool encompasses a comprehensive range of key performance indicators, and various intervention scenarios can be compared to analyse the impacts of the proposed strategies.

The PrioritEE DSTool is a flexible and user-friendly online application that enables local and regional authorities to calculate the potential energy and financial savings achievable by implementing various energy efficiency and RES adoption measures. It can be used with building-specific data, such as data from detailed energy audits, energy performance certificates or average pre-filled information for typical similar buildings in the MED region. This is one of the key advantages of this tool since it was specifically developed to be used under different regional contexts and with varying types of data availability. Furthermore, after several rounds of testing in other Mediterranean countries and local authorities, it was positively evaluated by more than 100 users [20], and it has been applied in multiple contexts since 2019.

The DSTool has a structure divided into nine domains corresponding to the building components: building envelope (external walls, windows and roof); ventilation; heating and cooling system; lighting; and renewable energy systems, to prioritise energy efficiency measures and potential future investments. The DSTool provides an overview of results ranked by savings, investment costs and return on investment for each building and building typology, allowing the evaluation of different combinations of energy efficiency measures (e.g., equipment replacement or passive measures such as insulation). The users can choose to only fill in the "basic input" section, which considers a list of country- or region-specific assumptions from the toolbox database, or to fill in the "advanced inputs" for more detailed results.

The DSTool is designed to evaluate each building separately, or the building stock or group of buildings can be compared in the benchmarking mode. However, the DSTool results are indicative and representative of the MED countries' buildings and should not replace an energy audit or an energy performance certificate output. To be a user-friendly web application and enable wide use, tutorials in six languages (English, Portuguese, Spanish, Greek, Italian and Croatian) are available, which should serve as a great explanation of the input data, methodology and filling-in process. Figure 6 illustrates the architecture of the tool.

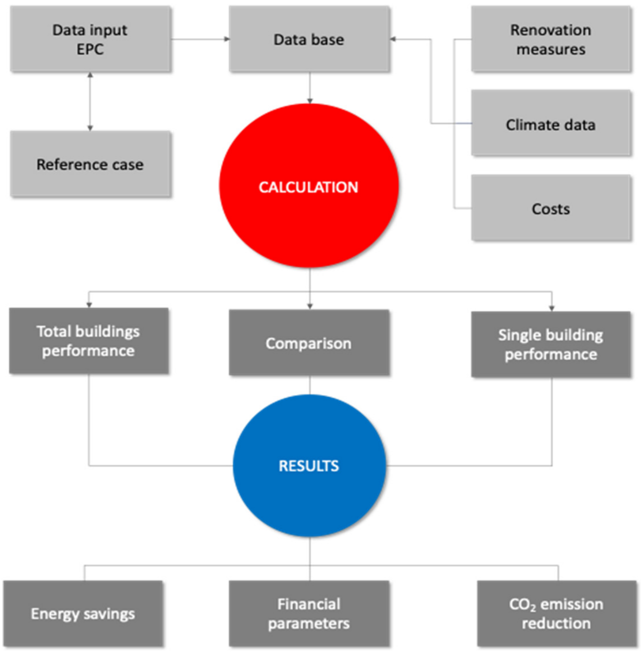

Figure 6. PrioritEE DSTool architecture.

It should be noted that the tool compares buildings chosen by the user based on certain energy renovation measures. Therefore, the measurements do not change depending on the buildings and are fixed variables. The renovation solutions identified (high level) by the DSTool were considered as follows:

Thermal insulation for the external walls, roofs and floors of about 10 cm, resulting in a U-value of 0.25 W/(m^2·K), and triple-glazed windows with argon, resulting in a U-value of 0.825 W/(m^2·K).

- Replacement of the current lighting systems with LEDs.
- Mechanical ventilation with a heat recovery system.
- Heat pumps for heating and cooling.
- Photovoltaic panels for the suitable ones.

However, it is also important to mention that the tool considers other levels of renovation for the passive solutions that are important to identify. The renovation measures for the low level are thermal insulation for external walls, roofs and floors of about 10 cm, resulting in a U-value of 0.4 W/(m^2·K), and double-glazed windows, resulting in a U-value of 1.5 W/m^2·K). The renovation measures for the medium level are thermal insulation for external walls, roofs and floors of about 10 cm, resulting in a U-value of 0.4 W/(m^2·K), and triple-glazed windows, resulting in a U-value of 1.2 W/m^2·K).

3. Results

The improvement of energy efficiency in public buildings is attainable through a variety of strategies, including enhancing the building envelope to mitigate heat loss or gains, optimising lighting by transitioning to LED lights and employing occupancy sensors, upgrading HVAC systems to high-efficiency alternatives, and integrating renewable energy sources such as solar systems.

In this section, we present a detailed analysis of the outcomes generated by the DSTool, focusing on a high-energy renovation scenario. Our objective is to identify optimal energy efficiency solutions, providing a foundation for public entities to guide local administration in informed decision making for building interventions. The obtained results encompass energy and financial savings as well as reductions in carbon dioxide emissions for each public building cluster.

To commence the analysis of the DST results, we present the cumulative results for each cluster, highlighting key parameters such as energy savings, reduction in CO_2 emissions and financial savings. Table 7 summarises these cumulative results, offering insights into the number of buildings and their respective typologies per cluster.

Table 7. Summary of indicators per cluster.

	LNEG (LEG)	AREANA Tejo (AR)	Arruda dos Vinhos (AV)
Number of buildings	3	12	7
Number of typologies	1	4	5
Primary energy savings (MWh/year)	3252	2302	415
CO_2 emission reduction (tCO_2e/year)	310	309	38
Financial savings (€)	217,523	658,624	56,855

3.1. Energy Savings and Carbon Dioxide Emissions Reduction

This section analyses the energy savings and reduction of CO_2 emissions achieved in each building and building cluster after implementing the tested energy renovation solutions. This enables each public entity responsible for a particular cluster to prioritise and evaluate the interventions. The trend of the CO_2 emission reduction follows that of the energy savings, i.e., the higher the energy savings, the more significant the reduction in CO_2 emissions, since natural gas is used in some of the buildings for space and water heating.

In the LNEG cluster (Figure 7), which comprises three office buildings with different characteristics and construction years, it is observed that LEG1, an old building with poor energy and thermal performance, achieved substantial energy savings of over 1400 MWh per year compared to LEG2, a recent office building with high energy performance (e.g., already with insulation and double glazing).

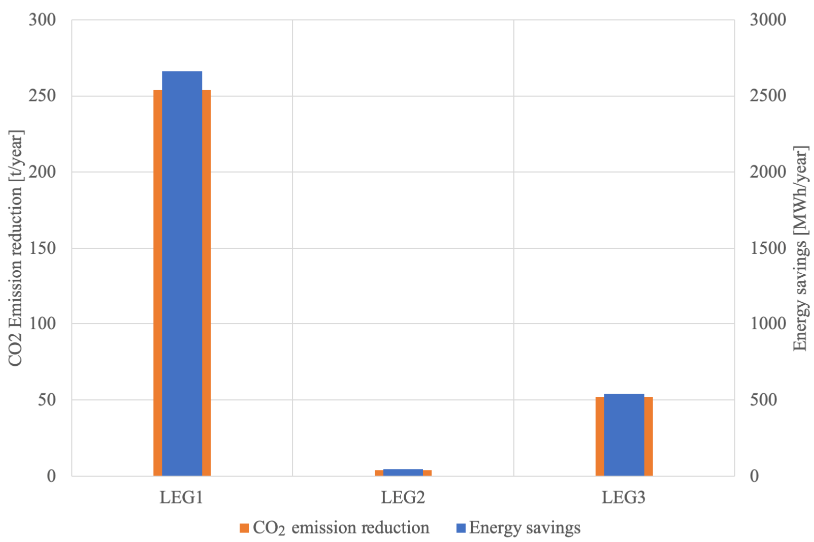

Figure 7. LNEG cluster: Energy savings (MWh/year) and CO_2 emission reduction (t/year).

The building cluster of AREANA Tejo is analysed in Figure 8, revealing considerable variations in energy savings and CO_2 emission reductions among the buildings. We assessed 12 buildings from four different typologies: the typology of Sports Facilities

(Arronches Municipal Stadium, Arronches Municipal Swimming Pool, Sousel Sports Complex, Ponte de Sor Municipal Stadium, and Ponte de Sor Municipal Swimming Pool), the typology of Offices (Arronches City Council, Sousel City Council, Ponte de Sor Aeronautic Campus, and Ponte de Sor Hangar 6), the typology of Cultural Buildings (Arronches Cultural Center, and Sousel Municipal Library) and the typology of Education Facilities (Sousel White House Kindergarten).

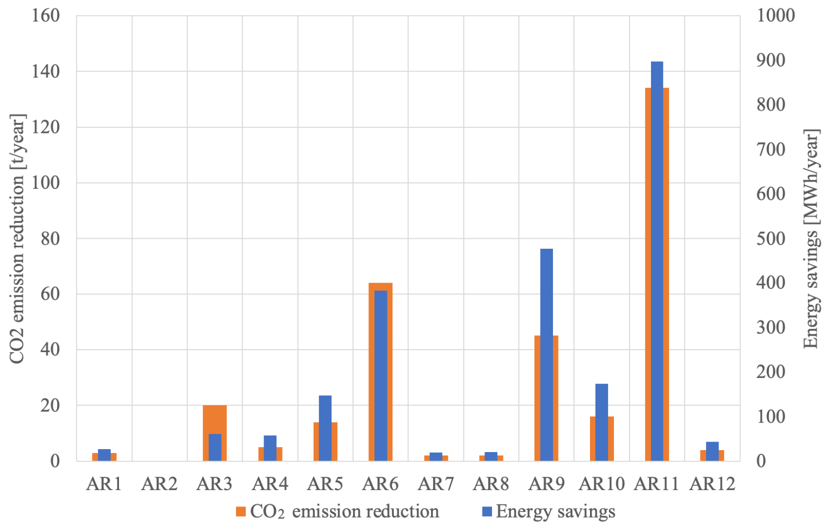

Figure 8. AREANA Tejo cluster: Energy savings (MWh/year) and CO_2 emission reduction (t/year).

Specifically, the Sports Facilities AR11, AR6 and AR9 have the most significant potential for energy savings. Comparing across entities, the LNEG buildings demonstrate the highest potential for energy savings (as shown in Table 2), nearly equivalent to the total energy savings potential of the AREANA Tejo buildings. In contrast, the buildings in Arruda dos Vinhos have the lowest potential due to their recent construction (Figure 9). Nevertheless, the results show that the savings impact still warrants taking action and further improving the energy performance of the buildings. For all the building cases analysed herein, it is essential to point out that the active renovation measures (such as more efficient HVAC systems and heat pumps) are those that play a more significant role, both in terms of energy savings and payback.

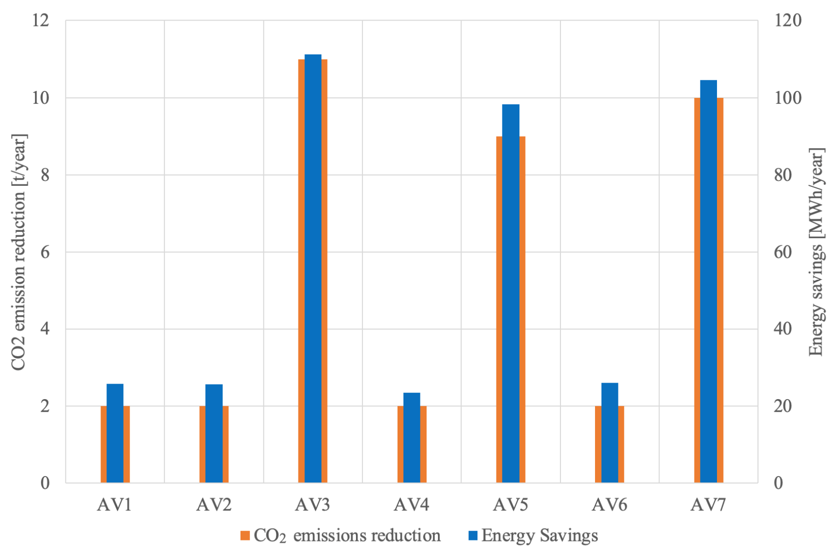

Figure 9. Arruda dos Vinhos cluster: Energy savings (MWh/year) and CO_2 emission reduction (t/year).

All seven buildings assessed that belong to the Arruda dos Vinhos cluster are, as referred to above, of different types, making a direct comparison harder. Within this group of public buildings, we have one building from the Sports Facilities typology, one from the Cultural Buildings typology (Municipal Library), one from the Educational Buildings typology (S. Tiago dos Velhos School Center), and four buildings that belong to the group of the generic typology of Offices, but are very distinct in their use (i.e., Citizen's Bureau, City Council, Study and Research Centre, and Youth Hostel). Buildings AV3 (office), AV5 (sports) and AV7 (office) stand out as the buildings with more potential for energy and emissions saving, related to a high potential for the adoption of solar PV on the rooftops (AV5) and the integration of heat pumps for space heating and cooling. It is important to note that these three buildings have a C-class energy performance, below thermal regulation standards for new and efficient buildings, also supporting the result that it would be beneficial to perform impactful energy renovations.

Despite the potential significant energy and emissions savings, public entities have budget limits for implementing renovation measures. In most cases, it is not possible to choose to implement all (and the most efficient) measures to improve energy performance; it is also important to identify which buildings will be most advantageous for the first renovations/investments.

3.2. Financial Savings

The potential financial savings resulting from the adoption of energy-efficient measures tested in each building cluster are presented in the following figures. Consistent with the trend observed in energy savings, the clusters with the highest energy savings also show the highest financial savings. Figure 10 displays the financial savings resulting from renovation measures in LNEG buildings, with LEG1 showing the highest value of financial savings at approximately 165,000 € per year, followed by LEG3 and LEG2 at just over 47,000 € per year and 4000 € per year, respectively.

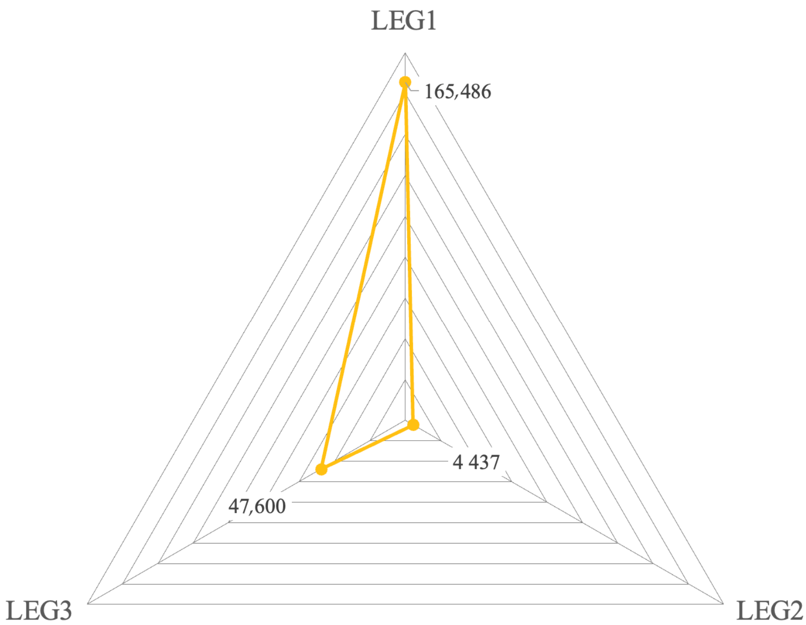

Figure 10. Financial savings in LNEG cluster (€).

The highest financial savings among the AREANA Tejo building cluster can be observed in the municipal pool of Ponte Sor, represented by building AR11, with around 501 k€ per year. Following that, the office building AR9 shows financial savings of about 120 k€ per year (Figure 11).

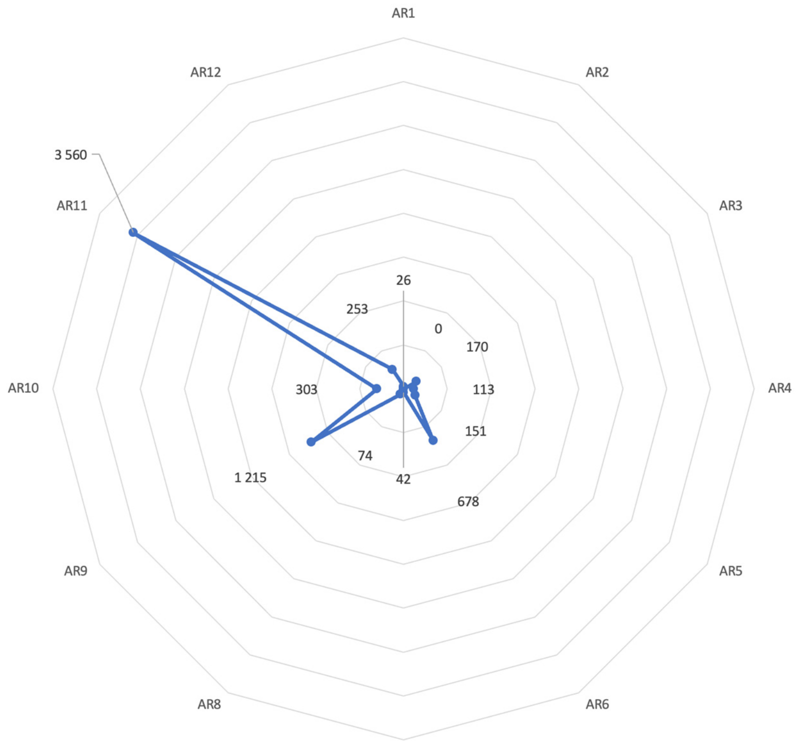

Figure 11. Financial savings in AREANA Tejo cluster (€).

The financial savings for the Arruda dos Vinhos building cluster are displayed in Figure 12 and range from 2500 € per year for the Social Centre building (AV4) to 15,000 € per year for the office building (AV7).

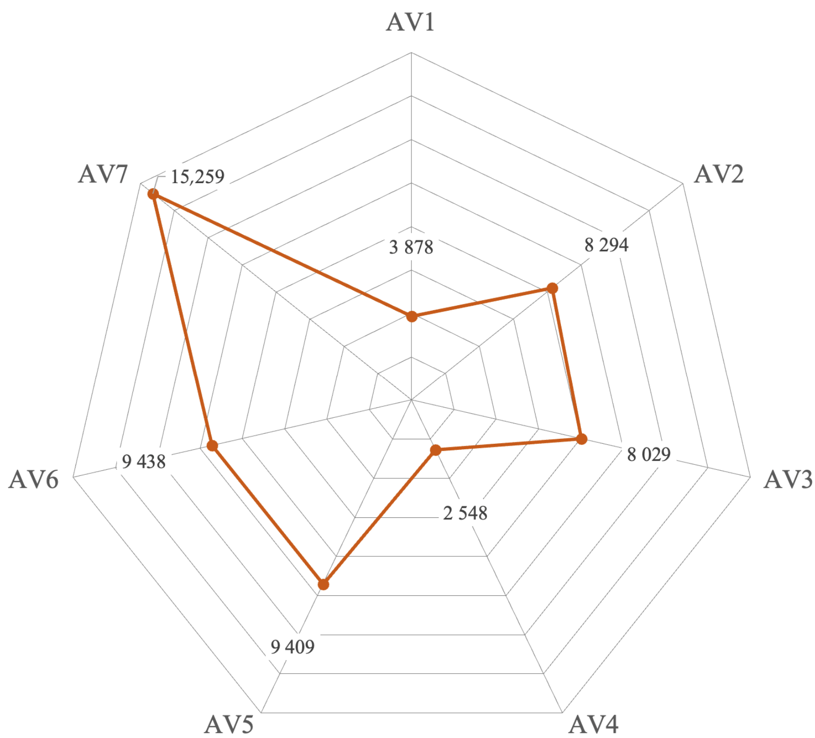

Figure 12. Financial savings in Arruda dos Vinhos buildings cluster (€).

4. Discussion

To strengthen the institutional capacities of the local administration in sustainable planning and management of public buildings, an expedited method in the form of a less complex simulation tool is needed. Therefore, the DSTool was developed with the primary objective of supporting municipalities in evaluating the efficiency levels of public buildings in a simple, rapid and efficient way in order to prioritise the decisions over building renovation.

The decision-making process for public buildings' energy efficiency improvements is highly dynamic and intricate, and it is constrained not only by budget limitations but also by municipal actors' knowledge of the current situation of their buildings' structure and related energy consumption. Whereas data availability and quality are critical for well-supported choices and the prioritisation of energy efficiency measures and buildings, as discussed by Morewood [36] in an extensive review of 162 articles, data quality lacks visibility in buildings-related assessment and monitoring studies. Complementarily, many decision support methodologies and tools have been developed (see an extensive review in, e.g., [37]), mainly based on energy consumption measurements or simulations, which require significant data inputs.

Low-density rural areas that cover a vast extension of local governments in the Mediterranean area usually have low resources, with technicians and decision makers having to deal with multiple areas of action in their municipality. Previous research [33] has shown that there are very different skills and competence levels among smaller local authorities. While certain authorities demonstrate high levels of expertise, others lack staff members with in-depth knowledge of energy efficiency. An additional issue regarding data in many local authorities is that data are usually scattered among the different offices of the same municipality, with poor communication between them.

Recognising this policy support gap, one of the advantages of using the PrioritEE DSTool 2.0 is that it was developed to allow for different levels of data availability and different uncertainty levels. While it does not provide detailed simulation outputs, it allows an overall prioritisation of measures, facilitating local authorities' first assessment of buildings and the potential of different measures. It creates a first layer of indicative results of a broad portfolio of buildings and priority actions, setting the basis for a deeper dive into follow-up actions. The use of a flexible tool is better suited to different types of users.

Another practical advantage of this tool lies in the extensive experience and application under various scenarios and regional needs identified in the territories of the MED countries (Croatia, Italy, Greece, Portugal and Spain). Additionally, a key strength is its simplicity of use, being spreadsheet-based and potentially utilising data available from multiple sources like energy bills, energy certificates or buildings' cadastral information.

Additionally, and as discussed already in [33] and further unfolded in this work, the PrioritEE DSTool structure and outputs were deemed particularly advantageous for showcasing the benefits of individual and/or combined interventions, comparing multiple interventions in terms of EE and cost-benefit analyses across various technology combinations, conducting benchmarking for both types of measures and specific building categories, and establishing prioritisation of energy efficiency interventions within a given territory. Furthermore, being an online tool with dedicated user logins, it can be used as a unified and transparent repository for consolidating technical data on public buildings and creating a transnational energy baseline.

In this work, relying on energy performance certification data for each of the buildings, we tackle reliability and poor-quality data problems, and use timely and comparable datasets. The EPC considers numerical calculation methods based on the International Organization for Standardization (ISO) standards. In contrast to the simplified certification process for residential buildings, the certification of large service buildings, as in the present case, is based on a calculation methodology using an hourly dynamic whole-building simulation software (ASHRAE 140-2004 [38] compliant). This methodology must be validated against energy audits and invoice analysis over a complete year. While the energy classification of these buildings is obtained by assuming nominal conditions of operation in terms of air conditioning systems, occupation, use of lighting or equipment, the level of confidence in the data obtained from the certificates is high.

Furthermore, by connecting directly with local authorities while testing their buildings on the DSTool, we also address the accessibility and clarity of data problems usually found in similar studies.

Our results validate a prevailing consensus in the field—older public buildings possess significant untapped potential for energy and financial savings [26]. This underscores the imperative for strategic and targeted renovations within this segment of buildings to effectively advance our collective energy efficiency objectives [7]. Often characterised by suboptimal thermal insulation and outdated energy systems, older structures can be notably enhanced through tailored interventions, resulting in substantial energy savings and subsequent financial benefits [34].

This analysis is a solid foundation for stakeholders, providing an in-depth understanding of the extensive improvements that can be accomplished through focused renovation endeavours in each building cluster. By acknowledging the specific needs and opportunities presented by older structures, public entities can strategically plan renovation priorities to maximise energy and cost efficiencies. Furthermore, this understanding is crucial given public institutions' prevalent budgetary constraints.

In practice, budgetary limitations frequently compel a phased approach to renovation efforts [20]. It becomes pivotal to conduct a meticulous analysis of the DSTool data to identify those buildings within each cluster that promise the most substantial return on investment (ROI) from initial renovations. Such a targeted approach ensures that the limited available resources are optimally allocated, leading to a judicious use of funds and a swift realisation of tangible benefits.

In conclusion, this comparison with existing studies reinforces the critical importance of addressing older buildings in the public sector, and it illuminates the potentially transformative impact that strategic renovations can achieve. By aligning our findings with the prevailing consensus and emphasising the significance of targeted renovation strategies, we advocate for a nuanced and informed approach that can significantly contribute to achieving overarching energy efficiency goals within the constraints of real-world budgetary considerations.

5. Conclusions

In recent years, energy renovation has emerged as a critical objective for achieving substantial energy savings and contributing to the decarbonisation of the building stock while aligning with European legislation and objectives, both at national and local levels, for example Sustainable Energy and Climate Plans (SEAP/SECAP) that the signatories of the Covenant of Mayors must develop. However, in most cases, local authorities have insufficient knowledge about their buildings' characteristics and energy consumption, or the best energy efficiency and renewable energy technological options for improving their buildings' thermal comfort and quality, and reducing greenhouse gas emissions and energy bills. New data sets and methods for supporting energy-related decision making for local governments are therefore paramount for supporting energy regulation at the local level.

The development and testing in multiple locations and building types of an interactive online calculator, the PrioritEE DSTool, address the imperative to support local and public authorities in enhancing energy efficiency within public buildings. This tool systematically ranks energy efficiency measures based on their potential savings, associated investment costs and return on investment, offering insights at both individual building and group levels.

In this work, we apply the PrioritEE DSTool for the Portuguese context in three case study locations/entities (i.e., LNEG, AREANA Tejo, and Arruda dos Vinhos Municipality), using 22 buildings that cover multiple building typologies. To feed information into the PrioritEE DSTool, we used as a key data source the detailed information available for each building's energy performance certificate on heating, cooling, lighting and building infrastructure status quo.

The cumulative analysis presented in this work serves as a guide so that stakeholders can have a full view of the improvements that can be achieved if the solutions are implemented in all the buildings belonging to the regional cluster in question.

The findings from this study for only a few buildings, for example, affirm the pressing need to renovate most public buildings in Portugal, as unfolded in the Portuguese National Building Renovation Strategy, and to align with ambitious energy renovation targets. Notably, active renovation measures are pivotal contributors to energy savings and financial viability. This paper has presented a comprehensive analysis encompassing energy and financial savings, and CO_2 emission reductions achieved through DST for various building clusters. Future research endeavours should delve into an in-depth evaluation of renovation solutions at the building level to provide a nuanced assessment for each public authority, aligning the conclusions more closely with the core focus of dedicated deep energy renovation plans and city-level energy and climate action strategies.

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Data Availability Statement: The data used in this study are available on request from the corresponding author. The data from energy performance certificates are not publicly available due to privacy restrictions.

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

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