23rd International Conference on Renewable Energies and Power Quality
(ICREPQ'25) Tenerife (Spain), 25th to 27th June 2025
ISBN-13: 978-84-09-66511-2

Energy Audit and Characterization of Special Technical Installations – Case Study – Municipal Civil Protection House and Coimbra Fire Brigade Headquarters

Daniel O. Gonçalves[1], R. M. Monteiro Pereira[1,2,3] Adelino J. C. Pereira[1,2,3]

[1] Polytechnic University of Coimbra
Rua da Misericórdia, Lagar dos Cortiços, S. Martinho do Bispo, 3045-093 Coimbra, Portugal
Phone number: 00351 239 790 200, e-mail: a21170075@isec.pt, rmfm@isec.pt, ajcp@isec.pt

[2] SUScita - Research Group on Sustainability, Cities and Urban Intelligence, Polytechnic University of Coimbra
Coimbra Institute of Engineering, Rua Pedro Nunes, 3030-199 Coimbra, Portugal

[3] INESC Coimbra - Instituto de Engenharia de Sistemas e Computadores de Coimbra
Pólo II, R. Sílvio Lima, 3030-290 Coimbra

Abstract. Climate change poses a growing threat with consequences for various areas of society. In Portugal, around 30% of final energy is consumed by the building sector, while in Europe, this figure is approximately 40%.

The building of the Municipal Civil Protection House and the Fire Brigade Headquarters in Coimbra is a public service building, constructed about 25 years ago, prior to the implementation of the Energy Certification System for Buildings (SCE) in Portugal, so its construction and technical systems are outdated compared to current regulatory requirements. As a building with unique operating conditions, hosting both the Fire Brigade services and Civil Protection services, both of which are highly relevant to the Municipality of Coimbra, it is necessary to ensure the proper functioning of special technical installations.

During the development of this study, the main forms of energy consumption were characterized, as well as the existing special technical installations. Subsequently, aiming the remodelling and updating of different technical installations, reducing energy bills, and Greenhouse Gas (GHG) emissions, opportunities for consumption rationalization and installation improvements were identified.

Key words. Energy Audit, Energy Efficiency, Installation Improvement and Remodelling, Opportunities for Consumption Rationalization, Special Technical Installations.

1. Introduction

Climate change is one of the greatest environmental threats of the 21st century, negatively impacting various areas of society. As a widely discussed issue in recent years on a global scale, there are still challenges in obtaining responses in terms of policies, both at the global and European, national, regional, and municipal levels [1].

It is estimated that currently, in Portugal, around 30% of final energy is consumed by the building sector. In Europe, this figure is about 40%. In light of these facts, Portugal has directed its strategy to align with European policies reflected in the current European Energy Performance of Buildings Directive (EPBD) [2], [3].

In 2007, through the transposition of the European Energy Performance of Buildings Directive [2], [3], the Energy Certification of Buildings was implemented, which allows for the assessment and classification of the energy performance of buildings within the framework of European and national energy policies, contributing to the improvement of their technical conditions and the consequent reduction of energy consumption.

As outlined in the Roadmap for Carbon Neutrality 2050 [4], aiming for the decarbonization of the building stock by 2050 in accordance with the EPBD [2], long-term rehabilitation strategies have been adopted to reduce energy consumption needs, increase energy efficiency, combat energy poverty, and promote the use of renewable energy sources.

Recently, an essential tool has emerged in Portugal to boost energy efficiency nationally: the Recovery and Resilience Plan [5]. Through this plan, a set of reforms and investments is intended to be implemented, guided by a sustainability concept inspired by the United Nations Sustainable Development Goals (SDGs) [6].

This paper aims to present and discuss the results from a recent energy audit of the Municipal Civil Protection House and Firefighters' Headquarters in Coimbra, with the goal of characterizing the main forms of energy consumption and the existing technical installations. Identifying opportunities for consumption rationalization, with a view to remodeling and updating the different installations, will contribute to reducing energy bills and greenhouse gas emissions [7].

2. Characterization of the Building

A. Architecture of the Spaces

The Municipal Civil Protection House and Coimbra Fire Brigade Headquarters is located within the urban area of Coimbra and consists of five main sections, featuring flat roofs, a concrete tower, three adjacent support blocks, and a diving tank. The total area of the building is 4,515.63 m², with an average ceiling height of 3.24 m. The main sections include two floors: the ground floor and the first floor, which encompass office spaces, a storage area, restrooms, changing rooms, dormitories, a transformer station and sectioning room, technical rooms, a cafeteria, among other areas.

B. Usage Profiles

As a building that houses emergency and disaster response services of great importance to the Municipality of Coimbra, it operates 24 hours a day, every day of the year, without interruption, with an estimated daily occupancy of 76 staff members.

C. Constructive Features of the Envelope

The building comprises exterior walls with and without thermal insulation, flat exterior roofs with and without thermal insulation, uninsulated glazed openings, and wooden and metal doors.

D. Facilities and Equipment

Heating in the building is of the water/air type, consisting of hot water production units, terminal units for air heating, and natural convection terminal units (radiators). On the roof, above the pantry and cafeteria area, there are three Air Treatment Units (ATUs) that provide air recirculation and heating for those spaces.

The thermal central, located on the ground floor, houses natural gas heating boilers, a hot water storage tank, pump groups, the hydraulic network, and associated electrical installations.

Restrooms, changing rooms, the cafeteria and bar area, the multipurpose room, and the current storage area are equipped with ventilation units and respective ducts.

On the first floor of the main building, particularly in the areas of bedrooms, suites, dormitories, and offices, there are direct expansion air conditioning units, both mono-split and multi-split types.

In the laundry area on the ground floor of the main building, there are four washing machines and one dryer.

The Municipal Civil Protection House and Coimbra Fire Brigade Headquarters in Coimbra is equipped with an elevator that ensures accessibility between the ground floor and the first floor for individuals with reduced mobility, as well as allowing for the transport of small goods from the ground floor to the kitchen area. This elevator has an estimated average daily downtime of 23.8 hours.

Regarding the electrical installations, the building is supplied with medium voltage power, featuring a transformer station, sectioning, and an emergency group installed in a dedicated room near the main entrance of the exterior atrium on the ground floor.

Interior lighting is provided by fluorescent tube lamps, LED lamps, compact fluorescent lamps, and halogen lamps, while exterior lighting consists of compact fluorescent lamps, LED technology lamps, metal iodide lamps, and halogen lamps.

The natural gas network installed in the building extends from the main cutoff box, reduction, and metering to the thermal central and the cafeteria area, where it supplies the combustion equipment installed there.

Hot water in the main building is primarily provided by the natural gas boilers installed in the thermal central, with an electric storage water heater located in one of the adjacent blocks.

3. Monitoring of the Facilities

To analyze natural gas and electricity consumption, invoices for the entire year of 2023 were collected, with the values presented in Tables 1 and 3.

Only the year 2023 was analyzed, as a previous assessment of 2022 revealed a similar consumption pattern. Since no significant variations were identified, the 2023 data is considered representative, making further analysis unnecessary.

A. Natural Gas

Natural gas consumption in the building is provided by the heating boilers located in the thermal central, as well as by the combustion equipment in the kitchen area.

Table 1. - Monthly natural gas consumption and billing costs in 2023

Month	Year 2023		
	m^3	kWh	€
January	6,894	85,963	15,010.76
February	4,995	58,063	12,783.11
March	4,096	47,885	10,550.78
April	1,251	14,612	3,375.47
May	1,345	15,837	3,634.50
June	1,683	19,799	2,740.16
July	1,405	16,609	3,930.15
August	1,482	17,244	4,013.38
September	1,434	16,735	3,968.15
October	1,994	23,077	5,280.04
November	2,568	29,974	7,030.74
December	3,817	50,419	9,472.25
Total	32,964	396,217	81,789.49

Based on the results presented in Table 1 and the graph in Figure 1, there is an annual natural gas consumption of 396,217 kWh, corresponding to an annual billing of approximately €81,789.49. The month of January stands out as the month with the highest natural gas consumption (85,963 kWh).

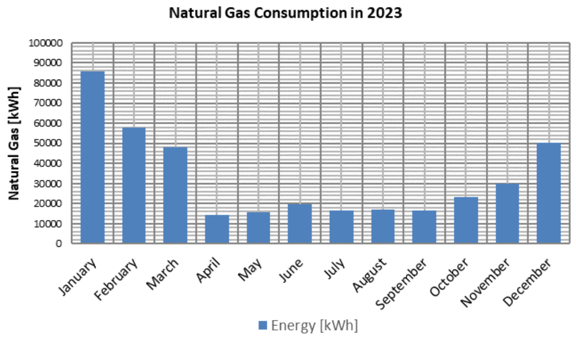

Fig. 1. Monthly Natural Gas Consumption in 2023

There is a noticeable increase in natural gas consumption during the winter months when the heating system is in operation. However, in the other months of the year, the contribution from hot water systems to natural gas consumption is significant.

Based on the characteristics of the natural gas appliances installed in the building and considering the usage profile of the facilities, it was possible to break down the annual natural gas consumption by different consumption sectors. The estimated results are presented in Table 2.

Table 2. - Breakdown of the facility's annual natural gas consumption by consumption sector

Natural Gas consumption sector	Natural Gas [kWh/year]	Percentage of total consumption %
Heating	202,071	51
Hot Water (HW) Production	134,714	34
Kitchen Equipment	59,432	15

B. *Electrical Energy*

Table 3 and the graph in Figure 2 display the monthly consumption broken down by different time periods throughout the reference year (2023).

Table 3. - Monthly Breakdown of Electric Energy Consumption in 2023

Month	Active Energy Consumption [kWh]				Power [kW]	Monthly Total Active Energy Consumption [kWh]
	Peak Hours	High Demand Hours	Normal Off-Peak Hours	Super Off-Peak Hours	Contracted Power	
January	2,944	7,339	4,183	2,148	116,25	16,614
February	2,367	5,910	3,225	1,742	116,25	13,244
March	2,492	6,429	3,029	1,709	116,25	13,659
April	1,255	4,939	3,342	1,331	116,25	10,867
May	1,199	5,202	2,592	1,333	116,25	10,326
June	1,333	4,882	2,771	1,356	116,25	10,342
July	1,025	3,905	1,841	994	116,25	7,765
August	1,248	5,417	3,007	1,472	116,25	11,144
September	1,232	5,415	2,836	1,441	116,25	10,924
October	1,475	5,588	3,299	1,431	116,25	11,793
November	2,191	5,533	3,280	1,565	116,25	12,569
December	2,275	5,927	5,266	2,017	116,25	15,485
Total	21,036	66,486	38,671	18,539	-	144,732

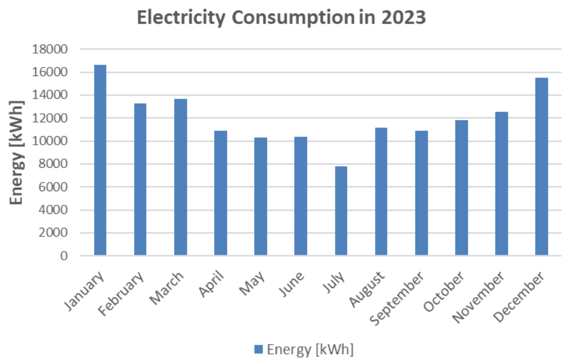

Fig. 2. Evolution of Monthly Electricity Consumption in 2023

To better understand the electricity consumption profiles of the building, various monitoring sessions were conducted on electrical panels that supply and protect key equipment, from May 2 to May 10, 2024, over a 24-hour period. Measurements were taken using Tinytag Energy Logger devices, model TGE-0001.

Based on the monitoring conducted and considering the characteristics and usage profiles of the different electrical equipment installed in the building, it was possible to break down the annual electricity consumption by consumption sector. The estimated results are presented in Table 4.

Table. 4 - Disaggregation of the annual electricity consumption, by consumption sector

Electricity consumption sector	Electricity [kWh/year]	Percentage of total consumption %
Heating	13,699	9,5
Cooling	1,801	1,2
Ventilation and Pumping	10,901	7,5
Lighting	15,506	10,7
Hot Water (HW) Production Equipment	105	0,1
Fans and Pumps	815	0,6
Elevators	1,803	1,2
Various Equipment (Workstations, Printers, Microwave Ovens, Refrigerators and Freezers, Emergency Equipment, Compressors, among others)	70,988	49,1
Laundry	12,092	8,3
Cafeteria	17,021	11,8

C. *Global Energy Consumption*

From the analysis conducted in the previous sections regarding energy consumption, it can be concluded that natural gas and electricity are the primary energy sources used in the Municipal Civil Protection House and Coimbra Fire Brigade Headquarters.

To provide a better understanding of the share of each energy source and its associated costs, Table 5 presents a summary of the total energy consumption and costs in the building for the year 2023.

Table 5. - Total Energy Consumption and Costs in 2023

Energy Source	Annual Consumption		Annual Cost	
	[kWh]	[%]	[€]	[%]
Natural Gas	396,217	73,24	81,789.79	71,58
Electricity	144,732	26,76	32,466.62	28,42
Total	540,949	100	114,256.41	100

From the analysis of the obtained results, it can be concluded that natural gas is the most consumed energy source in the building under study, accounting for approximately 73% of the annual energy consumption and 72% of the annual energy billing. This predominance of natural gas consumption is justified by the fact that the entire central heating system, a significant portion of the hot water supply, and the entire cafeteria area operate using this energy source.

4. Opportunities for Consumption Rationalization, Improvement, and Renovation of Facilities

A. Central Heating System and Hot Water Supply

Regarding the central heating system and the production of domestic hot water, considering that natural gas consumption in the boilers has a significant impact on the building's energy billing, and given the availability of more efficient technologies with lower environmental impacts, it is proposed that the production of hot water for central heating, as well as for other uses, be carried out using heat pump technology.

The installation will involve modifications to the building's thermal central, specifically connecting the system to the existing hydraulic network. The following equipment and works will be necessary:

- Installation of five high-efficiency heat pumps, with a total capacity of 135 kW, for heating both climate control and domestic hot water;
- Installation of an inertia tank;
- Piping and accessories needed to accommodate the heat pumps and other equipment;
- Electrical installation modifications;
- Supply and installation of thermal energy measurement equipment at the production points.

The proposed solution is based on a "pay per use" model, widely used in Nordic countries, which will allow the managing entity of the building, in this case, the Municipality of Coimbra, to obtain hot water as a service without any initial investment.

Table 6 presents the estimated costs associated with natural gas and maintenance for the current system compared to the new proposed solution.

Table 6. - Costs with natural gas and maintenance (current solution vs proposed solution)

Natural Gas and Maintenance Costs	Cost per MWh [€/MWh]	Annual Cost [€/year]
Current Solution	225,77	66,162
Proposed Solution	145,84	42,738

Based on the analysis of the results in Table 6 and estimating a thermal energy requirement for the building of approximately 293,05 MWh/year, it is projected that the new proposed solution will achieve annual savings of €23,424, totaling €234,240 by the end of the expected contract period (10 years - 35.4% savings). Figure 3 presents a graph showing the estimated expenditure evolution over 10 years, comparing the current scenario with the scenario using the new heat pump solution.

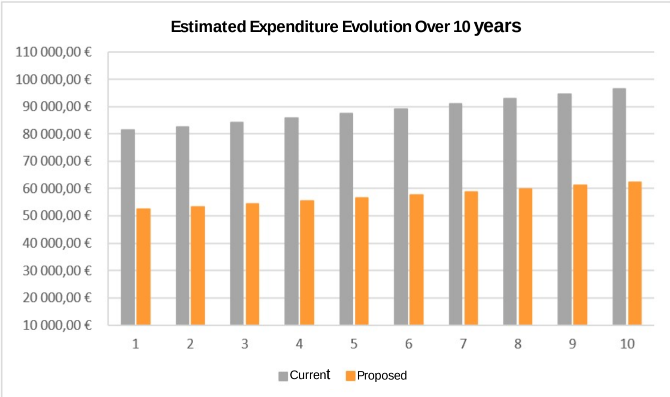

Fig. 3. Estimated expenditure evolution over 10 years (current solution vs proposed solution)

The entire installation is owned by the installing company and has an estimated value of €130,906 at this time. However, the client may choose to purchase the equipment after the 3rd year of consumption, based on the values outlined in Table 7.

Table 7. - Equipment acquisition costs after the 3rd year of usage

	Acquisition Cost of the Equipment [€]
Year 1	-
Year 2	-
Year 3	71,257.11
Year 4	62,243.08
Year 5	54,369.33
Year 6	47,491.61
Year 7	41,483.92
Year 8	36,236.21
Year 9	31,652.33
Year 10	27,648.31

B. Photovoltaic System for Electricity Generation

Solar energy is an inexhaustible resource, abundant in almost every part of the Earth. Portugal stands out as one of the European countries with the highest solar exposure, with average annual values of approximately 8 hours per day and solar radiation exceeding 1,200 W/m². The daily solar energy received in Portugal averages around 430,000 GWh. Within the European context, Portugal is one of the countries with the best conditions for solar energy utilization, with an average of 2,200 to 3,000 hours of sunshine per year on the mainland, and between 1,700 and 2,200 hours of sunshine annually in the Azores and Madeira islands, respectively.

Regarding the building under study, being a property with a flat roof available for the installation of photovoltaic panels and without shading and considering its consumption profile with the aim of minimizing electricity billing costs, several simulations were carried out for the implementation of photovoltaic panels for self-consumption.

1) Simulation 1 - Grid-Connected System without Batteries.

The entire study was conducted using the photovoltaic design and sizing software PV*SOL, considering an annual electricity consumption of approximately 150,403 kWh for the building. A total of 108 photovoltaic modules with a combined capacity of 59.4 kWp were projected, requiring an area of 279 m² for the system installation. The selection of equipment was based on various simulations, taking into account the building's characteristics to optimize self-consumption. Six strings were established, each consisting of 18 photovoltaic modules.

The placement of the different photovoltaic panels on the building's roof was carefully selected to maximize electricity production, considering solar orientation and the absence of shading. The design also ensured easy access for future installation and maintenance, avoiding overlapping with existing equipment in that space. Figure 4 illustrates the location of the photovoltaic panels on the building's roof.

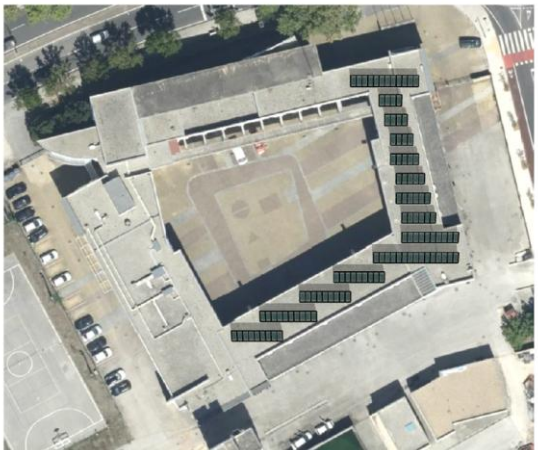

Fig. 4. Location of the photovoltaic panels on the building's roof

Since the average number of solar exposure hours in Portugal and the Coimbra region is known for each month of the year, and considering the building's consumption profile, the PV*SOL software estimates the energy production for each month, as shown in the graph in Figure 5.

From the analysis of the graph (Figure 5), it can be concluded, as expected, that in the months with higher photovoltaic energy production (spring and summer months), a considerable portion of that energy will be injected into the grid. In contrast, during the months with lower photovoltaic energy production, the percentage of energy injected into the grid decreases significantly, with particularly low values in December and January.

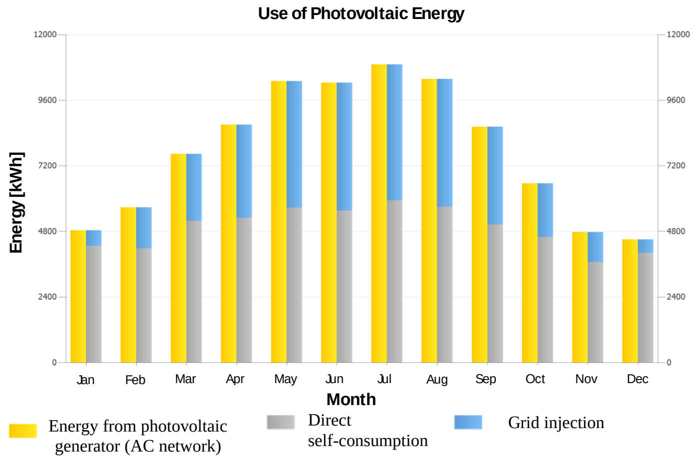

Fig. 5. Energy distribution across different months of the year (battery-free system)

From the financial analysis carried out, the key highlights are the simple payback period of 4.4 years and the estimated cost of energy production of €0.0247 per kWh. The total investment cost is projected to be €35,960.00, with an average panel lifespan of approximately 25 years.

2) Simulation 2 - Grid-Connected System with Batteries

The previous study was repeated, this time with energy storage batteries, maintaining the same number and type of photovoltaic panels, the same configuration, and the same layout on the roof. The results obtained are presented in the graph in Figure 6.

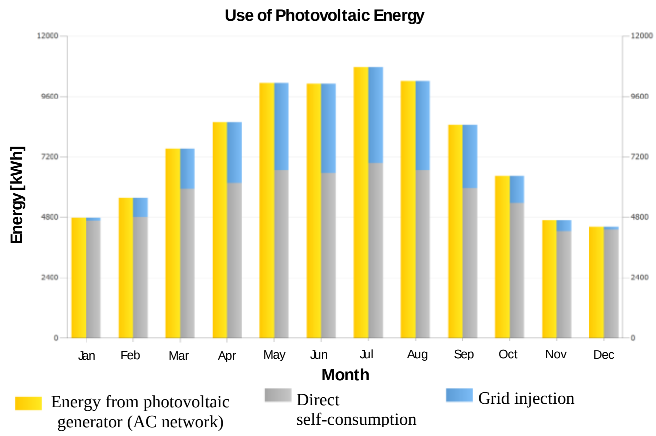

Fig. 6. Energy distribution across the different months of the year (battery system)

In this simulation, the simple payback period is estimated to be 7,1 years, with an energy production cost of €0,0419 per kWh. In this case, the total investment cost is projected to be €60,030.00, with an average panel lifespan of approximately 25 years.

5. Conclusion

This work aimed primarily at presenting and discussing the results of the energy audit recently conducted on the Municipal Civil Protection House and Coimbra Fire Brigade Headquarters, with the goal of characterizing the main forms of energy consumption and the existing special technical installations.

From the results obtained, it is concluded that regarding the main forms of energy consumption in the building, approximately 73% corresponds to natural gas consumption, with the remaining 27% being electricity consumption.

Regarding electricity consumption, despite the lighting sector and the equipment used in the cafeteria area representing around 10.7% and 11.8%, respectively, of total electricity consumption, the largest share of electricity consumption is directly related to various equipment installed in the building (49.1%), such as workstations, printers, microwaves, refrigerators, freezers, emergency equipment, compressors, portable heaters, among others.

Regarding natural gas consumption, it is concluded that approximately 51% of the total consumption is related to the heating sector, 34% pertains to hot water production (AQS), and the remaining 15% is due to its use in kitchen equipment.

Considering the objective of the work, proposals for energy consumption rationalization, improvement, and remodeling of the building's facilities were presented.

For the central heating system and hot water production, a "pay-per-use" system was proposed, with no initial investment or maintenance costs, based on heat pump technology, where the building operator will only pay for the hot water they use.

Currently, hot water used for space heating and most of the hot water for sanitary use in the building is provided by two natural gas boilers, the use of which significantly contributes to the high energy billing costs of the building, particularly through natural gas consumption. The proposal to replace these systems with more energy-efficient heat pump technology, which consumes electricity, will reduce the natural gas billing and could benefit from the potential installation of photovoltaic panels on the building's roof, leading to a reduction in overall energy billing. The costs associated with the initial investment and maintenance of these systems will not be the responsibility of the Municipality of Coimbra, and it is estimated that an annual savings of €23,424 will be achieved with the implementation of the proposed solution.

The proposal to implement a photovoltaic system for electricity generation in the Municipal Civil Protection House and Coimbra Fire Brigade Headquarters was made with the aim of reducing electricity consumption and the electricity billing previously recorded.

From the results obtained, comparing the two simulated options (with and without batteries), it was concluded that the inclusion of batteries, although contributing to an increase in the share of self-consumption and a corresponding decrease in the energy injected into the grid, does not fully eliminate the need to rely on the grid during periods when photovoltaic production is very low or even nonexistent.

Therefore, given the above and considering that the inclusion of the proposed battery system will result in higher investment costs and contribute to a longer payback period, it is considered more favorable, at this stage, to opt for the implementation of a photovoltaic system for electricity generation without batteries.

In summary, implementing the identified measures for consumption rationalization, improvement, and renovation will reduce the building's energy consumption, save on equipment maintenance, and minimize environmental impact. Potential challenges, such as technical, regulatory, and financial constraints, should be addressed with careful planning and innovative solutions. Additionally, further research into emerging technologies, like energy storage and smart consumption management, is recommended to boost efficiency and sustainability.

References

[1] Santos, Filipe Duarte; Ferreira, Paulo Lopes; Pedersen, Jiesper Strandsbjerg Tristan, “The climate change challenge: A review of the barriers and solutions to deliver a Paris solution”, Climate, 2022, 10.5: 75.

[2] Parliament, E. U. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. EU on energy efficiency, 2018.

[3] European Parliament. Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955 (Recast); European Union: Brussels, Belgium, 2023.

[4] Presidência do Conselho de Ministros, “Roteiro para a Neutralidade Carbónica 2050”, 2024 (in portuguese).

[5] Recuperar Portugal – Governo, “Adenda – Plano de Recuperação e Resiliência”, maio de 2023 (in portuguese).

[6] Fundo Ambiental – Governo, “Eficiência Energética em Edifícios de Serviços”, 2022 (in portuguese).

[7] Liberova, V.; Bremane, I.; Lauka, D.; Laktuka, K.; Bezrucko, T.; Zvirbule, K.; Bezrucko, A.E.; Blumberga, D. Unleashing Energy Potential: Insights of Energy Audit Practices. *Energies* **2025**, *18*, 522.