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Techno-Economic Evaluation of Energy and CO_2 Abatement Measures in Urban Environment: A Case Study in Malta

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Abstract: Malta faces a significant challenge in reducing carbon emissions, with energy consumption in its 153,100 occupied residences contributing to 30% of CO_2 emissions. This study focuses on a sample of an 1870s, 80 sq-m footprint, three-story residence, emblematic of similar properties facing marketability issues due to age, structure, and maintenance. The objective is to assess a techno-economic energy and CO_2 abatement framework, including advanced lighting devices, appliances, photovoltaics, wind turbines, energy storage, and vehicle-to-grid possibilities. The research evaluates comfortability and calculates potential 25-year kWh reduction and cost savings for each measure. The findings demonstrate the feasibility of implementing diversified renewable and alternative energy sources in such residences. Over 25 years, approximately 250 MWh of energy could be mitigated, leading to a reduction of approximately 140 metric tons of carbon dioxide. The study emphasizes the importance of housing stock efficiency in both new construction and retrofitting, focusing on building performance for health, comfort, and living standards. While most systems are viable, further research is needed for system-wide strategy implementation, particularly in areas like energy storage and wind turbine solutions. The study concludes that adopting emerging technologies could be advantageous in minimizing system costs through innovative building-integrated designs.

Keywords: energy; techno-economic; CO_2 abatement; urban environment

Citation: Azzopardi, B.; Zammit, M. Techno-Economic Evaluation of Energy and CO_2 Abatement Measures in Urban Environment: A Case Study in Malta. *Energies* **2024**, *17*, 446. https://doi.org/10.3390/en17020446

Academic Editor: George Halkos

Received: 6 September 2023
Revised: 30 December 2023
Accepted: 9 January 2024
Published: 16 January 2024

1. Introduction

The urgent need to address carbon dioxide (CO_2) emissions and transition towards sustainable energy sources has become a global priority, driven by international agreements such as the Paris Agreement [1,2]. With approximately 153,100 occupied dwellings, Malta faces the challenge of reducing its CO_2 emissions, with household energy consumption contributing to around 30% of the country's emissions. Furthermore, about 70,000 unoccupied dwellings add to the energy efficiency challenge [3,4].

Malta, a small island nation in the Mediterranean, faces unique challenges in its energy landscape. With limited indigenous energy resources, Malta heavily relies on imported fossil fuels for power generation. The energy sector is a significant contributor to carbon dioxide emissions, primarily due to the combustion of these fossil fuels. Despite efforts to diversify the energy mix, including interconnecting with mainland Europe and increasing the share of renewable energy sources, Malta has historically faced challenges in achieving significant reductions in carbon emissions. The country is actively exploring sustainable solutions, including energy efficiency measures and developing renewable energy projects, to mitigate its carbon footprint and enhance energy security. Globally, the total final energy consumption, including buildings and industry, stood at 33% per sector, with each adopting only around 15.5% and 16.8% of renewable energy, respectively. The transport sector accounted for 30% of the total final energy consumption, with a mere 4.1% derived from renewables [5]. To achieve over 90% reduction in CO_2 emissions by 2050, three-quarters of the currently occupied dwellings will remain in use. However, marketability issues arise due to the age, construction, and lack of maintenance of properties like an 80 sq-m footprint, 1870s, three-story household, which is a representative example in this paper.

This research paper aims to investigate energy and CO_2 abatement strategies for such 19th-century buildings, incorporating a techno-economic framework together with on-the-field data collection for comfortability. The study evaluates various energy-saving measures, including advanced lighting devices and appliances, photovoltaics, wind turbines, energy storage, and potential vehicle-to-grid possibilities for self-consumption. The analysis quantifies the potential reduction in kilowatt hours (kWh) and associated costs for each measure over 25 years.

This research is paramount in addressing the pressing challenge of carbon emissions in Malta, where residential energy consumption contributes significantly to the overall carbon footprint. By focusing on a representative 1870s, three-story residence, the study sheds light on the unique challenges faced by heritage structures and presents a comprehensive techno-economic framework for energy and CO_2 abatement. With nearly a third of CO_2 emissions originating from residential energy use, the outcomes of this research can inform policies and strategies for enhancing energy efficiency in existing buildings, impacting Malta's broader goal of reducing carbon emissions by 90% by 2050. The findings also contribute to the broader discourse on sustainable retrofitting, providing insights into the feasibility and economic viability of various energy-saving measures that can be applied to similar structures across the country.

Improving housing stock efficiency is crucial in addressing the residential sector's contribution to CO_2 emissions through new construction and retrofitting. In 19th-century building stock in Malta and the EU, some peculiarities have remained, such as energy-inefficient designs, including a lack of insulation, insufficient heating and cooling systems, and single-pane windows, contributing to higher CO_2 emissions, while attributing to renovation challenges and making heritage preservation and adaptation to Climate Change more difficult. living standards. It is worth noting that national values of CO_2 emissions per floor area range from 5 to 120 $kgCO_2/m^2$, while the EU average stands at approximately 40 $kgCO_2/m^2$ [6].

The European Union's renewable energy targets, including the recast of the Renewable Energy Directive, set ambitious goals for increasing the share of renewable energy sources in the final energy consumption. The directive aims for 32% renewable energy by 2030, requiring newly constructed buildings to adhere to Zero-Energy Building standards [7,8]. This transition to high-performance buildings relies heavily on renewable energy sources to achieve low energy consumption.

Despite the drivers and barriers to investment in retrofitting, building retrofits have gained attention in recent years [9,10]. Governments, particularly in North America and Europe, have focused on retrofitting initiatives to address energy efficiency and carbon reduction [11]. However, challenges such as financial constraints and low rate returns have slowed down progress in this sector.

Studies conducted locally and internationally [12–18] have examined the topic of energy efficiency through various methodologies, encompassing both technical and social perspectives. The integration of cost and greenhouse gas (GHG) abatement modeling is a specialized practice utilized not only within specific sectors but also by governments to conduct macro-level analyses of building stocks. One of the most comprehensive studies conducted in the United Kingdom pertains to the marginal abatement cost curve, which aims to reduce greenhouse gas emissions in residential and non-residential building stock [19].

This study proposes a comprehensive framework for assessing energy and CO_2 abatements throughout the retrofitting process. A marginal abatement cost curve will identify the most effective systems for achieving energy and CO_2 mitigation goals by evaluating different energy systems.

The theoretical foundation of this study is rooted in the techno-economic approach to energy and CO_2 abatement. Building upon the existing literature on energy efficiency and sustainable technologies, the research integrates economic considerations with technological solutions to address the specific challenges posed by 19th-century residences in Malta. The framework encompasses advanced lighting devices, efficient appliances, photovoltaics, wind turbines, and energy storage, reflecting a holistic understanding of the factors influencing energy consumption and carbon emissions in residential buildings. Drawing from theories related to sustainable architecture, renewable energy systems, and cost–benefit analyses, the study seeks to bridge the gap between theory and practical implementation. By establishing this theoretical background, the research aims to contribute not only to the understanding of energy efficiency in historic structures but also to the broader field of sustainable urban development and environmental management.

Considering Malta's building stock, which includes a substantial number of old buildings, retrofitting becomes crucial. Approximately 40% of the European building stock was constructed before 1960, with limited energy regulations. With a significant portion of its building stock being older than 50 years, Malta needs to prioritize energy efficiency improvements through retrofits.

The present manuscript, which is an extension of a previous publication [20], is structured in the following manner. Section 2 of the paper outlines the methodology-based framework employed in the study. Section 3 presents the demonstration of the methodology and framework through a study of a typical Maltese dwelling. Section 4 of the article presents the main findings and serves as the article's conclusion.

2. The Techno-Economic Assessment Framework

The techno-economic assessment framework [20] encompasses pertinent life cycle energy calculations and life cycle costing methodologies, as illustrated in Figure 1. To ascertain the energy reduction achieved per system, an initial step involves the computation of annual energy performances for both a conventional system and a newly proposed retrofit system. This is accomplished by utilizing system performance parameters and calculations, as well as yearly average climate input data in the case of renewable energy sources. A model of system degradation is utilized to represent the decline in efficiency or functionality of the device over the course of its operational lifespan. The life cycle costing technique is employed to ascertain the net present value (NPV) of a system, taking into account the computed life cycle energy, which may be abated energy in the case of a higher efficiency system or energy generated in the case of renewables, and the domestic residential energy tariffs. The net present value (NPV) is contingent upon various parameters and variables, such as the financing mode and lifetime. To assess the market feasibility, a marginal abatement cost is computed for both the energy expenses and the potential reduction in CO_2 emissions. The former is contingent upon the energy composition of the respective nation.

The study examines various renewable and alternative energy storage forms, including solar photovoltaic (PV), wind energy, and chemical energy storage. The first two alternative energy sources are contingent upon the spatial and climatic resources of the location. In contrast, the third alternative energy source involves utilizing energy storage from a grid-connected energy storage system or vehicle-to-grid approach. Table 1 displays the underlying assumptions utilized for renewable and alternative energy sources.

Table 1. Assumptions and boundaries on renewable and alternative energy systems.

	Climate Date		Unit System Cost		System Size		Maintenance
Solar PV	5.84 *	kWh	2	€/Wp	3500	Wp	2%
Wind	3.88 +	m/s	2	€/W	1000	W	5%
Storage			2000	€/kWh	1	kWh	5%

* at 30° inclination per m2 per day. + annual average wind speed at 60 m above sea level considering roughness length of 0.1.

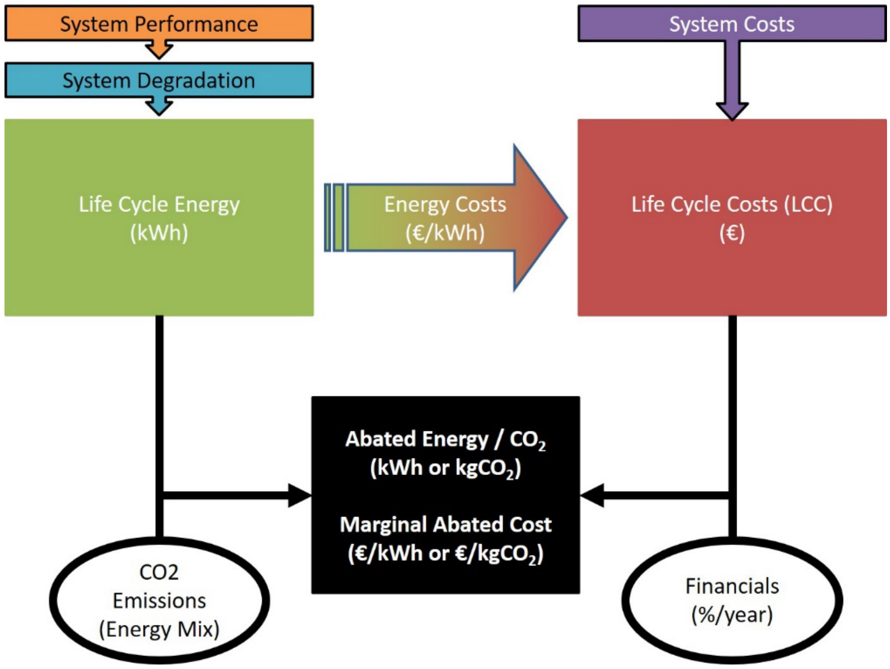

Figure 1. Methodology base framework [20].

The annual solar PV generation is calculated using (1) for 25 years, considering 1% degradation per year for 20 years as per most international warranties for PV modules.

$$E_{PV} = H \times PR \times PV_{size} \times 365\ days \tag{1}$$

where E_{PV} is the annual PV generated energy, H is the daily average solar insolation on PV modules, PR is the performance ratio taken as 0.8, and PV_{size} is the size of the PV system in kWp.

Similarly, the annual wind energy generation is calculated using (2) and assuming Rayleigh statistics for 25 years, considering 1% degradation per year for 20 years.

$$E_{Wind} = \frac{6}{\pi} \cdot \frac{1}{2}\rho A \overline{v}^3 \cdot \eta \cdot 8760/1000 \tag{2}$$

where E_{Wind} is the annual wind energy generated; ρ is 1.22 kg/m^3, which is the air density at air temperature of 15 °C and at atmospheric pressure; A is the area of the propeller assumed at 3 m^2; $\overline{v}$ is the average wind speed on site; η is the turbine efficiency assumed at 25%; 8760 is the number of hours; and 1000 is used to calculate the kW. The micro-wind turbine is considered to cover 80% of the load, hence an export rate of 20%, so as to benefit from a higher electricity tariff.

On the other hand, the energy storage lifetime is only considered to be ten years with a degradation factor of 1% per annum.

The use of potentially highly efficient appliances on the market considered white goods, such as cookers, hobs, washing machines and Fridge–Freezers, as well as a lighting system, was considered, as shown in Table 2. All systems were assumed to have a 1% maintenance rate on capital cost and a lifetime of 25 years.

The life cycle costing techniques also considered the following financial assumptions:

i. A 7% real interest rate.
ii. A EUR 0.155 per kWh for PV Feed-in-Tariff guaranteed for 20 years.
iii. A EUR 0.04 per kWh wind energy export.
iv. A EUR 0.11 per kWh for wind energy load usage and abated energy consumption. The rate is calculated as the overall average rate for a four-person household that does not exceed the eco-reduction thresholds with a total annual consumption of 7000 kWh.

Meanwhile, for the abated CO_2 calculation, the national maximum continuous rating is used as a reference at 0.56 kg/kWh.

Table 2. Assumptions and boundaries on the use of potentially highly efficient systems.

	Size	"Efficient" vs. Conventional	System Cost (€)		Consumption		
Cooker	66 L	Electric vs. Gas	319	589	0.85	1.00	kWh/cycle
Hob	4 burners	Induction vs Gas	499	254	0.504	0.900	kWh/cycle
Fridge-Freezer	350 L	A+++ vs. A+	900	529	149	297	kWh/year
Washing Machine	7 kg	A+++ vs. A+	399	339	179	217	kWh/year
Lighting		LED vs. Halogen	2.00/W	0.02/W	548	5480	kWh/year

3. Application of the Methodology Framework

The findings of the analyzed systems are presented in Figure 2, which provides a Marginal Abatement Cost (MAC) Chart [20]. Each bar's width represents the total reduction in or generation of potential electrical energy for each potential measure if prompt action is taken. Each bar's height represents the cost, in euros, of avoiding each kilowatt hour. The bars that are depicted negatively signify the cost incurred for each kilowatt hour (kWh) that is either mitigated or generated. Conversely, the bars that are depicted positively signify the gain that is obtained for each kilowatt hour (kWh) that is either mitigated or generated during the relevant system's lifetime.

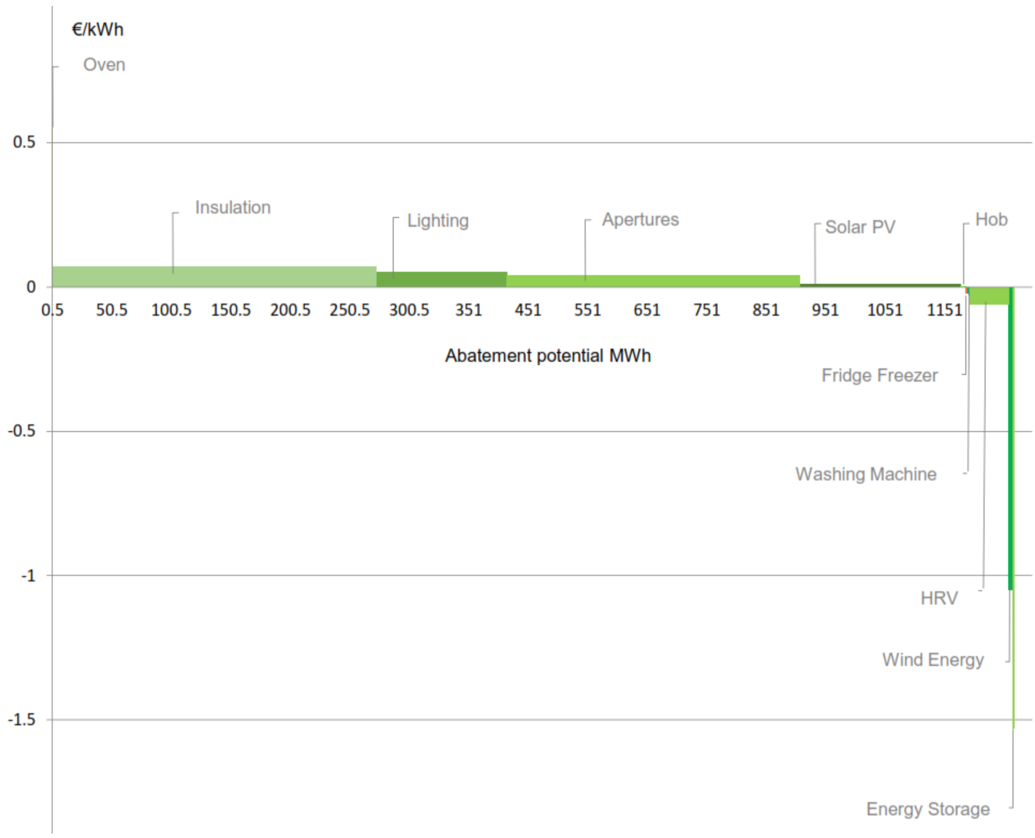

Figure 2. Marginal abatement kWh cost [18].

Figure 3 presents the conversion of the outcomes into the marginal abatement cost per kilogram of carbon dioxide equivalent.

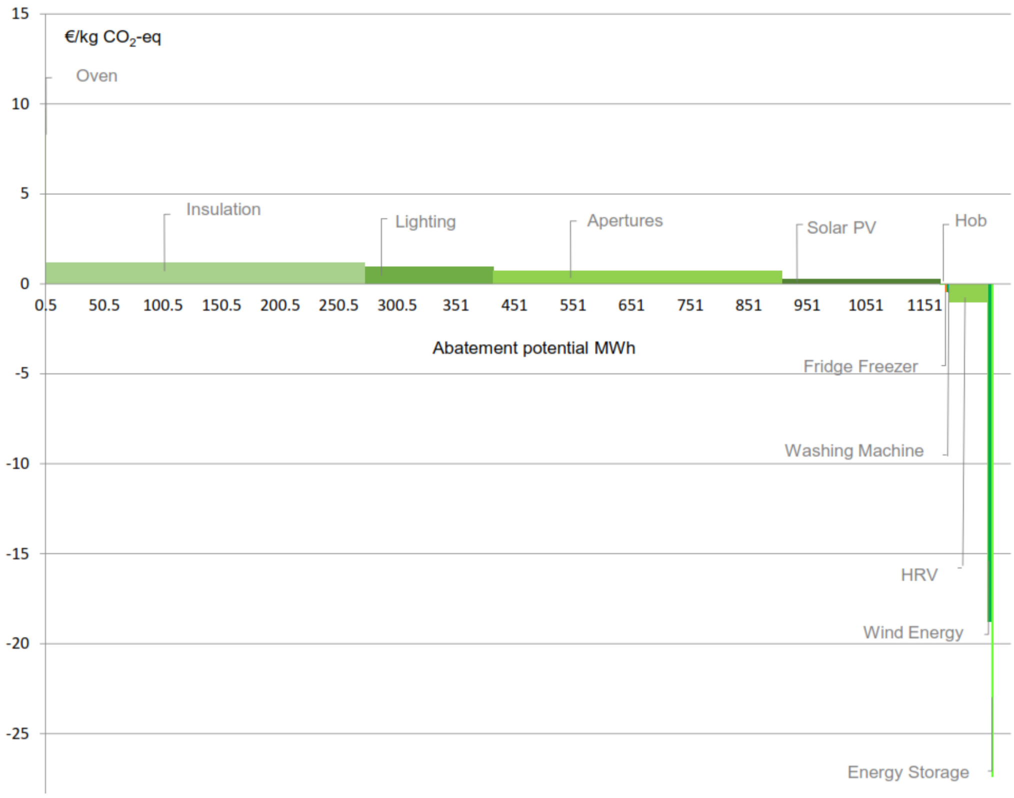

Figure 3. Marginal abatement kg CO_2-eq cost [18].

3.1. Extracted Data

The majority of home systems demonstrate a favorable return on investment. However, to optimize the investment, homeowners should classify the level of retrofitting required. The household is currently undergoing a comprehensive retrofitting process. The integration of various systems working in tandem is expected to enhance the overall performance of the entire system. This enhances the overall sustainability of the house's performance and efficiency.

Integrating wind energy systems within a retrofit in any location across the Maltese islands has been found to be an unsuitable option. From a geographical standpoint, Malta is characterized by relatively low wind speeds. The recorded wind speed at the coordinates of 35.899058 latitude and 14.464211 longitude exemplifies this.

Likewise, the implementation of HRV systems has presented challenges due to the elevated levels of humidity and air density (measured in kg/m^3) in Malta, necessitating the incorporation of supplementary systems for optimal functionality. Additionally, the operational complexity of the systems was compounded during the cooling phase owing to the elevated temperatures prevalent in Malta.

The requirement of high prices and limited lifetimes has imposed a constraint on energy storage. With proper charging and discharging, a battery system has the potential to provide a lifespan of ten years. However, advancements in technology and reduced costs may alter this outcome.

The proposed framework facilitates a precise delineation of the financial savings incurred by reducing the consumption of kilowatt hours over 25 years. The analysis of Figure 2 reveals that the most advantageous systems are insulation, lighting, solar, hob, and fenestration. The outcomes above appear credible and may be juxtaposed with the illustrative example delineated in [11], which entailed the conversion of a Mediterranean abode into a thermally comfortable and energy-efficient residence. This analysis examines some of the systems that were implemented in the study. The outcomes derived from implementing insulation and fenestration systems have yielded identical results. Insulation yields significant savings with a brief payback period, whereas fenestration entails a longer payback period. Nonetheless, such systems are strongly advised for deep retrofits.

3.2. kWh Abatement

Furthermore, the framework also enables the evaluation of the kilowatt hours (kWh) reduced during the entire lifespan. At the same time, it can be determined that the majority of systems are feasible. It is worth noting that additional systems, including HRV and appliances, also feature kWh abatement that has been shown to be significant. However, the high costs associated with implementation have resulted in reluctance to adopt these systems.

3.3. Fabric Analysis

The building physics of the household under study provides advantages for implementing a passive house methodology. This study aims to evaluate the impact of additional building systems, specifically insulation and windows. Log Tag analyzers were deployed for a duration of time within the residential premises. The aforementioned analyzers can quantify both temperature and relative humidity parameters. The study was carried out utilizing six strategically distributed recorders in bedrooms, the living room, and at every level of the three-story household, plus at a higher level close to the roof, with an additional recorder positioned externally to monitor ambient temperature. During the experimental period, the activity observed within the household was of a family of five persons with an annual electrical consumption of about 7000 kWh. Polyurethane boards, with a thickness of 25 mm, were installed on a single-leaf masonry wall that is 180 mm thick. This installation was carried out on the rear side of the house, facing west. Beforehand, the roof lacked insulation and was constructed with “deffun” material, which has a calculated U-value of 1.52 W/m^2K. This value falls within the acceptable range outlined in Document F of the EPC guidance. By implementing insulating boards and external protection, the fabric U-value of the single-leaf masonry wall was enhanced from 2.645 W/m^2K to 0.725 W/m^2K, as determined by the conducted calculations. Figure 4 comprises multiple charts of the recorders’ readings, indicating fluctuations in temperature. The red circles indicate the maximum and minimum external temperatures, whereas the green circle represents the internal temperatures with an average of around 17 °C. The outdoor temperatures reached a maximum of 38 °C and a minimum of 10 °C. The experimental findings indicate that despite the low level of activity within the house during the observation period, the indoor temperatures remained consistently comfortable without the aid of any mechanical systems, both during the day and at night. It was observed that the house was able to attain the optimal temperature range of 18–20 °C, as stipulated by ASHRAE 1997 Fundamentals, with minimal activity.

Windows can make a sustainable contribution to the building fabric by utilizing double-glazed aluminum or UPVC windows with thermal breaks, which offer a U-value ranging from 1.6 W/m^2K to 2.1 W/m^2K. In contrast, traditional wooden windows have a U-value of 3.0 W/m^2K and tend to experience high heat losses due to their high air changes per hour.

3.4. Thermal Imaging Assessment

Thermal imaging assessment was performed using a T-Series FLIR thermal imaging camera (Wilsonville, OR, USA). The analysis presented in Figure 5 pertains to the insulation installed at a 29° NE orientation, which is exposed to direct sunlight during the afternoon. The findings indicate that the area that was covered exhibits a decrease in temperature of approximately 4 degrees Celsius. This variance enables the household to prevent the accumulation of solar heat and facilitate a more pleasant indoor temperature. An analysis was conducted on windows, revealing that enhanced window materials effectively retain heat and prevent its transfer through the walls of buildings. The doors effectively absorb and impede heat via double glazing, resulting in a temperature differential of approximately 5 °C between the exterior and interior environments. Conversely, the non-retrofitted windows disperse heat, leading to higher temperatures within the inner room. The implementation of blinds on the retrofitted aperture can effectively regulate heat gains, thereby facilitating passive heating in accordance with the occupants' needs.

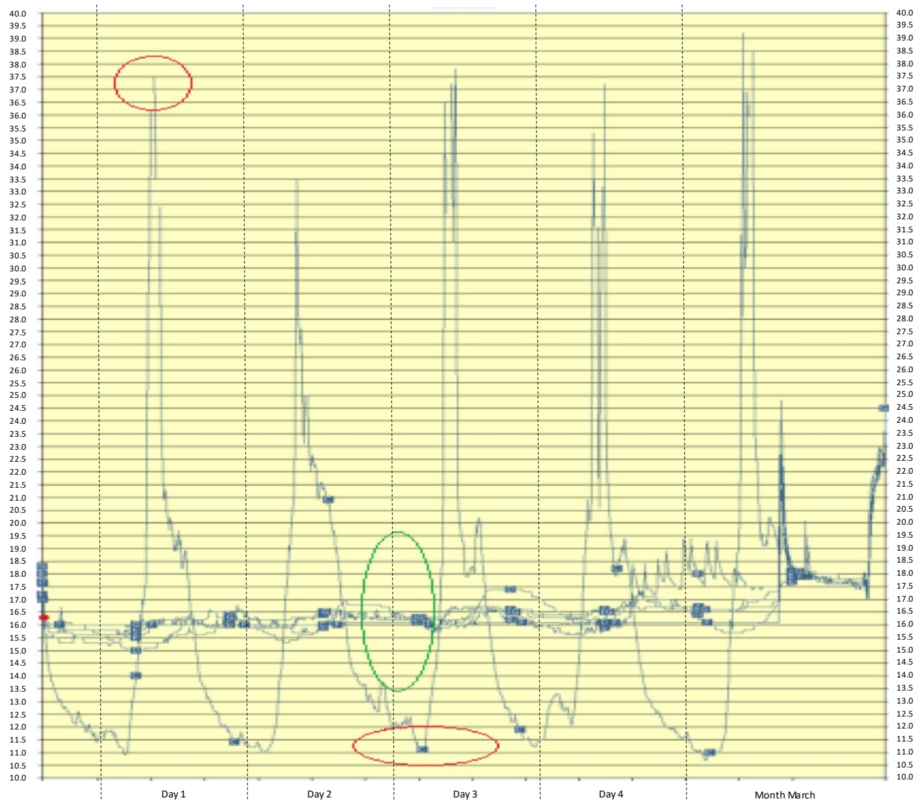

Figure 4. Log Tag analyzer cumulative temperature experiment.

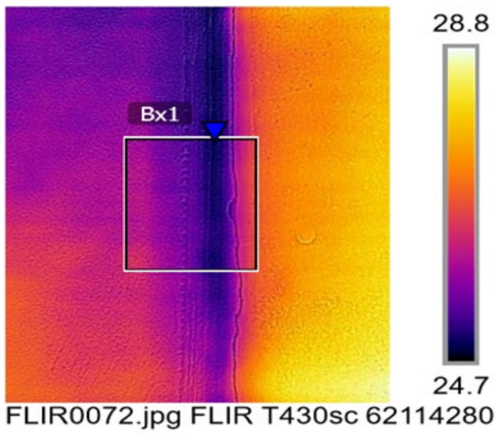

Figure 5. Indoor thermal imagining assessment with (**right**)/out (**left**) polyurethane insulation (May).

3.5. Psychometric Assessment

Psychometric readings refer to the use of standardized tests and assessments to measure psychological traits, abilities, and characteristics. These readings are commonly used in research and clinical settings to gain insight into an individual's cognitive, emotional, and behavioral functioning.

The AZ 8857 infrared Psychrometer, AZ Instrument, Taichung, Taiwan, was utilized to plot the temperature levels of the house. The dry bulb and wet bulb temperatures were recorded and plotted onto the recommended comfort levels, as illustrated in Figure 6. The psychometric chart was utilized to plot the values, which corresponded to the pressure of 0.1 MPa at an altitude of 36 m above sea level. Figure 6 displays the blue and red sections that indicate the range of temperature within which comfort can be achieved. The recorded data within the townhouse indicates that the two red points represent the dry bulb and wet bulb temperatures, which fall within the acceptable range of comfortable temperatures.

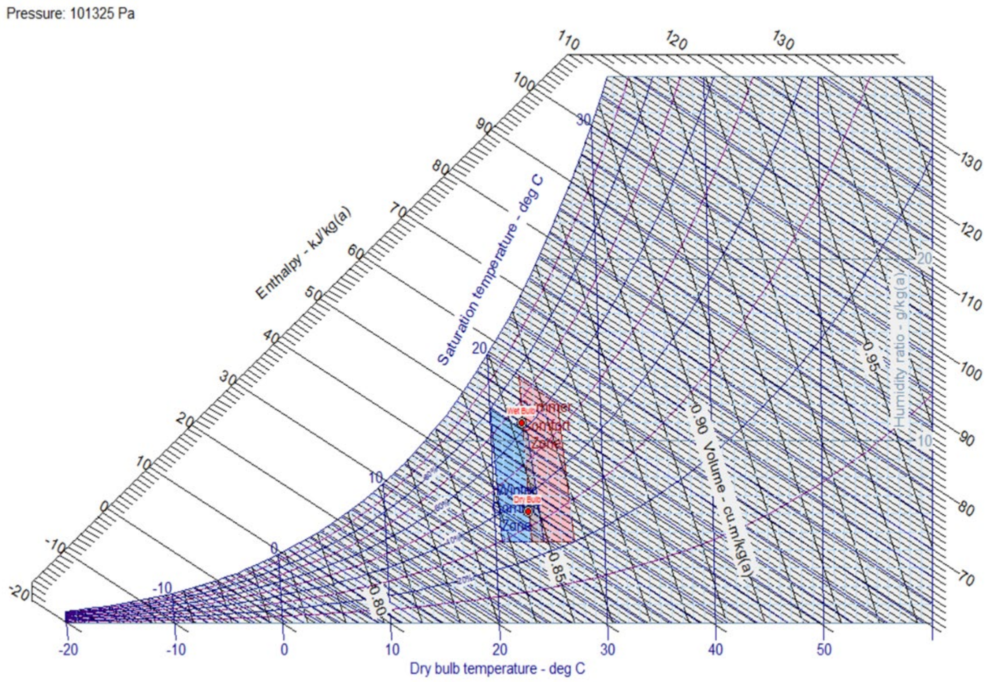

Figure 6. Psychometric readings.

4. Conclusions

This paper demonstrated the implementation of diversified renewable and alternative energy sources, as well as the utilization of highly efficient appliances, in a three-story property dating back to the 1870s, with an approximate 80 square meter footprint area in Malta. The implementation of comparable systems could be extended to a significant proportion of the 153,100 inhabited residences in Malta, with the remaining unoccupied residences being retrofitted to meet the standards of energy-efficient structures. It is imperative to acknowledge that the outcomes are contingent upon the presumptions and limitations that have been established or are mandated by the particular investigation.

The findings indicate that the majority of the systems exhibit feasibility, as evidenced by their energy cost abatement falling below the mean value of EUR 0.11/kWh. Currently, energy storage and possibly vehicle-to-grid integration and wind energy systems appear to be the only possibilities that may not be feasible. However, the latter is notably reliant on the geographical location. Over the course of the next 25 years, it is estimated that approximately 250 MWh of energy may be mitigated through the implementation of energy-efficient systems or harnessed through the utilization of PV solar technology. The aforementioned statement indicates that over a period of 25 years, approximately 140 metric tons of carbon dioxide can be mitigated. The cost of mitigating one kilogram of carbon dioxide ranges from EUR 0.13 for the most economically feasible systems to a gain of EUR 0.98 per kilogram of carbon dioxide mitigated.

This study represents the initial exploration of this characteristic, encompassing the techno-economic phase of the design process. Additional research is necessary to oversee and implement a comprehensive system-wide strategy.

Upon evaluating the implementation of energy abatement systems measures, the analysis revealed that the majority of the systems were already viable, with the exception of energy storage and wind turbine solutions. The cost of abatement is contingent not only upon the system cost, but also upon the performance of the system and the conventional system that is being abated, if it is extant. The adoption of emerging technologies that are currently not feasible could be significantly advantageous by minimizing system costs through innovative building-integrated designs.

While this study provides valuable insights into the techno-economic aspects of energy and CO_2 abatement in 19th-century residences in Malta, several limitations should be acknowledged. Firstly, the findings are specific to the sample 1870s, three-story residence, and variations may exist across different types of heritage buildings. Additionally, the economic feasibility and performance of the proposed measures are contingent on assumptions and limitations inherent in the study, such as local energy prices, the availability of renewable resources, and technological advancements. Furthermore, the research primarily focuses on the individual building scale, and a more comprehensive understanding could be achieved through considering broader urban planning and policy implications. The study also assumes a static scenario for energy costs and technology performance over the 25-year projection period, overlooking potential fluctuations in market dynamics and advancements in sustainable technologies.

To address the limitations identified in this study and contribute to a more holistic understanding of sustainable retrofitting in historic residences, future research should consider expanding the scope to include a diverse range of heritage buildings in Malta. Comparative studies across different architectural styles and periods could provide nuanced insights into the challenges and opportunities for energy and CO_2 abatement. Additionally, incorporating dynamic factors such as evolving energy policies, technological advancements, and socio-economic trends in long-term projections would enhance the robustness of the findings. Future research could also explore the social aspects of sustainable retrofitting, considering occupant behavior, the acceptance of new technologies, and the impact of energy-efficient measures on the overall well-being of residents. Finally, a system-wide analysis that integrates urban planning, infrastructure development, and policy recommendations could offer a more comprehensive approach to addressing the energy and environmental challenges faced by heritage structures in Malta and similar regions.

Author Contributions: Conceptualization, B.A. and M.Z.; methodology, B.A.; software, M.Z.; validation, M.Z. and B.A.; formal analysis, M.Z.; investigation, B.A. and M.Z.; resources, B.A.; data curation, M.Z.; writing—original draft preparation, B.A. and M.Z.; writing—review and editing, B.A. and M.Z.; Visualization, B.A. and M.Z.; supervision, B.A.; project administration, B.A.; funding acquisition, B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported in part by the European Commission H2020 TWINNING Project Networking for Excellence in Electric Mobility Operations (NEEMO) under Grant 857484 and Horizon Europe Project TRANSITion to sustainable future through training and education (TRANSIT) under Grant 101075747. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA) granting authority. Neither the European Union nor the granting authority can be held responsible.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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