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Towards the Renovation of Energy-Intensive Building: The Impact of Lighting and Free-Cooling Retrofitting Strategies in a Shopping Mall

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Abstract: One of the most energy-intensive types of buildings is commercial. Several works investigated the optimizations of Heating, Ventilation and Air Conditioning (HVAC) systems for achieving thermal comfort and indoor air quality. On the other hand, lighting systems play also a crucial role in minimizing energy consumption rates in a shopping mall and increasing its sustainability. Despite the relevant scientific research in the literature, to the best of our knowledge, there is no study that analyzes the impact of HVAC systems with and without the free-cooling option applied to a commercial building combined with lighting solutions. The combination of HVAC systems with free cooling and lighting retrofit strategies defines four energy scenarios, where the most efficient one is detected. The results show that the use of advanced technologies in lighting control systems has a double benefit: direct savings due to the better performance of the lighting fixtures and indirect savings due to the reduction in the thermal load with a consequent reduction in consumption levels for air conditioning. Additionally, a reduction of 51.7% in lighting consumption levels generated a 17.4% reduction in air conditioning levels. A total reduction in energy consumption rate of 33% was achieved. Since the lighting strategy demonstrates a relevant impact on reducing the global energy consumption of the shopping mall, a feasibility analysis is also presented.

Keywords: shopping mall; lighting; free-cooling method; energy efficiency

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1. Introduction

The goal of achieving climate neutrality set by the European Union is nearing. The efforts of Europe and member countries are increasingly focusing on industrial processes and also the energy requalifications of buildings that are responsible for 40% of energy consumption rates, at present [1–3]. Commercial buildings are one of the most energy-intensive types of buildings. Consequently, commercial buildings significantly contribute to sustainable development practices [4]. As a result, it is crucial to build energy-efficient buildings that have appropriate insulation, roofing materials, finishing materials, window types, sizes, and glazing to provide thermal comfort. There is a critical need for lighting and HVAC systems to have an optimal energy performance level, the intelligence to optimize energy use, and maintain renewable and non-polluting energy sources. The principal energy consumer sources in buildings, especially commercial buildings, are heating, cooling, and lighting [5]. The residential and non-residential buildings, HVAC systems are essential to achieving good thermal comfort and indoor air quality [6,7]. Several studies focus on the decision-making process to select adequate HVAC systems [5,6]. For a Moscow green multifunctional shopping center project, the fuzzy evaluation based on distance from average solution (Fuzzy EDAS) method was applied to solve the HVAC-AHU system selection problem [5]. This method was approved by the decision makers that have to manage the alternatives for selecting the proper HVAC-AHU system and its supplier [5]. A novel HVAC management system was presented in the work of [6] that tracks occupant preferences, learns from them, and automates HVAC management.

Building sectors are becoming more involved in demand response (DR) strategies that provide flexibility to transmission system operators to address the increasing demand [8,9]. By using multisource data for commercial building energy predictions, the study of [8] presented a framework for structuring transfer learning models, predicting the target building's peak electricity demand (PED) and total energy consumption (TEC). The work of [9] applied DR strategies to enhance the flexibility of the HVAC system in shopping centers. Another work [10] outlined the design, installation, and cost of a generalizable model predictive control (MPC) framework for the heating, ventilation, and air conditioning system in a food retail building in the UK. Air Handling Units (AHUs) are optimized through the use of the MPC scheme to reduce the overall cost or carbon emissions while ensuring comfort. As highlighted in the literature, the proper design and optimization actions of HVAC systems in shopping centers are still an attractive idea in this energy transition era [11].

Energy-intensive facilities, such as commercial, present significant heat gains all year round. Indeed, the use of free-cooling systems seems to be a convenient option [12]. There is a strong relationship between the heat production in a room and the outside air temperature when it comes to the applicability of free cooling [13,14]. Despite the relatively low air temperature outside, the system works when the water or air in the room is cool enough to prevent from overheating, which means, in the room, the appropriate temperature increase is required to reduce heat. Additionally, the daily occupancy schedule of visitors in the shopping mall can guarantee the heat gains required by the free-cooling system. Among this, the work of [15] presents an overview of the potentialities of adapting a free- cooling system in an existing commercial building, demonstrating a considerable reduction in cooling energy demands.

LED luminaires, which are energy efficient, have contributed to the change in commercial lighting systems. Since the level of illumination required by the industrial sector is very high, the application of LED luminaires and lighting control systems is a well-known method [16–18]. Almost 40% of lighting energy consumption levels can be reduced by using LED luminaires instead of other lighting technologies [16]. The transition from fluorescent lamps to LEDs provided a 43% decrease in energy consumption levels for a shopping center in Kenya [17]. However, shopping centers are often designed without taking into account the natural light. The tendency to pursue aesthetic goals during the phase design of shopping malls is common since the satisfaction of the investor's needs is predominant. Therefore, the integration of environmental aspects, such as daylight, is often excluded. In building design, daylight considerably affects our use of space. Daylight can improve comfort and reduce energy consumption levels. Daylight is also considered to be the best source of light. In [18], the researchers investigated the design parameters of indoor shopping mall skylights, including the opening ratios and materials that provide the best light distribution.

Using an existing shopping mall in Cairo as a case study, this study aims to assess the daylighting created by skylights. Studies, at present, analyzed the impact of sky light on daylighting [19,20]; others investigate the relation between sky light and thermal comfort [21–23]. A relevant step is to evaluate daylight's impact on artificial electrical consumption based on different sky conditions [24]. In this manner, this paper proposes the evaluation of different lighting scenarios, adopting advanced lighting control systems both for daylight inclusion and human-presence detection. Therefore, not only is the replacement of LED luminaires taken into account, as many of the mentioned studies investigate in the literature [16,17], but so is the addition of efficient lighting control systems [18].

Despite the relevant scientific research mentioned above, to the best of our knowledge, there is no study that analyzes the impact of HVAC systems with and without the free-cooling option applied to a commercial building combined with lighting strategies solutions. Additionally, this study contributes to the latter idea. To sum up, the study aims to (1) asses the most efficient lighting retrofit solution, analyze advanced lighting control systems, as well as the replacement of the spot lamps; (2) investigate the energy saving capability of HVAC systems with free-cooling options; and (3) evaluate the impact of combining the abovementioned retrofitting solutions through the definition of four energy scenarios. Since the lighting strategy demonstrates a relevant impact on reducing the global energy consumption of the shopping mall, a feasibility analysis is also presented. In the Materials and Methods Section (Section 2.1), the characteristics of the case study are illustrated. Section 2.2 describes the lighting properties of the case study and Section 2.3 shows the process adopted to calculate the energy needs of the air conditioning system. The four energy scenarios are presented in Section 2.4. Section 3 presents the main outcomes of the energy scenarios, as well as the feasibility study of the improved lighting scenario we propose.

2. Materials and Methods

2.1. Case Study: A Shopping Mall

The characteristics and dimensions of the presented shopping mall were in line with medium-sized Italian commercial buildings, since the process of defining this case study was to represent a typical shopping center in Italy [25]. Therefore, the presented shopping mall was not a real case study, but a representative type (archetype) of an Italian medium-sized shopping center. To perform the energy simulations, the location of the building was set in Rome (climatic zone D). Table 1 presents the shops and main zones of the shopping mall, such as clothing, footwear, culture and gifts, food, electronics, household, pet shop, health and beauty, and supermarket with the corresponding Gross Leasable Area (GLA), that represents the walkable area directly close to commercial purposes. The zones were distributed on two floors of around 2000 m^2 each, with an average storey height of 4 m. Figure 1 describes the main distribution of the zones per floor. Each zone had an alphanumeric identification code that described the category of the shop: AL restaurant, CU kitchen, G gallery, I and IM hypermarket, AB clothing and footwear, C housewares, R gifts and books, P cosmetics and personal care, AN animal care and food, EL home appliances, SG games room, and WC toilet. The zones highlighted in blue represent the courtyards.

Table 1. Average GLA (Gross Leasable Area) per zone included in the proposed shopping mall.

Category	Average GLA (m^2)	N° of Shop	GLA Tot (m^2)
Clothes (ms) [1]	1200	6	7200
Clothes	200	17	3400
Shoes (ms)	475	3	1425
Supermarket	7000	1	7000
Cosmetics and health	100	6	600
Personal care	150	4	600
Gift and books	130	4	520
Animal care and food	350	1	350
Phone and assistance	50	4	200
Home appliances	2250	1	2250
Jewelry	75	3	225
Housewares shop	450	3	1350
Small food market	80	3	240
Food and beverage	350	3	1050
Games room	1500	1	15,000
Other services	37.5	4	150
Total	14,397.5	64	28,060

[1] ms = medium size, i.e., clothing and footwear stores that have a surface area greater than 400 m^2 and which act as an attraction.

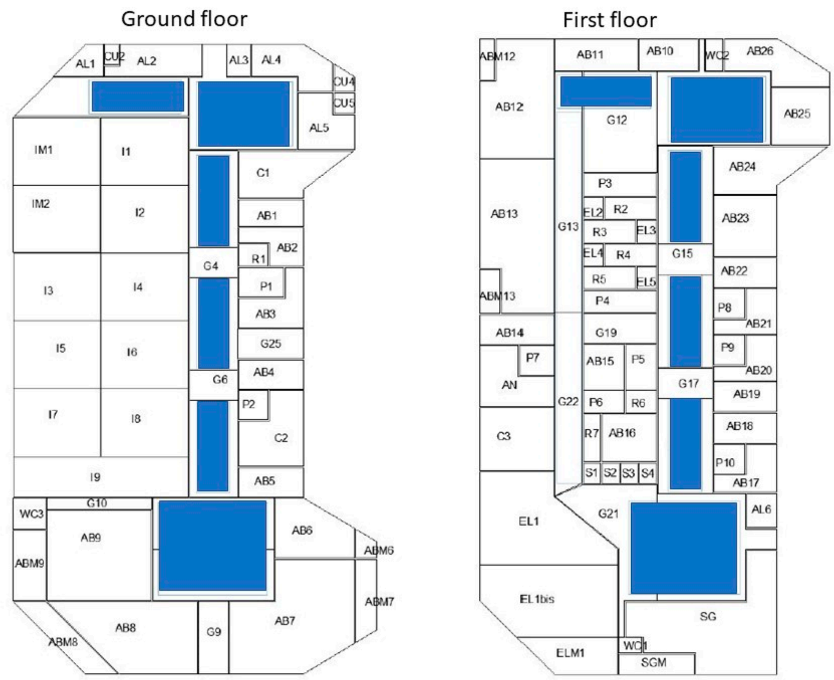

Figure 1. Zone distribution for the two floors [25].

In detail (Figure 1), the vertical glazed surface refers to the window of the restaurants following the Italian regulation of the aero-illuminant ratio, which requires the value of 1/10 of the room area [26]. Horizontal glazed surface refers to the courtyards, placed on the roof, for an extension of about 3000 m^2.

2.2. Definition of the Lighting System

The complexity of evaluating the application of lighting controls, daylight factor, and other sensors require specific software [27] that can compute the ratio of the total lighting energy used for a year and the surface analyzed [28]. To define the best-performance lighting system of the presented case study, several variables were considered, such as lighting controls (both daylight and occupancy-based), type of lighting sources (LED and fluorescent), and other sensors, to manage the flux of the lamps. More than one hundred simulations were performed, varying the mentioned parameters, to evaluate the best–worst lighting scenarios.

Table 2 shows the average illuminance suggested by UNI 12264-1 and the chosen one per zone. All values refer to the floor level, except for bathrooms, where illuminance is considered at a height of 0.9 m from the floor, and restaurants and kitchens, where the height is 0.8 m. Moving to the power installed in air-conditioned zones, 271.6 kW was calculated using LED lamps; on the other hand, 469.75 kW was achieved for installing fluorescent lamps.

Table 2. Average illuminance level per each zone.

Category	E_m Suggested by the UNI 12264-1 (lx)	E_m Applied (lx)
Gallery	100	500
Toilets	200	200
Stores	100	200
Shops	300	750
Restaurant kitchen	500	500
Parking	75	100
Entrance ramps	300	300
Games room shops	300	300

2.3. Energy Needs of Air Conditioning Systems

The list presented below summarizes the sensitive loads calculated for sizing the air conditioning system to estimate energy consumption levels.

- Dispersions through opaque and transparent walls;
- The internal load;
- The load of the electrical systems;
- The load due to solar radiation.

The latent loads considered were those due to people and kitchens. The thermal loads were estimated in two separate time phases: winter and summer. Finally, the sized plant could be modeled using MATLAB-Simulink.

2.3.1. Sensible Thermal Load

To calculate the peak powers of the air conditioning system, the extreme external temperatures for estimating the thermal loads were related to the geographical coordinates of the location (Rome, Italy—climatic zone D). Therefore, the main data are listed below [29]:

- A total of 0 °C for the winter regime;
- A total of 37 °C for the summer regime.
- The maximum solar irradiance on the horizontal plane is equal to I_{sol} = 970 W/m^2.

Table 3 presents the total surface values of opaque and transparent surfaces located in the shopping mall.

Table 3. Main characteristics of the opaque and glazed surfaces.

Surface Type	Ground Floor (sm)	First Floor (sm)	Transmittance (W/m^{2}K) [29]
Opaque vertical	2285	2691	0.3
Opaque horizontal	20,500	15,857	0.256
Transparent vertical	187	22	1.1
Transparent horizontal (courtyard)	-	3902	

The equations used for the calculations were obtained from UNI/TS 113000. The transmittance value for winter was around 320.4 kW and 176.2 kW for summer.

2.3.2. Internal Loads

Among the flow, a study [30] evaluated five wholesales in Rome, demonstrating that there is a proportional relationship between the afternoon peak and total daily turnout. Considering a flow average peak of 0.155, the daily peak was 1555 visitors with a thermal power of 150 W. Moving to the electric devices gains, it was assumed that, during opening hours and apart from the lighting system, there were no significant variations during the year, while during closing hours, only 10% of the load was active. Therefore, in commercial establishments, the fixed thermal load density was equal to 3 W/m^2 and the electrical loads during opening and closing hours were, respectively, 120 and 12 kW. Then, the installed hourly average power of the lighting systems was considered. During the closing time of the mall, it was assumed that the lighting plant worked at 15% of the nominal power.

2.3.3. Load from Solar Radiation

In the summer period, the most important thermal load was achived due to solar radiation. The maximum input power in the shopping center was the product of the reduction factor for shading related to external elements, the effective solar area (m^2), and the maximum solar irradiance on the horizontal plane (W/m^2).

Consequently, the maximum solar load obtained was 1611.2 kW. In detail, the total sensible load in the winter regime was composed of the transmission of heat through the surfaces, the load of the electrical equipment during closing times, and the load of the lighting system, reaching a value of 287 kW.

The total sensible load in summer mode, on the other hand, was defined by the transmission of heat through the surfaces, the endogenous load, the load of the electrical equipment during opening hours, the load from solar radiation, and the load of the lighting. Approximately 2432 kW was obtained.

2.4. Sizing of AHU (Air Handling Unit) and Definition of Scenarios

The energy system scenarios modeled with MATLAB/Simulink differed, as well as for the lighting system also used for the management of the air conditioning system, which can occur through free cooling or not. Table 4 presents the four scenarios developed for this case study. Two lighting scenarios were selected from the simulations performed: the base (fluorescent lamp, no sensor for the flux, no lighting control systems) and improved one (LED lamps, sensor of lamp's flux, lighting control systems activated). In detail, the lighting control system's technology adopted for the improved scenario was the automatic dimmed daylight-responsive control system and a system with automatic presence and/or absence detection (occupancy-based) [28]. The other two HVAC scenarios were developed with and without the free-cooling option.

Table 4. List of scenarios evaluated in the presented study.

Nomenclature	Scenario
A	Improved lighting scenario and free-cooling method
B	Base lighting scenario and no free-cooling method
C	Base lighting scenario and free-cooling method
D	Improved lighting scenario and no free-cooling method

The models were composed of various subsystems: the input subsystem, thermostat subsystem, AHU components, shopping center subsystem, and output subsystem. The inputs were the following:

- Outdoor temperature (mean hourly temperature in Rome);
- The average global irradiance on the horizontal plane;
- The flow of visitors;
- The power of the lighting system, considering that the power of the system varies between opening and closing times;
- The load related to electrical devices;
- The seasonal regime. A function ranging from 0 to 1 is necessary to activate the subsystems. In particular, the winter mode is associated to the value 1, while the summer mode is associated to 0. The seasonal regime directly influences the thermostat subsystem, since, according to the periods, the characteristics of the thermostat and the behaviour of the AHUs change;
- Set point temperature (in winter mode, it is set to 20 °C; in summer mode, it is set to 26 °C).

Figure 2 shows the flowcharts of a scenario modeled with Simulink.

The air conditioning subsystem included three independent configurations: heating through AHUs with a fixed flow rate at a design temperature of 26 °C (T_d) with AHUs fed by the thermal plant; cooling through AHUs with a fixed flow rate at a design temperature of 16 °C, with AHUs fed by the refrigeration plant; the free-cooling method introducing external air with a fixed flow rate equal to that of cooling. The power of the thermal heating ($P_{thermal,\ heating}$) of the model is expressed by Equation (1):

$$P_{th.,h.} = M \cdot c_P \cdot (T_d - T_{CC}) \cdot X_{On/Off} \quad (1)$$

where:

- M is the mass flow rate of the air introduced into the shopping center, expressed in kg/s;
- c_p is the specific heat of the air equal to 1000.5 J/(kgK);
- $X_{On/Off}$ is the thermostat control;
- The thermostat signal that varies between 0 and 1.

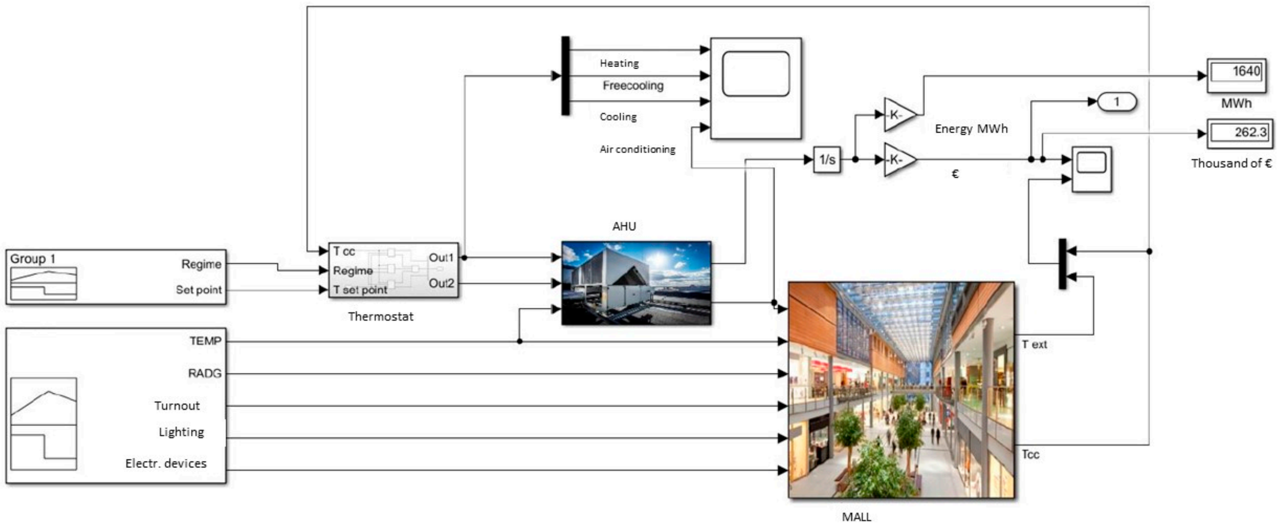

Figure 2. Simulink model of a scenario.

Since the inlet air temperature in the air system is between T_{CC} and T_{ext}, the mixing temperature has to be calculated using Equation (2):

$$T_m = \frac{T_{ext} \cdot W_e + T_{cc} \cdot W_r}{W} \tag{2}$$

where:

- T_{ext} is the outdoor temperature of the air (°C);
- T_{cc} is the mall temperature (°C);
- W_r is the return air flow rate expressed in m^3/h;
- W_e is the external air flow rate expressed in m^3/h;
- W is the total air flow rate expressed in m^3/h.

The final formula for electrical power is as follows (Equation (3)), considering also the power ($P_{v\ winter}$) of that of the AHU supply and return fans.

$$P_{el,heating} = \frac{M \cdot c_P \cdot (26 - T_m) \cdot X_{On/Off}}{3600 \cdot COP} + P_{v\ winter} \tag{3}$$

As for the heating subsystem, also in this case, the supply air temperature is considered constant and equal to T_1 = 16 °C and T_s = 14.4 °C. The total electrical power of the subsystem is obtained from three components: the power of the refrigeration plant, heating plant, and AHU fans (Equation (4)):

$$P_{el,cooling\ TU} = \frac{M \cdot c_P \cdot (T_1 - T_s)}{3600 \cdot COP} \tag{4}$$

The electrical power of the refrigeration units depends on the temperature T_m and is equal to (Equation (5)):

$$P_{el,cooling\ FU} = \frac{M \cdot c_P \cdot (T_m - T_s) \cdot X_{On/Off}}{3600 \cdot EER} \tag{5}$$

In the free-cooling configuration, the heating and refrigeration plants are off; only the supply and return fans of the AHU work, introducing air at a constant flow rate and the free-cooling temperature (T_{FC}). The T_{FC} has to be managed since too-cold air cannot be diffused into the room. Therefore, it was decided to limit the minimum temperature to 15 °C, where a damper triggers the mixing of the primary air with the return air if the temperature drops below that value to maintain a temperature of 15 °C. If the T_{FC} is greater than the T_{CC}, the system shuts down. The cooling power introduced into the shopping center by the plant is expressed in Equation (6):

$$P_{thermal,free-cooling} = \frac{M \cdot c_P \cdot (T_{FC} - T_{cc})}{3600} \tag{6}$$

The corresponding electrical power, on the other hand, is equivalent only to that of the supply and return fans (Equation (7)), where the SFP_{int} index indicates the specific internal ventilation power expressed in W/(m^3/s) or the ratio between the absorbed power and airflow.

$$P_{el,free-cooling} = 2 \cdot SFPint \cdot W_{est} \tag{7}$$

The shopping mall subsystem models collect the thermal behaviour of the building. The inputs of the shopping center are the thermal loads previously calculated, the thermal power of the air conditioning system in the various regimes, and the external temperature. As the output, the subsystem generates the temperature of the T_{CC} of the commercial building. It is necessary to unify the three transmittances of the walls in a $H_{equivalent}$ transmittance obtained from the weighted average. The thermal loads and thermal power of the system add up to obtain the resulting power level. Finally, the power capacity of the shopping mall is calculated as follows (Equation (8)):

$$C_{cc} = V_{cc} \cdot \left(0.1 \cdot \rho_{cls} \cdot c_{cls} + 0.9 \cdot \rho_{air} \cdot c_p\right) \simeq 21.169 MJ/K \tag{8}$$

$T_{cc,0}$ is the initial temperature of the shopping mall, set at 20 °C.

3. Results and Discussion

3.1. Lighting Results

Table 5 shows the results obtained for the base lighting scenario (fluorescent lamp, no sensor for the flux, no lighting control systems) and the improved one (LED lamps, sensor of lamp's flux, lighting control systems activated). In detail, the lighting control system's technology adopted for the improved scenario were the automatic dimmed daylight-responsive control system and a system with automatic presence and/or absence detection (occupancy-based) [28].

Table 5. Results of lighting simulations of improved and base lighting scenarios.

Month	Improved Lighting Scenario (kW)	Base Lighting Scenario (kW)
January	100,922.8	205,924.2
February	100,076.3	205,011.6
March	99,404.0	204,327.2
April	98,955.8	203,870.9
May	98,657.0	203,566.7
June	98,582.2	203,490.6
July	98,731.7	203,642.7
August	99,030.5	203,946.9
September	99,553.4	204,479.2
October	100,300.5	205,239.7
November	101,271.6	206,228.3
December	102,392.2	207,369.1
Year	1,197,877.8	2,457,097.0

The energy reduction between the two scenarios was greater than 50%, the effect of the combination of the variables considered. However, most of the energy savings occurred due to the change in the light source (from fluorescent to LED), which alone allowed for savings of up to 40%. However, the inclusion of the lighting control systems and sensor for the flux lamp's management contributed to significant electricity reductions.

3.2. Results of the Scenarios: Lighting and Free-Cooling Systems

Table 6 presents the main output results obtained for each scenario (Table 6), as well as the annual expenses of the air conditioning system. Considering that the shopping center had a connection to the medium-voltage national grid, the estimated cost of energy was equal to 0.16 EUR /kWh and included all items, both fixed and dependent on consumption levels.

Table 6. Results obtained per scenario.

Scenario	Energy Consumed (MWh/Year)	Expense (EUR /Year)
A	1636	261,836
B	3233	517,339
C	1982	317,186
D	2668	426,883

The first model (scenario A) represents the most efficient and, consequently, the cheapest scenario. The second model (scenario B), on the other hand, represents the least efficient and most expensive scenario. Table 7 presents the five comparisons evaluated to point out the following aspects:

- N 1. Analyze the differences between the base and improved scenarios.
- N 2. Investigate the effect of the lighting system on the consumption rate of the air conditioning system with the presence of free-cooling applications.
- N 3. Highlight the impact of free-cooling behavior on the consumption of the system where the improved lighting scenario is applied.
- N 4. Investigate the effect of the lighting system on the consumption levels of the air conditioning system without free-cooling applications.
- N 5. Highlight the impact of free-cooling behavior on the consumption levels of the system where the base lighting scenario is applied.

Table 7. Results obtained per scenario.

Comparison	Comparison between Scenarios	Savings (EUR)	Savings (%)
1	A and B	255,530	49.39
2	A and C	55,351	17.45
3	A and D	165,047	38.66
4	B and D	90,456	17.48
5	B and D	200,153	38.69

The best saving outcome was obtained by comparing scenarios A and B, which corresponds to EUR 255,503 saved in one year, with a decrease in the consumption rate (and expenses) by almost 50%. The savings were achieved due both to the use of free-cooling technology and more efficient lighting systems. The use of efficient technologies for lighting (e.g., lighting control system) had a double benefit: direct savings due to the better performance of the lighting fixtures and indirect savings due to the reduction in the thermal load with a consequent reduction in consumption levels for air conditioning. On the other hand, it turned out that the free-cooling method produces greater energy savings than the lighting system (38.6% against 17.4%); this is true, however, only if the energy saved using the air conditioning system was considered. Moreover, a reduction of 51.7% (scenarios

A and B) in lighting consumption levels generated a 17.4% reduction in air conditioning (N 4). A total reduction in energy consumption levels of 33% was achieved. Therefore, the total energy saving that included the improved lighting scenario (1951.9 MWh/year) had a major overall impact, compared to the free-cooling strategy (1251 MWh/year). Based on this evaluation, the relamping strategy and application of the lighting control systems played a key role in reducing the energy consumption level of an energy-intensive building.

3.3. Feasibility Analysis of the Improved Lighting Scenario

In this paragraph, the economic feasibility of spot relamping (shifting from fluorescent to LED lamps), as well as the installation of lighting control systems, was evaluated. The total energy saved from the post- and ante interventions is presented in Table 8.

Table 8. Results of ante and post interventions.

Energy Plant Type	Scenario	Energy Consumption (MWh/Year)
Lighting plant	Base scenario	2686.2
Lighting plant	Improved scenario	1299.7
Air conditioning plant	Scenario B	3233.4
Air conditioning plant	Scenario D	2668

Based on the value presented in Table 8, 1951.9 MWh was the energy saving level of the post-intervention scenario, obtaining a money-saving value of 312,304 EUR /year (considering 160 EUR /MWh as the final cost of the energy). In terms of "tonne of oil equivalent" (toe), a value of 364 toe/year was achieved (the electric efficiency of the national grid is equal to 0.46). Moving to the initial investment, Table 9 presents the number of lamps and the relative costs.

Table 9. Evaluation of the investment cost for the lamp's purchase [31,32].

Type of Lamp	Number of Lamps	Unit Cost	Total Cost
Ideal lux Fluo wide 1800	3000	210	630,000
Philips Master LED tube	4500	18	81,000
Ansorg-Coray CMT-02CMT	4300	32	137,600

An investment of approximately EUR 848,600 EUR is required to purchase the lamps. The cost of lighting control systems (e.g., building automation plant) was estimated at around EUR 70,000. Due to the complexity of the building type, the cost of the lighting project was almost EUR 50,000 [33]. The installation cost was also computed, considering an average hourly price of a company installer equal to 130 EUR /h and estimating the duration of the intervention at 2 months (about 460 h) [34]. The final cost of the investment was EUR 1,070,000, including a risk factor that was equal to 5% of the total investment.

During the maintenance phase, an inspection of the appliances was foreseen to replace any non-functioning lamps. The life span of LED lamps installed in the mall is over 60,000 h. In five years (about 25,000 working hours), only 3% of the lamps need to be replaced. Therefore, every five years, the maintenance of the lighting system requires an estimated cost of EUR 25,000. The payback time was approximately three years, in line with the economic needs of the mall. The NPV, ten years after the investment initial, is worth approximately 2 millions of €, this means that, ten years after the initial investment, the relamping produced a profit of more than two million euros, equal to 184% of the investment (Figure 3).

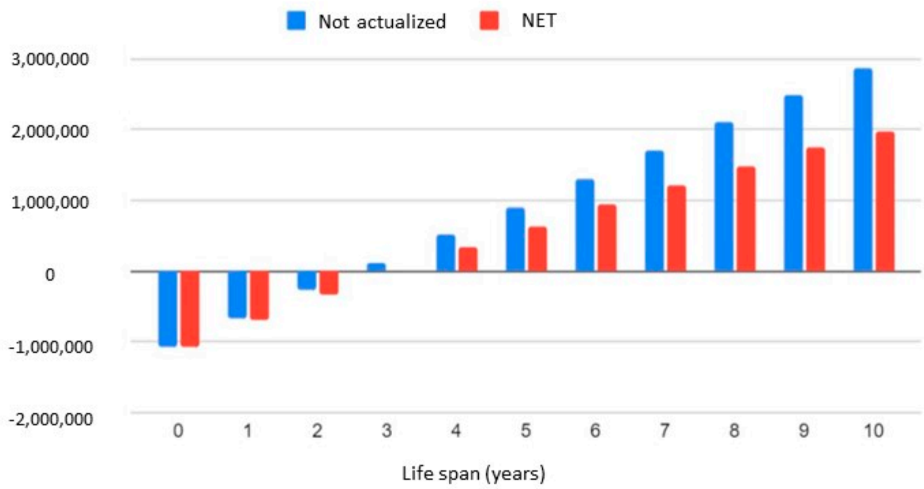

Figure 3. Cumulative cash flow trend.

4. Conclusions

Buildings are responsible for energy consumption and greenhouse gas emissions. Commercial buildings are recognized as energy-intensity structures, due to the high heating, cooling, and lighting demands. Many strategies were developed to optimize the HVAC systems and their components, from the installation of DR methods to the application of the decision-making process. Among the lighting methods, the advantages of spot relamping were also investigated, as well as the inclusion of daylight using advanced lighting control systems (daylight- and occupancy-based). In this framework, the presented study assessed lighting and free-cooling retrofitting strategies applied to a shopping mall. Using a dedicated lighting tool [31], it was possible to not only evaluate the benefits of luminaires' spot relamping methods, but also the impact of lighting control systems able to compute the contribution of natural light coming from the courtyards. The design of air conditioning systems was proposed, as well as their integration with free-cooling systems. Four energy scenarios were presented to provide the most efficient one, where the main results can be presented as follows:

- A reduction of 51.7% was achieved by shifting from the base lighting scenario to the improved one.
- The total energy saving that included the improved lighting scenario (1951.9 MWh/year) resulted in a major impact, compared to the free-cooling strategy (1251 MWh/year).
- Ten years after the initial investment, the relamping strategy produced a profit of more than two million euros, equal to 184% of the investment. This means that including the lighting retrofitting in an energy renovation plan of a shopping mall is very convenient.

It is worth mentioning that some limitations need to be acknowledged, which set the stage for future studies. It is essential to be aware that, while the results of this study can be used as a general guideline for similar buildings in Italy (varying, of course, the geographical location and the relative input), they cannot be generalized to buildings with different functionalities and construction technology. Therefore, further research in various climatic zones and construction typologies of international countries is required to develop a comprehensive investigation. As with any energy-saving project, the outcomes will be subject to many uncertainties, including global warming, variable energy prices, and human behaviour, throughout the building life cycle. However, this study was not meant to examine any of these uncertainties that could be evaluated in the future.

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