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Increasing energy efficiency in Smart Building through Internet of Things retrofitting intervention

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Abstract

Buildings are responsible for 40% of energy consumption in Europe, and 75% of them are energy inefficient. In this context, the opportunities enabled by improved management and conservation of energy in buildings are huge. There is a clear need to accelerate and finance building renovation investments and leverage smart, energy-efficient technologies if the EU wants to reach climate neutrality by 2050. IoT components enable new possibilities for improving efficiency in Smart Buildings, both in commercial and residential spaces. However, the literature misses some contributions aimed at evaluating the investment in IoT technologies used for improving the energy efficiency of a building used for different purposes. Thus, the objective of the present study is to provide an assessment of the main costs and benefits stemming from IoT technologies installation through retrofitting intervention and evaluate the sustainability of the investment. Data to feed the model were retrieved from academic literature and secondary sources. The results show that the investment can be recovered in the medium-short term. In particular, buildings with high consumption rates are the ones that benefit the most from this solution. The present study contributes to the academic literature by providing a model that considers a mixed building and multiple technologies at the same time. It also provides useful insights to whoever is interested in the application of IoT technologies to make a building smart, enabling the comprehension of necessary investment and economic returns.

Keywords: Internet of Things; Smart Building; Energy management.

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1. Introduction

Energy efficiency represents a central concern for companies, institutions, and international governments. Efficient use of energy is, indeed, a very attractive means to reduce energy-related effects on the environment [1]. As proof, the EU commission has committed to reach carbon neutrality by 2050 involving consumption reduction as well as energy usage optimization, improved control strategies and energy conservation, among the actions to pursue it. In this context, the Smart Energy paradigm emerges as a fruitful way to meet this objective. It is defined as the intelligent and on-demand provision of energy to applications and devices, with unconsumed energy being saved for later use or offered for other scopes [2]. To concretely apply this paradigm, the usage of smart technologies is necessary. Indeed, the sensors can record the interactions with the outside world and exchange this data with other devices or end-users thanks to the connection through embedded systems. The "adapt and react" capability of Smart Energy embeds the use of the Internet of Things (IoT). This technology enables many sustainability practices, such as convenient access to real-time machines and consumer usage information.

The application of IoT in the energy supply chain can be sub-categorized under different levels: generation, transmission, distribution and consumption. Among them, the present study deals with end-consumption, and in particular building consumption. Indeed, "the reduction of energy demand in buildings through the adoption of energy efficiency policy is a key pillar of the European Union (EU) climate and energy strategy" [3]. Buildings are associated with a significant untapped energy saving potential, as they account for about 40% of the EU's final energy and 36% of CO_2 emissions [4]. In addition, in Europe, 75% of buildings are considered inefficient [5]. Among the strategies that could be implemented to make a building more efficient, the adoption of smart technologies is the one that does not require structural changes. IoT devices application can limit energy waste as they enable data collection on consumption, that opportunely analysed can provide useful insights on energy management. In addition, this technology enables remote control and autonomous adjustment of building systems. It is estimated that a Smart Building with integrated systems accounts for around 30-50% savings compared to traditional buildings [3], [6], [7].

However, the literature presents little evidence of studies aimed at investigating multiple systems of a building simultaneously. The majority of them deal with a system at a time [8]–[14]. In addition, they consist of literature reviews or general market analyses. The application of a quantitative method, such as mathematical models or simulations, that considers in an extensive way multiple technologies in a single building was scarcely found. Looking instead at the typology of building under study, two main perspectives were adopted by academics. Some of them focused on building used for commercial purposes, a key target for energy optimization strategy through IoT, representing the largest part of energy consumption [15]–[18]. On the other side, many papers deal with residential buildings, as smart technologies are key enablers of people's life quality improvement [19], [20]. Nevertheless, there are very few examples in the literature of studies dealing with energy efficiency solutions in the residential sector and the commercial one, jointly.

Given the above, the objective of the present study is to estimate the benefits and the costs brought by the installation of IoT devices in a building for commercial and residential usage, to increase energy efficiency, through retrofitting intervention. The paper is organized as follows. Section 2 describes the objectives and the methodology adopted. Section 3 provides the model application and the sensitivity analysis. Section 4 summarizes the evidence found and conclusions of the work.

2. Objectives and methodologies

The objective of the present work is to fill the gap present in the literature, by estimating the economic impacts stemming from the implementation of innovative solutions for energy efficiency. In particular, the main costs and benefits deriving from IoT devices installation for energy management purposes were assessed through the development of an analytical model, in comparison with a case where no IoT solutions are installed. The model was first applied to a base case scenario. Then, a sensitivity analysis on relevant parameters was run, in order to test the reliability of the outcomes of the model application, and the robustness of the model itself. Data to feed the model were collected through secondary sources and literature review.

The model considers a retrofitting intervention for a building with the application of IoT-based technologies aimed at obtaining energy savings, optimisation, and consumption reduction. The IoT technologies considered for the investment are used to increase the level of smartness of Heating, Ventilation and Air Conditioning (HVAC) and lighting systems.

The costs related to the investment in IoT technologies considered in the model are the following.

- Acquisition costs, intended as the costs to purchase the necessary infrastructure. Number of components was dimensioned starting from the heating and cooling requirement per square meter and the lumens required by law. The unitary cost of each IoT application was retrieved from producers' websites. However, they are influenced by economies of scale, introduced according to the number of pieces needed. This relation is not linear but depends on the single provider and its cost structure.
- Installation costs, which refers to costs that must be incurred to professionally install each device. They are calculated by multiplying the acquisition costs by a pre-defined percentage (i.e., 20%).
- Period costs, which include the single component's preventive maintenance (operation, repair, and servicing costs). They are considered annual costs and are calculated as the installation costs.

The benefits achievable through the installation of IoT devices in a building were estimated as follows. First, the actual consumption levels were calculated, based on the average consumption statistics of buildings (ENEA, BSRIA). Starting from that, the savings were computed by multiplying the actual consumption level by the saving percentage. The savings percentages were retrieved from the existing literature in the energy management field [21]–[24]. Lastly, the amount of energy saved was multiplied by the unitary cost of energy, retrieved from Eurostat.

Focusing on the kind of building taken as reference, it is used for different purposes, both commercial and residential. Indeed, it considers three different space typologies: open space offices, offices of professionals and apartments within the same building. In each space, different technologies are installed according to specific needs, even if with the common objective of energy saving.

The economic evaluation of the investment was performed by considering the following financial indicators:

(i) NPV (Net Present Value), which represents the value of cash outflows over a period of time. The time period taken as reference is 20 years, corresponding to the declared lifespan of the components considered. A value equal to 2% was, instead, used as the cost of capital. Indeed, there are no alternative investments for the building owner. In addition, in order to have price stability, inflation rates should be low but close to 2% according to the European Central Bank.

(ii) Payback time, the time in which the investment is repaid, expressed in years. It is calculated by actualizing the net annual benefit using inflation as the cost of capital. All the acquisition and installation costs are assumed to be faced in year 0.

3. Model application

3.1. Base case scenario

The model was applied to a base case scenario consisting of an 8-floors building, each of 500 m^2 of surface area, for a total surface of 4.000 m^2. The floors have different usage destinations. The ground and the first floor are made of open space offices. On the second and the third floor there are professional offices. From the fourth to the seventh floor there are residential apartments.

Professional office floors are divided into multiple offices of different dimensions, in particular of three different sizes according to the usage destination. There are 8 offices of 15 m^2, 4 bigger offices of 40 m^2, and a greater open space office of 100 m^2 where are located the desks for the employees. The bath area extension is about 60 m^2. There is also a 60 m^2 common area. For what concerns the open space offices, they are composed of a large environment with no boundaries to divide the zones, which could also have separations, but the system is managed like one single zone. Therefore, the environment is considered as one single area of 440 m^2. The remaining 60 m^2 is occupied by the bathroom area.

The lighting system of offices consists of ceiling LED lights, bathroom lights, DALI light sensors, dimmer actuators, venetian actuators and window sensors. Table 1 resumes the costs incurred in their purchase and installation. In particular, the unitary cost and the number of units needed are displayed, on the basis of which the purchasing cost was computed. Then, a discount was applied to this value, given the number of items purchased. For a great number of components purchased, a discount equal to 15% of the order was applied, while for smaller batches, a 5% discount was considered. The installation cost was then considered equal to 20% of the purchasing cost. The total acquisition cost was finally computed by summing the installation cost and the discounted purchasing cost. The period cost is assessed as a percentage of the purchasing cost, whose value is displayed in the last column of Table 1.

Table 1. Office lighting investment.

Lighting device	Unitary cost (€)	Number of units	Purchasing cost (€)	Discount percentage (%)	Installation cost (€)	Total acquisition cost (€)	Period cost percentage (%)
Ceiling LED lights	100	224	22.400	15	4.480	23.520	2
Bathroom LED lights	50	32	1.600	15	320	1.680	2
DALI light sensors	80	54*	4.320	15	864	4.536	5
Dimmer actuators	10	365	3.650	5	730	4.197,5	3
Venetian actuators	8	352**	2.816	5	563,2	3.238,4	3
Window sensors	168	30	5.040	15	1.008	5.292	5

*The estimation of the number of the sensor required was based on the following constraints: max number of input sensors per dimmer = 8; max number of output lighting groups per dimmer = 8; max number of lights connected = 64.

**In the estimation of the number of venetian actuators needed, firstly, the number of windows present in the building was hypothesized, to be equal to 168. Subsequently, two constraints must be satisfied: connectable objects per one actuator = 249 venetians and max number of groups to be controlled by one actuator = 4 groups / actuator. In the end, the maximum between these estimations was taken as a reference value.

The estimation of the quantity of LED lights needed starts from the requirements of the law, which is equal to 1 lux/m^2. The LED light component taken as a reference has 4.000 lumens. The DALI light sensor is used to communicate with the DALI network, and it represents an important part of the whole savings system. It is installed on the ceiling, and it covers the height of each floor of the building, equal to 3 meters, and an area of a square area of 8x8 meters. The number of window sensors to be installed is equal to the number of windows in order to exploit the benefits. Focusing on the HVAC, Table 2 reports the related costs, calculated as above.

Table 2. Office HVAC investment.

HVAC device	Unitary cost (€)	Number of units	Purchasing cost (€)	Discount percentage (%)	Installation cost (€)	Total acquisition cost (€)	Period cost percentage (%)
Temperature sensors	120	54	6.480	15	1.296	6.804	5
HVAC actuators	400	8	3.200	5	640	3.680	3
Thermostats	200	28	5.600	5	1.120	6.440	4

For the estimation of the temperature sensor's price, a market average value was taken as a reference, given the huge variety depending on the shape of the room to monitor. The quantities needed were computed by considering the same coverage of the DALI sensor. The quantity of HVAC actuators, meaning the actuators for the fan coils, is strictly dependent on the number of indoor units of the HVAC system. They were calculated on the basis of ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile) guidelines on power requirements for offices according to their dimensions. Concerning the thermostats, it was decided to include one control point per office, meaning that the number of thermostats was imposed equal to the number of offices. It has also been assumed to control the temperature of common areas and bathrooms from the central panel.

Lastly, an additional cost related to the investment in the software was added, as needed to manage the IoT infrastructure. The cost computation is related to the yearly cost of the software which is equal to 200 € per user. Considering one different user per floor 4 licenses are needed, for a total amount of 800 €. There is not an initial investment, but it is taken as software as a service. Only an annual cost should be paid to exploit its functionalities.

The residential floors are also composed of different spaces, which in this case are different-sized apartments. On each floor, there are two small apartments (85 m^2), one medium apartment (120 m^2) and a bigger one (180 m^2). The cost computations are similar to those of the office floors. In this case, the discount applied on products is equal to 15%, because most of the devices are supplied by a single provider, to build a coherent set of installations.

Table 3 displays the cost incurred in equipping apartments on one floor with smart devices.

Table 3. Residential investment.

Smart Home device	Unitary cost (€)	Number of units	Purchasing cost (€)	Discount percentage (%)	Installation cost (€)	Total acquisition cost (€)	Period cost percentage (%)
Gateway Zigbee	115	4	460	15	46	437	3
Presence and motion sensor	22	30	660	15	66	627	3
Windows opening/closing Sensor	16	30	480	15	48	456	3
Automated TRVs	80	30	2.400	15	240	2280	1,5
Smart Socket	35	30	1.050	15	105	997,5	2
Smart Thermostat	180	4	720	15	72	684	4

Some components are present as single pieces in houses while others are quantified based on the number of rooms. There is one smart switch, smart socket and presence sensor per room, to exploit the maximum benefits. For what concerns smart thermostats and the Zigbee gateway, there is one of them per apartment. Please note that the gateway includes the software to manage IoT applications. Considering the automated TRVs, the number of valves strictly depends on the number of radiators, which is one per room. Likewise, it has been hypothesized the presence of one window per room, and therefore one window sensor per window.

The total acquisition cost for one floor is, therefore, equal to 6.336,5 €. Considering the four levels, it raises to 25.346 €. The total residential period costs are, instead, equal to 607,2 €.

Switching the focus to the benefits side, the overall monetary and energetic savings were estimated. The unitary energy cost was retrieved from the Eurostat website, which publishes all the statistics relating to the price of energy in the European Union. The average price value of the 2013-2021 years was taken as reference, being equal to 0,2 €/kWh. The same approach was adopted for the calculation of the gas unitary price, having an average value of 0,073 €/kWh.

Concerning office spaces, the following formulas sum up the HVAC consumption and the lighting consumption.

$$HVAC\ System\ Energy\ Consumption\ (kWh) = 155{,}84\ kWh/(m^2y) \cdot 4\ floors \cdot 500\ m^2/floor = 311680\ kWh \quad (1)$$

$$Lighting\ System\ Energy\ Consumption\ (kWh) = 45{,}36\ kWh/(m^2y) \cdot 4\ floors \cdot 500\ m^2/floor = 90720\ kWh \quad (2)$$

The values of energy consumption were retrieved from ENEA statistics [25]. The percentages of energy savings were retrieved, instead, from the literature review. For what concerns lighting, they range from 38% to 73%, according to different authors [21], [22], [26]. Therefore, an average value equal to 55% was considered. Switching to HVAC savings, the values of 30% for HVAC in professional offices and 10% for HVAC in open space offices were considered. The former represents an average value of HVAC energy savings for traditional offices [23], [27], [28]. The latter, instead, is a conservative value of HVAC energy savings in offices, since the open space configuration differs from the traditional ones [29]. Table 4 summarises the savings computations in the office.

Table 4. Office savings.

HVAC	Professional Offices	Open Space Offices
Total HVAC energy consumption (kWh/year)	155.842	155.842
HVAC percentage savings (%)	30%	10%
Thermal energy consumption savings (kWh/year)	46.753	15.584
Monetary savings for HVAC (€/year)	3.411	1.137
LIGHTING	Professional Offices	Open Space Offices

Total electrical energy consumption (kWh/year)	45.357	45.357
Lighting percentage savings (%)	55%	55%
Electrical energy consumption savings (kWh/year)	24.946	24.946
Monetary savings for lighting (€/year)	4.989	4.989
Total monetary saving for offices (€/year)	8.401	6.126

Focusing on residential spaces, Table 5 sums up the heating consumption, lighting consumption, and related savings. The energy consumption was retrieved from the BSRIA report on consumption values of residential buildings in Europe [30]. The savings percentages were defined as follows. The savings stemming from smart heating device installation were retrieved both from literature and smart thermostats product information on producers' websites. The 15% value was then selected, being the average value among the contributions with a major weight to thermostatic radiator valve savings papers [24], [31]. In the same way, lighting savings, equal to 20%, represents an average value among those found in the literature [21]. Please notice that the cooling system is not retrofitted.

Table 5. Residential savings.

HEATING	Values
Average consumption value for heating (kWh/(m^2*year))	144
Total consumption for heating (kWh/year)	270.720
Total costs for heating (€)	19.753,19
Automated thermostatic valves percentage savings (%)	15%
Monetary savings for heating (€/year)	2.962,98
LIGHTING	Values
Average consumption value for lighting (kWh/(m^2*year))	5
Total consumption for lighting system (kWh/year)	9.400
Total costs for lighting (€/year)	1.880
Lighting percentage savings (%)	20%
Monetary savings for lighting (€/year)	376
Total monetary saving for residential floors (€/year)	3.339

Table 6 reports the overall initial investment for the 8-levels building, the estimated running costs and the total savings achievable through IoT devices application. Starting from that, the financial indicators of NPV and Payback time are computed, as stated above.

Table 6. Base case scenario model results.

Initial investment (€)	Period costs (€)	Annual benefits (€)	Net annual benefits (€)	NPV (€)	Payback time (years)
84.734	3.193	17.866	14.673	145.312	6,2

As observable from the NPV, the application of this type of installation is largely positive in the long term (20 years) and the investment can be repaid in a short-medium term (6,2 years).

3.2. Sensitivity analysis

Afterwards, a sensitivity analysis was performed by varying the energy performance of the building, with the objective to assess the convenience of the investment in relation to different consumption levels.

The analysis started from the building's classification based on its energetic status, certified by the APE (Attestato di Prestazione Energetica). This ranking presents seven main classes from A to G, corresponding to seven different energy consumption rates. To estimate the energy class of a building, a plurality of factors is usually considered, including the materials of the windows and walls, the type of heating system used and the primary energy requirement for winter heating.

The building of the base case scenario was considered to be in class F. Indeed, the average consumption was around 150 kWh/m^2y. Starting from that, the percentage variation in consumption for the classes in correspondence to class F was calculated. Then unitary heating consumption (kWh/m^{2}y) was then adjusted considering this percentage increase/decrease. Table 7 summarises the consumption levels and the resulting economic outcomes.

Table 7. Consumption levels and economic outcomes (variation of the energetic class) of the sensitivity analysis.

Energetic Class	Average heating consumption (kWh/m^2y)	Percentage Variation class "X" to F	Initial Investment (€)	Period costs (€)	Annual Benefits (€)	Net Annual Benefits (€)	PBT (years)
A	15	11%	84.734	3.193	11.159	7.966	12,08
B	40	29%	84.734	3.193	12.501	9.308	10,15
C	60	43%	84.734	3.193	13.574	10.381	9,00
D	80	57%	84.734	3.193	14.647	11.454	8,09
E	105	75%	84.734	3.193	15.988	12.795	7,18
F	140	100%	84.734	3.193	17.866	14.673	6,20
G	180	129%	84.734	3.193	20.012	16.819	5,37

As observable, the Payback time increases if the energetic performance of the building improves. This result is not surprising since the lowest classes correspond to the highest energy waste that can be saved thanks to IoT installations.

4. Conclusion

The present study intended to provide an overview of investments in IoT technologies employed to increase energy efficiency in a building, through retrofitting intervention. By looking at the results, this kind of intervention provides great benefits, enabling energy saving and repayment of the investment in the short-medium term (6,2 years). In particular, the cases in which the energy consumption is substantial are the ones that benefit the most from the installation of smart devices. As observable from the results of the sensitivity analysis, the buildings with a low energetic class (E-G) are the ones that could exploit the advantages brought by IoT devices at their maximum. However, the benefits achieved through the installation of this kind of device are not high in absolute terms, as no masonry works or structural changes were required. On the other side, the results show that energy savings can be achieved with relatively low effort.

From the academic perspective, the present model aims at filling the literature gap, by assessing the investment in different kinds of IoT technologies to implement energy efficiency policies in a mixed building, both residential and commercial. Its application considering different scenarios enabled an in-depth understanding of the variables involved. For what concerns the managerial contribution, the proposed model provides useful insights and suggestions to whoever is interested in the application of IoT technologies to make a building smart, enabling the comprehension of the necessary investment and economic returns.

Nevertheless, this work presents some limitations. The savings percentages on energy consumption are retrieved from the literature and kept fixed in the model. To better represent the variability that could originate from the level of usage and the kind of devices installed, a certain margin of variation should be considered. The calculation of costs and benefits is therefore approximated, but it enables the evaluation of the variables involved.

Further development of the research could aim at enlarging the perspective to other functionalities enabled by the installation of IoT devices, such as security or safety. Given the rate of adoption of IoT and the development of the market, it will not be surprising if those technologies will improve fast. Thus, an updated version of the model could better represent the evolved market scenario.

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