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Energy Use in Residential Buildings: Impact of Building Automation Control Systems on Energy Performance and Flexibility

Francesco Mancini [1,*], Gianluigi Lo Basso [2] and Livio de Santoli [2]

1 Department of Planning, Design and Technology of Architecture, Sapienza University of Rome, 00197 Rome, Italy
2 Department of Astronautics, Electrical Energy Engineering, Sapienza University of Rome, 00184 Rome, Italy
* Correspondence: francesco.mancini@uniroma1.it; Tel.: +39-06-4991-9172

Received: 5 July 2019; Accepted: 25 July 2019; Published: 27 July 2019

Abstract: This work shows the results of a research activity aimed at characterizing the energy habits of Italian residential users. In detail, by the energy simulation of a buildings sample, the opportunity to implement a demand/response program (DR) has been investigated. Italian residential utilities are poorly electrified and flexible loads are low. The presence of an automation system is an essential requirement for participating in a DR program and, in addition, it can allow important reductions in energy consumption. In this work the characteristics of three control systems have been defined, based on the services incidence on energy consumptions along with a sensitivity analysis on some energy drivers. Using the procedure established by the European Standard EN 15232, the achievable energy and economic savings have been evaluated. Finally, a financial analysis of the investments has been carried out, considering also the incentives provided by the Italian regulations. The payback time is generally not very long: depending on the control system features it varies from 7 to 10 years; moreover, the automation system installation within dwellings is a relatively simple activity, which is characterized by a limited execution times and by an initial expenditure ranging in 1000 € to 4000 €, related to the three sample systems.

Keywords: residential users; demand response; building automation control; energy efficiency

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1. Introduction

Energy efficiency measures will play a key role in attaining net-zero greenhouse emissions by 2050, lessening energy consumptions by 50% approximately, compared to those related to 2005 [1]. The energy demand reduction has to be mainly found in both residential and tertiary buildings, which up to date represent 41.7% of energy consumption [2]. Since the major part of building stock of 2050 already exists now, higher renovation rates, improved materials for insulation, and fuel switching are surely required. Moreover, a growing number of homes are going to use the renewable sources for heating purposes (i.e., renewable electricity, 4th generation of district heating, electro-fuels, biogas or solar thermal) along with more efficient products and appliances deployment.

Energy efficiency digitalization and home automation will play a key role in the modernization of the building stock. In order to handle the transition towards a decentralized energy model involving the renewable energy sources as much as possible [3] it is necessary to build a flexible system. To do so, several interventions such as the energy storages application, the users smart interconnection [4,5], the demand side response [6], and smart building/appliances management systems [7] have to be taken into account.

The existing building stock is wide, heterogeneous, and it is basically composed of buildings with poor energy characteristics [8]. The European Union (EU) residential energy consumption, in terms of status and foreseeable trends, were analyzed in [9], referring mainly to the impact and effectiveness of energy efficiency policies implemented for this sector [10,11].

In that scenario, energy retrofit actions may reduce significantly the building energy demand [12]; by implementing some basic interventions on a large scale it is possible to accomplish remarkable energy savings, as reported in literature [13–15]. The ideal objective to reach is represented by the nZEB target [16]. In many cases the suitable retrofitting options have to be evaluated accurately; indeed, many research projects focused on identifying which were the most effective refurbishment strategies to improve the existing buildings performance [17–19] considering market and political context influence [20] as well as ecological aspects [21,22].

Thus, in the short-medium term the digitalization and automation have been considered as some of the most promising and forceful pathways for the competitiveness enhancement and to get higher efficiency gains as well as lower greenhouse gas emissions [1]. Indeed, further energy savings can be attained by implementing control strategies together with the interaction of appliances and domestic devices, so as to run at their rated efficiency during their operation. To do so, ICT tools able to coordinate all energy facilities within the households, are very often required [23]; in [24] and in [25] the accomplished energy savings owing to an improvement of the distribution and regulation system concerning the heating systems, were highlighted; in [26] and in [27] it was indicated that the occupant-driven demand control systems in dwellings, especially for keeping under control thermal loads, visual and indoor air quality plants, was hampered due to the lack of occupancy information.

Building controls effectiveness and reliability have been considerably improved favouring the BEMS (building energy management systems) development. Those ones are usually customized systems for monitoring and managing all the building services as well as the energy flows so as to maximize the occupants' comfort conditions.

Recent research projects have been carried out to study the implementation of BEMSs in residential buildings [28–31]. Another research investigated households' perceptions of smart technology usage to get energy savings [32]. Ożadowicz and Grela [33] proposed different methods to properly compute the energy demand profile by means of time-driven and event-driven mechanisms for programming BACs (Building Automation and Control systems) package. Favuzza et al. [34] investigated the effects, on the distribution grid, of some control logics implementation within BACs dedicated to residential buildings once renewable energy sources have been installed. In [35], the deferrable loads, appliance time scheduling, as well as the energy resources management for a smart home (SH) were analyzed. Zehir et al. [36] investigated on smart meters and building automation system for residential users discussing the design issues on the basis of outcomes hailing from on-field tests of a demonstrator device. In [37] the Energy Scheduling and Distributed Storage (ESDS) algorithm were proposed to be implemented within the consumers' smart meters of Time-of-Use (TOU) pricing, where energy storage devices were installed.

The research project in [38] dealt two different hydraulic configurations of heat pump with thermal energy storage and four different control strategies were analyzed. Thus, in [39] a strategy for the optimal control of building HVAC systems with chilled water thermal energy storage was proposed.

On the basis of the aforementioned research projects, this work presents the analysis of the effects of the energy consumptions related to the residential end-users by introducing BAC systems.

2. Materials and Methods

2.1. Methodological Approach

The analyses presented in this work are based on the energy simulation of sample dwellings carried out by the dissemination of an online questionnaire/simulation tool, comparing also the simulation outcomes to collected information.

By the questionnaire, the following useful inputs for simulation performing have been collected: (i) the building envelope characteristics (building location, surfaces, orientation, building envelope

U-value, ventilation rate, shadings); (ii) plants characteristics (heating system, cooling system, Domestic Hot Water plant, solar collectors, PV array); (iii) the appliances characteristics and the use time-scheduling (kitchen, refrigeration, washing, cleaning and ironing, lighting, audio/video, personal care, and other equipment); (iv) the house occupancy rate (times, attendance); the actual consumption data reported in the energy bills.

The questionnaire is based on a VBA Macro implemented in MS Excel, where the source code has been entirely developed by some of the authors. That tool allows to perform the building dynamic simulation by the single thermal zone modeling. In detail, the building energy simulations are performed using the Heat Balance Method (HBM) with a solver algorithm based on conduction finite differences (CondFD) [40]. The simulation tool was validated by the comparison with the most common dynamic simulation programs (i.e., TRNSYS and EnergyPlus); the tool has already been used in previous works [41–43] and it has been adapted to get better simulation results for residential users; additionally, a user-friendly interface has been developed to allow its use by non-expert users as well [44,45].

The energy needs hailing from simulations are compared in a systemic overview with the billing data entered by the end-user [46,47] and with benchmark values. Those ones were computed according to the Italian TSO report [48] and of the ISTAT survey on dwellings energy consumption [49]. When the simulation data drift away the actual ones, warning messages and suggested solutions for inputs correction are prompted. This is due to the fact that the common users do not know well their own consumption habits [50,51].

Since that tool has the scope to characterize the energy needs in terms of management flexibility, it allows a classification, distinguishing four types of load, according to [52]: (1) storable load (heating, cooling, domestic hot water); (2) shiftable load (laundry, dishwasher, tumble dryer, vacuum cleaner, stove); (3) curtailable load; (4) non-curtailable load (base load).

In this work, the analysis for assessing how the introduction of building automation affects the energy savings, has been carried out gathering data concerning 412 dwellings: Those data have been collected by the online questionnaire, from September 2018, thanks to the collaboration of the attending students of the Faculty of Architecture of Sapienza University of Rome (Italy).

The same statistical sample has been considered in two previous works of the authors in order to provide a reference characterization for identifying flexible loads [44] and to assess energy retrofitting effects on the energy flexibility [45].

In the first one [44], a comparison between the simulated consumptions and the real ones which were entered by the user has been made to validate the model; a good correlation coefficient has been detected between simulation results and collected data: regarding the electricity consumption such a coefficient is equal to 0.8993, whereas it is 0.7716 for natural gas. In the same work, a first characterization of the Italian residential utilities was made, it was remarked that (1) heating, domestic hot water (DHW) and cooking services represent the highest fraction in dwellings primary energy consumption (70% approximately); (2) the average electrification degree is limited to 36.5%; and (3) the flexible loads average value is equal to 1042 kWh/y.

In the second one, [45] it was observed that adopting energy requalification measures there are reductions in energy consumption and reductions in the potential houses flexibility; exceptions are the interventions to replace heat generators for heating and DHW with heat pumps, for which energy savings and a substantial increase in flexible loads are jointly achieved.

In this work, by the use of such a simulation tool, the authors want to focus attention on the potential effects on the end-user energy consumptions once a better management strategy is adopted by means of an automatic device to for participating in DR programs. Indeed, it is well known that the application of automation systems can lead to energy savings in the residential sector as well [53] and it is clear how such controllers are essential equipment for participating in a DR program [52]. The need for a greater automation in the residences was also recognized by the Italian legislator, with the introduction of incentives in terms of tax deductions [54].

The implications related to the BACs adoption within dwellings have been widely investigated in several works available in literature; the paper [33] focused on the impact evaluation of the BAC systems on the energy efficiency of university; the paper [55] focused on the evaluation of the impact on residential buildings of BAC systems, referring to the Italian case, using a static simulation to estimate the heating and cooling energy consumptions and a bottom-up statistical approach to estimate systems electrical consumptions. Chen et al. [56] presented the achieved energy savings once the fully automatic window/HVAC control system has been applied; that allows to optimize the role of natural ventilation showing different effects with changes in climatic conditions [57] and leading also to remarkable benefits in terms of air pollution.

In [58], an interesting literature survey related to the BACs was presented. In that work the essential components of the automation systems, along with their main characteristics have been evaluated and discussed.

In order to define the peculiarities of an optimized automation system for the Italian residential sector a sensitivity analysis on energy consumption was carried out with varying some input data. Indeed, the effects of changes in the outdoor temperature and the indoor temperature on energy consumption related to heating and cooling loads were simulated [59,60]. Additionally, the effects of a different occupancy rate of dwelling were considered as well, due to the fact that the occupant behavior has a large impact on the energy consumption of buildings [61].

Thus, three possible configurations of the automation kit were identified and thereafter, their implications on energy consumption, on the expenditures for buying energy and on the potential of flexibility, were assessed by the simulation tool. The costs of energy bills were also evaluated using the online tool developed by ARERA (Italian Regulatory Authority for Energy, Networks and Environment) [62].

As aforementioned three different case studies have been hypothesized which are characterized by a growing number of devices for monitoring and controlling [63]. Referring to the single dwelling the system core consists of an Energy Box (EB) which is able to collect data from home sensors, to keep under control the appliances and to operate as a gateway to communicate all the information in a bidirectional way from the smart home to laptop or smartphone (Figure 1); the EB can integrate sensors with different communication protocols, such as Z_Wave and EnOcean, it can plot also the load profile of each appliance and home management logics can be programmed. In all cases electricity meters have been installed (together with the existing utility meter). Thus, depending on the kit typology, further monitoring devices can be connected (i.e., gas meter, multi-sensors for temperature, presence, and illuminance detection), and window/door opening and closing detectors with controller function as well (i.e., smart valve, smart plug, and smart switch).

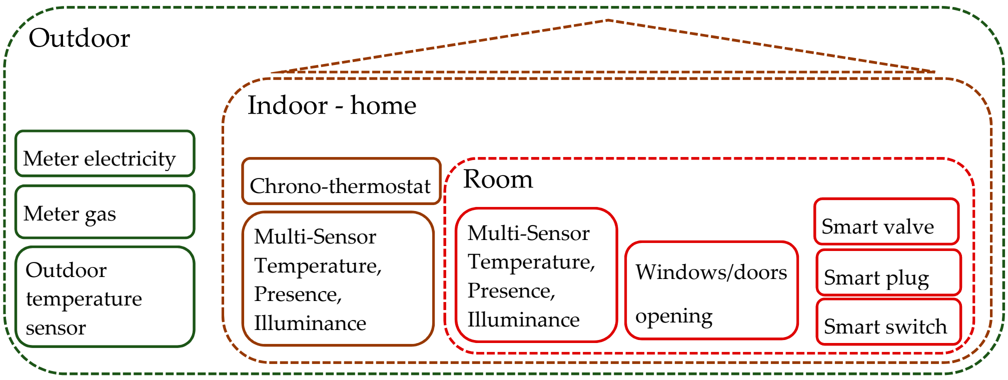


Figure 1. System architecture.

Improvements deriving from the installation of automation and control systems are computed following the EN15232 [64]. The recent standard calls for two different methods to evaluate how the building automation system affects the building energy performance, along with management functions; in this paper, the so-called "BAC factor method" has been considered by the authors. In accordance with that method, the BACS influence on the building's energy performance can be computed using two efficiency factors, namely BAC factor for thermal energy ($f_{BAC,hc}$) and BAC factor for electrical energy ($f_{BAC,e}$), respectively. Their values for residential buildings are listed in Table 1. They have been calculated by comparing the energy performance of two different scenarios. The first one refers to a reference building (class C) and once the technical plants have been fixed (i.e., ventilation, and lighting) the yearly energy consumption have been calculated. The second one consists of the same reference building with the same technical systems for energy supply which run in the same operating conditions (occupation time, load profile, weather, solar irradiation, etc.). Thereafter, when the BAC system class has been chosen (Class A: High energy performance BAC systems; Class B: Advanced BAC systems; Class C: Standard BAC; Class D: Non-energy efficient BAC) and it has been adopted, the energy consumptions have been recomputed and compared each other.

Table 1. BAC efficiency factors for thermal and electric energy for residential buildings.

BAC Efficiency Factors	Efficiency Classes			
	A	B	C	D
Thermal energy BAC efficiency factor $f_{BAC,hc}$	0.81	0.88	1.00	1.10
Electric energy BAC efficiency factor $f_{BAC,e}$	0.92	0.93	1.00	1.08

The determination of the average BAC class related to thermal and electrical uses has been evaluated applying a modified approach compared to the standards' stringent indications. Indeed, the standard requires that the BAC class of a building is determined by the lowest BAC classes of each functionality chain; it is therefore sufficient that only one "weak point" is within the generic service to invalidate the overall building class. The rigorous application of that methodology leads to classification levelling down and hence to the lessening of the expected savings, that does not correspond to the objective of this work. To perform more flexible calculation accounting for regulatory system in force, a numerical value has been associated to each class, so that the final class can be calculated by averaging the BAC classes of each function.

After evaluating the achievable energy and economic savings owing to the introduction of a BAC system, an estimate of the installation costs has been provided. It refers to the most common components available on the market.

Finally, the discounted payback period (DPP) of the investment related to the BAC system installation has been evaluated, according to [65].

2.2. Dwellings Description and General Anlysis on Consumptions Typology

The analyzed database consists of 412 dwellings with uneven characteristics in terms of construction years, size and occupation [44].

From data it emerges that a large part (64.1%) of the sample buildings was built before 1976, the year in which the first Italian law on energy saving was issued; only 17 houses (4.1%) were built after 2005. Many houses (55.1%) underwent renovations; the most frequent redevelopment intervention is the windows replacement (46.6%). The apartments average size is equal to 112.4 m^2 and the most common class is the middle one (85–115 m^2). The average number of occupants is 3.2; 38.8% of houses are occupied by 4 people; 26.0% of houses are occupied by 3 people; and 20.6% of houses are occupied by 2 people.

The sample dwellings are all equipped with a heating system and a domestic hot water production system. Most heating systems are autonomous (73.3%); gas is the most used energy vector in heating systems (98.8%) and in domestic hot water preparation (85.4%), since the heat generator is able to supply both services very often. The terminals of heating systems are generally radiators (95.9%); only in some cases there are fan-coils (1.5%) or radiant floors (2.7%).

In the reference houses there are no automation devices; there are control systems for heating plants (Figure 2), although very often they consist only of a programmable thermostat (56.3%); in 26.5% of cases there is also a temperature adjustment for each room, where programming tools are available only in 3.4% of cases. Cooling systems are present only in 207 homes (49.4%), serving only a few rooms.

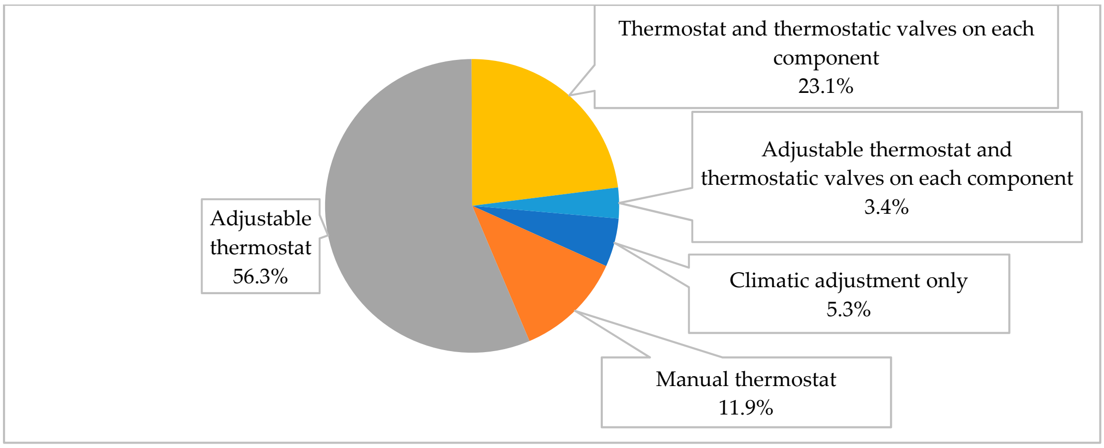
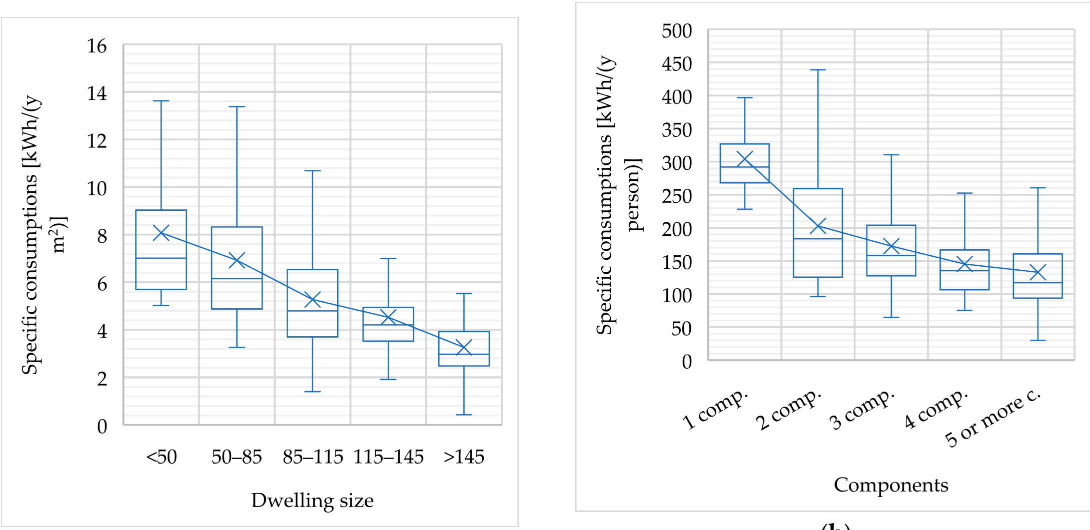


Figure 2. Heating systems control.

Moreover, some of the sample dwellings are not equipped with the most common devices dedicated to the different services (e.g., washing 1.0%; cleaning and ironing 3.6%; video audio 0.5%; Internet computer 2.9%; and care person 1.9%).

The energy characterization reported in [44] shows that a large part of energy consumption is attributable to the heating purpose (on average equal to 43.5%); the average incidence of the other services is lower (DHW 14.1%; cooking 12.4%; washing 5.6%; computer/Internet 4.1%; refrigeration 3.8%; cooling 3.6%; cleaning and ironing 3.5%; care person 2.9%; lighting 2.7%; audio/video 1.8%; and other equipment 1.9%).

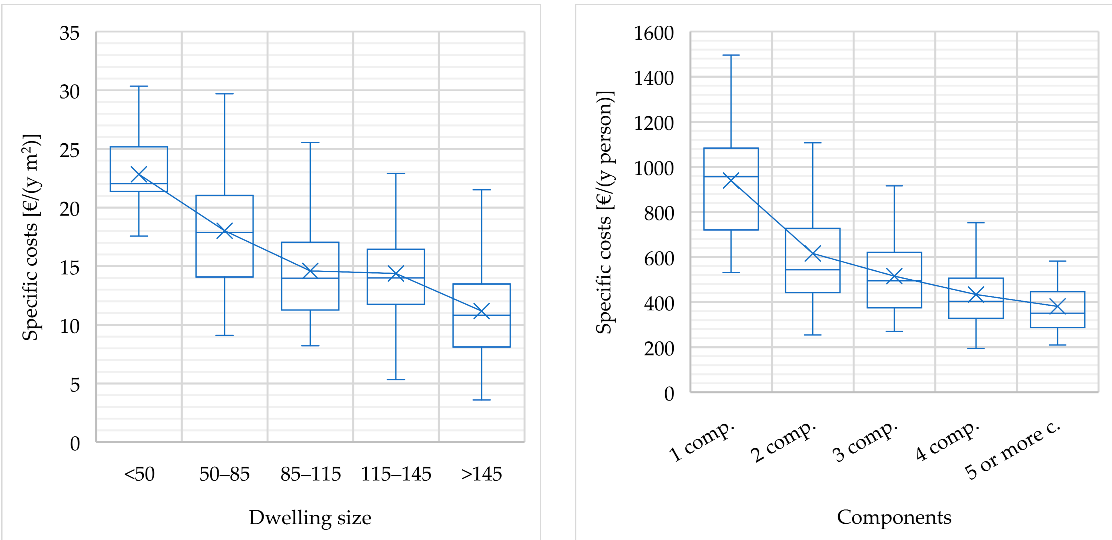
Parametric-based evaluation of primary energy and costs have been carried out. It focused both on the number of components and on the building floor surface. Those KPIs are in accordance with the current Italian building energy certification system, that provides technical information related to the building characteristics and to the inhabitants' behavior. However, by processing data it is possible to calculate the most common environmental and economic KPIs as reported in literature [66]. The average specific primary energy consumption associated to the sample dwellings is 5.4 kWh/(y·m^2). As shown in Figure 3, the specific primary energy consumption per unit of surface decreases with increasing housing size, from 8.1 kWh/(y·m^2) (small households) up to 3.3 kWh/(y·m^2) (large households); similarly, per capita consumption decreases as the number of family members increases, from 304.1 kWh/(y·person) (1 component) up to 132.9 kWh/(y·person) (5 or more components).



(**a**) (**b**)

Figure 3. Specific primary energy consumptions (**a**) by unit of surface vs. dwelling size; (**b**) per capita consumptions vs. components.

Referring to the Figure 4, the specific costs show decreasing trends as for primary energy consumption, accordingly. In detail, specific costs for gas purchase decrease from 22.8 €/(y·m^2) (small households) up to 11.2 €/(y·m^2) (large households); the specific per capita costs decrease as well, starting from 939.6 € /(y·person) (1 component) up to 381.3 €/(y·person) (5 or more components).



(**a**) (**b**)

Figure 4. Specific costs (**a**) by unit of surface vs. dwelling size; (**b**) per capita costs vs. components.

The linear regressive analysis has been used for both primary energy consumptions and costs, since the outcomes deriving from the data forecasting model are characterized by large standard errors.

The yearly PEC (primary energy consumptions) equation (expressed by kWh/y) reads as follows:

$$\text{PEC} = 197.70 + 0.67110 \cdot S_{floor} + 76.514 \cdot N \tag{1}$$

where S_{floor} denotes the dwelling floor surface and N is the number of occupants.

Similarly, for the yearly costs (€/y) the analytical function is:

$$EC = 538.98 + 5.3935 \cdot S_{floor} + 126.50 \cdot N \quad (2)$$

In addition, the R^2 values and the standard errors are R^2 = 0.2365, STDE = 197.31, and R^2 = 0.4241, STDE = 466.12, respectively.

Finally, as reported in [45] further performance indicators for characterizing the sample dwellings have been assessed: (i) local carbon emissions; (ii) renewable energy use; (iii) flexible loads amount.

The local emissions, in terms of equivalent CO_2 are fundamentally equal to 20.1 kg/m^{2}y, ranging in the span 27.9 kg/m^{2}y (small dwelling) and 16.1 kg/m^{2}y (large dwelling). Renewable energy consumption per unit of area is on average equal to 13.0 kWh/m^{2}y (small dwelling 24.1 kWh/m^{2}y; large dwelling 8.5 kWh/m^{2}y. Then, flexible loads per unit of area are on average equal to 10.5 kWh/m^{2}y (small dwelling 12.4 kWh/m^{2}y; large dwelling 6.9 kWh/m^{2}y).

3. Results and Discussions

3.1. Energy Consumption Sensitivity to Input Data

Energy consumptions of a residential building depend on a series of factors such as (1) building physical and thermal properties; (2) climatic conditions (outdoor temperature, wind speed, outdoor relative humidity, solar radiation); (3) occupancy behavior (occupancy activities, interaction with the building); and (4) population size (number of occupants, indoor activities).

This section shows the simulations results carried out with the aim of evaluating the sensitivity of energy consumption to some input data; specifically, it has been decided to verify the following correlations: (1) heating consumption vs. outdoor temperature; (2) heating consumption vs. indoor temperature; (3) cooling consumption vs. outdoor temperature; (4) cooling consumption vs. indoor temperature; and (5) overall consumption vs. employment.

3.1.1. Effects of Changes in the Outdoor or Indoor Temperature on Heating Consumption

The correlation between heating consumption and outdoor temperature has been studied by simulating the effects of small variations in the average daily temperature (+0.5 °C; +1.0 °C; −0.5 °C; +1.0 °C). The results of the simulations are shown in the charts of Figures 5 and 6, where the variations in heating consumption are expressed by absolute terms and by percentage terms depending on the primary energy consumption for heating; in the same graphs are also superimposed the respective trend lines, together with their equations. The larger the variations in the outdoor temperature (positive or negative), the larger the variations are, referring to heating consumption.

According to the graph of relative changes, although a less precise correlation is computed, it can be stated that a change in the outdoor environmental temperature entails a leverage effect for all those houses characterized by lower heating consumption; this circumstance finds its justification in the minor importance that, the inner gains have, generally, in a house characterized by a high heat demand.

The correlation between heating consumption and the indoor comfort temperature has been studied by simulating the effects of small changes in the indoor temperature (+0.5 °C; +1.0 °C; −0.5 °C; +1.0 °C).

The simulations results are depicted in Figures 7 and 8, where the heating consumption changes are reported in absolute terms and in percentage terms, as a function of the primary energy consumption for heating; in the same graphs are also reported the respective trend lines, together with the computed equations.

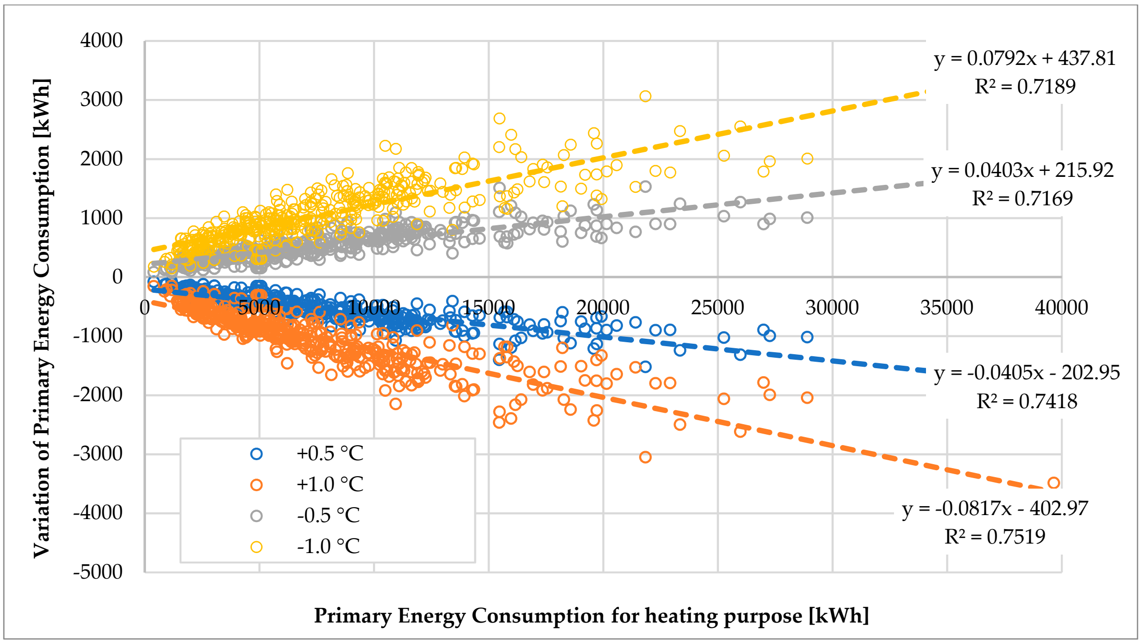


Figure 5. Absolute variation of heating consumptions with changes in outdoor environmental temperature.

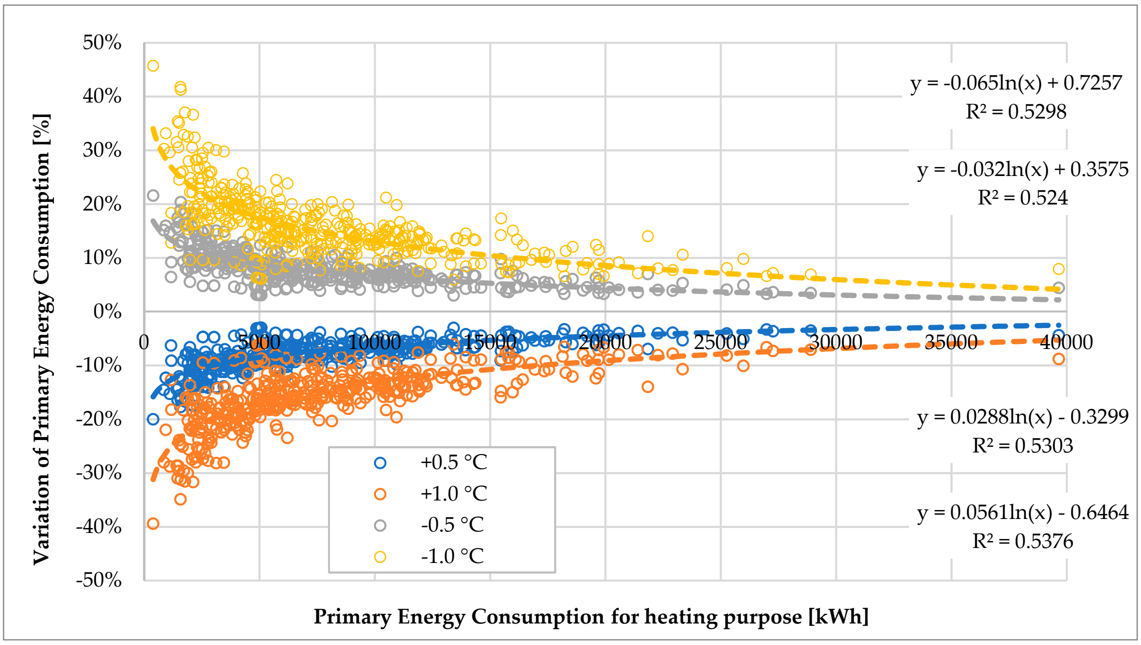


Figure 6. Relative variation of heating consumptions with changes in outdoor environmental temperature.

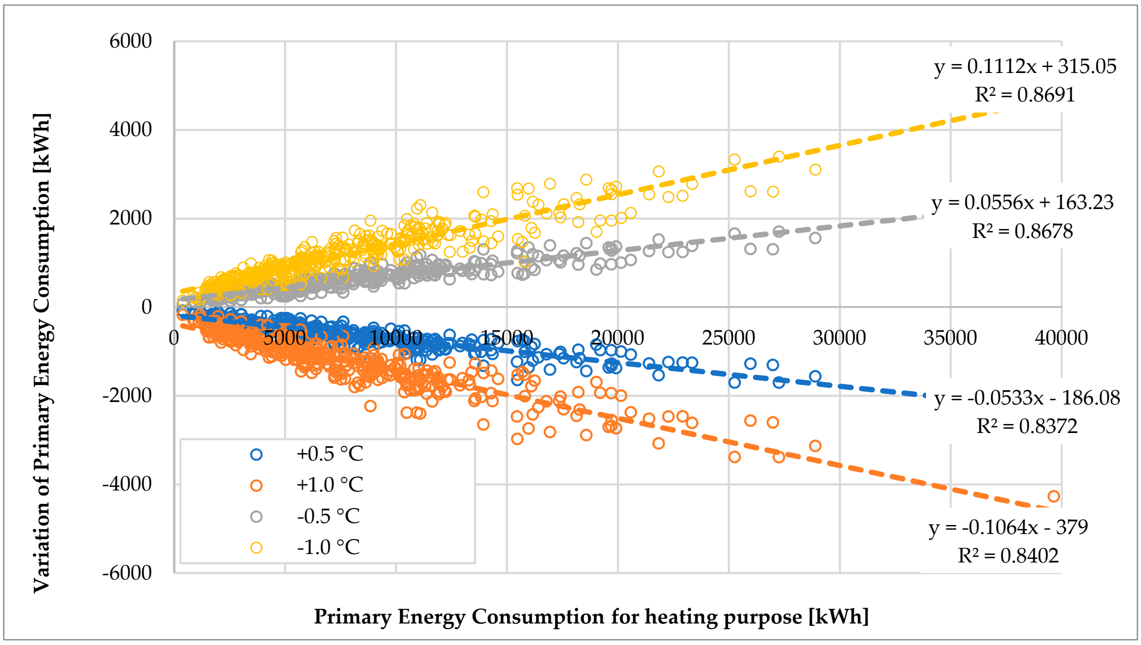


Figure 7. Variation of heating consumptions with change in indoor temperature.

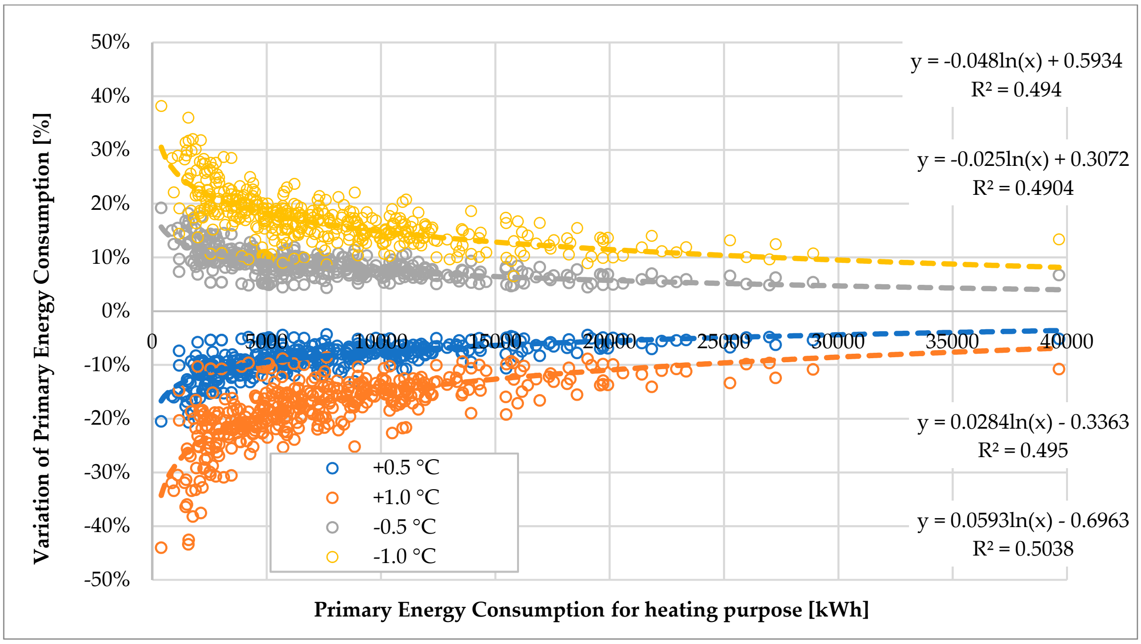


Figure 8. Percentage variation of heating consumptions at changing indoor temperature.

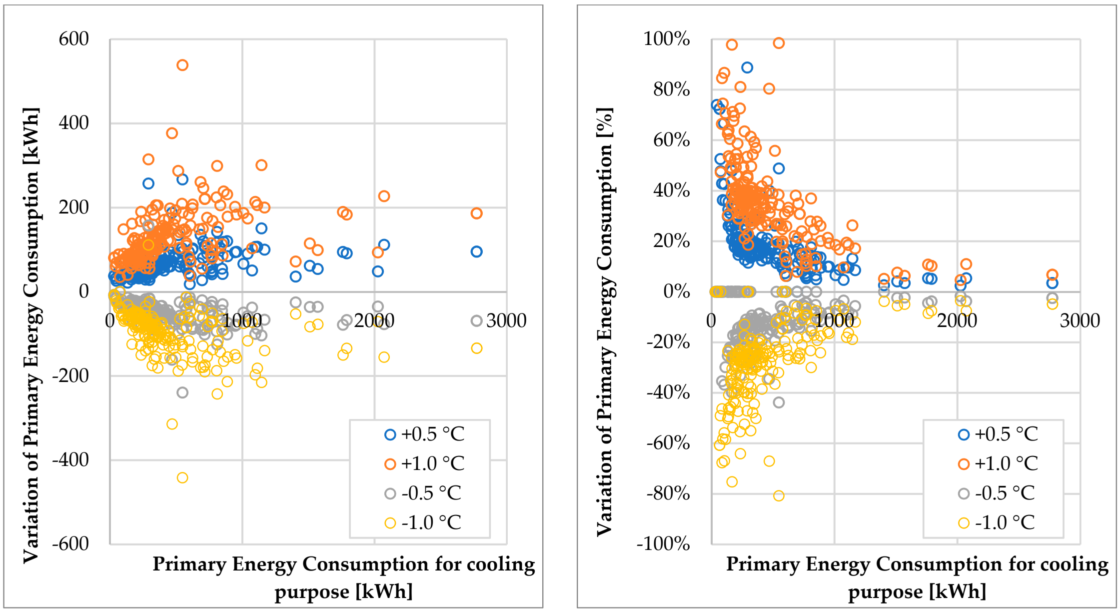
Remarks are similar to those related to the outdoor environmental temperature variations: the larger the variations in indoor temperature (positive or negative) the larger heating consumption are.

Referring to the graph of the relative changes, it is possible to notice the same behavior leading to very similar conclusions.

Furthermore, making a comparison in pairs between the graphs shown (Figure 5 vs. Figure 7; Figure 6 vs. Figure 8) allows further remarks: the effects of an indoor temperature variation are higher than those homologous, however they have opposite sign; that issue is caused by the different effects, related to the two temperature variations, on the heating period duration (i.e., the particular temperature trend of a location) and by the different capacity to use the free gains.

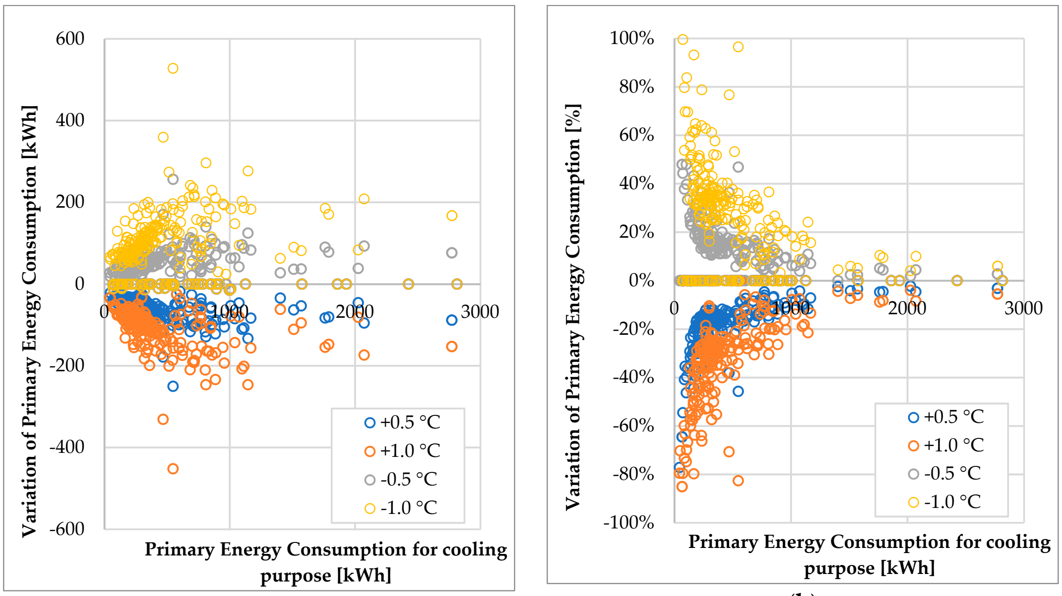
3.1.2. Effects of Changes in Outdoor or Indoor Temperature on Cooling Consumption

The effects of a variation in both outdoor and indoor temperature change on the cooling consumption have been simulated and presented similarly. The results are shown in the graphs of Figures 9 and 10; changes in cooling consumption are reported in absolute terms and in percentage terms as a function of primary energy consumption for cooling purpose.



(**a**) (**b**)

Figure 9. Variation of cooling consumptions with changes in outdoor temperature: (**a**) absolute values; (**b**) relative values.



(**a**) (**b**)

Figure 10. Variation of cooling consumptions with changes in indoor temperature: (**a**) absolute values; (**b**) relative values.

In qualitative terms, it can still be affirmed that the larger the temperature variations (outdoor or indoor, positive or negative) and the larger the variations are. Nevertheless, the correlation in this case is decidedly weaker and therefore no trend line is superimposed.

Regarding the lower correlation between temperature variations and cooling consumption, the first reason can be identified in the smaller sample population, which is just limited to houses equipped with useful equipment for cooling (207 homes, 49.7% of the total).

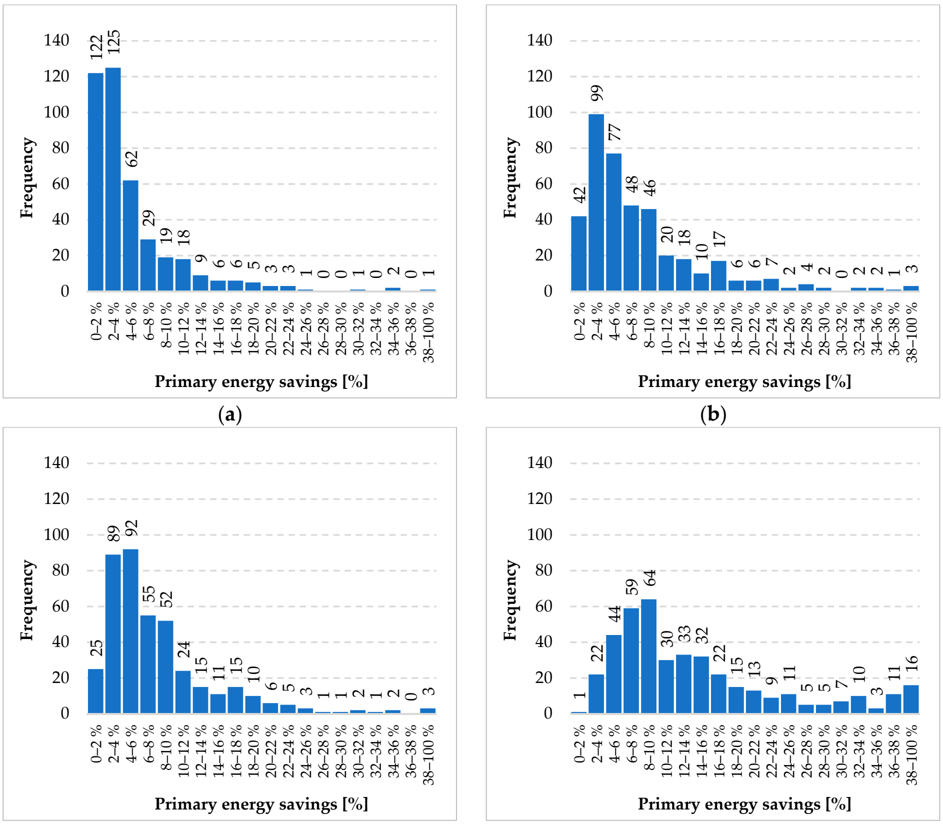
The second one is stronger and it lies instead in the different nature of the hot season load as much as the energy needs for cooling; those ones are influenced both by exogenous and endogenous loads whose relationship significantly determines the cooling period duration; when the temperature changes (outdoor or indoor) this ratio can vary importantly, altering thereby the energy consumption for cooling.

Furthermore, what has been already stated about the heating consumption, related to the loads' variability in lower energy houses, is still valid; for the cooling case, it is noteworthy how the largest variations are concentrated in the span 0–1000 kWh. That feature is mainly due to the fact that only a few rooms in the house are air-conditioned; consequently, it is not so easy to correlate temperature and the effect of variations in input data once the sample cases are characterized by a plurality of inputs.

3.1.3. Effects of a Different Dwelling Use

The different dwelling use, caused by the occupancy rate time-shifting, affects the energy consumption related to services, such as heating, cooling, and lighting.

In order to evaluate the results on dwellings associated to the occupation changes, the maximum number of persons declared in the questionnaire has been used as a reference scenario. That occupancy rate has been firstly considered constant over the day. Subsequently, the number of occupants has been set equal to zero in one of the time slots indicated in the data collection questionnaire (8–13; 13–19; 19–0; 0–8). Figure 11 outlines those simulation results.



(**a**) (**b**) (**c**) (**d**)

Figure 11. Achieved percentage savings on primary energy consumption related to heating, cooling and lighting compared to the refence scenario (**a**) zero occupancy in time slot 8–13; (**b**) zero occupancy in the time slot 13–19; (**c**) zero occupancy in the time slot 19–0; and (**d**) zero occupancy in the time slot 0–8.

In all cases energy savings are achieved due to the lower occupancy rate and the highest values can be attained when the occupants are equal to zero over the night-time. More in detail:

- for zero occupants in the 8–13 range the average savings are 4.6%, ranging between zero and 39.3% as the maximum value;
- for zero occupants in the range 13–19 the average savings value can get 7.8% (min 0.4%, max 47.7%);
- for zero occupants in the 19–0 range the average savings are slightly higher up to 8.0% (min 0.1%, max 46.7%);
- for zero occupants in the 0–8 range the average savings are equal to 14.6% (min 2.0%, max 89.3%).

3.2. Introduction of an Automation System: Energy and Economic Savings Analysis

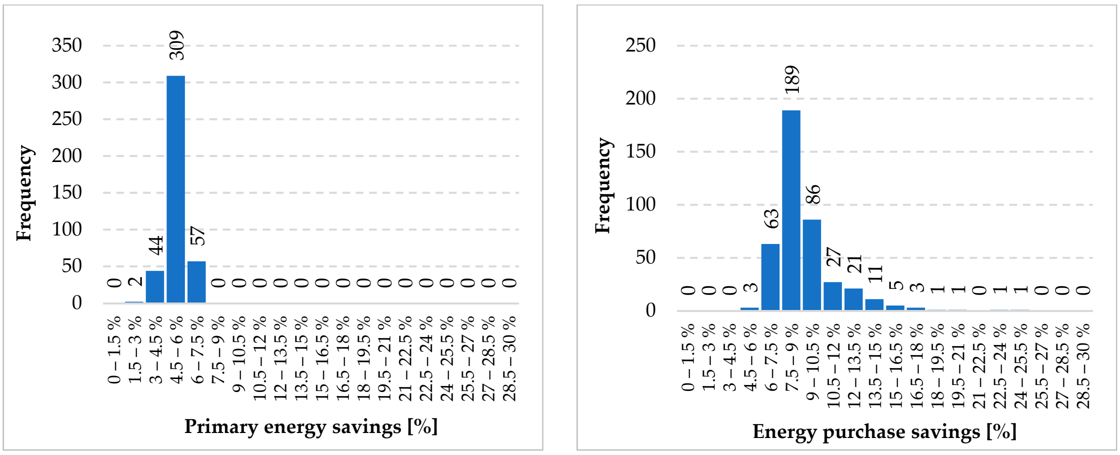
Participation in a DR program necessarily involves the use of control systems to guarantee the coordination and automation of all energy uses. Nowadays, Italian residential buildings are generally lacking in automation systems and therefore the installation of suitable devices is an essential prerequisite for the common user participation in a DR program. The presence of these devices favors the energy uses optimization and can lead to an important energy saving compared to the original situation.

The characteristics and composition of the automation system depend on the activities to be controlled and include a central control unit, meters, sensors and actuators [67]. Based on the incidence of individual energy uses [44] and considering the previous sensitivity analysis, it is believed that an automation system must necessarily include sensors for measuring outdoor and indoor temperature, presence sensors, door and window opening detectors. Furthermore, it is required to keep under control the terminals of the heating system as well as those household appliances related to the various flexible loads. For having an evaluation of potential benefits hailing from automation systems adoption, three different configurations of them (called Low kits, Medium kits, and High kits) have been hypothesized, where each one is characterized by a different number of devices and different setups (Table 2).

Table 2. Characteristics of automation kit.

Device		Kit Low	Kit Medium	Kit High
Function	**Type**	**Quantity**	**Quantity**	**Quantity**
Energy box	Gateway	1	1	1
Monitoring	Electricity meter	1	1	1
	Gas meter			1
	Outdoor temperature sensor	1	1	1
	Multi-sensor (temperature, presence, illuminance)	1	1 per room	1 per room
	Windows/doors opening and closing detector	1	1	1 per window + 1
Control	Smart valve		1 per radiator	1 per radiator
	Smart plug	2	4	6
	Smart switch	1 per room	1 per room	1 per room

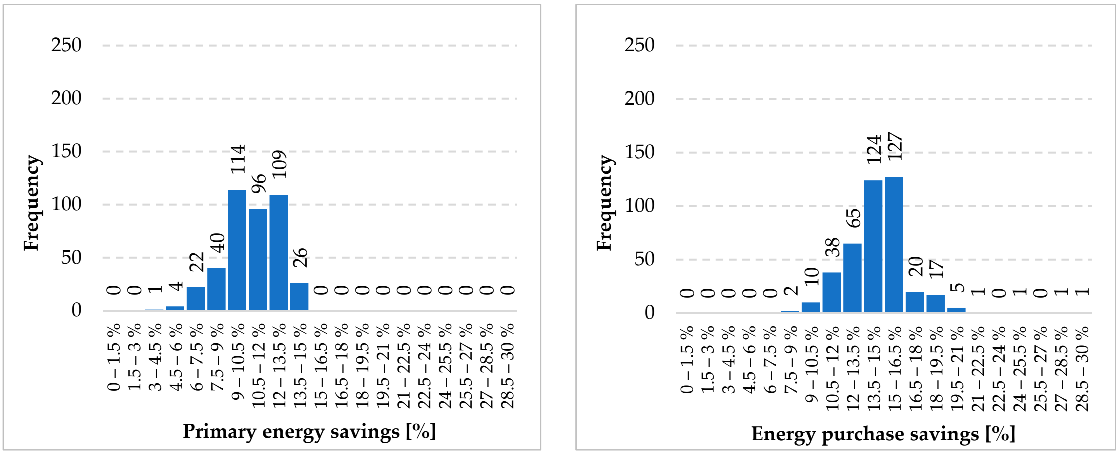
Figure 12 shows the achievable energy and economic savings by the Low kit introduction. The primary energy savings are on average 5.3%, ranging between the minimum value of 2.2% and the maximum value of 6.6%; the economic savings are higher and are on average equal to 9.2%, ranging between 5.3% and 24.4%.



(**a**) (**b**)

Figure 12. Achievable percentage savings due to the Kit Low: (**a**) primary energy savings (**b**) energy purchase.

Similarly, Figure 13 shows the achievable energy and economic savings owing to Medium kit introduction. The primary energy saving is on average equal to 10.8% (4.1% ÷ 14.9%), while the economic saving is on average equal to 14.6% (8.5% ÷ 29.5%).

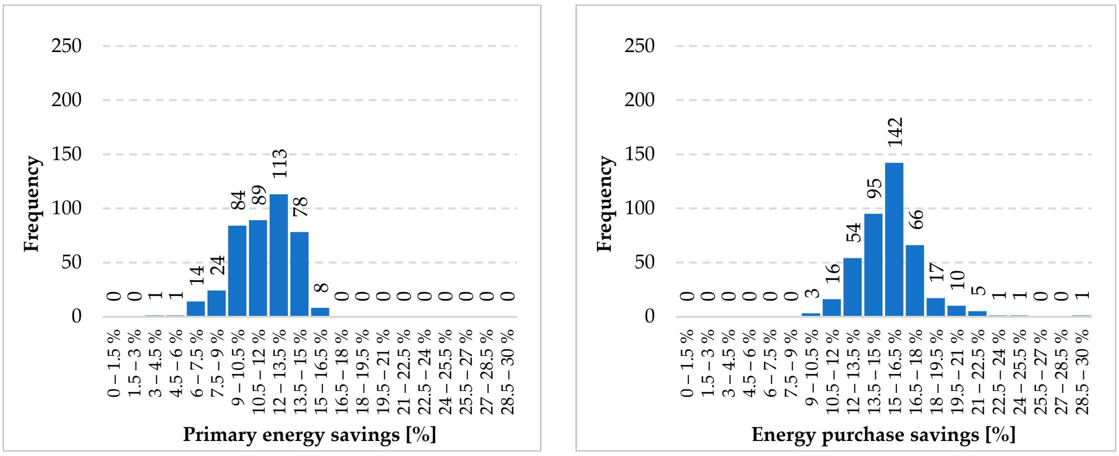


(**a**) (**b**)

Figure 13. Achievable percentage savings due to the Kit Medium: (**a**) primary energy savings (**b**) energy purchase.

Finally, Figure 14 shows the same achievable savings by the High kit installation. The primary energy saving is on average 11.7% (4.3% ÷ 15.8%), while the economic saving is on average 15.5% (9.2% ÷ 30.2%).

The automation kit introduction results in a reduction in energy consumption along with the lessening in the potential of flexibility (i.e., less storable loads, shiftable loads). The energy saving average values and changes in the potential of flexibility are reported in Table 3. The same table also shows the residual potential of flexibility, starting from the current value of 1.042 kWh/y [44].



(**a**) (**b**)

Figure 14. Achievable percentage savings due to the Kit High: (**a**) primary energy savings (**b**) energy purchase.

Table 3. Energy saving and changes in potential of flexibility: average values.

Automation Kit	Energy Saving [kWh-p/y]	Potential of Flexibility Variation [kWh-e/y]	Residual Potential of Flexibility [kWh-e/y]
Kit Low	910	−33	1009
Kit Medium	1850	−68	974
Kit High	1999	−74	968

3.3. The Automation System Introduction: Benefits-Costs Analysis

The energy and economic savings that can be accomplished are quite interesting, but they must still be evaluated accounting also for the capital expenditure related to such a system. For assessing the installation costs associated to each listed device, reference the indicative costs shown in Table 4 have been assumed as reference.

Table 4. Indicative costs.

Function	Type	Description	Price [Euro]
Energy box	Gateway	Gateway Apio	289
	Dongle Z-Wave	USB Adaptor with AeonLabs battery	69
Monitoring	METER electricity	Power meter (2Clamp 60A), v. G2	98
	METER gas	Gas consumption recorder for meters NorthQ—9121	91
	Outdoor temperature sensor	Fibaro sensor	30
	Multi-sensors	Fibaro motion sensor	48
	Opening and closing	Opening detector with dry contact and analogue sensor Fibaro	41
Control	For Chrono-thermostat operation	Micro Double Switch Module Z-WAve Plus Qubino with metering	50
	Smart valve	Radiator Thermostat Danfoss LC13	66
	Smart plug	Fibaro	60
	Smart switch	Hidden On/Off switch AeonLabs (G2) with metering	50

Based on dwellings and kits characteristics, different installation costs occur, as shown in Figure 15.

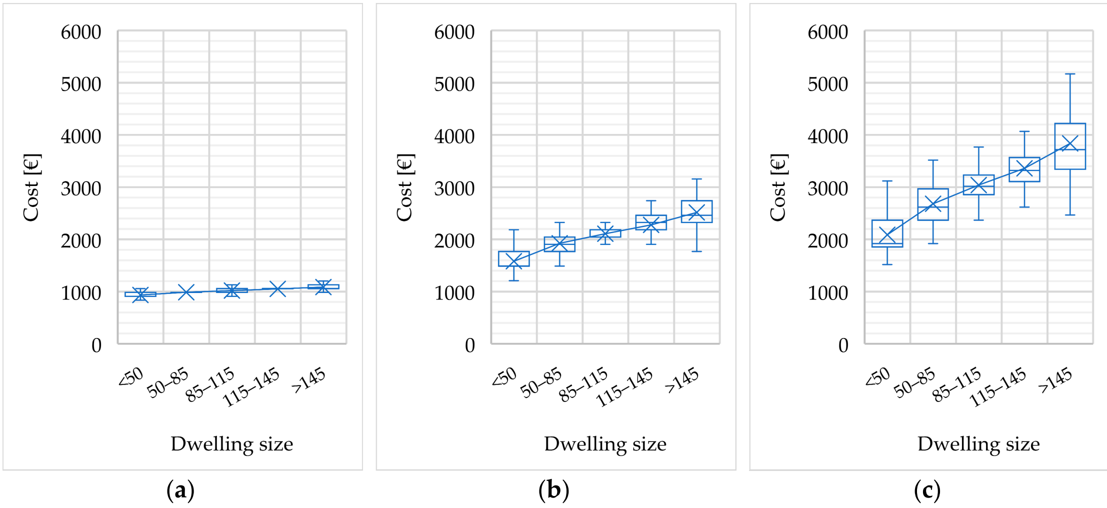


Figure 15. Costs for automation and control systems: (**a**) Kit Low; (**b**) Kit Medium; and (**c**) Kit High.

The discounted payback period (DPP) of the automation kits installation has been calculated, having considered a discount rate of 2% and maintaining both the electricity and gas costs constant.

As can be seen from Figure 16, the DPP is very high, in all cases; for the Low kit it is on average 14.3 years, for the Medium kit it is on average 18.7 years; for the High kit it averages 26.4 years.

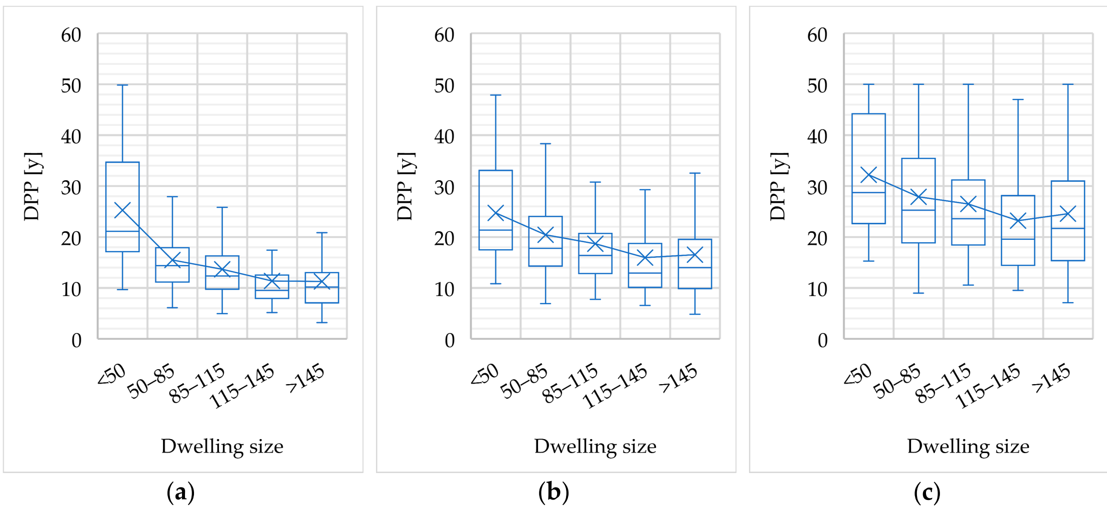


Figure 16. Discounted payback period (DPP) for selected interventions: (**a**) Kit Low; (**b**) Kit Medium; and (**c**) Kit High.

For smaller dwellings, although they are characterized by specific consumption and higher specific costs, the highest return times have been registered; this is caused by the automation kit configuration which foresees in any case a variable number of devices as the dwelling size increases.

In Italy, the automation systems introduction in residences is encouraged and supported by a mechanism of tax deductions. A total deduction equal to 65% of the eligible costs can be discounted over 10 years [54]. The discounted payback period (DPP) associated to those interventions has been calculated accounting also for such an incentive scheme.

From data reported in Figure 17, it emerges how DPPs values are strongly accelerated: for the Low kit implementation, 7.1 years are required, while for the Medium and the High ones 8.3 years 10.4 years are necessary respectively.

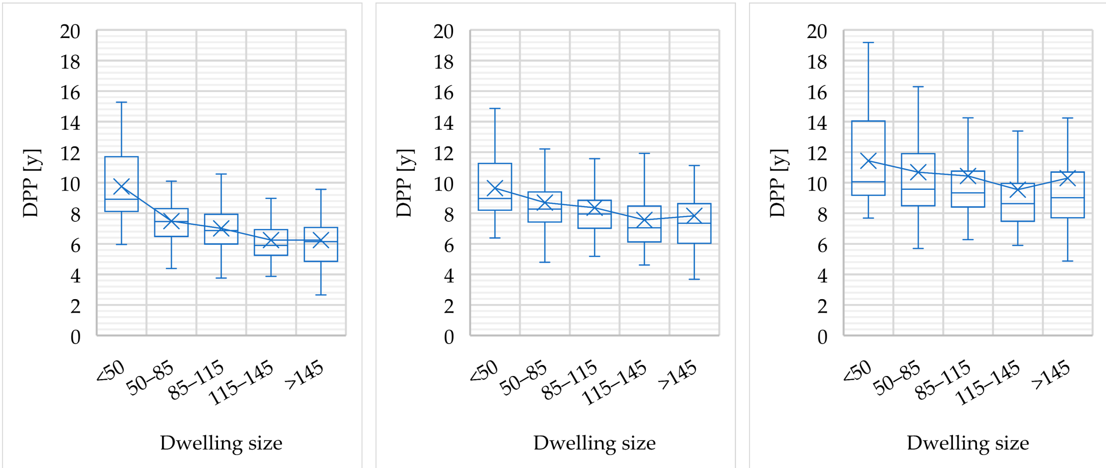


Figure 17. DPP for the selected interventions, with tax deductions: (**a**) Kit Low; (**b**) Kit Medium; and (**c**) Kit High.

To identify the best refurbishment strategy, the newly calculated DPPs must be compared with those related to other interventions typology on residential buildings, such as envelope improvement, plant systems, and household appliances.

For properly comparing the different options, further issues have to be taken into account. A first positive aspect is represented by the low investment total cost ranging from a thousand to around 4000 € in the worst case. Another positive aspect is represented by easy installation and very short execution times.

However, the most important strength point is that the BAC systems are configured as a technology enabling DR programs, even though they offer today a limited remuneration, but in the next future larger revenues are going to occur.

4. Conclusions

The growing RES share in the Italian electricity system entailed higher balancing features due to the renewables non-programmability. In order to level off the demand and production curves as much as possible, the demand/response program can be beneficial for the electric system enhancing loads flexibility. The application of DR programs to residential users can allow to increase the demand flexibility, facilitating the spreading out of renewable energies; however, it shows significant implementation complexities which are mainly represented by the strong loads' fragmentation. Indeed, the Italian building stock consists approximately of 24 million dwellings which are poorly electrified showing flexible loads that are generally low for each single unit.

To enable the participation of residential users in a DR program, the presence of BAC systems the ability to communicate rapidly and effectively with the energy spot market as well as with the utilities is required.

This work uses collected data collection by an online questionnaire based on the Excel platform, allowing to estimate the dwelling energy consumption by a real-time simulation. In order to define the essential characteristics of the automation system to be installed in residential users, a study has been carried out to highlight the correlation and sensitivity of energy consumption to some input data, such as the outdoor temperature, the indoor comfort temperature and the building occupancy rate.

Based on the outcomes, three different automation kits have been defined; for that purpose, the established procedure by the European Standard EN 15232 has been applied so that the accomplished energy and economic savings have been computed. It can be stated that:

- Using the Low automation kit, the primary energy savings are on average 5.3%, while the economic savings are on average equal to 9.2%;

- using the Medium automation kit, the primary energy savings are 10.8% and the economic savings are 14.6%;
- using the High automation kit, the primary energy savings are 11.7% and the economic savings are 15.5%.

The financial analysis on the investments, considering also the incentive scheme provided by the Italian government, indicates that the DPP is generally lower than 10 years. Further positive features related to that intervention typology consist of a limited installation and setup time together with a low capital expenditure. Indeed, the overall costs are approximately equal to 1000 € for the Low kit and up to 4000 € for the High one in larger houses. It entails that such an option it is not capital intensive leading to marginal gains comparable with other basic interventions.

The results hailing from the simulation process certainly seem interesting for Italian residential users; the same procedure applied in this work can be used to verify the impact of BAC systems in other contexts, characterized by different energy uses, different energy costs, and different incentive mechanisms. The pathway of this research will continue with a validation process by an experimental investigation on pilot homes that will necessarily include, at least, one home for each of the following typology: (1) A house with heating and DHW natural gas-based; (2) a house with natural gas boiler and heat pump-based domestic hot water preparation systems; (3) a house with a heat pump for both heating and DHW; (4) a house equipped with a heat pump for heating and DHW production together with photovoltaic systems for on-site electricity generation.

Author Contributions: F.M. contributes to this paper by the conceptualization, software implementation and validation; G.L.B. provided the formal analysis and was the writer of final draft along with the reviewing and editing process; L.d.S. was the project scientific coordinator taking care of funding acquisition and project administration.

Funding: This research received no external funding.

Acknowledgments: This work is a part of a wider research activity dealing with: "Study of an aggregator model for a smart district ". The project has been carried out in cooperation with ENEA-DTE-SEN-SCC (Italian National Agency for New Technologies, Energy and Sustainable Economic Development-Department of Energy Technologies-Smart Energy Division) and CITERA (Sapienza University of Rome-Interdepartmental Research Centre for Territory, Construction, Restoration and Environment). The aforementioned institutions are gratefully acknowledged by the authors for their support and funding.

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

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