Energy Efficiency (2023) 16:83
https://doi.org/10.1007/s12053-023-10158-w

ORIGINAL ARTICLE

Feasibility analysis of the application of building automation and control system and their interaction with occupant behavior

Marta Bottero · Giulio Cavana · Federico Dell'Anna

Received: 15 March 2023 / Accepted: 12 September 2023 / Published online: 20 October 2023

Abstract Occupant behavior is among the main causes for the mismatch between simulated and in-use energy performance of buildings. One of the strategies considered capable of reducing user's behavior induced energy consumption, while increasing indoor environmental quality is the application of Building Automation and Control Systems (BACS). In this study, three building user's profiles have been considered depending on their energy consumption. The energy savings due to BACS class increase have been calculated, and a cost–benefit analysis (CBA) has been performed to evaluate the feasibility of different scenarios. Additional co-benefits perceived by the individuals have been accounted for in the form of willingness-to-pay (WTP). The methodology is applied to two case studies: a nearly zero-energy building (NZEB) rural single-family house and a recently renovated dwelling in an apartment block. The results show that the main reductions are achieved by the users' behavior alone, and the adoption of BACS is economically feasible only when an incentive program is in place, and the WTP is repeated as a recurrent co-benefit over the years. In particular, relying only on energy reduction due to higher BACS class introduction is not economically desirable. The greatest savings are achieved by the behavioral change of the user when coupled with BACS, supporting their potential role in improving user's energy literacy. Finally, incentive schemes are necessary to reduce the investment costs of such projects, being these the most influential variables in the feasibility of BACS applications.

M. Bottero · G. Cavana (✉) · F. Dell'Anna
Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino, 10125 Turin, Italy
e-mail: giulio.cavana@polito.it

M. Bottero
e-mail: marta.bottero@polito.it

F. Dell'Anna
e-mail: federico.dellanna@polito.it

Keywords Nearly zero energy building (NZEB) · Energy efficiency · Smart building · Occupant behavior · Building management systems · Iterative bidding game

Introduction

Nowadays, cities host more than half of the world's population (United Nations, 2019), consume about 75% of the primary energy supply, and account for about 50–60% of the greenhouse gases (GHG) emitted globally (Schiera et al., 2019). Being the building sector one of the main contributors to these emissions (Allouhi et al., 2015), several European policies such as the Energy Efficiency Directive (EED) and the Energy Performance of Building Directives (EPBD) have targeted it to limit its impact. Besides calling for a great reduction of energy consumption, these policies stress the need for the implementation of smart technologies and the increase of digitalization in the building industry (European Commission, 2020b; 2021a, b).

Among the factors that influence energy consumption in buildings (i.e., climate, envelope and systems characteristics, indoor environmental quality (IEQ) requirements), occupants' behavior has been recognized to play a major role (Buso et al., 2015). In particular, when comparing the performance of a building in the simulation phase with the operational one, a consistent difference between the two has been highlighted in several studies (Barthelmes et al., 2016; Fabi et al., 2012; Yan et al., 2015). This "performance gap" has been ascribed to several reasons. For instance, buildings are becoming increasingly complex systems, with final users not fully able to comprehend their functioning, thus, leading to their suboptimal operation (Karjalainen, 2016). A possible solution to this issue has been seen in the enhancement of the building-occupant interaction: by receiving continuous feedbacks from the building, the users might modify their behavior, reducing energy consumption (Abrahamse et al., 2005; Darby, 2001; Faruqui et al., 2010; Fischer, 2008; Grønhøj & Thøgersen, 2011). Several studies indicate that increasing the knowledge of the occupant does not necessary lead to a reduction of energy consumption (Abrahamse et al., 2005; Hargreaves et al., 2013; Nilsson et al., 2014), revealing a lack of agreement on this matter. Another reason for the non-optimal operation of the building resides in the occupant passiveness: users often act in response to a discomfort situation rather than to optimize their energy use, sometimes resulting in over-compensatory measures (Karjalainen, 2016). Considering these limitations, some authors have proposed to opt for design solutions able to diminish the effect of the occupant on energy consumption (Karjalainen, 2016), thus designing "occupant-proof buildings" (O'Brien et al., 2013). For instance, Hoes et al. (2009) proposed the concept of "Robustness" as the sensitivity of a performance indicator to design assumptions when comparing its predicted and actual performance.

One of the strategies to alleviate the performance gap has been individuated in the introduction of smart technologies such as Building Automation and Control Systems (BACS) (Sanseverino et al., 2013). BACS are network of interconnected devices with the aim of reducing energy losses (Bode et al., 2019) and optimize consumption (Su & Wang, 2021), by monitoring the external climate, and controlling both building characteristics and its operational energy. BACS have been considered capable of achieving energy efficiency results in a short to medium time horizon (Mancini et al., 2019), while increasing the indoor comfort of occupants (Felius et al., 2020c), thus avoiding the possible need for them to increase their energy consumption to achieve higher IEQ levels or, vice versa, to reduce their level of comfort in order to save energy (Litiu et al., 2017).

Another advantage of the integration of BACS in households has been recognized in the flexibility provided to the grid through aggregated energy demand management. This has led to some policy experimentations, such as the land transfer conditions in Kalasatama (Helsinki), requiring mandatory minimal integration of automation systems in new-built dwellings (Härkönen et al., 2022). Furthermore, BACS have been recently proposed as self-reporting tools to assess the Smart Readiness Indicator (SRI) of buildings (European Commission, 2020a, b). Similar to other intelligent energy efficiency systems, BACS are able to provide a variety of positive impacts other than financial ones. Reducing consumption, they indirectly reduce GHG emissions (Della Valle & Bertoldi, 2022; Ejidike & Mewomo, 2023) and use of resources (Ejidike & Mewomo, 2023) thus providing environmental benefits. Furthermore, as an energy efficiency measure, they may increase the level of comfort and wellbeing of occupants (Buckman et al., 2014), while reducing energy poverty (Della Valle & Bertoldi, 2022). Finally, thanks to the enhanced capacity of the users to monitor their consumption, these systems have been deemed capable of increasing energy literacy (DeWaters & Powers, 2011), thus aiding in personal energy-related decision taking.

Despite these possible benefits, high level of BACS implementation is relatively limited, representing one of the reasons for their high costs of purchase and installation (Ippolito et al., 2014). In light of the above, it is important to investigate the economic feasibility of this retrofit measure (Felius et al., 2020c), and, also, households' attitude toward these investments (Bottero et al., 2019; Dell'Anna et al., 2022), in order to evaluate both impact and desirability of their widespread adoption. Particularly considering the economic feasibility, a wide range of co-impacts alongside the primary objective (consumption reduction) could be reached by energy efficiency measures, often defined as co-benefits (Becchio et al., 2017; Bisello et al., 2017; Ferreira & Almeida, 2015). With reference to energy efficiency projects, co-benefits have been identified, for example, in the increase in asset values, and better IEQ conditions, but also in more social impacts, such as the increase of air quality due to the reduction of fossil fuel use (Becchio et al., 2018; Garzia et al., 2022; Wang et al., 2015).

The assessment of co-benefit has experienced an evolution in its conceptual framework: regarding IEQ, for example, EU Guidelines (European Commission, 2014), and Fang et al. (2012) initially suggested that in case of consumption reduction and increase in indoor comfort due to an energy efficient project, these two should be valued together; on the contrary, more recent studies showed that co-benefits related to indoor comfort could be estimated independently by means of WTP approaches (Buso et al., 2017), thus testifying an alignment with the paradigm shift also present in sectorial EU policies (EPBD).

In light of the above, the aim of the present study is to investigate the increase or decrease in BACS implementation desirability depending on the specific energy consumption of different building users and the capability of these smart systems to reduce the negative impacts deriving from highly consuming patterns of use, or to further increase savings due to energy-conscious behaviors. The feasibility evaluation is performed with a cost–benefit analysis (CBA) considering user's perceived co-benefits evaluated through the estimation of householders' willingness-to-pay (WTP) for energy-efficient automation technologies. This latter aspect has not been analyzed yet in the literature on BACS feasibility and has been evaluated in the present study by means of a proxy in an iterative bidding game (IBG). Finally, from the literature review on BACS application in the residential sector, it seems that the maintenance costs are rarely taken into consideration. The present study uses the global cost calculation (Becchio et al., 2016) in order to evaluate the project feasibility during its entire lifecycle.

The analysis is applied to two real buildings in Piedmont (Italy). The energy consumption of the two case studies has been already presented in previous publications and has been calculated considering three user's profile to generate input data (average, low, and high consumer). BACS classes A and B are applied to each user profile in each case study as possible retrofit measures, with and without financial incentives in place. Finally, the effect of combining BACS class A and B application with the change in consumption profile of the user is evaluated.

The evaluation of people's attitude, in particular, is fundamental in the analysis of the feasibility of retrofitting interventions: their priorities and preferences, in addition to more properly financial indicators such as payback period and financial capacity and subsidies, might have a crucial role in the willingness to undergo these processes (Edonomidou et al., 2011; Felius et al., 2020c; Bottero et al., 2019; Della Valle & Bertoldi, 2022). This aspect differentiates the present study from previously published ones (see next section), in which the main focus was on the financial aspects alone. The outcomes of this study will be beneficial to estimate the market maturity of these systems and to evaluate the need for financial support in order to promote their wider adoption and, thus, their consequent cost reduction (Ippolito et al., 2014).

The rest of the study is structured in the following way: "Workflow" introduces the workflow and the methods used, "Application" describes the two case studies in which the methodology has been applied; in "Results and discussion," the results are discussed, while in "Conclusions," the conclusions are presented. Finally, in Appendix 1 and 2, an example of the questionnaire used in the IBG and a detailed CBA table are displayed.

Previous works

At the European level, the EN ISO 52120–1:2022 (CEN, 2022) norms the minimum requirements and specifications regarding BACS. In particular, the standard identifies four efficiency classes for building automation based on the types of function that the installed BACS guarantee. The four classes are labeled from A to D. Class C presents minimal automation functionality requirement like central control of the systems with fixed scheduling (e.g., day-night schedule) (Felius et al., 2020c) and represents the standard level of BACS in buildings (EN ISO 52120–1:2022), while class D is characterized by an almost complete absence of automation functionalities. Classes B and A are the most advanced ones in terms of automation level, with the former able to achieve the individual room level of control based on presence, also monitoring the use of energy and faults detection, and the latter extended to include the demand-based control of individual rooms integrating all systems controls (Felius et al., 2020c). The standard provides two different methods to calculate the possible energy savings from the implementation of BACS: a detailed method and a simplified one based on efficiency coefficients.

Several studies have focused on the evaluation of energy consumption reduction by means of the introduction of these automation systems. For instance, Marinakis et al. (2013) proposed an integrated system for buildings' energy-efficient automation and applied it to a supermarket building in Greece. Ożadowicz and Grela (2017a, 2017b) evaluated the energy efficiency effect of BACS implementation in a university building, while Gruber et al. (2015) calculated an energy consumption reduction between 12 and 19% in office buildings, and Colmenar-Santos et al. (2013) calculated potential reductions in a range between 10 and 30% in the same building typology. Chen et al. (2019) analyzed a fully automated window/HVAC control system to optimize natural ventilation. Among the benefits provided by the system, the authors proved a remarkable increase in air quality. Ożadowicz and Grela (2017b) propose the implementation of BACS in the street lighting field.

Considering the low level of automation in the residential building stock, and thus, the potential energy savings achievable, several studies have focused on this sector (Felius et al., 2020a, 2020b; Ippolito et al., 2014; López-González et al., 2016; Mancini et al., 2019; Sanseverino et al., 2013; Van Thillo et al., 2022). López-González et al. (2016) applied the four levels of automation as defined by EN ISO 52120–1:2022 to the Energy Performance Certificates (EPC) dataset of the Autonomous Community of La Rioja (Spain) and evaluated the possible increase in buildings energy ratings. According to the results provided, applying BACS class C, 7.23% of the considered buildings improved their primary energy consumption rating; the application of the second class (class B) increases this number to 23.59%, and the highest performing class resulted in 39.20% of the buildings improving their primary energy rating. A particularly insightful research is the review conducted by Van Thillo et al. (2022). In that study, the authors examined the scientific literature regarding detailed performance analysis of BACS in residential buildings focusing on four functionalities: (i) heating control, (ii) DHW supply control, (iii) lighting control, and (iv) shading control. The analysis concluded that despite the wide variability in the range of savings for the four analyzed functions, the difference between the average energy savings of the detailed calculation and BACS efficiency factors ranges from − 6% for heating emission control function (BACS efficiency coefficient overestimate the detailed calculation savings) to + 16% for lighting control (BACS efficiency factor underestimates the detailed calculation savings).

Few other studies (Table 1) focused on the application of packages of measures to increase the level of automation in residential buildings and estimated the economic feasibility of such interventions. For instance, Mancini et al. (2019) evaluated the application of three different BACS packages (a low level, medium level, and high level ones) to consumption data gathered via an online questionnaire. The application of the three packages resulted in primary energy savings between 5.3 and 11.7% (low level package and high level package respectively), with a discounted payback period (DPP) of 14.3, 18.7, and 26.4 years for the low level package, medium level package, and high level package respectively, and a further reduction below 10 years in case of the presence of financial subsidies. Sanseverino et al. (2013) applied a discounted cash flow analysis (DCFA) to test the feasibility of BACS implementation in a single-family house of 100 m^2 useful floor area. In particular, seven EPC classes have been simulated (from A to G) and the further implementation of BACS has been evaluated. Considering a DCFA over 30 years with 2% discount rate, a 4% energy cost increase, and an investment cost of 6500€, the authors calculated a payback period of 18 years for the implementation of BACS in the lower performing house configuration (class G) and 29 years for the one in the second to best class (class B). For the best EPC class (class A), the payback period exceeds the 30 years of calculation. The inverse correlation between EPC performance and feasibility of BACS implementation has been confirmed by another similar study conducted by Ippolito et al. (2014). In that paper, BACS and Technical Building Management (TBM) systems have been applied to a 140 m^2 dwelling in Rome (Italy), characterized by minimal automation system in place (thus categorized as BACS class D). With the same input data for the DCFA as the previous study (30-year period, 2% discount rate, 4% energy cost increase, 6500€ investment cost), the authors calculated a payback period of 10 years for the class G building, and more than 30 years for the class A one.

As it appears clear from Table 1, the studies that aim to analyze the feasibility of BACS adoption in the residential sector are based on financial indicators such as DPP and discounted lifecycle cost (dLCC). It is also worth noting that all these studies considered the investment cost as input parameters while neglecting other operational costs such as the ones related to the maintenance of the systems. Overall, only one study has investigated the effect of

Table 1 Studies evaluating feasibility analysis of BACS implementation in residential sector

	Case study	Indicator	Input data	Results
Sanseverino et al. (2013)	100 m^2 single-family house from BACS D to A	DPP	• 30 years • 2% discount rate • 4% energy cost increase • 6500€ investment cost	• 18 years DPP for house with EPC class G • > 30 years DPP for house with EPC class A
Mancini et al. (2019)	Various dwelling size from survey + 3 alternative BACS packages	DPP	• 2% discount rate • 65% tax deduction incentives • 1000–4000€ investment cost	• 14.3–26.4 DPP depending on BACS package • 7.1–10.4 DPP depending on BACS package with incentives
Ippolito et al. (2014)	140m^2 single-family house from BACS D to A	DPP	• 30 years • 2% discount rate • 4% energy cost increase; • 6500€ investment cost	• 10 years DPP for house with EPC class G • > 30 years DPP for house with EPC class A
Felius et al. (2020a)	170m^2 single-family house with BACS D, C, B, and A	DPP	• 3% interest rate • 0.03% inflation rate • 3.15% price escalation	• 2.5–8 DPP (compared to BACS class D)
Felius et al. (2020b)	173m^2 single-family house and 4 floors Apt. block BACS together with other retrofit measures	dLCC	• 3% interest rate • 2.1% inflation rate • 3.15% price escalation	Energy consumption reduced to 85% and 76% only with implementation of class A BACS in single-family house and Apt. building respectively

subsidies on the acceptability of BACS implementation, while none has considered other benefits rather than the financial ones. On top of that, no previous study has evaluated the interaction of different occupant's energy consumption behaviors with savings deriving from BACS, nor users' WTP for improvements in IEQ and occupant satisfaction as possible co-benefits arising in this kind of operations (Garzia et al., 2022), or for the reduction of environmental impacts related to energy consumption.

Workflow

As stated previously, the aim of this work is to evaluate the impact that BACS application could have on residential buildings as potential retrofit measures, together with different occupant energy behavior and, in particular, to assess the feasibility analysis of such interventions. To do so, the workflow represented in Fig. 1 has been followed. In step 1, three user's profiles have been defined to model occupants characterized by either an average, high-, or low-energy intense behavior, and their energy consumption has been calculated for two case studies. In the second step, the savings achieved by the upgrade from BACS class C (a building with standard level of automation and control features in place) to BACS classes A and B as retrofit measure have been calculated according to EN ISO 52120–1:2022 (CEN, 2022) for each of the user profiles. Furthermore, the WTP for smart energy efficient devices has been evaluated to consider the attitude of the users toward these types of goods (step 3). Finally, in step 4, the economic feasibility of the implementation of BACS has been evaluated for the three user's profile and different scenarios using the previously calculated parameters and possible incentive schemes as input data. In the following section, the steps of the workflow are explained in details.

Occupants' behavior characteristics

To take into consideration the influence of occupants' behavior lifestyle on energy consumption, three consumers' profiles have been considered (Barthelmes et al., 2016): low consumer (LC), average consumer (AC), and high consumer (HC), according to the comfort categories permitted by EN 16798–1:2019 (CEN, 2019). The comparison of different user profiles' energy consumption in identical buildings is a common practice to understand the impact of occupant behavior on energy

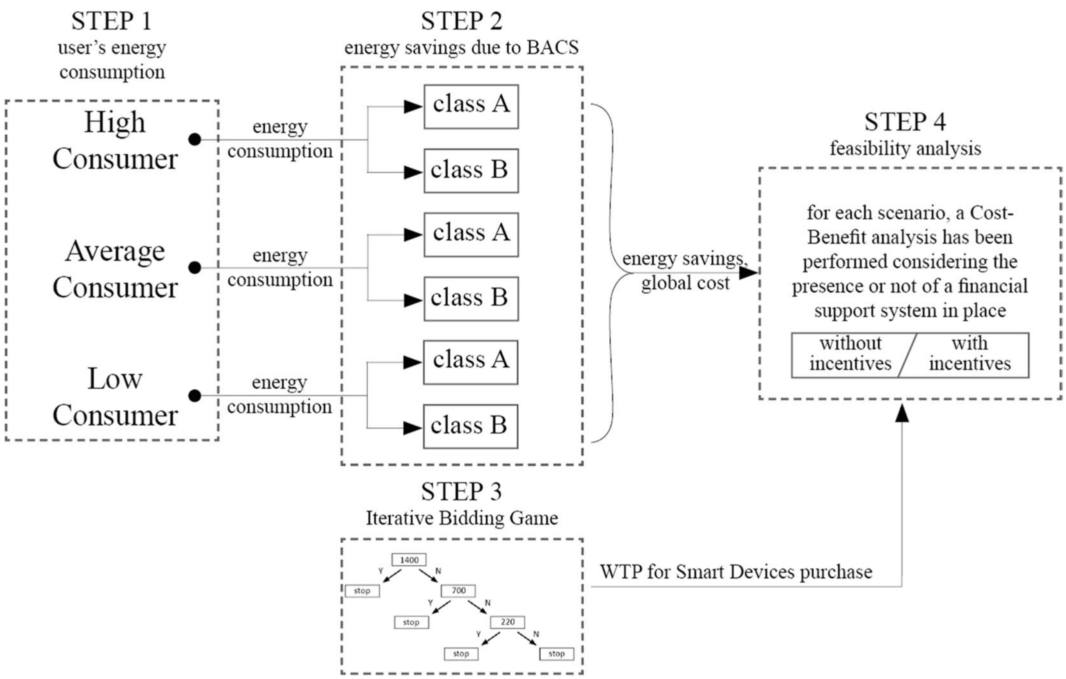

Fig. 1 Scheme of the workflow of the study

consumption (Fabi et al., 2012) and is justified by the attempt of the analysis to assess the effect that the application of automation and control systems could have when applied to different user's consumption patterns, and to test if the building performance dependency from the user's behavior could result, on the one hand, in the mitigation of the performance gap, or, on the other hand, in a virtuous overlapping of effects in case of energy conscious consumption patterns. The three profiles used in this study are characterized through the different assumption made to define the input parameters to calculate their energy consumption (Table 2). In particular, the set points for heating and cooling services as well as ventilation rate have been assigned using the comfort categories as defined by the EN 15251:2007 (CEN, 2007) and confirmed by EN 16798–1:2019 (CEN, 2019): I category, II category, and III category for the HC, AC, and LC, respectively. The HC profile has a constant temperature set-point, while AC and LC present a set-back temperature during night of 2 K in heating season (October 15–April 15), and 1 K in cooling season (April 30–September 30). The electric consumption schedule for lighting and appliances of the AC has been taken from reference residential building occupancy as from the dataset of the Department of Energy (DOE), with power densities equal to 3.88 W/m^2 and 5.89 W/m^2 for lighting and electric appliances, respectively. The same consumption schedule with a decrease of 10% constitutes the assumption made to calculate the energy consumption of the LC, while an increase of 10% has been used to define the HC (Barthelmes et al., 2016). Considering the opening/closing schedule of the blinds, for HC, they have been assumed always open, while AC is assumed to close them when the solar radiation is higher than 300 W/m^2 and LC controls the opening and closing schedule depending on the optimization of daylight. Finally, for domestic hot water (DHW) previous literature has been used to define this consumption (Barthelmes et al., 2016).

Standard EN ISO 52120–1:2022 "Energy performance of buildings — contribution of building automation, controls, and building management"

As it has been shown in the previous section, the user profile dependent variables used in the energy simulation result in different consumption values for each of the three. By combining each profile with BACS efficiency classes B and A, plus the status quo (BACS

Table 2 Low consumer (LC), average consumer (AV), and high consumer (HC)

	LC	AC	HC
Heating operation and set point	5 a.m.–11 p.m. 18 °C 11 p.m.–5 a.m. 16 °C	7 a.m.–8 p.m. 20 °C 8 p.m.–7 a.m. 18 °C	0 a.m.–12 p.m. 21 °C
Cooling operation and set point	5 a.m.–11 p.m. 27 °C 11 p.m.–5 a.m. 28 °C	7 a.m.–8 p.m. 26 °C 8 p.m.–7 a.m. 27 °C	0 a.m.–12 p.m. 25.5 °C
Ventilation rate (AHC)	0.5	0.6	0.7
Appliances	− 10% compared to AC	Typical operational levels (DOE dataset)	+ 10% compared to AC
Lighting schedule	− 10% compared to AC + optimized control (continuous/off dimming)	Typical operational level (DOE dataset)	+ 10% compared to AC
Blinds	Optimized through daylight control (if glare index > 22)	Only if solar radiation > 300 W/m^2 on glazed surface in summer	Always open
Domestic hot water (DHW)	40 [l/pers*day]	60 [l/pers*day]	80 [l/pers*day]

class C), the achievable energy savings are calculated. In the present study, six functions from the ones listed in EN ISO 52120 1:2022 Table 5 have been considered: (i) heating and (ii) cooling control, (iii) ventilation and air-conditioning control, (iv) lighting control, (v) blind control, and (vi) technical home and building management. DHW functions have not been considered due to the possible discomfort reasons and potential health hazards that could emerge from such applications (i.e., increased Legionella contamination risks) (Van Thillo et al., 2022). The reader is referred to ISO 52120 1:2022 Table 6 for a detailed overview of the different BACS classes functions.

The estimation of the building energy consumption reduction after BACS implementation has been performed according to EN ISO 52120–1:2022 simplified method, with the following Eq. (1):

$$E_{i,v,BAC} = E_i \times \frac{f_{BAC,v}}{f_{BAC,v,ref}} \quad (1)$$

where $E_{i,v,BAC}$ is the energy consumption for a generic service i using energy vector v, and E_i is the energy consumption for the same service i with the original class of BACS, $f_{BAC,v}$ is the efficiency factor of the applied class for the energy vector v, and $f_{BAC,v,ref}$ is the efficiency factor of the service with the original class of BACS.

IBG

Being the knowledge about advanced BACS relatively limited (Ippolito et al., 2014), it is not possible to directly estimate the WTP of consumers toward them (Bottero et al., 2019; Dell'Anna et al., 2022). To solve this issue, a proxy has been considered, to account for the consumer's WTP for smart devices capable of reducing energy consumption through the interaction with the user. In this work, three possible intelligent appliances commonly known by purchaser and characterized by a high degree of smartness have been defined as proxies in order to estimate the consumers' WTP towards this type of goods (considering BACS belonging to this broad category of smart devices). To guarantee the consistency of the evaluation, the price of each of those appliances has been defined through a real price market analysis and has been used to build an iterative bidding game (IBG) in the framework of conjoint valuation methods (CVM). The IBG is an evaluation method based on asking an individual for their intention to accept or not an offer at a certain price, if the respondent accepts the offer, then the interviewer asks again for the same offer at a higher price. The process is reiterated until the interviewee declines the offer. The interview could also be conducted in the other way round, starting from a certain price and lowering it down until the respondent accepts. The outcome of this analysis will be an estimation of the indiaviduals' WTP to purchase energy-efficient smart goods and, as an assumption, to invest in BACS. The use of the chosen proxy is justifiable for two main reasons: on the one hand, it is likely that the respondent would be more familiar with such common devices, thus being able to take decisions related to purchase acceptance or denial that better reflect their real preferences, and, on the other hand, allows to provide the respondent with consistent costs and energy savings data, independent from the specific respondent's

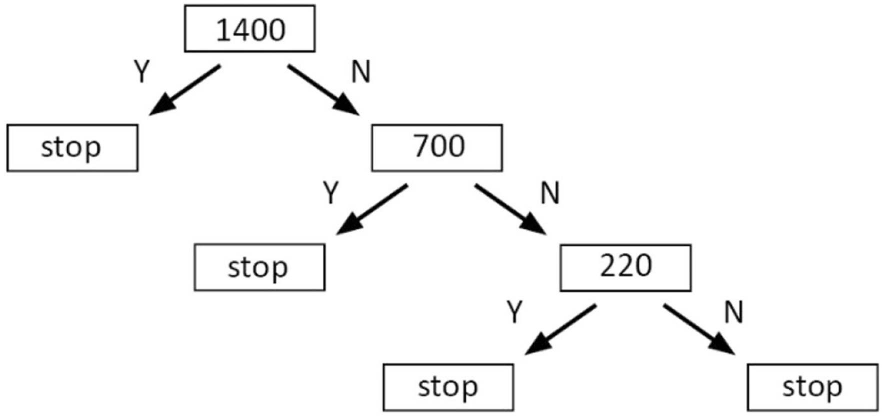

Fig. 2 Example of one bidding game scheme

energy consumption data. Nonetheless, it is worth noting that the price for the three appliances proposed in the IBG is well below the cost for the installation of BACS; therefore, we could reasonably say that the estimation will be conservative. IBM SSPS[1] software is used to analyze the collected data. Figure 2 provides an example of one IBG scheme.

CBA

Cost–benefit analysis (CBA) is an analytical tool used in investment decision. From a theoretical point of view, it integrates the economic dimension into the financial analysis typical of a life-cycle cost (LCC) evaluation (Becchio et al., 2019a, 2019b), in order to take into consideration externalities (positive and negatives) in the assessment process (Becchio et al., 2018). Performing a CBA is not a trivial task. In fact, if on the one hand the monetization of direct costs and benefits are a relatively straightforward procedure, on the other hand, the assessment of non-market values requires specific evaluation approaches (i.e. WTP and Opportunity Cost, for instance) (Rosso et al., 2014; Beria et al., 2011).

In a CBA, different indicators are used to evaluate the feasibility and performance of the investment. In the present study, the net present value (NPV), internal rate on return (IRR), and discounted benefits-cost ratio (B/C) have been considered. The net present value calculates the difference between the discounted cash flow and the initial investment costs according to Eq. (2):

$$NPV = \sum\nolimits_{t=1}^{n} \frac{C_t}{(1-r)^t} - C_0 \tag{2}$$

where n is the time horizon, t is the cash flow period, C_t is the net cash flow at time t, C_0 is the initial investment costs, and r is the discount rate. Three are the possible situations that could arise from this calculation: (i) if NPV > 0, then the benefits are greater than the costs resulting in an acceptability of the project; (ii) on the other way round, if NPV < 0 than the project is not acceptable; and (iii) NPV = 0, in which case the position toward the project is indifferent because discounted costs and benefits are equivalent. IRR is a metric of the risk of an investment and is calculated solving Eq. (3) for r when NPV = 0:

$$0 = \sum\nolimits_{t=1}^{n} \frac{C_t}{(1-IRR)^t} - C_0 \tag{3}$$

Finally, B/C is the ratio between the discounted benefits cash flow and the discounted costs cash flow, according to Eq. (4):

$$B/C = \frac{\sum_{t=0}^{N} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{C_t}{(1+r)^t}} \tag{4}$$

Application

Case studies, energy consumption of user's profile, and BACS-related savings

Two case studies from previous publications (Barthelmes et al., 2016; Boggio, 2017; Vandelli, 2018) have been examined in the present paper to evaluate the feasibility

[1] IBM Corp.: Released 2020. IBM SPSS Statistics for Macintosh. Version 27.0.

Table 3 CorTau House energy consumption for each user's profile in kWh/m^2 year (Source: Barthelmes et al., 2016)

User profile	Heating	Cooling	Ventilation	Lighting	Appliances	Pumps	Tot
LC	3.56	1.76	4.65	5.91	27.19	0.15	43.22
AC	3.94	2.62	5.58	11.17	31.90	0.18	55.39
HC	5.38	3.10	6.27	14.30	36.07	0.36	65.47

Table 4 Retrofitted apartment energy consumption for each user's profile in kWh/m^2 year (Source: Boggio, 2017)

User profile	Heating	Cooling	Ventilation*	Lighting	Appliances	Pumps	Tot
LC	6.60	1.31	-	10.51	19.98	0.09	38.49
AC	8.75	2.15	-	12.59	20.83	0.12	44.44
HC	12.22	2.95	-	14.51	30.65	0.15	60.48

*In the retrofitted apartment no ventilation service has been considered

of BACS application as a retrofit measure in existing buildings. The first one refers to CorTau house, a 147-m^2 retrofitted traditional rural single-family house located in Piedmont region (Italy) (Barthelmes et al., 2016), while the second case study is a 78.5 m^2 retrofitted dwelling in a six-story apartment block dated between 1991 and 2005, located in Turin (Italy) (Boggio, 2017). The CorTau house is a nearly zero energy building (NZEB) building, with high-performance solutions for energy reduction. The second case study presents characteristics compliant with the national standard (see provided references for more details). The energy consumption for each of the two case studies combined with the three users' profile is displayed in Table 3 for CorTau House and Table 4 for the retrofitted apartment.

In both case studies, the status quo has been considered with BACS class C already in place (the two buildings are recently retrofitted ones; therefore, a minimal level of automation has been accounted for, and the categorization of them in the class D has been rejected). The energy savings have been calculated using the percentages for classes A and B compared to the reference building (BACS class C), as provided by EN ISO 52120–1:2022 simplified method. The coefficients provided by the standard are displayed in Table 5.

For example, in order to calculate the energy saving determined by the increase from BACS class C to BACS class A concerning the heating service for the AC in the retrofitted apartment (6.60 kWh/m^{2}y) as reported in Table 4; using Eq. (1), it is possible to calculate the energy reduction due to the increased efficiency:

Table 5 BACS efficiency factors for single-family houses (elaboration from EN ISO 52120 1:2022)

Building energy need	BAC efficiency factors			
	D	C	B	A
Thermal energy	1.10	1.00	0.88	0.81
Electric energy	1.08	1.00	0.93	0.92
Heating	1.09	1.00	0.88	0.81
Cooling	-	-	-	-

$$E_{h,e,BAC} = 6.60 \times \frac{0.81}{1.00} = 5.35\left(\mathrm{kWh/m^2year}\right) \quad (5)$$

A specific efficiency factor for cooling in residential building is not provided by the standard. For this service, the thermal energy efficiency factor has been used (0.88 for class B and 0.81 for class A). Also, the efficiency factor for the appliances is not given by the standard, a coefficient equal to the electrical one (0.93, and 0.92) has been hypothesized.

The prices for the installation of the two classes have been calculated referring to a well-known automation system provider's price list (bticino). In particular, in Table 6, an overview of the prices for each of the considered functions is given.

The main difference in terms of investment costs is represented by the heating and cooling function and the lighting control one. For the former, the main difference is presence of advance feedback control systems in the heating and cooling functions (thermal probes) for class A, while in both cases, individual room thermostats and relative feeders are the main voice of cost. For the latter, the absence in BACS class B of presence detection and dimming systems represents the main reason for the lower investment cost, while in both applications, actuators for lights automatic switch-off are introduced. For both applications, the main voice of expenses is the TBM, where the communication interfaces with the user, the data logger, and the smart sockets for the smart control of the appliances (including audio/video web server for remote control) are accounted for.

Determination of willingness-to-pay

The IBG has been designed using three high-performance smart home devices considered as proxies to evaluate the respondents' WTP for intelligent energy-savings goods. The three devices are (1) a washing machine, (2) a dishwasher, and (3) smart sockets able to program energy uses. To determine the prices of these devices, a market survey has been conducted, and an average of their selling prices has been calculated. These prices are shown in Table 7, along with the energy savings calculated according to the National Energy Regulation Authority (ARERA) using a price for electricity of 0.195891 €/kWh (value referred to the last four months of 2017).

The survey has been performed by means of questionnaire distributed both online (using Google Form) and in face-to-face interviews. The prices calculated for the smart appliances have been used to define the different offers with which the interviewee had to be presented in the IBG: (i) 220€ was the purchasing price of five smart sockets, (ii) 700€ has been set as the cost of either a dishwasher or a washing machine, and (iii) 1400€ is the prices for the purchase of both dishwasher and washing machine (these prices are not an exact average or a sum, but a representative price chosen to make the communication of the IBG easier to the respondent). In particular, the choice to use the price for five sockets instead of only one was motivated by the low price of this device and the necessity to ask a consistent question in the questionnaire (asking for a purchase of just one socket would have been useless within the aim to represent a proxy for a much bigger investment as it would be the installation of BACS). Following the example displayed in Fig. 2, the typical procedure to perform the IBG is to ask the interviewee if they would accept to purchase the good at 1400€ price ("would you spend approximately 1400€ to purchase a "smart-dishwasher" and a "smart-washing machine" that would result in an annual saving of 46€ compared to traditional appliances?"); if yes, then the experiment is concluded. If the interviewee declines, a second offer with a lower price is proposed ("would you spend approximately 700€ to purchase a "smart-dishwasher" that would result in an annual saving of 16€ compared to traditional washing machine?"). The process is repeated until the last offer is proposed and the respondent either accepts or denies it.

The design of the questionnaire is important in relation to the gathering of data; to define if a different starting price in the experiment does affect the results, three types of questionnaires have been designed changing the starting point of the IBG (see Appendix 1 for an example). Fifty-one questionnaires for each typology

Table 6 Investment costs for different BACS classes in the two case studies

	CorTau house		Retrofitted apartment	
Functions	Class A	Class B	Class A	Class B
Heating and cooling	7216.29	5562.72	3458.08	2914.79
Ventilation and air-conditioning*	971.75	971.75	-	-
Lighting	6278.82	4118.84	3111.18	2185.60
Blind	526.92	526.92	403.80	403.80
TBM	7574.96	7574.96	4644.88	4644.88
Total	22,568.74	18,755.23	11,617.94	10,149.07

*As stated before, the retrofitted apartment does not have a mechanical ventilation service in place

Table 7 Average cost, energy consumption, and annual cost savings of the three appliances

	Averaged purchase price [€]	Energy consumption [kWh/year]	Savings compared to class A [%]
Washing machine	720.68	152	49
Dishwasher	690.71	255	27
One smart socket	42.73	-	-

Table 8 Declared purchasing price

Proposed cost [€]	Questionnaire 1 (starting price = 1400€)		Questionnaire 2 (starting price = 220€)		Questionnaire 3 (starting price = 700€)	
	No. of answers [*N*]	Frequency [%]	No. of answers [*N*]	Frequency [%]	No. of answers [*N*]	Frequency [%]
0	5	9.8	24	47.1	6	11.8
220	5	9.8	3	5.8	6	11.8
700	6	11.8	11	21.6	19	37.2
1400	35	68.8	13	25.5	20	39.2
Declared purchasing price		1064.71€		520.78€		835.69€

have been filled, resulting in a total of 153 questionnaires collected between January and February 2018. Detailed information regarding the responses to the IBG is provided in Table 8.

Averaging the declared amount resulted from the three types of questionnaires, a WTP for the purchase of smart appliances of 807.06 € has been calculated.

It is worth noting that the three typologies of questionnaires had an interesting pattern of responses. In particular, the two typologies with higher starting points for the IBG (1400€ and 700 €) have also the highest percentage of positive answers (68.6% and 78.4% respectively), while the one with the starting point at 220€ (the price of the smart sockets) has a lower rate of positive answers (52.9%); this could be explained by the difficulty of stating an unambiguous saving potential for the smart sockets and, therefore, a cull out of a significant number of respondents in the initial phase of the survey.

CBA

In the last step of the evaluation, the feasibility of the installation of BACS class A and B has been analyzed. The CBA has been performed in Excel, using a 30-year horizon, with a discount rate of 2% (Becchio et al., 2019b; European Commission, 2012). The costs considered in the calculation are the initial investment cost, the installation cost, and maintenance cost, while the discounted residual value (20% of the investment cost) and energy savings constituted the benefits, together with the WTP calculated by means of the IBG. The replacement of the system components is not considered in the present study. This hypothesis has been taken due to the high uncertainty related to the expected life-span of BACS components (Vandenbogaerde et al., 2023), and again, this choice is consistent with the previously mentioned studies on the topic ("Previous works"). The price of electricity has been calculated according to ARERA (ARERA) using an electricity price of 0.23369€/kWh (average of prices for 2021). A first scenario has been evaluated calculating WTP as a one-off benefit and therefore considering it just in the first year; in a second scenario, it has been calculated as a recurrent benefit every 5 years after the first. This assumption is justified considering the fact that such appliances often have medium lifespans (about 10 years in the case of washing machines and dishwasher according to Cooper, 2004), and thus, it is assumed that the respondent would replace these devices more than once in the time span considered in the CBA, while their cost is sensibly lower than a BACS; therefore, the 5 years choice for the recursive allocation of the co-benefit has been taken as a fair assumption. Furthermore, the distribution of such benefit during the 30-year lifespan is conservative considering that the discount rate contributes to reduce its value. Furthermore, in the second scenario, a tax deduction scheme has been considered as a common financial incentive (Bertoldi et al., 2013; Della Valle & Bertoldi, 2022). This latter consists of a 65% tax deduction incentive scheme of the initial costs (investment cost and installation cost) over a period of 10 years. As mentioned earlier, in CorTau house, the investment cost for the class A and B is 22,568.74€ and 18,755.23€ respectively, while for the retrofitted apartment, they amount to 11,617.94€ and 10,149.07€ for class A and B respectively. The installation cost has been estimated in 3134€ and the maintenance cost in 100€/year in both case studies and scenarios.

Results and discussion

Figures 3 and 4 provide the energy savings achievable with the application of the BACS class A and B to the considered case studies, while Tables 9 and 10 display the financial savings.

Considering Tables 9 and 10, it is possible to highlight how the different uses of energy due to the different energy performance of the two case studies determines a difference in the aggregated impact of the application of the BACS classes. In particular, in the CorTau house case study, the application of BACS class B and A results in a reduction of energy expenditure in the range between 7.6 and 9.4%, while in the second case study, these figures increase to around 8 and 10%. This difference is explainable in the impact that heating-related consumption has on the total: in the retrofitted apartment, the consumption for heating is low but not negligible, and the BACS efficiency factor for this service is the highest among the one provided by the standard (0.81 and 0.88 for class A and B), while in the CorTau house, this efficiency factor reduces a consumption value that is negligible compared to the total (less than 10% of the total energy costs). Regarding the energy consumption for appliances, this component of the energy consumption is predominant in the two case studies. It becomes worth remarking that the BACS efficiency factor used for this service has been hypothesized as equal to the electrical energy use. Such consideration could justify other experimentation and, especially considering future trends of distributed energy generation and demand-response research, further investigation in the quantification of the actual impact that BACS could have on this service (also with the goal of proposing a specific efficiency parameter to integrate the standard).

When compared to the average consumer, in the first case study (CorTau house), the HC profile spends 18.2% more than the AC one, and the application of both BACS classes sensibly reduces their energy demand. Nonetheless, the application of both classes is not enough to compensate the increase in energy consumption determined by the occupant's behavior and both the class B and class A scenarios resulted in an increase of costs of 9.2% and 7.1% respectively when compared to an average consumer. The LC profile already spends 22.0% less, and the implementation of the two classes of BACS further contributes to increase this figure, reaching 27.9% and 29.3% energy savings. Also, the results for the second case study show that the LC and HC profiles have an impact on the energy costs sustained, with bigger effect linked to a non-environmentally conscious behavior, and smaller savings granted by the conscious occupant in comparison to the highly efficient house case study (CorTau house). In particular, the LC has an expense lowered by 13.4% compared to the AC, while this profile coupled with the highest class of BACS achieves savings of 22.3% and 20.3% in case of the application of the class B. Similar to the previous case, the HC profile sees a reduction in costs when applying the BACS compared to the AC, but, nonetheless, this improvement is not able to compensate the higher energy intense behavior of the occupant. More in detail, the HC coupled with BACS class B spend 24.9% more in energy compared to the AC, while the application

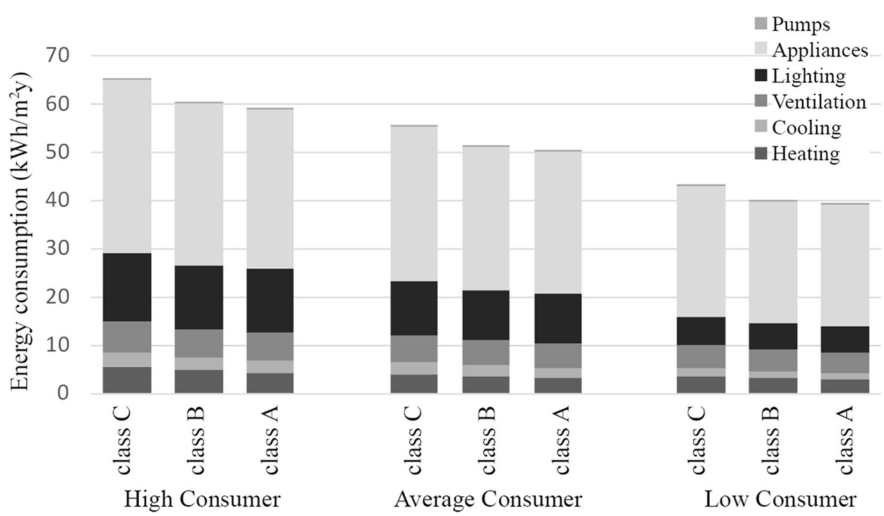

Fig. 3 CorTau house savings potential in different scenarios

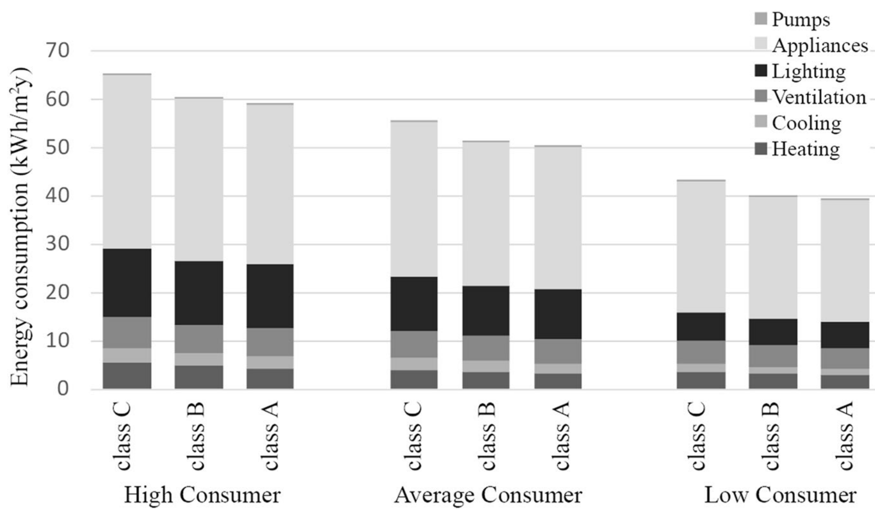

Fig. 4 Retrofitted apartment savings potential in different scenarios

Table 9 CorTau house costs and savings potential in different scenarios

	Average consumer			Low consumer			High consumer		
BACS class (-)	C	B	A	C	B	A	C	B	A
Heating (€/m^2 year)	0.92	0.81	0.75	0.83	0.73	0.67	1.26	1.11	1.02
Cooling (€/m^2 year)	0.61	0.54	0.50	0.41	0.36	0.33	0.72	0.64	0.59
Ventilation (€/m^2 year)	1.30	1.21	1.20	1.09	1.01	1.00	1.47	1.36	1.35
Lighting (€/m^2 year)	2.61	2.43	2.40	1.38	1.28	1.27	3.34	3.11	3.07
Appliances (€/m^2 year)	7.45	6.93	6.86	6.35	5.91	5.85	8.43	7.84	7.75
Pumps (€/m^2 year)	0.04	0.04	0.04	0.04	0.03	0.03	0.08	0.08	0.08
Total (€/m^2 year)	12.94	11.96	11.74	10.10	9.33	9.16	15.30	14.13	13.86
Cost variation (%)*	-	−7.6%	−9.3%	-	−7.6%	−9.4%	-	−7.6%	−9.4%
Cost variation (%)†	-	−7.6%	−9.3%	−22.0%	−27.9%	−29.3%	18.2%	9.2%	7.1%

*Compared to the same user profile, †compared to the AC

Table 10 Retrofitted apartment costs and savings potential in different scenarios

	Average consumer			Low consumer			High consumer		
BACS class (-)	C	B	A	C	B	A	C	B	A
Heating (€/m^2 year)	2.04	1.80	1.66	1.54	1.36	1.25	2.86	2.51	2.31
Cooling (€/m^2 year)	0.50	0.44	0.41	0.31	0.27	0.25	0.69	0.61	0.56
Ventilation (€/m^2 year)	-	-	-	-	-	-	-	-	-
Lighting (€/m^2 year)	2.94	2.74	2.71	2.46	2.28	2.26	3.39	3.15	3.12
Appliances (€/m^2 year)	4.87	4.53	4.48	4.67	4.34	4.30	7.16	6.66	6.59
Pumps (€/m^2 year)	0.03	0.03	0.03	0.02	0.02	0.02	0.04	0.03	0.03
Total (€/m^2 year)	10.39	9.53	9.27	8.99	8.27	8.07	14.13	12.97	12.61
Cost variation (%)*	-	−8.2%	−10.7%	-	−8.0%	−10.3%	-	−8.3%	−10.8%
Cost variation (%)†	-	−8.2%	−10.7%	−13.4%	−20.3%	−22.3%	36.1%	24.9%	21.5%

*Compared to the same user profile, †compared to the AC

Table 11 Results of CBA with application of class B

	AC to AC + B		LC to LC + B		HC to HC + B	
Incentives	(-a) without	(-b) with	(-a) without	(-b) with	(-a) without	(-b) with
NPV [€]	− 8855.01	− 1251.52	− 9073.56	− 1470.07	− 8317.03	− 713.54
IRR [%]	− 5.95	− 1.27	− 6.14	− 1.46	− 5.51	− 0.79
B/C	0.37	0.91	0.35	0.89	0.41	0.95

of the highest performing class of BACS lowers the cost increase for the occupant to 21.5% more than an AC.

Considering the relatively low savings, the particularly high cost of investment of the first case study makes it unfeasible even considering the most advanced application of BACS class A in combination with a hypothetical change of user's habits (LC + BACS class A compared to an AC). Thus, the CBA has been applied only on the second case study (the retrofitted apartment). In particular, BACS classes A and B have been applied to each of the three profiles; thus, AC + B considers the application of BACS class B to the average consumer, while AC + A considers the application of BACS class A to the same profile. Analogously, HC + B and HC + A refer to the application of the two classes to the high consumer profile respectively, and LC + B and LC + B the application to the last profile. Furthermore, each of the scenarios has been evaluated without incentives (-a) and with incentives (-b). The WTP is calculated as a recurrent benefit occurring every 5 years.

Table 11 shows the summary results for the application of BACS class B to each profile, while Table 12 presents the results for the application of class A. The best performing scenarios are the two applying BACS class A and B to the HC profile, but, nonetheless, none of the simulated cases shows feasibility indicators determining the acceptability of the intervention (positive NPV and IRR and B/C greater than 0). This is in line with the results from the literature review by Vandenbogaerde et al. (2023), where the authors reported the correlation between high-energy savings and high prior energy consumption. Furthermore, the absence of incentives drastically affects the feasibility indicators, highlighting economic performance of the proposed scenarios far from desirability.

The monetary benefit of energy savings is limited: the application of BACS class A to a LC (LC to LC + A) results in a reduction of energy cost of 0.92 €/m^2 year (and a total of 72.22€/year), while the scenario considering the HC profile (HC to HC + A) achieves savings of 1.52 €/m^2 year (119.32€/year in total). Among the three applications considering BACS class B, the best performing one is the one involving HC profile, with energy savings as low as 1.17 €/m^2 year (91.84€/year), severely hindering the profitability of the intervention.

A further analysis has been performed combining the effect of the application of BACS classes, together with a simulated change of behavior of the user passing from an AC to a more conscious LC profile. Table 13 shows the results for these two simulated scenarios, while in Appendix 2, the case in which the application of BACS class B coupled with the change of user profile from AC to LC (AC to LC + B) is displayed in detail (being that the more profitable scenario).

In these last two cases, the savings achieved result in a slightly higher expenditure reduction compared to the previous cases and in particular of 2.31€/m^2 year (181.33 €/y) for BACS class A, and of 2.11€/m^2 year (165.63 €/year) for BACS class B. This determines a positive outcome: when the incentives are present, both the applications are economically feasible, with a positive NPV and a B/C greater than one. Nonetheless, the profitability of the intervention is quite limited, with IRR as low as 0.34%, and 0.49% in case of the application of class A and B respectively, and, in particular, a PBP of 30 years for both the

Table 12 Results of CBA with application of class A

	AC to AC + A		LC to LC + A		HC to HC + A	
Incentives	(-a) without	(-b) with	(-a) without	(-b) with	(-a) without	(-b) with
NPV [€]	− 9695.79	− 1251.49	− 10,015.21	− 1570.91	− 9006.51	− 562.21
IRR [%]	− 5.77	− 1.14	− 6.01	− 1.40	− 5.27	− 0.61
B/C	0.37	0.92	0.35	0.90	0.41	0.96

feasible scenarios. The results of the combination of both BACS classes and user's behavioral change present some interesting discussion points. First of all, it results clear that the high initial investment cost deeply affects the feasibility of the interventions: the difference between the two applications is as low as 1469€, but the increase in the initial investment is not repaid by higher enough energy savings during the analysis lifecycle, determining that the behavioral change alone has greater influence on the reduction of operational costs. Compared to the previous studies reported in "Introduction," the upfront cost of the proposed intervention is quite high: in Sanseverino et al. (2013) and Ippolito et al. (2014), the investment cost amounts to only 6500€, while in Mancini et al. (2019), that figure was as low as 4000€ for a high level package of intervention.

These feasibility results add insight from the economic sphere supporting the emerging framing of the energy efficiency in building as deeply connected to the human dimension of building performance (Hong et al., 2015). Such research line affirms that, being buildings Cyber-Physical-Social Systems (Bavaresco et al., 2019), it is not possible to meet highly efficient levels of performance in buildings by excluding the human component and solely relying on technology (D'Oca et al., 2018). The results of the present study suggest that such an attempt would also be a sub-optimal strategy from the monetary point of view. Several scholars suggest the importance of introducing behavioral theory such as theory of planned behavior (TPB) in the human-building interaction (Bavaresco et al., 2020). In this direction, an optimization of the costs preferring communication strategies that could affect the user behavior through an increase of user's awareness (Bottero et al., 2023) might imply lower initial investment costs, while resulting in satisfactory reductions of energy expenditure.

In the present study, for instance, the costs related to the lighting function amount to 3111.18 € and 2185.60 € for class A and B respectively, driven mostly by occupancy sensors, while the marginal saving for the improvement from the lower to the highest class is 0.02 €/m^2 year, representing this a potential area of optimization: demanding the variation of on/off-switching to a user-defined scheduling, and, also, optimizing the integration of different levels of BACS class functionalities as defined by EN ISO 52120 1:2022, considering case-specific consumption patterns. A similar reasoning could be made for the CorTau case study. In this case, already very low heating- and cooling-related energy consumptions result in negligible extra savings due to the increase of BACS class up to the highest level, while the cost difference for these functions between the two classes is as high as 1653.53 €. Here also, the savings for ventilation function in both classes and the extra savings from BACS class B to A for lighting one are not justified compared to the investment cost required, while a better focus on the appliances, and thus TBM, could result in promising outcomes. Also, in the retrofitted apartment, the savings related to the appliances could be promising, this representing also an interesting focal point considering the increase in distributed energy generation and the consequent matching of generation and consumption, supporting the necessity to specifically address this aspect in the standard.

Furthermore, the studies analyzed in the literature review seem to not properly consider the annual maintenance costs of the automation system that, on the contrary, has a limiting effect on the monetary benefits achieved by the annual energy savings. Indeed, among all the scenario analyzed in the present study, the only ones in which the annual energy savings are greater than the maintenance costs are the HC with BACS class A (119.32 €/y) and the two applications of BACS class A and B combined with behavioral change of the occupant (165.56€/year and 181.34€/year for class B and A respectively). This latter represents one of the main causes of the economic unfeasibility of the interventions, being the operational costs higher than the operational savings for the majority of the analyzed scenarios.

A final analysis has been performed to test the robustness of the CBA results for the most profitable scenario (AC to LC + B) with incentives in place, by applying a sensitivity analysis to evaluate the variation of the outcomes due to changes in the assumptions made. The sensitivity analysis is based on "what-if" statements and has been calculated by varying the input parameters (investment cost, cost of energy, incentives, WTP, maintenance) by fixed percentages ($\pm 5\%, \pm 10\%, \pm 15\%$).

Table 13 Results of CBA with application of BACS class A and B and the change in user profile

	AC to LC + B		AC to LC + A	
Incentives	(-a) without	(-b) with	(-a) without	(-b) with
NPV [€]	−6737.55	866.75	−7678.39	756.91
IRR [%]	−4.29	0.49	−4.37	0.34
B/C	0.52	1.06	0.50	1.05

The sensitivity analysis shown in Fig. 5 highlights that the variation of the incentives scheme has the highest potential to influence the performance of the project (IRR value), with a variation of the output of the analysis as high as two times the values of the investment cost, WTP, and cost of energy. Indeed, the presence of an incentive scheme has been recognized as fundamental in previously mentioned research (Mancini et al., 2019), and in this study, this is further stressed, and the magnitude of such a supporting framework results pivotal. Also, the cost of energy has the possibility to highly influence the feasibility of the project, especially considering the uncertainty related to the variation of its price due to geo-political reasons. Furthermore, the fact that the WTP has a non-negligible influence on the feasibility of the project might support the argument that a better link between the application of BACS and related co-benefits such as the improved IEQ and users' comfort achievable, together with the reduction of emitted pollutants related to energy use, might increase the acceptance of these interventions. Finally, even though the variation of maintenance cost has the lowest impact on the feasibility of the project, it is nonetheless non-negligible its counterbalancing effect on the operational savings realized.

Conclusions

User behavior has a great impact on the total amount of energy consumed in buildings. To mitigate this aspect, several authors have proposed to introduce design solution that would decouple the energy consumption from occupant usage patterns, such as Building Automation and Control Systems. Thus, it becomes important to evaluate the viability of these solutions when applied to different users, in order to analyze the possible energy savings yelled, as well as their overall economic feasibility.

In this paper, this feasibility analysis has been performed to evaluate the application of BACS to two case studies in Italy. Three user's profiles have been used to understand the interaction between the consumer's behavior and the implementation of two BACS classes as retrofit options. The results have shown that in both case studies, the behavior of the occupant has the highest impact on the energy consumption, and the implementation of BACS alone is not enough to compensate the increase in energy used due to less conscious behaviors (high consumer profile). In case of a low consumer profile, the application of BACS class A

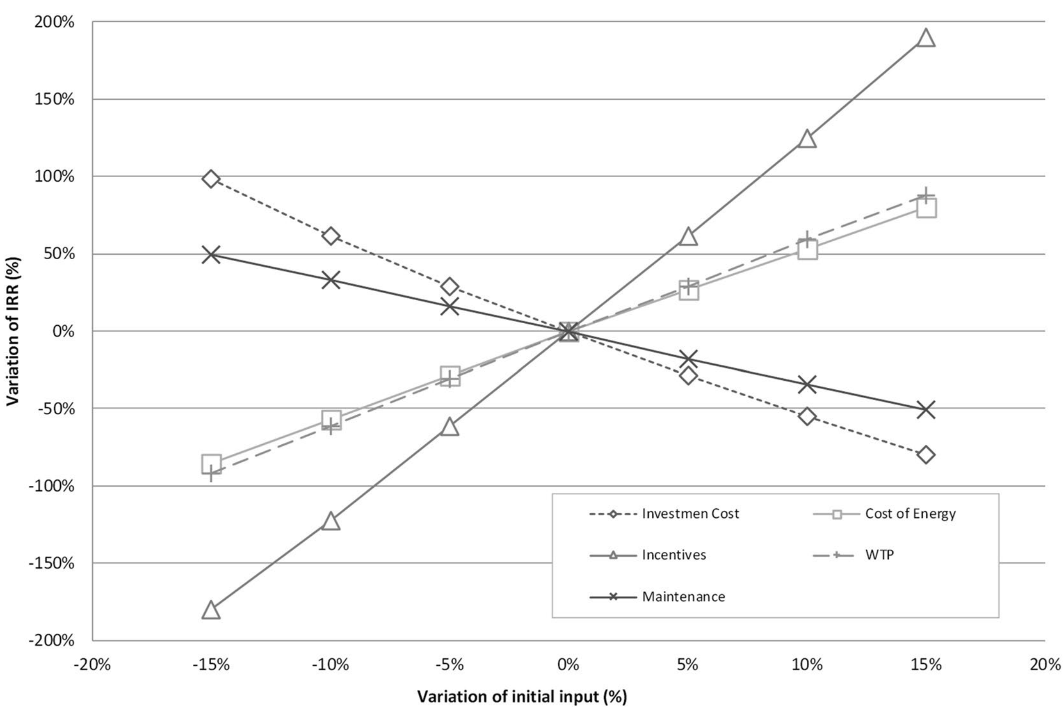

Fig. 5 Sensitivity analysis

increases savings from an initial 22.0 to 29.3% in the NZEB (CorTau house), while in the retrofitted apartment, the savings rise from an initial 13.4% (BACS class C) to 22.3%, representing a sensible increase in energy efficiency thanks to the automation and control systems. Furthermore, the high consumer sees their energy consumption increased by 18.2% and 36.1% in the two case studies (CorTau and apartment respectively); these values are reduced to 7.1% and 21.5% if the higher BACS class A is implemented, thus slightly mitigating the occupant's impact.

One of the aspects of novelty of the present study has been to account for co-benefits in the feasibility analysis of the application of BACS. The individuals' willingness-to-pay for smart appliances has been calculated using an iterative bidding game and has been introduced in the cost–benefit analysis. Several scenarios have been evaluated. All the scenarios considering the technological solution alone (application of BACS without changing user's behavior) resulted in the unfeasibility of the project. The only economically acceptable solutions were the one characterized by the application of BACS together with a behavioral change from the user, with tax deduction incentive scheme in place, accounting for WTP as a recurrent benefit (applied every 5 years after the first one). With these assumptions, two scenarios have been proved acceptable with a NPV of 756.91€, and 866.75€ in the case of a BACS class A and class B together with a behavioral change from average to low consumer. These results show that the behavioral impact of the occupant outperforms the energy reduction achievable by the technological solutions alone, limiting the idea that an "occupant-proof building" (O'Brien et al., 2013) might be a sustainable solution for energy reduction in the sector. Finally, by means of the sensitivity analysis, the parameters mostly affecting the results have been individuated in the investment costs and in the magnitude of the incentives scheme.

It is important to mention that the study presented here considers the implementation of BACS as an independent installation: applying such system in the framework of a more holistic intervention could increase its feasibility (Felius et al., 2020b).

Some of the limitations of the present study reside in the determination of the willingness-to-pay and the proxy chosen to quantify its value. Future development of this work could be to further investigate the aspects related to improved levels of indoor comfort (Garzia et al., 2022), as well as reduced environmental impacts (Becchio et al., 2018) related to the application of BACS, and also to evaluate different WTP for different BACS classes depending on the level of comfort achievable. Lastly, recalling the work from López-González et al. (2016), the application of BACS could result in an increase of the energy performance rating of a dwelling, and, therefore, an increase in the asset values (Becchio et al., 2018). All these co-benefits could be integrated in the cost–benefit analysis in order to better evaluate the feasibility and desirability of BACS applications from a more holistic point of view.

Furthermore, the selection of different proxies, as well as the use of other methods to evaluate individuals' WTP, such as choice experiments for example (Bottero et al., 2019), could corroborate the findings of the present study, and test for the user's awareness about these energy efficiency measures.

The present study has analyzed the potential positive outcomes of BACS adoption in the analyzed case studies and the possible limitations arising in the implementation of such projects. In particular, the results presented are in contrast with other studies that evaluated the feasibility of BACS application. In particular, it is worth noting that these studies are characterized by relatively low initial cost of investment, while neglecting other operational costs like maintenance ones (Ippolito et al., 2014; Mancini et al., 2019; Sanseverino et al., 2013), that in the present evaluation plays a substantial limiting effect on benefits from energy savings. Considering the recent direction of the European policies in terms of investments risk reduction in energy-efficient projects and digitalization of the building sector (European Commission, 2020c; 2021a), it is necessary for public decision-makers to design dedicated incentive schemes to support the adoption of these smart technologies, in order to boost their market maturity, as well as to consider binding regulations in case of major building renovation projects (Härkönen et al, 2022).

Declarations

Conflict of interest The authors declare no competing interests.

Appendix 1

Ques

The following questionnaire has only a research purpose with the aim to investigate the Willingness-to-Pay (WTP) for "Smart" appliances in households, with the goal of an intelligent management of electric energy.

PART1_INFORMATION ON HABITS

The questions in the following section aim at investigate the most common habits toward energy savings.

1. Are you attentive to environmental sustainability?

- o Yes
- o No

2. Have you ever considered adopting sustainable practices in order to reduce the energy consumption in your house?

- o Yes
- o No

3. Do you own high efficiency appliances and/or devices?

- o Yes
- o No

4. How often do you leave appliances such as TV, PC, microwave, etc. in stand-by mode?

- o Never
- o Seldom
- o Occasionally
- o Often
- o Always

5.Would you be willing to change your habits and turn-off the appliances and devices after using them in order to reduce energy consumption?

- o Yes
- o No

6. Have you installed renewable energy generation systems (PV-panels, solar panels, geothermal heat pumps, etc.) in your house?

- o Yes
- o No
- o Possibly in the future

7. Do you own a washing machine?

- o Yes
- o No (go to question 11)

8. How many times you use the washing machine in a week?

- Less than 3 times
- 4 times
- 5 times
- 6 times
- More than 6 times

9. When do you most frequently use this appliance?

- Morning (7-12)
- Afternoon (12-19)
- Evening (19-24)
- Night (24-7)

10.When during the week?

- From Monday to Friday
- Weekend
- Everyday

11. Do you own a dishwasher?

- Yes
- No (go to question 15)

12. How many times do you usually use it?

- Less than 3
- 4
- 5
- 6
- More than 6

13. When do you most frequently use this appliance?

- Morning (7-12)
- Afternoon (12-19)
- Evening (19-24)
- Night (24-7)

14.When during the week?

- From Monday to Friday
- Weekend
- Everyday

15.Do you wait until the washing machine is fully loaded before using it?

- Never
- Seldom
- Occasionally
- Often
- Always

16. Do you wait until the dishwasher is fully loaded before using it?

- Never
- Seldom

- Occasionally
- Often
- Always

17. Have you ever purchased “Smart-plugs” to control the electric consumption in your house (these sockets allows the user to control the energy consumption of the devices to which they are plugged, thanks to the planning of energy uses. The control of their functioning could be done also remotely)?

- Yes
- No (go to question 20)

18. If the answer was yes, do you think they were useful for energy management?

- Yes
- No (go to question 20)

19. If the answer was yes, what advantages did you have from using these “Smart-plugs”?

- Monetary savings
- Management of electric loads
- Comfort
- Other……….. (please specify)

20. Could you approximately tell your annual energy expenses (lightning+electric appliances)?

- Less than 500€
- 500€-1000€
- 1000€-2000€
- More than 2000€

PART1.1_INFORMATION ON HABITS

The questions in this section investigates in the individual knowledge regarding the “Smart” appliances

21.Have you ever heard about last generation appliances defined as “Smart”?

- Yes
- No (go to question 25)

22.If the answer was yes, do you think they could bring any advantages compared to traditional appliances

- Yes
- No (go to question 24)

23. If the answer was yes, what do you think these advantages could be?

- Financial savings
- Comfort
- User-friendliness
- Other………(please specify)

24. If the answer was no, why?

- High cost
- Uselessness
- They don’t bring savings
- Hard to be used

- Other……….(please specify)

PART2_WILLINGNESS-TO-PAY

Please, read carefully what is written below before answering the questions.

In this survey, "smart-dishwashers" and "smart-washing machines" characterized by high performances have been considered. Furthermore, "Smart-plugs" allowing the user to control the electric consumptions of the household devices have been considered.

The considered dishwashers have the following characteristics:

- Energy class: A+++;
- 8kg-12kg Load capacity, with the possibility of half-loading;
- Eco programs (quantity of water and detergent use depending on the load);
- Smart remote control.

The considered washing machines have the following characteristics:

- Energy class: A+++;
- Low water consumption;
- Smart remote control.

The considered "Smart-plugs" have the following characteristics:

- Smart remote control (possibility to remotely control the appliances with an App);
- Possibility to plan the use of devices depending on needs;
- Energy monitoring: real time analysis of energy consumption and of consumption in time.

25. Considering the characteristics above described, would you spend approximately 1400€ to purchase a "smart-dishwasher" and a "smart-washing machine" that would result in an annual saving of 46€ compared to traditional appliances?

- Yes (go to question 29)
- No

26. If not, would you spend approximately 700€ to purchase a "smart-dishwasher" that would result in an annual saving of 16€ compared to traditional washing machine?

- Yes (go to question 29)
- No

27. If not, would you spend approximately 220€ to purchase five "smart-plugs" that would allow you to monitor the appliances of your house (washing machine, dishwasher, microwave, PC, TV)?

- Yes
- No

PART 3_SOCIO-ECONOMIC DATA

28. Age (years):

- ………………………..

29. Gender?

- Male
- Female

30. City of residence?

- ……………………….

31. How many people, a part from you, compose your family unit?

- ……………………….

32.Educational qualification?

- Primary school
- Middle school
- High school
- Bachelor degree
- Master degree

33. Profession?

- Student
- Self employed
- Autonomous worker (Craftsman/Farmer/Retailer)
- Manager
- Employee
- Retired
- Homemaker
- Other…………(please specify)

34.Approximately, to which monthly wage category do you belong?

- Less than 1000€
- 1000€-2000€
- 2000€-3000€
- More than 3000€
- I would prefer not to answer

Appendix 2

Table 14 Cost–benefit analysis of scenario AC to LC + B with incentive

Year	1	2	3	4	5	6	7	8	9	10
Investment cost (€)	10,049									
Maintenance cost (€)		100	100	100	100	100	100	100	100	100
Installation cost (€)	3134									
Residual value (€)										
Total costs (€)	13,283	100	100	100	100	100	100	100	100	100
Energy savings (€)		166	166	166	166	166	166	166	166	166
WTP (€)	807					807				
Incentives (€)		863	863	863	863	863	863	863	863	863
Total benefits (€)	807	1029	1029	1029	1029	1836	1029	1029	1029	1029
Discounted cash flow (€)	− 12,476	893	875	858	841	1,542	809	793	777	762
NPV (€)	866.75									
IRR (€)	0.49									
B/C (−)	1.06									
Year	11	12	13	14	15	16	17	18	19	20
Investment cost (€)										
Maintenance cost (€)	100	100	100	100	100	100	100	100	100	100
Installation cost (€)										
Residual value (€)										
Total costs (€)	100	100	100	100	100	100	100	100	100	100
Energy savings (€)	166	166	166	166	166	166	166	166	166	166
WTP (€)	807					807				
Incentives (€)	863									
Total benefits (€)	1836	166	166	166	166	166	166	166	166	166
Discounted cash flow (€)	1396	52	51	50	49	636	47	46	45	44
NPV (€)										
IRR (€)										
B/C (−)										
Year	21	22	23	24	25	26	27	28	29	30
Investment cost (€)										
Maintenance cost (€)	100	100	100	100	100	100	100	100	100	100
Installation cost (€)										
Residual value (€)										− 2030
Total costs (€)	100	100	100	100	100	100	100	100	100	− 1930
Energy savings (€)	166	166	166	166	166	166	166	166	166	166
WTP (€)	807					807				
Incentives (€)										
Total benefits (€)	166	166	166	166	166	166	166	166	166	166
Discounted cash flow (€)	576	43	42	41	40	521	38	38	37	1157
NPV (€)										
IRR (€)										
B/C (−)										

Acknowledgements The authors want to recognize the support received by Sonia Vandelli in the drafting of the survey and collection of data.

Author contribution Conceptualization: Marta Bottero, Federico Dell'Anna, Giulio Cavana

Methodology: Marta Bottero, Federico Dell'Anna, Giulio Cavana

Investigation: Marta Bottero, Federico Dell'Anna, Giulio Cavana

Writing—Original Draft: Marta Bottero, Federico Dell'Anna, Giulio Cavana

Funding Open access funding provided by Politecnico di Torino within the CRUI-CARE Agreement.

Data availability No data was used for the research described in the article.

References

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology, 25*(3), 273–291. https://doi.org/10.1016/j.jenvp.2005.08.002

Allouhi, A., el Fouih, Y., Kousksou, T., Jamil, A., Zeraouli, Y., & Mourad, Y. (2015). Energy consumption and efficiency in buildings: Current status and future trends. *Journal of Cleaner Production, 109*, 118–130. https://doi.org/10.1016/J.JCLEPRO.2015.05.139

ARERA. Autorità di Regolazione per Energia Reti e Ambiente. https://www.arera.it/it/index.htm (accessed December 2018 and April 2022)

Barthelmes, V. M., Becchio, C., & Corgnati, S. P. (2016). Occupant behavior lifestyles in a residential nearly zero energy building: Effect on energy use and thermal comfort. *Science and Technology for the Built Environment, 22*(7), 960–975. https://doi.org/10.1080/23744731.2016.1197758

Bavaresco, M. V., D'Oca, S., Ghisi, E., & Lamberts, R. (2019). Technological innovations to assess and include the human dimension in the building-performance loop: A review. *Energy and Buildings, 202*, 109365. https://doi.org/10.1016/j.enbuild.2019.109365

Bavaresco, M. V., D'Oca, S., Ghisi, E., & Pisello, A. L. (2020). Assessing underlying effects on the choices of adaptive behaviours in offices through an interdisciplinary framework. *Building and Environment, 181*, 107086. https://doi.org/10.1016/j.buildenv.2020.107086

Becchio, C., Ferrando, D. G., Fregonara, E., Milani, N., Quercia, C., & Serra, V. (2016). The cost-optimal methodology for the energy retrofit of an ex-industrial building located in Northern Italy. *Energy and Buildings, 127*, 590–602. https://doi.org/10.1016/j.enbuild.2016.05.093

Becchio, C., Bottero, M. C., Casasso, A., Corgnati, S. P., Dell'Anna, F., Piga, B., & Sethi, R. (2017). Energy, economic and environmental modelling for supporting strategic local planning. *Procedia Engineering, 205*, 35–42. https://doi.org/10.1016/j.proeng.2017.09.931

Becchio, C., Bottero, M. C., Corgnati, S. P., & Dell'Anna, F. (2018). Decision making for sustainable urban energy planning: An integrated evaluation framework of alternative solutions for a NZED (Net Zero-Energy District) in Turin. *Land Use Policy, 78*, 803–817. https://doi.org/10.1016/j.landusepol.2018.06.048

Becchio, C., Bottero, M. C., Corgnati, S. P., Dell'Anna, F., Fabi, V., Lingua, C., Prendin, L., & Ranieri, M. (2019). The effects of indoor and outdoor air pollutants on workers' productivity in office building. *E3S Web of Conference, 111*, 02057. https://doi.org/10.1051/e3sconf/201911102057

Becchio, C., Bertoncini, M., Boggio, A., Bottero, M., Corgnati, S. P., & Dell'Anna, F. (2019). The impact of users' lifestyle in zero-energy and emission buildings: an application of cost-benefit analysis. In F. Calabrò, L. Della Spina, & C. Bevilacqua (Eds.), *New Metropolitan Perspectives. ISHT 2018. Smart Innovation, Systems and Technologies* (Vol. 100, pp. 123–131). Springer. https://doi.org/10.1007/978-3-319-92099-3_15

Beria, P., Maltese, & I., Mariotti, I. (2011). Comparing cost benefit and multi-criteria analysis: the evaluation of neighbourhoods' sustainable mobility. *XIII Riunione Scientifica della Società Italiana degli Economisti dei Trasporti e della Logistica (SIET),* 1–26

Bertoldi, P., Rezessy, S., & Oikonomou, V. (2013). Rewarding energy savings rather than energy efficiency: Exploring the concept of a feed-in tariff for energy savings. *Energy Policy, 56*, 526–535. https://doi.org/10.1016/j.enpol.2013.01.019

Bisello, A., Grilli, G., Balest, J., Stellin, G., & Ciolli, M. (2017). Co-benefits of smart and sustainable energy district projects: an overview of economic assessment methodologies. In A. Bisello, D. Vettorato, R. Stephens, & P. Elisei (Eds.), *Smart and Sustainable Planning for Cities and Regions. SSPCR 2015. Green Energy and Technology.* Springer. https://doi.org/10.1007/978-3-319-44899-2_9

Bode, G., Schreiber, T., Baranski, M., & Müller, D. A. (2019). Time series clustering approach for building automation and control systems. *Applied Energy, 238*, 1337–1345. https://doi.org/10.1016/J.APENERGY.2019.01.196

Boggio, A. (2017). Towards a low carbon future: users' lifestyle supporting building performances: occupants behavior impact on zero emission buildings in mediterranean and nordic climate. Master thesis in Architecture, Politecnico di Torino, tutors Corgnati, S., Bottero, M., Becchio, C., and Heiselberg, P. Retrieved from https://webthesis.biblio.polito.it/6141/. Accessed Dec 2021

Bottero, M., Bravi, M., Cavana, G., Dell'Anna, F., Becchio, C., & Corgnati, S. P. (2019). Energy retrofit and investment decisions: Individuals' preferences valuation through a choice experimenT [Retrofit energetico e decisioni di investimento: Valutazione delle preferenze degli individui attraverso un esperimento di scelta]. *Geoingegneria Ambientale e Mineraria, 158*(3), 11–25.

Bottero, M., Cavana, G., & Viazzo, S. (2023). A methodological framework to assess individual sustainable behavior. In O. Gervasi, B. Murgante, A. M. A. C. Rocha, C. Garau, F. Scorza, Y. Karaca, & C. M. Torre (Eds.), *Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science* (Vol. 14104, pp. 392–404). Springer.

bticino. Online catalogue. https://catalogo.bticino.it/ (accessed January 2018)

Buckman, A. H., Mayfield, M., & Beck, S. B. M. (2014). What is a smart building? *Smart and Sustainable Built Environment, 3*(2), 92–109. https://doi.org/10.1108/SASBE-01-2014-0003

Buso, T., Fabi, V., Andersen, R. K., & Corgnati, S. P. (2015). Occupant behaviour and robustness of building design. *Building and Environment, 94*(2), 694–703. https://doi.org/10.1016/J.BUILDENV.2015.11.003

Buso, T., Dell'Anna, F., Becchio, C., Bottero, M. C., & Corgnati, S. P. (2017). Of comfort and cost: Examining indoor comfort conditions and guests' valuations in Italian hotel rooms. *Energy Research & Social Science, 32*, 94–111.

CEN. (2007). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. (EN15251:2007)*. Ente Italiano di Normazione (UNI), Milano.

CEN. (2019). *Energy performance of buildings - ventilation for buildings - part 1: Inddor environmental input parameters for design and assessment of energy performance of building addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6. (UNI EN 16798-1:2019)*. Ente Italiano di Normazione (UNI), Milano.

CEN. (2022). *Energy performance of buildings - contribution of building automation controls and building management - part 1: General frameworks and procedures*. (EN ISO 52120-1:2022). British Standards Institution (BSI), London.

Chen, Y., Tong, Z., Wu, W., Samuelson, H., Malkawi, A., & Norford, L. (2019). Achieving natural ventilation potential in practice: Control schemes and levels of automation. *Applied Energy, 235*, 1141–1152.

Colmenar-Santos, A., Terán de Lober, L. N., Borge-Diez, D., & Castro-Gil, M. (2013). Solutions to reduce energy consumption in the management of large buildings. *Energy and Buildings, 56*, 66–77. https://doi.org/10.1016/j.enbuild.2012.10.004

Cooper, T. (2004). Inadequate life? Evidence of consumer attitudes to product obsolescence. *Journal of Consumer Policy, 27*, 421–449. https://doi-org.ezproxy.biblio.polito.it/10.1007/s10603-004-2284-6.

D'Oca, S., Hong, T., & Langevin, J. (2018). The human dimensions of energy use in buildings: A review. *Renewable and Sustainable Energy Reviews, 81*(1), 731–742. https://doi.org/10.1016/j.rser.2017.08.019

Darby, S. (2001). Making it obvious: designing feedback into energy consumption. In P. Bertoldi, A. Ricci, & A. de Almeida (Eds.), *Energy Efficiency in Household Appliances and Lighting* (pp. 685–696). Springer. https://doi.org/10.1007/978-3-642-56531-1_73

Dell'Anna, F., Marmolejo-Duarte, C., Bravi, M., & Bottero, M. (2022). A choice experiment for testing the energy-efficiency mortgage as a tool for promoting sustainable finance. *Energy Efficiency, 15*, 27. https://doi.org/10.1007/s12053-022-10035-y

Della Valle, N., & Bertoldi, P. (2022). Promoting energy efficiency: Barriers, societal needs and policies. *Frontiers in Energy Research, 9*, 804091. https://doi.org/10.3389/fenrg.2021.804091

DeWaters, J. E., & Powers, S. E. (2011). Energy literacy of secondary students in New York state (USA): A measure of knowledge, affect, and behaviour. *Energy Policy, 39*(3), 1699–1710. https://doi.org/10.1016/j.enpol.2010.12.049

Edonomidou, M., Atanasiu, B., Despret, C., Maio, J., Nolte, I., & Rapf, O. (2011). *Europe's buildings under the microscope: a country-by-country review of the energy performance of buildings*. Buildings Performance Institute Europe (BPIE).

Ejidike, C. C., & Mewomo, M. C. (2023). Benefits of adopting smart building technologies in building construction of developing countries: Review of literature. *SN Applied Sciences, 5*, 52. https://doi.org/10.1007/s42452-022-05262-y

European Commission. (2012). *Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements*. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0244. Accessed Dec 2021

European Commission. (2014). *Guide to cost-benefit analysis of investment projects: structural funds, cohesion fund and instrument for pre-accession*. Brussels: Directorate-General for Regional Policy.

European Commission. (2020a). *C/2020/6930 final. ANNEXES to the COMMISSION DELEGATED REGULATION (EU) …/... supplementing Directive (EU) 2010/31/EU of the European Parliament and of the Council by establishing an optional common European Union scheme for rating the smart readiness of buildings*. (C/2020/6930 final) Brussels. https://eur-lex.europa.eu/resource.html?uri=cellar:840914e2-19fd-11eb-b57e-01aa75ed71a1.0012.02/DOC_2&format=PDF. Accessed Dec 2021

European Commission. (2020b). Final report on the technical support to the development of a smart readiness indicator for buildings. Brussels. https://op.europa.eu/en/publication-detail/-/publication/bed75757-fbb4-11ea-b44f-01aa75ed71a1/language-en?WT.ria_f=3608&WT.ria_ev=search. Accessed July 2022

European Commission. (2020c). Taxonomy: final report of the Technical Expert Group on Sustainable Finance. Retrieved from https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en#documents. Accessed Apr 2022

European Commission. (2021a). *Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast) (COM/2021/802 final)*. Brussels. https://eur-lex.europa.eu/resource.html?uri=cellar:c51fe6d1-5da2-11ec-9c6c-01aa75ed71a1.0001.02/DOC_1&format=PDF. Accessed July 2022

European Commission. (2021b). Proposal for a Directive of the European Parliament and of the Council on energy efficiency (recast) (COM/2021/802 final). Brussels. https://eur-lex.europa.eu/resource.html?uri=cellar:a214c850-e574-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF. Accessed July 2022

Fabi, V., Andersen, R. V., Corgnati, S. P., & Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment, 58*, 188–198. https://doi.org/10.1016/J.BUILDENV.2012.07.009

Fang, X., Bianchi, M. V., & Christensen, C. (2012). Monetization of thermal comfort in residential buildings. *ACEEE 2012 Summer Study on Energy Efficiency in Buildings*, 64–75. Available online at: https://www.aceee.org/files/proceedings/2012/start.htm. Accessed Dec 2021

Faruqui, A., Sergici, S., & Sharif, A. (2010). The impact of informational feedback on energy consumption—a survey of the experimental evidence. *Energy, 35*, 1598–1608. https://doi.org/10.1016/j.energy.2009.07.042

Felius, L. C., Hamdy, M., Hrynyszyn, B. D., & Dessen, F. (2020a). The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house. *IOP Conference Series: Earth and Environmental Science, 410*, 012054. https://doi.org/10.1088/1755-1315/410/1/012054

Felius, L. C., Hamdy, M., Dessen, F., & Hrynyszyn, B. D. (2020b). Upgrading the smartness of retrofitting packages towards energy-efficient residential buildings in cold climate countries: Two case studies. *Buildings, 10*(11), 200. https://doi.org/10.3390/buildings10110200

Felius, L. C., Dessen, F., & Hrynyszyn, B. D. (2020c). Retrofitting towards energy-efficient homes in European cold climates: A review. *Energy Efficiency, 13*, 101–125. https://doi.org/10.1007/s12053-019-09834-7

Ferreira, M., & Almeida, M. (2015). Benefits from energy related building renovation beyond costs, energy and emissions. *Energy Procedia, 78*, 2397–2402. https://doi.org/10.1016/j.egypro.2015.11.199

Fischer, C. (2008). Feedback on household electricity consumption: A tool for saving energy? *Energy Efficiency, 1*, 79–104. https://doi.org/10.1007/s12053-008-9009-7

Garzia, F., Van Thillo, L., Verbeke, S., Pozza, C., & Audenaert, A. (2022). Co-benefits of building automation and control systems: an analysis of smart office buildings. *CLIMA 2022 Conference*. https://doi.org/10.34641/clima.2022.316

Grønhøj, A., & Thøgersen, J. (2011). Feedback on household electricity consumption: Learning and social influence processes. *International Journal of Consumer Studies, 35*(2), 138–145. https://doi.org/10.1111/j.1470-6431.2010.00967.x

Gruber, M., Trüschel, A., & Dalenbäck, J.-O. (2015). Energy efficient climate control in office buildings without giving up implementability. *Applied Energy, 154*, 934–943. https://doi.org/10.1016/j.apenergy.2015.05.075

Hargreaves, T., Nye, M., & Burgess, J. (2013). Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. *Energy Policy, 52*, 126–134. https://doi.org/10.1016/j.enpol.2012.03.027

Härkönen, K., Hannola, L., & Pyrhönen, O. (2022). Advancing the smart city objectives of electric demand management and new services to residents by home automation—learnings from a case. *Energy Efficiency, 15*, 25. https://doi.org/10.1007/s12053-022-10032-1

Hoes, P., Hensen, J. L. M., Loomans, M. G. L. C., de Vries, B., & Bourgeois, D. (2009). User behavior in whole building simulation. *Energy and Buildings, 41*(3), 295–302. https://doi.org/10.1016/j.enbuild.2008.09.008

Hong, T., D'Oca, S., Turner, W. J. N., & Taylor-Lange, S. C. (2015). An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework. *Building and Environment, 92*, 764–777. https://doi.org/10.1016/j.buildenv.2015.02.019

Ippolito, M. G., Sanseverino, E. R., & Zizzo, G. (2014). Impact of building automation control systems and technical building management systems on the energy performance class of residential buildings: An Italian case study. *Energy and Buildings, 69*, 33–40. https://doi.org/10.1016/j.enbuild.2013.10.025

Karjalainen, S. (2016). Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption. *Energy Efficiency, 9*, 1257–1270. https://doi.org/10.1007/s12053-015-9422-7

Litiu, A., Brook, B., Corgnati, S. P., D'Oca, S., Fabi, V., Keel, M., Kranz, H., Kurnitski, J., & Schoenenberger, P. (2017). *Introduction to building automation, controls and technical building management. REHVA Guidebook No 22*. REHVA. Brussels.

López-González, L. M., López-Ochoa, L. M., Las-Heras-Casas, J., & García-Lozano, C. (2016). Update of energy performance certificates in the residential sector and scenarios that consider the impact of automation, control and management systems: A case study of La Rioja. *Applied Energy, 178*, 308–322. https://doi.org/10.1016/j.apenergy.2016.06.028

Mancini, F., Lo Basso, G., & de Santoli, L. (2019). Energy use in residential buildings: Impact of building automation control systems on energy performance and flexibility. *Energies, 12*(15), 2896. https://doi.org/10.3390/en12152896

Marinakis, V., Doukas, H., Karakosta, C., & Psarras, J. (2013). An integrated system for buildings' energy-efficient automation: Application in the tertiary sector. *Applied Energy, 101*, 6–14. https://doi.org/10.1016/j.apenergy.2012.05.032

Nilsson, A., Bergstad, C. J., Thuvander, L., Andersson, D., Andersson, K., & Meiling, P. (2014). Effects of continuous feedback on households' electricity consumption: Potentials and barriers. *Applied Energy, 122*, 17–23. https://doi.org/10.1016/j.apenergy.2014.01.060

O'Brien, W., Kapsis, K., & Athienitis, A. K. (2013). Manually operated window shade patterns in office buildings: A critical review. *Building and Environment, 60*, 319–338. https://doi.org/10.1016/j.buildenv.2012.10.003

Ożadowicz, A., & Grela, J. (2017). Impact of building automation control systems on energy efficiency—university building case study. In *Proceedings of the 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Limassol, Cyprus, 12–15 September 2017 (pp. 1–8). IEEE: Piscataway, NJ, 2017. https://doi.org/10.1109/ETFA.2017.8247686

Ożadowicz, A., & Grela, J. (2017b). Energy saving in the street lighting control system—a new approach based on the EN-15232 standard. *Energy Efficiency, 10*, 563–576. https://doi.org/10.1007/s12053-016-9476-1

Rosso, M., Bottero, M. C., Pomarico, S., La Ferlita, S., & Comino, E. (2014). Integrating multicriteria evaluation and stakeholders analysis for assessing hydropower projects. *Energy Policy, 67*, 870–881. https://doi.org/10.1016/j.enpol.2013.12.007

Sanseverino, E. R., Zizzo, G. D., & Cascia, D. L. (2013). Economic impact of BACS and TBM systems on residential buildings. *International Conference on Clean Electrical Power (ICCEP), 2013*, 591–595. https://doi.org/10.1109/ICCEP.2013.6586914

Schiera, D. S., Minuto, F. D., Bottaccioli, L., Borchiellini, R., & Lanzini, A. (2019). Analysis of rooftop photovoltaics diffusion in energy community buildings by a novel GIS- and agent-based modeling co-simulation platform. *IEEE Access, 7*, 93494–93432. https://doi.org/10.1109/ACCESS.2019.2927446

Su, B., & Wang, S. (2021). A delay-tolerant distributed optimal control method concerning uncertain information delays in IoT-enabled field control networks of building automation systems. *Applied Energy, 301*, 117516. https://doi.org/10.1016/J.APENERGY.2021.117516

United Nations. World Urbanization Prospects_Population Division, https://population.un.org/wup/; (accessed: March 2019).

Van Thillo, L., Verbeke, S., & Audenaert, A. (2022). The potential of building automation and control systems to lower the energy demand in residential buildings: A review of their performance and influencing parameters. *Renewable and Sustainable Energy Reviews, 158*, 112099. https://doi.org/10.1016/j.rser.2022.112099

Vandelli, S. (2018). *Implementing smart systems for energy saving, feasibility studies and users' attitudes*. Application to Italian existing buildings. Master thesis in Architecture, Politecnico di Torino, tutors: Corgnati, S., and Bottero, M.

Vandenbogaerde, L., Verbeke, S., & Audenaert, A. (2023). Optimizing building energy consumption in office buildings: a review of building automation and control systems and factors influencing energy savings. *Journal of Building Engineering*, 107233. https://doi.org/10.1016/j.jobe.2023.107233

Wang, X., Lu, M., Mao, W., Ouyang, J., Zhou, B., & Yang, Y. (2015). Improving benefit-cost analysis to overcome financing difficulties in promoting energy-efficient renovation of existing residential buildings in China. *Applied Energy, 141*, 119–130. https://doi.org/10.1016/j.apenergy.2014.12.001

Yan, D., O'Brien, W., Hong, T., Feng, X., BurakGunay, H., Tahmasebi, F., & Mahdavi, A. (2015). Occupant behavior modeling for building performance simulation: Current state and future challenges. *Building and Environment, 107*, 264–278. https://doi.org/10.1016/J.ENBUILD.2015.08.032