An IoT-based integrated tool for testing energy consumption user awareness

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Summary

An unaware behaviour of occupants can affect energy consumptions even more than installations and building envelope inefficiencies, with significant overconsumptions widely documented. To reach an adequate awareness of energy consumptions, real time data and an effective and frequent billing of actual consumptions are required. From this point of view, the European Directive 2012/27/EU already imposed the use of metering and submetering systems, setting the minimum criteria for billing and related information based on the real energy consumptions. To assess the ability of buildings to exploit new ICT technologies and sensitise both owners and occupants to related savings, the new European Directive 2018/844/EU introduces a smart readiness indicator. In this paper the authors address the problem of gathering, processing and transmitting energy consumption data in the framework of an IoT-based integrated tool aimed at increasing residential user awareness through the use of consumption and benchmark indexes. Two case-studies in which thermal and electrical energy monitoring systems have been tested are presented and discussed. Finally, the suitability of the communication of energy consumption in terms of temporal, spatial and typological aggregation has been evaluated.
Keywords - user awareness, energy consumption, individual metering, feedback strategies, NZEB, IoT

1. INTRODUCTION

How to encourage energy savings in buildings is a topic of scientific interest since the 1970s, when the energy crisis made people aware on the possible exhaustion of fossil fuels. Almost 50 years later, it is clear that all intervention addressed to improve the energy efficiency should be combined with actions aimed at increasing awareness and participation of end users, even through a more frequent and detailed information on energy consumption (Håkon et al, 2013). In the absence of frequent information two buildings with similar thermo-physical characteristics and energy performances, even designed consistently with N-ZEB criteria, can consume one twice the other depending upon occupant' behaviour. In recent years, smart home and ICT technologies allowed the possibility to set up integrated systems to support decisions at the building, district and city stages, but they are not common due to the complexity of the problem, the reduced interoperability among the different systems and high costs (Marinakis and Doukas, 2018). In addition, the effectiveness of user's feedback actions addressed at the energy savings is a still debated topic in the scientific literature.

Based upon the results of 38 different studies addressed to the effectiveness of interventions aimed at encouraging families to reduce their energy consumption (Abrahamse et al., 2005) two macro-categories are identified, depending on the kind of information provided to families: i) antecedent strategies; ii) consequent strategies. Antecedent strategies include media campaigns, workshops, educational conferences and energy audits for targeted and personalized information (Brandon et al., 1999; Guerrasimoff et al., 2015). It is proven that antecedent strategies raise the user awareness, but do not necessarily lead to behavioural changes or sure energy savings. This category includes any type of user feedback e.g. real-time feedback, information presented on in-home displays, mobile apps or online services (Anderson et al 2009, Chen et al., 2014, Gans et al., 2013). Feedback actions can be direct when learned directly from the instrument display (counter, sub counter etc.) or indirect when information on data consumption are preliminary processed before reaching the user. The inconsistencies in behaviours related to the use of energy in families are due to (Wilson and Dowlatabadi, 2007): i) temporal coherence of decisions, ii) difficulty in processing consumption data and in assuming simple decisions; iii) effects of presentation.

Available literature identifies three key problems related to the feedback: the poor evidence of effectiveness, the need for involving users and the potential occurrence of unwanted consequences. The main finding is that actual in-home displays could not be effective in orientating users' behaviours. Thus, it is necessary to develop and test novel feedback devices accounting the degree of user involvement (Buchanan et al., 2015). In a recent experimental campaign (Nilsson et al., 2018), many interviewed users reported difficulties in the interpretation of the units (kW, kWh) and a poor feedback (e.g. lack in the corresponding economic value). This research also highlighted the usefulness of presenting disaggregated data for each device (sub-metering), at least for the most energy-consuming devices (stove, oven, dishwasher, washing machine, dryer, etc.) and of benchmarks with historical consumption.

In this scenario, low-income families, as those living in public housing, are a particular category of users to be approached in a specific way. A recent experimental study in 7 EU countries highlighted several problems both in the implementation of smart-metering solutions and in the use of personalized feedback for low-income families in the Mediterranean region (ELIH-Med Smart Metering, 2014). Experimental results proved that the use of smart-meters associated with in-home displays is not so effective. On the other hand, the monitoring of individual electrical devices, the distribution of consumption inside the dwelling and the suggestions for energy retrofits are appreciated. The joint implementation of these measures and the personalization of user feedback resulted in electricity consumption savings varying in the range from 22 and 27% (Podgornik et al., 2016). Unfortunately, the adoption of energy saving strategies in social housing could lead to a potential worsening of comfort conditions (Boomsma et al., 2019). For example, the reduction of the average winter indoor air temperature could result in condensation phenomena and mould. In the same research paper, the authors also point out that information to users is more effective when people lives in relatively energy-efficient dwellings but is less useful for users living in public housing.

However, these technologies can result in a series of problems related to the access to confidential information on users' activities and habits, privacy, confidentiality and availability of data (also considering the greater quantity and vulnerability of data). This is for authorized parties (e.g. utility companies, metering companies), unauthorized parties (eg competitors, thieves, real estate owners), and, finally for final users who are often unbale to access and use their own data (Deniz et al., 2015). In addition, the remote billing brings up problems related to data security and integrity (e.g. the risk of deletion / modification of information). Different privacy preservation techniques may be based on information theory, multiple source energy engineering, and cryptographic network protocols.

In this paper the authors address the problem of measurement, processing and transmission of energy consumption data proposing the use of consumption and benchmark indicators applicable to residential buildings. To this aim, some case-study in which thermal and electrical energy monitoring systems are tested have been discussed. Finally, the suitability of the communication of energy consumption in terms of temporal, spatial and typological aggregation has been evaluated.

2. THEORY AND METHODS

2.1 Architecture and data transmission

In this work, the authors implemented an integrated IoT-based tool for monitoring, transmitting and processing energy consumption data based on three levels. The first level is represented by metering and submetering systems for gathering energy consumption data of electrical, thermal and natural gas devices (nodes) of the relative plants. The second level is the data concentration by wireless personal area networks (zigbee protocol) and remote transmission data with home router connected to the Internet. Smart meters may also directly communicate with the cloud. The third level is the web-based data management providing parallel solutions for data entry, storage, analysis and processing. In particular, in this latter level data for user feedback are processed by creating reports (e.g. indirect feedback), as well as real-time displaying via dashboard (e.g. direct feedback). Therefore, the IoT-based tool combines and stores information and data, as follows:

- the measurement module, which collect data from different sources (electric, thermal and gas energy consumption and production);
- the configuration module which collect data from the different source (i.e. energy prices, weather data and end-users' behavior);

Figure 1 shows a simplified sketch of the IoT-based integrated tool.

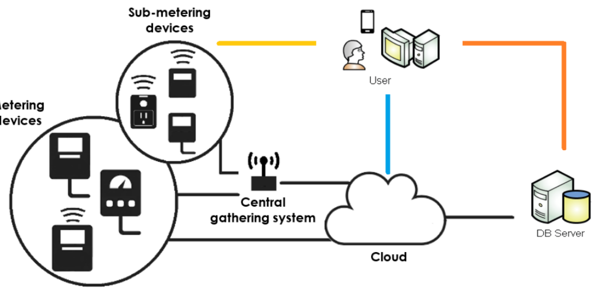


Figure 1 – IoT-based integrated tool scheme

2.2 Smart metering and submetering systems

2.2.1 Heating plant: Metering and submetering of the heating plant allows the control and monitoring of energy consumption of heating, cooling and domestic hot water (Celenza et al., 2016). At the output of the boiler a smart direct thermal energy meter can be installed (Celenza et al., 2013). The thermal energy meter is made up of a flow sensor, generally of mechanical type (e.g. axial turbine), volumetric (e.g. Woltmann, single-jet, multi-jet,) or static (e.g. electromagnetic, ultrasonic). The submetering of the heating plant can be obtained through indirect accounting system with two-sensors electronic heat cost allocators; ii) insertion time counters compensated with fluid temperature or with degree days. The submetering of domestic hot water can be achieved by means of a direct thermal energy meter or, alternatively, a water meter approved for hot water.

2.2.2 Electrical plant: A smart electric energy meter is generally made up of a static type sensor with an associated processing system. Smart non-fiscal devices monitoring current flows via the electric system phase are also available on the market with the function, in addition to measurement and consumption control, also of wireless signal repeater for the other devices installed. Electricity submetering multifunction devices also allow to monitor and control energy consumption of single appliances (e.g. refrigerator, dishwasher, oven, hairdryer) and they are often associated with the so-called smart plugs.

2.2.3 Natural gas plant: In residential buildings, the natural gas plant generally performs cooking, heating and, in some cases, the production of domestic hot water. Gas smart meters can simply allow the measurement of gas volumes or, more effectively, directly the amount of energy. In this case, the volumetric flow sensor is associated with temperature and pressure sensors, whose signals are processed by an electronic calculation module. On the market, "hybrid" smart gas meters equipped with electronic correction/transmission modules and static ultrasonic or thermal mass are also available. For submetering functions (e.g. cooking, hot water), small domestic gas meter can be used (e.g. class G2.5), but optimal operating conditions should be adequately considered, since the measured flow rates are often very low. Table 1 shows the technical specifications of the metering and submetering systems used by the authors in the case studies for the various consumer centres investigated.

Table 1 – Technical characteristics of metering and submetering (case studies)

Plant	*Function*	*Description*	*Accuracy*	*Format*	*Range*
Heating	Metering**	Turbine th. energy meter	Class 2 MID	0.1 kWh	240:1
	Submetering	Two-sensor electronic heat cost allocator	n.a.	0.001 UR	n.a.
		Insertion time counter comp. fluid temperature	n.a.	1 Wh	n.a.
Electric	Metering*	Static electricity meter	Class 1 MID	1 kWh	n.a.
	Submetering**	Current clump meter	n.a.	1 Wh	n.a.
	Submetering**	Smart Plug	n.a.	1 Wh	n.a.
Natural Gas	Metering*	Hybrid gas meter	1.5 MID	1 dm^3	150:1
	Subm.cooking**	Hybrid gas meter	1.5 MID	0.1 dm^3	150:1
	Subm. hot water**	Hybrid gas meter	1.5 MID	0.1 dm^3	150:1

*fiscal **non-fiscal

2.3 Information Strategies

The evaluation of effective strategies to make end users aware of their energy consumption in "smart homes" is influenced by numerous aspects such as (Aghajan 2010, Arpino et al. 2013): i) the quality of the perceived interaction (e.g. speed, brevity/easiness); ii) information efficiency (e.g. accuracy and completeness); iii) usability (e.g. ease of use, intuitiveness, user satisfaction); iv) the aesthetics; v) the usefulness (e.g. offered functions); vi) acceptability (e.g. low cost, number of potential users). The feedback of monitored data should reach end users over time and the most adequate way to allow the full understanding of the phenomenon, before it is irreversible or no longer visible, linking it to specific retrofit actions. (Fischer C., 2008). To identify the most effective feedback, the authors analyzed the most relevant features, as shown in Table 2.

Table 2 – Types of feedback

Characteristic	Description
Frequency	Continuous feedback (1/4 hour, hourly, daily) Deferred feedback (weekly, bi-monthly, half-yearly, yearly)
Content	consumption, kWh (absolute),% (relative) costs, € (absolute),% (relative) environmental impacts, CO2 (absolute),% (relative)
Data aggregation	by location (e.g. room, living / sleeping area, apartment) for use (e.g. heating, cooling, ventilation, ...) for plant / appliance (e.g. refrigerator, washing machine) by energy carrier (e.g. electricity, heating, gas)
Presentation	Analog data (e.g. dashboard) Numerical data (e.g. display) Traffic lights, colors and ideograms Historical trend (e.g. trend, histograms) Diagrams (e.g. pie, bar, ring, ..)
Benchmark	Historical consumption Consumption of other users (e.g. building average) Expected theoretical consumption (e.g. based on climatic data, characteristics of energy systems, type of user)
Further information	Diagnosis (e.g. faults and malfunctioning) Retrofit (e.g. indications and tips for rational use and efficiency)

In the technical practice, the simplicity and/or cost of information system is sometimes favored, in others the completeness and/or the effectiveness of the information. The different types of feedback can have very different costs and customer satisfaction levels, but a crucial issue should be the awareness and immediacy of information to lead users at performing higher energy savings. A unanimous judgment of end users is the greater appreciation of a detailed, frequent and actual feedback. Therefore, authors decided to differentiate between direct and indirect feedback: i) by using a frequent, synthetic and immediate information in the case of direct feedback, ii) by providing detailed and disaggregated information for each consumption area (i.e. bedrooms, living, bathroom, kitchen), for each energy carrier (i.e. thermal energy, electrical and natural gas) and for device/system in the case of indirect feedback.

Other aspects positively evaluated in the technical literature (Canale et al., 2018, Arpino et al. 2016) are the diagnosis of faults and malfunctions, the comparison with historical consumption, simplicity and effectiveness in understanding user information. Therefore, for indirect feedback and for each consumption area authors presented: i) historical consumption benchmark, ii) benchmark with average consumption of other users (building average), iii) theoretical expected consumption obtained on the basis of the specific characteristics of the user (e.g. characteristics of energy systems, type of user) and of climate data. To enhance the communication effectiveness, pie charts (for allocation), bar charts (for comparisons with previous periods and with other users) have been prepared.

3. CASE STUDIES

In the following, two case studies are presented and discussed by the authors highlighting the potential and criticality of the IoT-based integrated tool. In order to magnify user awareness, the authors designed and implemented specific experimental campaigns by carrying out:

1) installation of metering and submetering systems;
2) administration of surveys aimed at assessing energy use and user satisfaction with respect to the systems installed;
3) design and implementation of an IoT-based integrated tool for monitoring and analyzing energy consumption data (feedback tool);
4) gathering and analysis of energy consumption data for a reference period of 12 months through the IoT-based integrated tool;
5) validation of the IoT-based integrated tool through meetings with 28 end users.

3.1 The investigated buildings

For the experimentation of feedback strategies on the consumption of thermal energy for heating, an experimental campaign is currently underway in three social housing buildings of ATER in the district of Frosinone (Central Italy), served by a centralized natural gas system for (Dell 'Isola et al., 2018). The buildings, built in the '70s, present very low energy performance and would require relevant energy retrofit intervention, both to improve the insulation of the building envelope and to increase the efficiency of the heating plant. End users are mostly low income and elderly with limited ability to interact with automation systems. In each building a thermal energy meter for the direct measurement of the thermal energy produced by the boiler (metering level) and two different indirect heat metering systems have been installed (submetering level): i) insertion time counters compensated with fluid temperature and thermostatic electronic valves controlled by programmable thermostat (building n.1); ii) two-sensors electronic heat cost allocators, mechanical thermostatic valves and programmable thermostat (buildings n.2 and n.3).

On the other hand, with regards to electrical energy consumption, an experimental campaign is currently underway in a detached house located in the district of Frosinone (Central Italy) built in the first decade of 2000s and inhabited by a family of four people. The house is a two-floor detached building, divided into two apartments, of which only one actually inhabited by the family, but both served by the main electrical energy meter with a maximum power installed of 4.5 kW. A current clamp meter has been installed on the main power line of the sole inhabited apartment (metering level), whereas, on the submetering level, two different devices were installed: i) current clamp meter on the main light's powerline; ii) smart plugs on the more energy consuming electrical appliances.

In Figure 2 the investigated buildings have been reported.

a) *b)*

Figure 2 – a) Heating plant case study building, b) Electrical Plant case study building with location of devices (red dots: smart-plugs, green dots: current clump meters).

Through the administration of specific designed surveys in the ATER buildings, the authors assessed user's attitude to adopt energy saving strategies and to interact with monitoring and control systems. The response rate to the questionnaires provided was 100%. Figure 3 shows the list of the questions together with the overall analysis of the answers obtained. With regard to the installation of monitoring and control systems, the users, although they declare themselves satisfied (100%) and quite familiar with such systems (64%), were wary of the potential effectiveness in terms of savings (71%). As for indoor temperature perception, most users feel that they do not perceive too high (71%) or too low (78%) indoor temperatures.

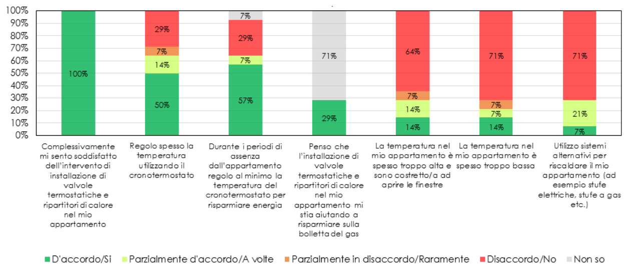


Figure 3 – Results of surveys analysis

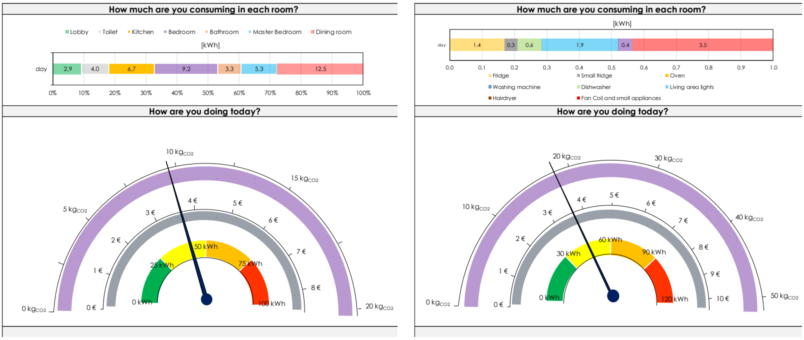
Based on the results of the survey, and considering the characteristics of the monitored energy systems and user behavior, the authors designed the direct and indirect feedback strategies, as summarized in Table 3.

Table 3 – Technical specification of direct and indirect feedback

Characteristic	*Direct feedback*	*Indirect feedback*
Frequency	Daily	Monthly
Content	Consumed energy (kWh, %) Cost (€) CO_2 emitted (kg)	Consumed energy (kWh, %) Cost (€) CO_2 emitted (kg) Consumption indexes
Aggregation	By room / appliance By apartment	By room /appliance By apartment By building
Presentation	Energy dashboard	Bar charts Ring diagrams Histograms
Benchmark	-	Historical consumption With other users (building) Expected consumption (tailored rating) Share of consumption for appliance
Further information	-	Useful tips for savings and efficiency

3.2 Direct feedback

The dashboard built for direct feedback (daily frequency) is made up of two sections. The first one for sub-metering shows the energy consumption (kWh and %) of each room, using a bar graph. In the second section (metering), through a multi-scale display, the user can simultaneously access the energy data consumed by the apartment (in kWh and in €) and the corresponding CO2 emitted (in kg). In this way, the user receives in real time information about his own energy consumption, the related costs and environmental impact, as well as on their distribution among different environments, leading, at the same time, to adopt energetically, economically and environmentally efficient behaviours. A daily frequency of this feedback was chosen by the authors due to metering and submetering devices characteristics and to the related costs of data transmission (e.g. battery consumption). Figure 4 shows the dashboard developed by the authors to display the daily energy consumption of a typical user both for heating and for electrical energy consumption.



a) b)

Figure 4 – Direct feedback: a) Heating Plant, b) Electrical Plant

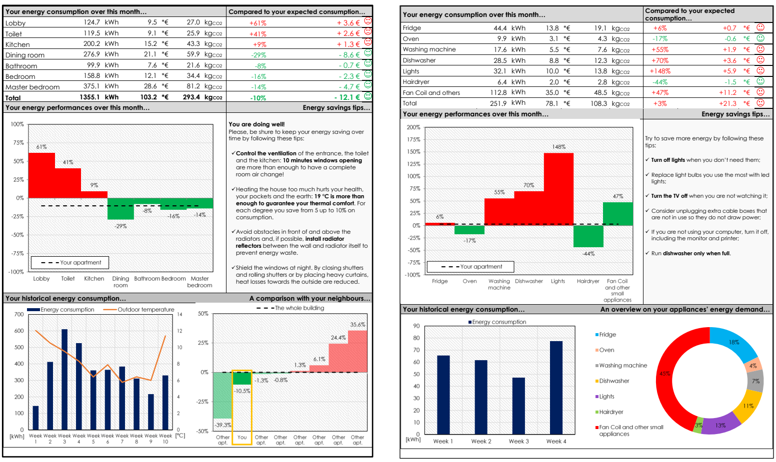
3.3 Indirect feedback

As above reported, through indirect feedback (monthly frequency), users receive information on their consumption also in terms of performance indices, personalized suggestions, comparisons with historic consumption, etc. In the following, the two case studies are presented and discussed separately, due to the corresponding peculiarities.

Heating Plant: In the heating plant case study, the performance benchmarks have been calculated as the ratio between the energy consumption measured at actual conditions of use (i.e. operational rating) and the estimated primary energy consumption adjusted to the actual conditions of use and climate (i.e. tailored rating), for each room, apartment and the whole building. In this way, authors tried to capture user's attention also by using emoticons, colors and “user friendly” information. To all users involved in the experimentation, the authors provided indirect feedback sheets, collecting impressions and suggestions. In particular, from the meetings carried out it emerged: i) a high participation (about 95%) of the users, ii) almost no user was able to understand the non-rated units provided by heat cost allocators, iii) users who had a poorly aware and responsible behaviour generally did not perceive the over consumption since before the experimentation heat accounting was carried out exclusively by floor area and costs due to building inefficiencies were divided into tenants accordingly,

iv) not all users were familiar with the control systems perceiving the intervention of thermostatic valves as a malfunction of the same, v) the cultural level of the users strongly affects the understanding of energy consumption data and, consequently, the adoption of retrofit actions, vi) the information received during initial installation was not sufficient to understand operation and use. Figure 5a shows the form designed by authors for indirect feedback of heating divided into six sections:

1) aggregate and disaggregated monthly energy consumption for each room (energy consumed and related costs and environmental impact);
2) local consumption indexes in percentage and economic units;
3) total user's consumption indexes;
4) personalized advice and tips aimed at saving energy;
5) historical consumption and related average outdoor temperature;
6) benchmark with the other apartments in the building



(a) Heating plant) (b) Electrical plant

Figure 5- Indirect feedback

<u>Electrical Plant</u>: In this case study, no comparison with other user was possible, as the family lives in a detached house. A ring chart shows the share of energy usage for each monitored appliance in the reference period (month). The benchmarking indexes have been built by the authors as the ratio between the measured and the expected energy consumption of the appliance analysed. It is well known that energy consumption of an appliance strongly depends on its use, which in turn, rely on the number of family components, characteristics of the house (e.g. floor area, outdoor spaces etc.) and on end-user (e.g. income, work, age, presence of children and/or elderly people).

Thus, in order to determine the expected energy consumption of each electrical appliance, the authors made a preliminary analysis of statistical data about electrical energy use from the Italian National Institute of Statistics (ISTAT) and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). Specific data were obtained about: i) number of cycles per week for given electrical appliances (dishwasher and washing machine); ii) lights turn-on period; iii) expected expenditure for different numbers of family components.

Figure 6 shows the data about dishwasher and washing machine usage per week and the trend of the expenditure for electrical energy of different family sizes. These data were used to determine energy usage coefficients as function of the family components and used as base to determine, for each electrical appliance, the time of use (in hours) in the reference period. Table 5 shows the usage coefficients determined by normalizing all data in respect to the ISTAT reference family (2.4 components). The reference energy consumption was then calculated by multiplying the above-mentioned calculated hours and the electrical energy consumption per cycle of the appliance declared by the manufacturer.

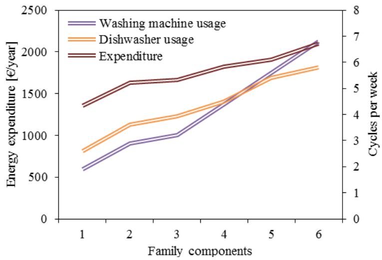


Figure 6 – Data usage for main appliances (ISTAT, 2014)

The benchmarks have been calculated as the ratio between the measured energy consumption of the appliance and the estimated energy consumption adjusted to the conditions of use of the appliance. Table 6 shows the calculated energy consumption of appliances. Figure 5b shows the form designed by authors for indirect feedback of electrical energy.

Table 5 – Calculated usage coefficients (ISTAT, 2014)

Family components	*Expenditure coeff.*	*Washing machine coeff,*	*Dishwasher coeff.*
1	0.80	0.37	0.61
2	0.96	0.87	0.92
2.4	1.00	1.00	1.00
3	1.05	1.16	1.10
4	1.12	1.37	1.23
5	1.17	1.53	1.32

Table 6 – Calculated energy consumption of appliances (ISTAT, 2014)

Appliance/device	*No.*	*Max. Power [W]*	*Energy label [kWh/year]*	*Usage coefficient*	*Expected consumption [kWh/year]*
Refrigerator Rex FI 22/10 H	1	n.a.	511	1.12	511
Oven Rex FR63	1	1865	105	1.12	146
Microwave Panasonic NN-k-108 WM	1	1000	n.a.	1.12	25
Washing mach. Electrolux EWF1286	1	2200	134	1.37	138
Dishwasher Bosch SMV 46 KX 01 E	1	2400	262	1.23	204
Iron De'Longhi PRO1847	1	2200	n.a.	1.12	60
Hairdryer Bosch PHD9760/01	2	2000	n.a.	1.12	139
Television Sharp, LC-40LE630E	2	108	70	1.12	15
Laptop HP 15-bc014nl	3	120	n.a.	1.12	328
Energy saving fluorescent lamps	46	9	n.a.	1.12	158
Fluorescent lamps	5	11	n.a.	1.12	
LED strips	1	13	n.a.	1.12	
LED lamps	14	7	n.a.	1.12	
Fan-coils	6	50	n.a.	1.12	462

4. CONCLUSIONS

In this work, authors presented the first results of a study on IoT-based energy consumption monitoring systems. Particular importance was given to user awareness in relation to adopted feedback and to consumption indexes. Two case studies have been presented and discussed related to heating and electrical energy consumption in residential buildings. It can be pointed out that:

- although there are numerous limits of interfacability and interoperability of monitoring devices and systems, these can be overcome through the use of web-based ICT platforms;
- the huge number of measured data and the complexity of the monitored systems make analysis and feedback particularly complex for non-skilled users;
- the characteristics of the feedback provided by the authors were: frequency, content, aggregation, presentation, benchmark and additional information;
- in the case of direct feedback, the authors favored the simplicity and immediacy of information;
- detailed data sheets of user consumption were presented for indirect feedback, emphasizing the comparison based on performance indices and personalized suggestions on user energy consumption behavior.

The adopted IoT technologies demonstrated high potential in terms of energy savings, as effective and frequent feedback contributes significantly to motivate and support the change in occupant behaviour. The analysis of the data showed some incorrect behaviour that users were not aware of, such as excessive ventilation of some rooms (eg entrance, bathrooms and kitchens), incorrect management of the thermostatic valves, incorrect management of some domestic appliances.

The use of IoT-based integrated tool also allowed end users to know precisely how much energy is actually consumed together with the estimate of their impact and comfort, to more effectively evaluate alternative technological solutions for heating, ventilation, lighting and choice of household appliances. Further developments will concern the integration of thermal, electric and gas energy consumption.

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