Sensor Networks for Energy Sustainability in Buildings

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Abstract

The topic of energy saving in buildings is increasingly raising the interest of researchers for its practical outcomes in terms of economic advantages, and long-term environmental sustainability. Many sensory devices are currently available that allow precise monitoring of every physical quantity; in particular it is possible to obtain estimates of energy consumption which can be used to enact proper energy saving strategies. Such devices may be considered part of a complex sensor infrastructure permeating the whole site of interest, which may be characterized by the adopted protocols and architectural models.

This work provides a comprehensive review of the current literature about sensory devices for energy consumption measurement, and global architectures for implementing energy saving in buildings.

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1 Introduction

The issue of energy efficiency is nowadays raising the interest of researchers and developers all over the world, due to the ever increasing awareness about the economic and environmental costs of a misuse of available resources. The attention devoted to the development of models for sustainable global energy consumption stimulates the adoption of suitable policies for cutting unnecessary energy consumption; however, in order to effectively enforce such policies, it is necessary to properly characterize energy consumptions so as to identify the main causes of wastes. Specialized studies [1] show that a relevant fraction of worldwide energy consumption is tightly related to indoor systems for residential, commercial, public, and industrial premises.

In literature, many systems have been proposed, with varying degrees of complexity, for building energy management; they often rely on the assumption that the environment is permeated by a large set of sensory and actuator devices, remotely controllable according to some defined policy, in order to bring the environmental conditions closer to the user's desires while also taking into account some globally defined constraints (see Figure 1).

This assumption is supported by the off-the-shelf availability of cheap and unintrusive sensors that may be easily distributed in the environment in order to sense relevant measurements. Wireless Sensor Networks (WSNs) [2], for instance, are one of the most interesting and investigated approaches for reliable remote sensing, and WSANs extend their functionalities by adding control devices, i.e., actuators. Such networks do not only passively monitor the environment, but represent the tool by means of which the system interacts with the surrounding world and modifies the environment according to the observed data in order to meet high-level goals (e.g., energy efficiency).

This work will chiefly focus on the sensory infrastructure for the specific purpose of energy consumption monitoring in buildings, without neglecting its potential use in the context of an overall, complex system. This entails taking into account not only specialized technologies used for the construction of efficient buildings, but also the overall ICT control architecture. A tight correlation exists among the chosen technology, the architectural

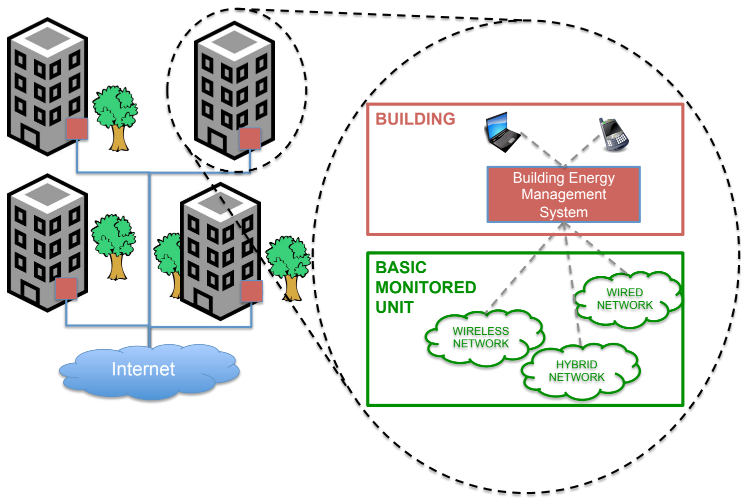

Figure 1: Exemplary infrastructure for a building energy management system.

paradigm and the energy saving policies. Indeed, the choice over the available technologies and the architectural paradigm represents a constraint over the viable energy saving policies; on the other hand, the complexity of such policies is dictated by the corresponding complexity of the sensory and actuator infrastructure.

In the following, we will provide an overview on the solutions reported in literature about the basic devices composing the sensory infrastructure for energy monitoring. The possible approaches for the realization of global monitoring systems will also be discussed, as well as their integration into comprehensive architectures. Finally, we will conclude by providing some insights about higher-level intelligent data analysis techniques that may leverage the use of the discussed architectures.

2 Towards Eco-sustainability in Buildings

Four main general approaches have been identified in literature for optimizing, or at least reducing, the electrical energy consumptions in buildings [3]; namely: user's awareness about energy consumptions, reduction of standby consumptions, scheduling of flexible tasks, and adaptive control of electrical equipments.

The simplest approach to energy efficiency consists in providing appropriate feedbacks about energy consumptions to users so as to increase their awareness and encourage eco-friendly behaviors. User awareness has been leveraged in many commercial and prototype systems such as Google PowerMeter, Microsoft Hohm, Berkeley Energy Dashboard, AlertMe, and Cambridge Sensor Kit (CSK) for Energy. Providing simple feedbacks can valuably influence the user's behavior [4]. However, to reduce costs, these systems typically provide only aggregate measures of energy consumption. Hence, they do not allow to identify the specific device or behavior causing the highest energy waste.

More detailed information is provided by monitoring systems that can measure the energy consumption of individual appliances, such as the device-level energy monitoring system proposed in [5], which allows users to monitor and compare the energy consumption of each appliance in a building, through a web-based interface. A hybrid solution, consisting in a monitoring system providing real-time information about the energy consumption of HVAC (Heating, Ventilation and Air Conditioning) and artificial lighting is proposed in [6]. Instead of relying on a fine-grained energy monitoring, it exploits a simple rule-based approach for correlating energy consumptions with contextual information.

Although user awareness is the basic approach to energy efficiency, its effectiveness is quite limited. Experimental studies carried out in a real building have shown that the sole provision of feedbacks is not sufficient to ensure significant energy savings in the long term. Specifically, the authors of [7] measured the energy consumption in the building before and after the installation of a monitoring system. While a reduction of more than 30% was observed in the week immediately following the installation, the energy savings became negligible just one month after the beginning of the experiment. Moreover, the authors of [8] claim that feedbacks can actually stimulate a virtuous behavior in home users, while they are not so effective in a work environment.

Another viable approach consists in eliminating, or drastically reducing, energy wastes due to electrical appliances left in stand-by mode. Despite its apparent simplicity, such an approach can produce significant energy savings. It has been estimated that most consumer electronics (such as TVs, set-top boxes, hi-fi equipments) and office devices (e.g., printers, IP phones) consume more energy in standby mode than in active mode, as they remain in standby for very long times [9]. The standby mode can be detected by monitoring the energy consumption of the specific device. This requires a metering infrastructure which, of course, should have a very low energy consumption by itself [10]. Once the standby mode has been detected, the device can be switched off. To this end, different strategies can be used to trade off energy saving for user satisfaction. The easiest way is to let the user decide about the time to switch off a device that entered the standby mode [3]. A more sophisticated approach consists in taking into account information related to the user's presence, or in learning their behavior. Such a strategy is used, for instance, in [11]. The authors propose a control system for generic electronic devices that leverages the hourly habits of users and turns off appliances whose relevance for user is currently negligible, while keeping the other ones in standby mode. The Energy Management Device (EMD) [12, 13] is able to autonomously detect devices in standby mode and to switch them off. The automatic detection can be performed by exploiting basic knowledge about the time zone and the user's presence, the appliance energy profile and, whenever possible, by catching signals generated by innovative appliances just before entering the standby mode.

The widespread adoption of smart technology in many electrical appliances enables the scheduling of their activity plans for energy optimization. In case of constraints on the energy peak demand, or in the presence of time-dependent fares, ad-hoc strategies can be implemented for determining the optimal scheduling of energy-hungry tasks that do not require user interaction (e.g. washing machine, dishwasher). The system proposed in [3] allows the user to specify the exact time (or time period) when a certain task is to be executed by a specific appliance (e.g., dishwasher). Such a policy makes sense only when energy fares vary over time, but their variations are known a priori. In [3] the identification of the most convenient time intervals is left to the user. However, it is foreseeable that energy providers will be able to supply information about the current contractual offer, scheduled shortages and low-fare hours [14] so that the overall system can autonomously plan for an optimal scheduling of flexible tasks. A similar approach is also used in the AIM Project [15]. Here users are allowed to specify a set of time requirements that will be regarded as constraints, when computing the optimal scheduling, based on information received from the energy provider.

A final approach is based on the consideration that both in residential and commercial buildings a significant fraction of energy is wasted due to electrical appliances that are left unnecessarily on (e.g., when no user is present). Hence, the most effective approach to energy savings consists in enforcing a more intelligent utilization of such appliances so as to avoid energy wastes. As previously mentioned, HVAC and artificial lighting systems account for the major fraction of energy consumption, both in residential and commercial buildings. Thus, adaptive control on such systems is essential for effective energy management in buildings. On the other side, adaptive control strategies should consider user wellness in addition to energy savings. The enacted policies should not negatively affect the comfort perceived by the user, otherwise the reaction would be an immediate rejection of any automatic control, thus discarding the possibility of energy saving. For instance, daylight-harvesting systems currently available on the market have a limited penetration because of their side-effects on the user's comfort. Half of these systems, whose control is only based on daylight, with no additional intelligence, exhibit an intolerable latency in adapting to external light conditions and, typically, they are soon de-activated by users. The use of intelligent techniques for user-presence detection and/or prediction is advised to adaptively tune the activation time of electrical equipments, especially those whose latency in bringing the environment into the desired conditions is non negligible (e.g., HVAC systems).

In the next Section, we will start by discussing the available devices for the creation of the monitoring infrastructure.

3 Sensor Networks for Energy Monitoring

Regardless of the particular choice adopted towards sustainability, researchers have specifically considered the basic requirement for enforcing any energy saving strategy, namely a precise and timely knowledge of energy consumptions. A relevant issue to be addressed during the design phase of a complex monitoring system is in fact how to select the technology to be used for creating the sensory infrastructure, specifying the required precision and granularity while preserving the users' privacy.

A wide selection of sensory technologies for energy sensing is today available off-the-shelf, and the choice of a given technology directly affects the complexity of the ICT architecture supporting the monitoring system.

When a coarse-grained monitoring is sufficient, sensory devices may be installed at the root of the power distribution network. This represents an extremely simple and inexpensive solution, but, even though many devices have been designed to implement such "single-point-of-sensing" approach, it is still advisable to carefully assess the impact of the technology on pre-existing premises, as well as its ease of deployment. The authors of [16] propose RECAP (RECognition of electrical Appliances and Profiling in real-time), a system for the identification of energy fingerprints of appliances, which relies on a single wireless energy-monitoring sensor clipped to the main electrical unit. Using wireless communication links avoids the need for the deployment of a communication infrastructure from scratch. In the described supervised approach, the user is guided through the phase of profile creation for various devices, thus allowing the construction of a fingerprint database. Such data is then used in real time by a neural network aiming at recognizing all appliances operating at a given moment.

At a finer grain, devices for monitoring energy consumption differ mainly with respect to the density of deployment. The monitoring system proposed in [7] exploits a sensory system consisting in a network of heterogeneous wireless sensors, made of AC meters and light sensors. The energy sensing nodes allow to collect active, reactive, and apparent power measurements [10]; each node implements the IPv6/6LoWPAN stack, and the entire wireless sensor networks is connected to other TCP/IP networks via a router.

Other solutions for AC power metering through a sensor network have been proposed. In [17] the "Plug" network is described, which is composed by nodes fulfilling all the functional requirements of a normal power strip, and equipped with an antenna and a CPU. Additionally each node, thanks to some on-board sensors, is able to provide measurements of temperature, light exposure and noise. Such a device allows to realize a comprehensive sensor network for the observation of environmental conditions and energy consumptions. However, the conspicuous size and weight of sensor nodes prevented their use for an unobtrusive sensory infrastructure, which is instead a basic requirement for any pervasive system.

The design of a pervasive sensor network for energy monitoring might benefit from a special focus on the more energy-hungry actuators, such as those for offices HVAC, or for domestic appliances. A possible solution consists in using integrated sensor/actuator platforms for energy consumption monitoring, through commercially available devices such as Plogg and WiSensys, as suggested by the authors of [3]. Currently such devices are still expensive, so it might be convenient to allow for coarser granularity of monitoring, by coupling a single energy sensor to a group of devices.

Monitoring and efficiently managing the energy consumption of the sensing infrastructure itself would deserve a separated discussion. This issue is extremely important in case of sensor nodes powered by batteries with a limited energy supply, as in typical WSNs for environmental and context monitoring; however, this topic is beyond the scope of our present discussion, and we refer the reader to [18] for a detailed overview on power management in WSNs .

Whenever any of the previously mentioned devices is used as part of a complex system, the main issues need to be addressed with regards to the architectural choices are the integration of various different technologies, and the scalability with respect to the diversity of devices and to the number of monitored areas. In particular, the first two points arise from the availability of very different technologies for the same functionality, while quite often one of them is not sufficient to perform all sensory/actuator duties by itself.

As regards the choice of protocols, a possibility consists in the adoption of one of the standards used in the field of home automation, which are typically based on wired communications, or alternatively to use wireless technologies, allowing to create a Wireless Home Automation Network (WHAN). The former class of home automation protocols includes for instance the Modbus protocol, used for serial connection of electronic devices; it also comprises the standard for communications over different physical media, such as the KNX standard, the LonWorks platform, and the BACnet protocol; other protocols exploit the pre-existing power lines in order to connect different devices: those include the HomePlug protocol [19], LonWorks again, or the X10 standard. A brief overview on this class of solutions is reported in [20].

The latter class of protocols, based on wireless, includes instead the protocols of the ZigBee family, Z-Wave [21], Insteon (which also allows communication over powerline and X10 compatibility), and Wavenis technology. The most significant difference with respect to wired system is that wireless technology is more suitable for pervasive and non intrusive deployment, thanks to the possibility of installing devices virtually everywhere and with negligible impact on the environment even in the presence of high-density deployment. However, such kind of technology makes it harder to design and implement the systems, due to the typical issues of wireless communication, such as the possibility of interference, the presence of reflective surfaces, or the need for multi-hop communication. For a detailed overview on WHAN technologies and the related design issues, the reader may refer to [22]. Table 1 provides a reference for the mentioned technologies and protocols.

Regardless of the wired or wireless nature of the communication link, one technology is generally not sufficient on its own to cover all the necessary functionalities of a complex system for managing entire buildings; for instance, it may be required to integrate specialized technology, such as RFId for user tracking, or sensors for energy monitoring, or even all kinds of actuators. It is thus evident that those approaches aimed at the cooperative connection of heterogeneous devices are to be preferred.

4 Systems for Energy Sustainability

A precise and timely knowledge of energy consumptions is an essential requirement for enforcing any saving strategy, and it must be the basic functionality of any energy-aware system. In this Section we will review some of the approaches to monitoring recently proposed in the literature, as well as the corresponding architectures and protocols.

4.1 Approaches to Energy Monitoring

Systems for energy monitoring can be classified according to different criteria, e.g., the type of sensors they use, or the spatial granularity used for collecting data. With respect to sensors, it is possible to distinguish between *direct*, *indirect*, and *hybrid* monitoring systems. Direct monitoring systems use electricity sensors for directly measuring energy consumptions, while indirect systems infer energy consumptions by measuring other quantities such as temperature and/or noise. Finally, hybrid systems rely on both approaches. Direct monitoring systems can be further classified into *fine-grained*, *medium-grained* and *coarse-grained* systems, depending on the

Table 1: Home automation technologies and protocols.

Technology	**Reference**
BACnet	`http://www.bacnet.org`
HomePlug	`https://www.homeplug.org/home`
Insteon	`http://www.insteon.net/pdf/insteondetails.pdf`
KNX	`http://www.knx.org/knx-standard/knx-specifications`
LonWorks	`http://www.echelon.com/technology/lonworks/lonworks-protocol.htm`
Modbus	`http://www.modbus.org/specs.php`
Plogg	`http://www.plogginternational.com`
Wavenis	`http://www.wavenis-osa.org`
WiSensys	`http://www.wisensys.com`
X10	`http://www.x10.com`
ZigBee	`http://zigbee.org`
Z-Wave	`http://www.z-wavealliance.org`

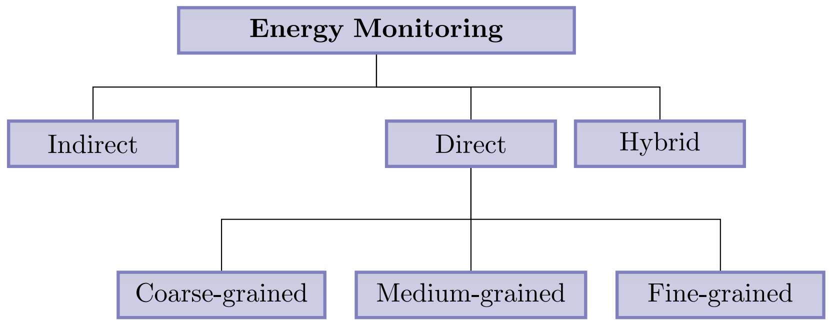

Figure 2: Taxonomy of Energy Monitoring Systems.

level of spatial granularity they use in collecting data about electrical energy consumptions. The whole taxonomy is graphically summarized in Figure 2.

Following this general taxonomy, indirect monitoring systems are so called because they do not use electricity sensors for measuring the energy consumption of appliances. Instead, they indirectly infer information about energy consumptions by measuring other physical quantities that are somewhat related with energy consumptions. This approach leverages the fact that appliances typically affect other observable environmental variables, such as temperature, ambient noise, vibrations or electromagnetic field. Specifically, data provided by sensors are combined with a consumption model of the appliance in order to obtain an estimate of its energy consumption. An indirect monitoring system is proposed in [23], where a wireless sensor network is used to measure physical quantities such as noise, temperature and vibrations. Each appliance is identified by a specific pattern of its sensory measurements. For instance, switching on a kettle is associated to temperature rising, and to a variation in vibration and ambient noise. However, the paper does not specify how the system is provided with the association between sensory patterns and the specific operating appliance.

Whenever a model for appliance energy consumption is available, any system able of automatically detecting appliances could be used for performing indirect energy monitoring. Those systems include the approach proposed in [24], which exploits information coming from the energy distribution network, other than explicit energy consumption. The proposed approach performs the analysis of the high frequency electromagnetic interferences (EMI) generated by the electronic devices powered through a switch mode power supply (SMPS) (used in fluorescent lighting and in many electronic devices). Due to the limited applicability to a specific class of actuators, such technology should be just regarded as complementary to the energy monitoring system.

Unlike indirect systems, direct monitoring system measure energy consumptions through ad hoc electricity sensors, typically referred to as power meters. The granularity used for direct energy monitoring spans from a single point of metering to the monitoring of individual appliances. The rationale for using only a single power meter is keeping intrusiveness at a very low level. Accordingly, these coarse-grained systems are referred to as *NILM (Non-Intrusive Load Monitoring)* systems, or *NALM (Non-intrusive Appliance Load Monitoring)* systems if the focus is on individual appliances. On the opposite side, fine-grained systems allow to monitor individual appliances with a high precision but require the deployment of a large number of power meters. Obviously, the granularity of monitoring affects the approach to the artificial reasoning carried on the collected sensory data and, indirectly, also the possible energy-saving policies than can be used.

The NALM approach has been initially introduced by Hart [25], who proposed a system for measuring current and voltage at the root of the energy distribution network, which is typically organized as a distribution tree. Variations in collected measurements, after pre-processing, are compared to consumption profiles for the various appliances in order to infer their activation or de-activation. Hart's work has been seminal for a number of subsequent works in the field of energy monitoring. The work presented in [26] follows the NALM approach in order to disaggregate the overall consumption into those components that can be attributed to the more relevant end users in a home environment. As in the original NALM approach, this work requires the consumption pattern for each appliance to be manually extracted by a human operator and explicitly coded into the disaggregation algorithm. The NILM/NALM approach provides only a high-level view of the energy flows [7]; it is straightforward to use such information to provide feedback to the users in order to trigger virtuous behavior, which is indeed the aim of some projects, such as the previously mentioned Google PowerMeter, and Microsoft Hohm.

Several approaches proposed in literature are based on the processing of measurements collected by a single point of measurement [27], and on the use of complex algorithms, such as Genetic Algorithms [28] or Support Vector Machines [29] in order to decompose the measurement into its components. However, some authors question the effectiveness of such disaggregation techniques in environments like office rooms, where many loads are based on switched power supplies [7]. A survey of disaggregation techniques for sensing energy consumption is presented in [30].

The alternative approach to a single point of sensing consists in monitoring energy consumption at a finer grain. Brought to its ideal extreme, this approach would require a detailed knowledge of every branch of the power distribution network, which, of course, is not feasible in practice. Works presented in literature only attempt to come close to this ideal goal. The authors of [7] explore several practical techniques for approximately disaggregating the load tree using a relatively sparse set of power meters. They also propose some techniques for modeling and estimating the energy consumption along three directions, namely *functional*, by identifying which functionality requires a specific slot of energy; *spatial*, by identifying the area where the energy slot is consumed; and *personal*, by identifying the end user of that energy slot.

Within the broad spectrum of granularity, there exists an intermediate position between NILM systems and systems targeting each device individually. The authors of [31] propose to measure energy consumption only for those branches of the energy distribution tree where some particular devices are connected. With respect to a fine-grained approach, this proposal requires the installation of fewer monitoring devices, while, in comparison to a NILM system, it allows to monitor the behavior of low consumption devices, whose fingerprints would otherwise be overshadowed by high-powered devices. In particular, this can be obtained by powering the latter class of devices on a separated circuit. Within one specific branch, it is however necessary to use data analysis algorithms allowing for a disaggregation of partial data. One of the approaches proposed in [31] uses a probabilistic level-based disaggregation algorithm. Samples about active and reactive power are collected at various devices; after normalization, samples are clustered in order to extract representatives for each operating status. Extracted clusters represent the consumption models for each device, starting from which a classifier is built that takes into account all the possible combinations of activated devices. A similar approach is adopted in [32] for the monitoring of the energy consumption of buildings in a university campus. In particular, the proposed monitoring system consists of a power meter at the root of the distribution network of each building, whereas a finer-grain monitoring system is deployed in one of the buildings, by partitioning the network supplying that building into 15 separately monitored circuits. Such partition allows to isolate plug loads, lighting, and the machine/server room for each floor. The authors just report a visual representation of the consumption of the different devices, without proposing any algorithm for further data disaggregation.

Finally, a hybrid approach to monitoring - including both a direct and an indirect part - involves using both specific sensors for energy measurement (typically consisting in a single power meter at the root of the distribution tree), and indirect sensors for recognizing the operating status of appliances. An example of such a complex approach may be found in [33], where the authors propose a monitoring system based on WSNs with magnetic, light and noise sensors, and including a power meter for monitoring the overall energy consumption. The authors propose an automated calibration method for learning the combination of appliances that best fits the collected sensory data and the global consumption. The calibration method integrates two types of models. Specifically, a model of the influence of magnetic field, depending on two *a priori* unknown calibration parameters, is used for more complex appliances with many operating modes, whereas appliances with fewer operating modes only require models associating the relative con-

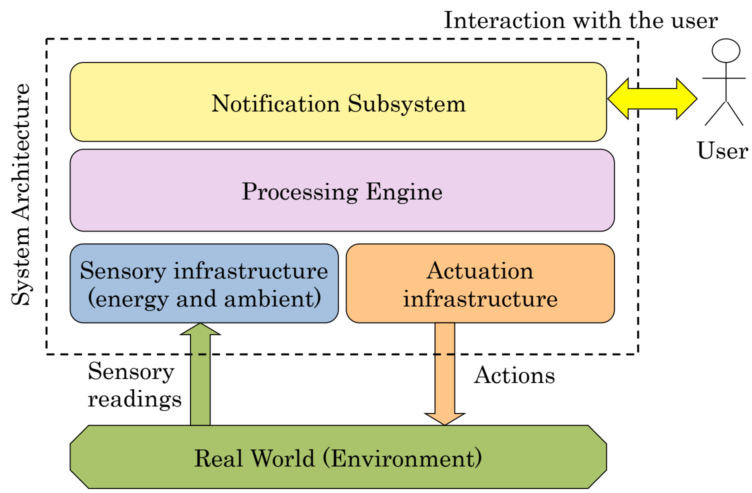

Figure 3: Logical layers of an architecture for building energy management.

sumption to each specific mode, which is estimated via the noise and light sensors. The main disadvantage of this work is that the calibration is to be performed *in situ* and cannot be carried out before the deployment since many unpredictable external factors may influence the measured environmental variables. It is worth pointing out that hybrid systems are typically characterized by a coarse-grained direct monitoring of energy, with a single sensor at the root of the energy distribution tree. This is usually coupled with a fine-grained indirect monitoring.

4.2 Architectures and protocols

To be effective, the previously described approaches need to be implemented as part of an overall automated system capable of enforcing effective use of electrical appliances so as to reduce electrical energy consumptions in the building without negatively affecting the user's comfort. The logical layers which are likely present in such architectures are depicted in Figure 3.

A number of architectural solutions have been proposed in literature, which can be analyzed and compared from different viewpoints, such as *architectural model* (i.e., centralized or distributed), *internal organization* (i.e., single layer or multi-layer organization), *networking protocols*, ability to support *heterogeneity* in sensing technologies, etc.

One of the proposed solutions is a monitoring system based on Web-enabled Power Outlets [5]. Each appliance is connected through a (Plogg) Power Outlet, i.e., a power meter that measures the energy consumption of the appliance and sends the acquired information to a Gateway, using a standard communication protocol (e.g., Bluetooth or ZigBee).

A further evolution consists in a direct integration of power meters, and possibly any other smart device, by exploiting the *Web-of-Things* (WoT) paradigm. The latter is the extension of the well-known *Internet of Things* (IoT) paradigm to the Web [34]. Following the WoT approach, any smart object (e.g., power meter, sensor/actuator device) hosts a tiny web server. Hence, it can be fully integrated in the Web by reusing and adapting technologies and patterns commonly used for traditional Web content.

A centralized architecture is also leveraged by the *iPower* system [35]; here, a central server interacts with heterogeneous sensory and actuator devices. Specifically, a WSN is used to monitor environmental conditions and to measure energy consumptions, while actuation is performed by X10 devices connected to the server via Power Line Communication (PLC). Since wireless sensors have a limited transmission range they may not be able to communicate directly with the server. Hence, to extend the system coverage, sensing devices send their data to a local base station. Base stations are then connected to the server through an Ethernet high-speed Local Area Network. To manage heterogeneity with a sufficient degree of abstraction *iPower* relies on a multi-layer architecture.

A more complex architecture, capable of providing advanced support to heterogeneous sensory and actuator infrastructures, is used in the *Sensor9k* system [14], which is internally organized according to a 3-tier model. The *Physical* layer includes all the sensory and actuation devices, the *Middleware* layer is composed by a set of building blocks for implementing basic services, and, finally, the *Application* layer hosts the control logic and consists of various AmI applications. The inclusion of a *Physical Abstraction Interface* ensures support against the heterogeneity of physical devices, as it takes care of exporting higher-level abstractions identifying the basic monitored units. Furthermore, it deals with basic connectivity issues among devices, and groups together all the functionalities related to message relaying, monitoring and control of the infrastructure health, and reconfiguration due to changes in the underlying physical infrastructure. *Sensor9k* aims to address scalability with the number of monitored areas, which is typically the major limitation of centralized solutions.

The idea of a hierarchical architecture with gateways interconnecting different technologies is also proposed in [11], in the context of the AIM project [15]. The main goal is the construction of a bridge between a smart home and the smart power grid in order to control the energy consumption of appliances.

Unlike the previously mentioned architecture, the Sensor-Actuator Network proposed in [36] is a fully distributed architecture that does not fall into the same general scheme, since the control logic is widely embedded into the sensor and actuator infrastructure. The resulting wireless network consists of three components, namely a WSN for environmental monitoring, a set of actuator devices, and a number of control nodes that interconnect sensors and actuators. The system is specifically targeted to lighting system control and, because of the tight binding between the sensor and actuator systems, the introduction of additional functionalities does not appear straightforward. Moreover, the scarcity of computing and storage resources available in wireless nodes makes impractical to accomplish complex functionalities, such database maintenance.

The main features of the described architectures are summarized in Table 2.

5 Final Considerations

The significance of the adoption of energy saving strategies in building management has now been fully recognized both from industry and academy. In this work, we aimed at providing a detailed overview of the available sensory devices for energy consumption measuring, and of the different energy monitoring systems, analyzing the trade-off between costs and precision.

Table 2: Comparison among different architectures.

	Web-enabled Power Outlets	**iPower**	**Sensor9k**	**AIM Architecture**	**Sensor-Actuator Networks**
Ambient Sensor Technologies	None	WSN	WSN, RFId, User action sensors	WSN, RFId	WSN
Energy Sensor Technologies	Power meters	Wireless power meters, power actuators (X10)	Root power meter, Wireless power meters	Energy Management Devices (EMD)	None
Architecture Model	One-tier	Multi-tier	Multi-tier	Multi-tier	Zero-tier
Abstraction for Heterogeneity	None	OSGi	OpenGIS-based	OSGi	None
Control Logic Deployment	None	Centralized	Centralized	Distributed	Distributed

Even though devising a sensory infrastructure for energy monitoring is a fundamental step in the creation of an energy-aware system for environment management, this is not sufficient to obtain a relevant impact with respect to energy saving.

In order to improve the overall outcome, it would be necessary to devise complex systems made up of multiple specialized modules, i.e.: a sensing component, a data processing engine, a user interface, and an actuation component. Maintaining the emphasis on the sensory module, which has been the focus of this work, different solutions have been examined; however, efficient energy monitoring requires a broader view, which necessarily includes reasoning about other quantities of interest, ranging from physical quantities, such as temperature or lighting, to higher-level ones, such as user activities. Technologies for environment and context monitoring have been in fact widely discussed in several specific surveys [20, 22, 37].

In order to obtain a coherent vision of the sensory infrastructure, particular relevance derives from the adoption of a global architecture able to integrate all the different technologies pervading the buildings. A few approaches presented in literature have been described here, targeting energy-awareness; some works have also been published on the topic of choosing the ICT architecture for developing smart spaces [38, 39]. To the best of our knowledge, however, none of them focuses on the suitability with respect to the specific goal of energy saving.

Furthermore, in our opinion, the global sensory infrastructure must be driven by a data processing engine implementing the full system logic, starting from data pre-processing, up to user/appliance profiling, prediction of the quantities of interest, and the overall planning. Such engine might require the use of advanced techniques of artificial intelligence (AI) in order to have the system comprehensively show an "intelligent behavior". Many works presented in literature focus on the design of individual intelligent functionalities, such as user profiling, predicting the occupancy status of the monitored premises, or detecting the activity patterns of users, even though different approaches may also be found where comprehensive modular architectures, either agent-based or service-oriented, allow for embedding several intelligent modules as previously mentioned in the present work [40, 14, 41, 42].

There is still however a yet unattended demand for a comprehensive analysis of the issues related to the design of a complete system for energy saving in buildings, where the topics of the present work would fit as a basic building block.

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