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The Role of Smart Meters in Enabling Real-Time Energy Services for Households: The Italian Case

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Abstract: The Smart Meter (SM) is an essential tool for successful balancing the demand-offer energy curve. It allows the linking of the consumption and production measurements with the time information and the customer's identity, enabling the substitution of flat-price billing with smarter solutions, such as Time-of-Use or Real-Time Pricing. In addition to sending data to the energy operators for billing and monitoring purposes, Smart Meters must be able to send the same data to customer devices in near-real-time conditions, enabling new services such as instant energy awareness and home automation. In this article, we review the ongoing situation in Europe regarding real-time services for the final customers. Then, we review the architectural and technological options that have been considered for the roll-out phase of the Italian second generation of Smart Meters. Finally, we identify a collection of use cases, along with their functional and performance requirements, and discuss what architectures and communications technologies can meet these requirements.

Keywords: smart meter; smart metering; real-time services; load shifting; demand response; distribution system operator (DSO); in-home device (IHD); Internet of Things; Time-of-Use; Real-Time Pricing; energy awareness; home automation

1. Introduction

Smart metering plays a crucial role in the electricity value chain. Availability of metering data is a prerequisite for the management of the energy flows exchanged between the private low voltage (LV) consumers/prosumers and the utilities. The "smartness" of the metering infrastructure basically refers to the possibility of a Distribution System Operator (DSO) reading the metering data remotely, hence avoiding the need to send technical personnel on site and reducing or eliminating the need for customer estimations of consumption. In all the EU Member States, a separation is required between the DSO and the retail supplier, which has commercial contracts with final customers and prosumers. In this paper, we assume that the metering system is owned and operated by a DSO, while the billing is managed by the retailers for the whole price (including the network tariff). This is the most frequent situation among the EU Member States. The Smart Meter (SM) is placed at one end of the chain, the other end being the Head-End System (HES) of the DSO. The SM samples the energy flows withdrawn from or injected into the electric network. These measurements are transmitted to the HES through an Automated Meter Reading (AMR) infrastructure. Thanks to frequent and accurate digital measurements, SMs make it possible for retailers to activate special contracts differentiating energy prices throughout the day. This also waives the necessity of consumption estimations and self-reading, enabling a Time-of-Use (ToU) or even Real-Time-Pricing (RTP) regime [1–4]. By contributing to the final goal of keeping demand and offer curves as close as possible during the day, ToU and RTP are known to have a positive effect for both DSOs and final customers [5–7]. In addition, SMs can enable newer services such as Automated Demand Response or prepaid contracts.

An additional advantage of SMs is feedback to customers about energy flows at their connection points, which allows them to have a better awareness of their consumption behaviors. The more information is available, the higher the customer flexibility and their capability to control their own consumption. There are several use cases requiring that metering data reach the customer as quickly as possible in order to let them react close to the time of utilization. DSOs and retailers cannot provide such data with a low latency, because the data-collection process is engineered to maximize the availability and correctness of the collected data, thus implementing time-consuming data retransmission and validation processes. The only feasible solution is to enable direct transmission of raw data from the SM to devices located near the customer's premises [8]. In-Home Devices (IHDs) such as simple displays, smartphones, or web-based portals fed by SM raw metering data, can increase energy savings. They can even combine electric measurements with other data (e.g., tariffs, saved CO_2, neighbors' consumption, etc.) with the goal of supplying more valuable and enriched information for energy savings [9,10]. Some studies [11,12] show that real-time feedback can be interesting to the final customers if:

- It is displayable on different devices (smartphones, tablets, dedicated devices, etc.)
- It is clear and intuitive (through smart charts and aggregated results)
- IHDs have a good design and are cheap and easy to install [13].

A lack of the mentioned features can lead customers to lose interest after some months [11]. With a more complex infrastructure, IHDs fed by SM measurements and other entities can automatically control a set of deferrable appliances, thereby reducing the usage of energy during peak hours with no direct customer intervention. IHDs are also a viable alternative for providing frequent data to users without incurring the legal and technical difficulties of involving third-party service providers [14,15].

This paper has the following goals:

(1) To review a set of use cases enabled by communications of metering data to the customer, such as energy awareness and demand-response.
(2) To review the set of possible architectures for data communications from the SM to the IHDs.
(3) To review the available communications technologies for connecting SMs and IHDs.
(4) To discuss the advantages and drawbacks of the identified architectures and technologies in terms of cost, applicability to diverse scenarios, and ability to meet performance and regulatory requirements.

Our discussion is general, but we will consider as a reference the generation of SMs whose roll-out is currently taking place in Italy. This new generation is expected to bring to almost 30 million customers a new set of features like the acquisition of different kinds of data (among which are active/reactive power, voltage, and outages) and increased sampling frequency. Such data will be delivered both to the DSO, for billing and other monitoring purposes, and, with low latency, to customers' devices. With respect to other surveys on Smart Metering [16–18], we focus on the technology options for direct communications to the customer devices and for providing low-latency services. In addition, we focus on flexible architectures capable of meeting the requirements of different use cases with small provisioning costs.

The paper is structured as follows: Section 2 reports the state of the art of the smart metering infrastructure with a focus on the standardization process in the EU and in Italy specifically; Section 3 presents the Italian second generation SM; Section 4 describes real-time services; Section 5 illustrates different architectures for bringing data to customers; and Section 6 lists a set of wired/wireless enabling technologies for smart metering. Finally, Section 7 summarizes the previous sections to identify the combination of architectures and technologies suitable for the new services. Conclusions are left for the final section.

2. Smart Meter Overview

A smart meter (SM) is a device able to measure the physical quantities flowing through its boundary, record events (e.g., outages or changes in contractual rated power), and digitalize and transfer such information to a central acquisition system. An electric SM is in charge of collecting data on not only energy flows, but also power and voltage levels at the customer's premises, and then sending those measurements to the DSO. In turn, the DSO uses the acquired information for both managing the network (e.g., controlling network losses) and providing retailers with validated data to be used mainly for billing reasons but also for customer management.

In this article we only consider the electricity value chain and we refer to electric SMs as simply SM. Given the crucial role of the SM in the electricity value chain, various regulatory authorities have defined its main characteristics. According to Directive 2004/22/EC of the European Commission regarding measuring instruments (MID), SM must show the results of the metering process directly at the customer's premises at least through a display or other more sophisticated system. It has to be user-friendly and long-lived, ensuring a future-proof nature. More than one physical quantity can be collected (e.g., active energy, reactive energy, power usage, and voltage) and even stored within the SM registers for many days in order to cope with the possible unavailability of the communications channel used for data exchange with the HES.

Metering data exchanged between SM and the DSO's HES usually travel across two hops. In the most common architecture of smart metering systems, the first link connects the SM with the so-called "data concentrator" (usually situated in a Secondary Substation where the MV/LV transformer is located), while the second link enables the acquisition of the measurements from the concentrators to the HES. The data concentrator is an intelligent station that receives hundreds of measurements coming from different SMs, processes and repackages the data before sending them to the HES. It can also ask for a new data acquisition should the communication with some SMs fail. The SMs, the concentrators, and the HES required for a smart metering system belong to the so-called Advance Metering Infrastructure (AMI) [19]. Communications within an AMI can in theory enable data acquisition from SMs to HES but, in almost all cases, can be used both ways (upward from the SM to HES and downward from HES to SM); of course, this requires a more complex infrastructure that allows DSOs to execute several actions through the SM such as remote customer disconnection for unpaid bills. The former architecture is called Advanced Metering Reading (AMR), while the latter implies the upgrade from AMR to Advance Metering Management (AMM).

For communicating metering data to the data concentrator, different technologies can be used. Usually, Power Line Communications (PLC) is the preferred solution since it does not require a dedicated infrastructure (as coverage is provided by the existing electrical system); it ensures good reachability even in deep-indoor installations and can be managed directly by the utilities, reducing the need for the DSO to procure telecommunication services (although these services are commonly used for the second link from the data concentrator to HES). Wireless technologies operating at sub-GHz frequencies, such as the Wireless Meter-bus (wM-Bus) protocol, are popular alternatives for collecting data from the SM, ensuring long-distance communications. The main drawback is that they require the installation of a dedicated communications network and frequency planning to ensure low interference.

At the HES, raw measurements are analyzed in the so-called validation process, which checks if the collected data are complete and valid or, failing that, uses advanced algorithms for missing-data reconstruction. Finally, the validated measurements can be forwarded upstream for the billing phase managed by retailers. In a scenario of several millions of customers and daily readings with fine granularity, considering best-practice checks for validation, it can take many hours before the data become available to the suppliers for the billing process.

Some SMs can even send raw, non-validated measurements directly to the final customer in real time for awareness purposes and, possibly, home automation. Thanks to a set of IHDs communicating directly with the SM or through a Home Area Network (HAN), metering data can be visualized on a local display or smartphone application, giving consumption feedback and tips for reducing electricity absorption and thus saving money.

In addition, an SM capable of two-way communications can receive requests from the IHD asking for specific data or to execute operations. Such systems are inherently more subject to electrical- and cyber-security issues, which must be taken into account.

A Review of Energy Metering Deployment Strategies

According to European directive 2009/72/CE [20], all EU Member States are required to make a cost/benefit analysis (CBA) for introducing smart meters on a large scale, in order to have an economic assessment of all the long-term costs and benefits to the DSO, market players (like suppliers and aggregators), and the individual consumer. Where roll-out of SMs is assessed positively, Directive 2009/72/CE requires that at least 80% of consumers be equipped with intelligent metering systems by 2020. The European Commission has accompanied this Europe-wide huge process with many initiatives, among which is Recommendation 2012/148/EU [21], the publication of a state-of-progress benchmarking report and issuing a mandate for smart metering standardization to the three European Standardization Organizations: the European Committee for Standardization (CEN) and the European Committee for Electro technical Standardization (CENELEC), both based in Brussels (Belgium), and the European Telecommunications Standards Institute (ETSI), based in Sophia Antipolis (France).

Recommendation 2012/148/EU indicates 10 functional requirements that are intended to be of common interest for all Member States; however, the details of the roll-out strategies on technical and regulatory criteria are defined independently by each Member State. In most of the countries where SMs have already been installed or are going to be, the benchmarking report [22] shows that smart metering requirements satisfy a common set of functionalities such as: fine granularity of metering data, remote reading and AMM installation with bi-directional communications for DSOs, ToU pricing schemes, cryptographic techniques for preserving privacy, tamper-proof hardware, and the capability of providing readings directly to the user or an authorized third party [21].

Currently, a few Member States have already completed the roll-out (like Italy, Sweden, and Finland), some are in progress (like The Netherlands, Spain, and Poland) and most of the others have plans for a total of about 200 million smart metering units by 2020. By that date, it is expected that around 72% of European electricity customers will have a SM installed at their premises, which will potentially lead, according to benefit assessments in positive CBAs, to average energy consumption reductions of up to 5% and peak load shifting up to 9.9%. Only a few Member States (among which are Germany, Belgium, and Cyprus) will not proceed with a wide-scale substitution [22].

In terms of non-validated, real-time metering data provision to final customers, in some countries DSOs are testing new solutions and technologies: for instance, the utility NRGi (Aarhus N, Denmark) in Denmark installed around 200,000 SM with a HAN interface for IHDs allowing energy awareness. It also includes an M-Bus interface, which allows non-electric SM (e.g., gas or water) to communicate, transforming the electric SM into a data collector [23]. In Poland, Energa Operator SA is supplying SMs with USB-like solutions for HAN interfaces plus a wired/wireless bus for letting third-party devices collect customers' metering data and reply with saving advice. The Swedish company Sundsvall Elnat AB is trying to install a SM with a simple display at the customer's premises. In France, a first lot of 300,000 SMs installed by Enedis Operator (Paris, France) will communicate to IHDs thanks to a Zigbee or KNX interface [24]. Zigbee technology is also used by the Brazilian utility EDP Bandeirante, which integrates their SMs with a serial port and a web portal accessible for consumers. Dutch companies are equipping their SMs with physical ports (e.g., RS-232 or RJ-11) for real-time data reading.

In Italy, the distribution company of the Enel group started in 2001 to replace its 30 million conventional meters (85% of the country) with an infrastructure comprising the same amount of SMs able to be remotely read and controlled; the Enel roll-out was completed in 2006 and is by far the largest application of a single utility around the world. The Enel project "Telegestore" was concluded before the retail market full liberalization (which started mid-2007), and thus is outdated; back then, DSOs fitted the whole process, from meter reading to billing, to their own captive customers.

The goal of the Enel "Telegestore" project was originally to substitute the personnel previously in charge of reading the old mechanical meters door to door with an automated system able to protect the point of delivery from frauds and energy theft, reducing the costs for interventions and improving the accuracy and efficiency of the billing process. Additionally, the increased number of measurements allowed the activation of new services for customers such as the exploitation of ToU pricing regime with three time bands for households and small business customers [25], invoices on real consumption, remote contract management, together with network management (e.g., loss reduction) whose benefits can pass to the final customers thanks to the regulation.

The new system was so successful that, in 2006, the Italian Regulatory Authority (AEEGSI) issued a decision (292/2006) that forced all the DSOs of the country to adopt AMM within 2011. This first generation of SM was able to collect four incremental energy totalizers in different time bands of the day. The data concentrator collected metering data from SMs on a monthly basis. Data concentrators were able to manage the communications in both directions: to/from the DSO's HES (via the public telecommunications network) and to/from SMs (via a private distribution line carrier communications band A [26], half–duplex mode, net speed rate of 2400 bit/s). In addition, 400,000 data concentrators were installed in secondary substations for managing more than 30 million SMs. Communications is guaranteed by the Telegestore protocol, which was recently standardized with the name of "SMITP" [27] and has been adopted for the current Spanish SM roll-out managed by Endesa (Ponferrada, Spain).

In a pilot project [8] conduced in 2012 by the Enel group's DSO "e-distribuzione", around 5000 households received an IHD kit called "*Smart info* +" including a data collector, a full color, touch screen display, and software for smartphones and laptops. The kit enabled the possibility to collect real-time metering data receiving information directly from the SM and let customers control their daily energy curves. Moreover, they received customized tips, based on their consumption, directly on the same device.

After two years, 94% of study participants declared they had increased their consumption awareness, while 60% modified their common habits with the scope of reducing peak-hours consumption and, thus, saving money.

3. The Second-Generation Italian Smart Meter

According to the Italian transposition of the new European Directive on energy efficiency, AEEGSI was made in charge of issuing a decision regarding the minimal functional requirements to be accomplished for second-generation smart meters (SM-2G). Thus, a public consultation took place for exploring the main features required, as well as the future-proof design criteria. The audience involved not only DSOs, but also retail suppliers, SM manufacturers, energy service companies, electricity industry associations, TLC regulator, standardization bodies, and telecommunications companies. Finally, the Regulatory Authority issued the decision 87/2016/R/eel and identified the minimal functional requirements for SM-2G and the expected performance levels for the new smart metering systems.

The new SM-2G was conceived with the goal of improving services for customers, further reducing the practice of billing estimated consumption instead of actual consumption, and enhancing accuracy and precision of the metering data for all the customers connected in LV.

The SM-2G communications features have two objectives: one is to bring raw metering data directly to the customers, while the other is to forward measurements to the corresponding DSO. The former stream comprises non-validated data, which are supposed to be used for provisioning services such as customer awareness and home automation. The latter stream conveys metering data to be used for billing operations, which, therefore, need a specific validation treatment by DSOs before being delivered to the retailer. Table 1 shows metering data managed by SM-2G, sampling data granularity, and a comparison with SM-1G for households and small business customers (up to 55 kW rated power).

Table 1. Second generation Smart Meter (SM-2G) data comparison with respect to the first generation (SM-1G).

Metering Data	SM-2G	SM-1G
Active energy withdrawn	15 min	3 values per month
Active energy Injected	15 min	3 value per month
Reactive energy withdrawn	15 min	3 values per month
Reactive energy Injected	15 min	3 values per month
Active power withdrawn	15 min (peak) and instantaneous value (1 s)	15 min (peak)
Active power Injected	15 min (avg)	No
Min/max voltage	1 per week	Only occasionally
Voltage in limits	Yes, compliant with EN50160	Only occasionally and not compliant with EN50160
Outages	On event occurrence	Implemented but not used

The regulatory decision is technology-neutral, hence the choice of the two communications technologies is left to the DSOs, with some constraints mainly regarding the usage of standardized technologies and frequency bands. It can vary from the consolidated PLC but also the newer Low Power Wide Area (LPWA) technologies, such as LoRa or SIGFOX, operating over unlicensed spectrum, or the forthcoming NB-IoT, operating over licensed spectrum.

Figure 1 illustrates the new Italian electricity value chain after the SM-2G roll-out phase:

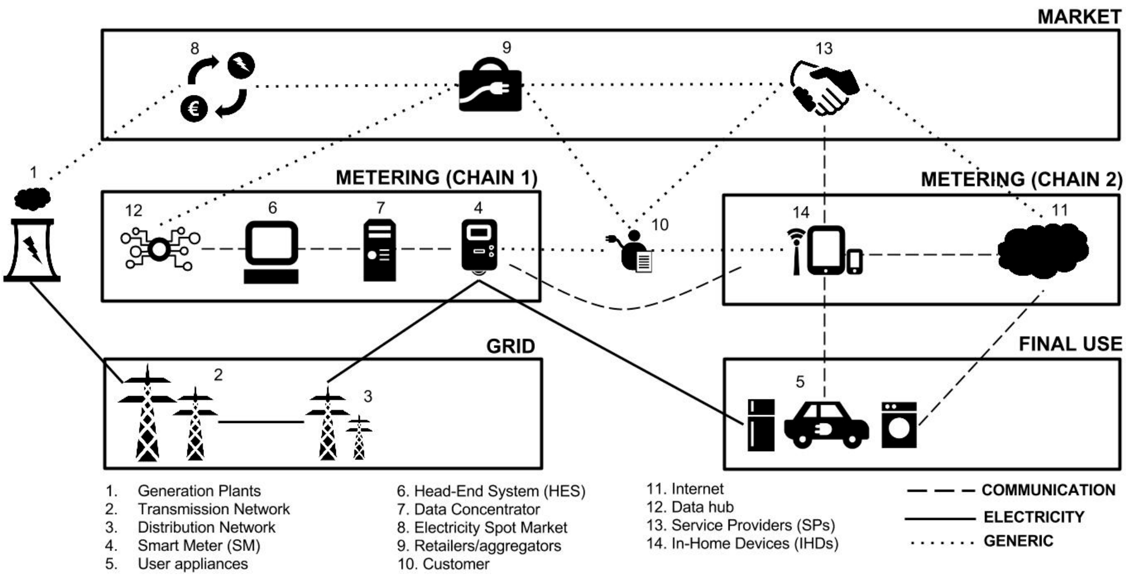

Figure 1. Electricity value chain for second generation Smart Meters (SM-2G).

3.1. Validated Metering Data on "Chain 1"

The energy meter acquires consumption data and, in case of customers with Distributed Generation (DG), production data as well. The DSO collects these measurements and makes them available to the retailer through the so-called "data management hub". This dataflow is called "chain 1" and has the main goal of providing suppliers with validated consumption data for billing.

The validation process ensures that collected data are sufficient and consistent for the billing phase using advanced data reconstruction algorithms.

One of the main differences with respect to the SM-1G is the mandatory provision of a backup technology for chain 1 with the goal of reaching those meters that cannot be properly read by the concentrators due to PLC interferences (in Italy, around 2% of the total [28]). The most common backup technology is expected to be the wM-Bus operating at 169 MHz radiofrequency, which is suitable for long-range communications for deep-indoor cases (half of SMs are located in basements) and for the power consumption. It is also worth noting that the Italian standard UNI/TS 11291 for remote gas metering suggests the same technology. It has yet to be verified whether and how the two systems could share the telecommunication infrastructure, thereby avoiding costly network duplications, taking into account that the 169 MHz frequency is non-licensed and that almost everywhere gas and electricity distribution are operated by different companies.

Another important difference is the presence of a data management hub [29], which acts as a central switch hub in a star network and is in charge of exchanging metering data between DSOs and retailers, avoiding direct exchange of information.

3.2. Non-Validated Metering Data on "Chain 2"

In the SM-1G context, the standard way for customers to receive information about their energy consumption and production is a periodic bill. Nevertheless, the display mandated by the MID [30] and integrated in the SM is not suitable for automated, real-time reading. Thus, SM-2G has been conceived from the beginning for supplying directly to the customers real-time metering data by means of paired IHDs for data acquisition, visualization, and utilization. It can provide instantaneous active power, daily energy curves, alerts, and contractual information. The sending frequency can be chosen according to the customer's needs and the available bandwidth of the communications channel. The choice of the communications technology is left to the DSOs, which, as resulted from the public consultation conducted by AEEGSI, have to use two different physical channels for Chain 1 and Chain 2. In case PLC is used for Chain 2, the CENELC PLC band C (PLC-C) [26] is the best suited, whereas Chain 1 operates on CENELC PLC band A. A well-established protocol operating in the PLC-C band is still not available, but proposals are currently discussed in standardization bodies and a nationwide standard is expected to be available soon.

Customers will receive metering data thanks to IHDs communicating with the SM-2G. Examples of IHD can be a simple external display used by those customers who have their SM in the basement, or a more evolved dashboard showing the daily energy curves of the past days, a smart appliance, or even an Energy Management System (EMS). Moreover, dashboards and automated systems can receive information coming from other market players (e.g., energy market, service providers, etc.) and cross check them with the metering data in a sophisticated system that aims to make customers aware of the advantages of responsible use of energy.

Currently, due to SM-1G limitations, retailers can only offer contracts with fixed time bands, in which energy prices vary according to a predefined time structure. Thanks to SM-2G, time bands can virtually become one hour long and vary between days. The tariff regime moves towards RTP, where the customer pays for energy according to the same price fluctuations imposed by the wholesale energy market. The scope of a similar strategy is to encourage load shifting in exchange for bill savings.

In addition, DSOs can inform their customers about network outages or ask for a DR request in exchange for a reimbursement in case of network emergency or vulnerability. Integrated with a more evolved home automation system, IHDs can allow automatic scheduling consumptions and thus savings with no human interaction.

Due to the sensible nature of the data exchanged and the openness of the PLC band C protocol, the Regulatory Authority imposed some requirements on the communications for privacy reasons, as required by Directive 2012/27/EU [31]. According to the decision 87/2016/R/eel [32], both communications channels (between SM and IHD and between SM and HES) must ensure confidentiality, authenticity, and integrity. Moreover, metering data have to be encrypted for obtaining adequate privacy levels. Figure 2 shows the new Italian AMI for SM-2G, highlighting the main actors involved.

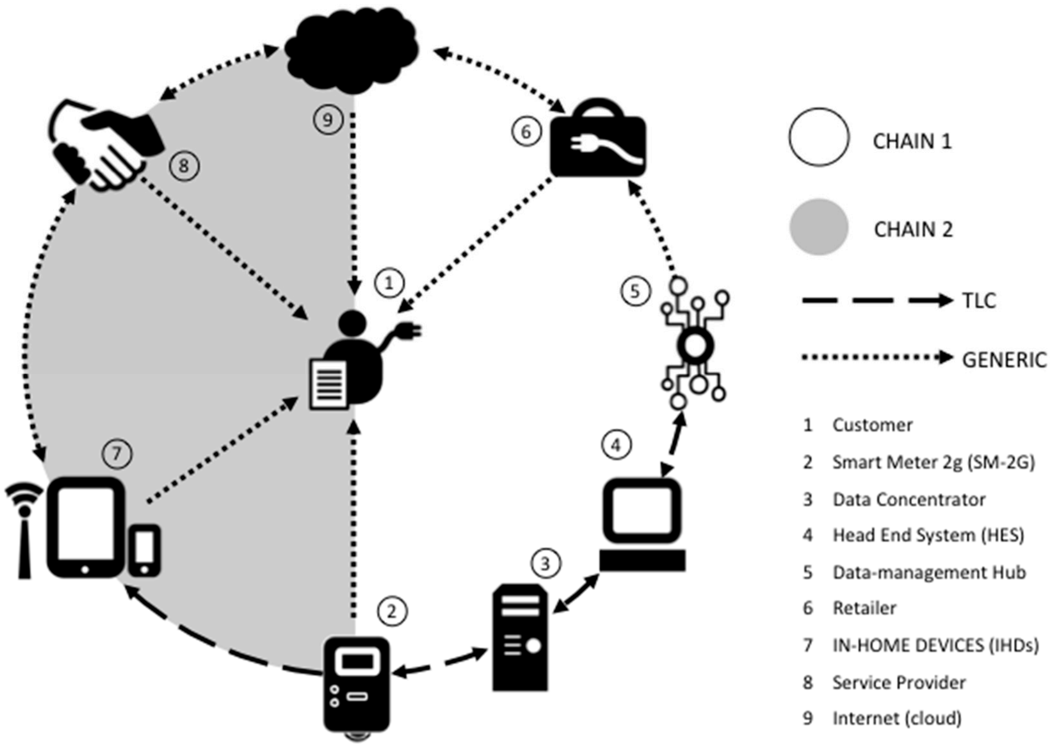

Figure 2. Second generation Smart Metering: Advance Metering Infrastructure (AMI) and chain 1/chain 2 explanation.

4. Services for Final Users

Feedback programs are crucial for stimulating the customers to change their usual habits [33]. Real-time direct feedback is particularly important compared to the indirect solution, where measurements are available many hours later due to validating processes performed by DSOs for billing purposes. According to [33], real-time feedback programs can ensure an energy savings of up to 8.6%, while indirect measurements affect just 2% of the total energy consumption.

Such information will be acquired by IHDs located in customers' premises with the goal of supplying them a set of new services for consumption awareness, customized contracts and, if located in a smart context (e.g., a smart home), home automation. Moreover, the same services have positive effects on other stakeholders of the electricity value chain.

For a SM, we defined "sampling time" as the periodic interval of time passing from the acquisition of a measurement to the following acquisition of the same measurement, and "latency" as the interval of time passing from the generation of the information in the source field to the complete delivery to the final entity, identified according to the use case considered. Consequently, we define "real-time service" as any service characterized by a sampling time requirement finer than 15 min and a maximum latency requirement tighter than 1 h. It is worth noting that we include real-time and near real-time services in the same category. The combination of the two mentioned constraints satisfies most of DSOs' and the market's needs and enables the activation of the real-time services identified in Table 2. This list of services can be grouped into four categories: Awareness, Market, Scheduling & Control, and Network Services.

Table 2. Real-time services: time requirements and stakeholders involved.

Category	Code	Use Case	Data Required	Maximum Sampling Time	Maximum Latency	Interested Stakeholders		
						Customer	DSO	Retailer
Awareness	A1	Dashboard for consumption and production awareness	energy data withdrawn and injected (only prosumers)	15 min	15 min	X	-	-
	A2	Ex-post analysis of an electric event (e.g., defrost cycle)	Active power withdrawn, injected, produced	1 min	1 h	X	-	-
	A3	Consumption awareness and cost estimation (revenue estimation for prosumers)	Instant active power withdrawn (injected and produced for prosumers)	15 min	1 h	X	-	X
	A4	Contractual information	All data regarding contractual information	-	15 min	X	X	X
	A5	warning for exceeding available power thresholds	event type, instant active power, timestamp	30 s	5 s	X	-	-
	A6	Warning for exceeding power thresholds (chosen by the customer)	event type, instant active power, timestamp	-	30 s	X	-	-
	A7	Information about a scheduled outage	event type, date, time, duration	-	1 h	X	X	-
	A8	information about a possible blackout	event type, date, time	-	1 h	X	X	-
	A9	information about a recently occurred blackout	event type, date, time	-	1 h	X	X	-
	A10	realtime power curve visualization	Instant active power withdrawn (injected and produced for prosumers)	1 s	1 s	X	-	-
Market	M1	Dynamic pricing contracts (ToU, RTP)	energy withdrawn	15 min	1 min	X	-	X
	M2	Prepaid contracts	energy totalizers grouped according to timebands	15 min	15 min	X	-	X
	M3	multi-contract customer	energy data withdrawn (injected/produced for prosumers)	15 min	15 min	X	-	X
	M4	contract change awareness	Contractual information	-	15 min	X	-	X
Scheduling & control	SC1	Scheduling for appliances	Instant active power withdrawn (injected/produced for prosumers)	5 s	5 s	X	-	-
	SC2	PV self-consumption with appliances and storage systems	Instant active power withdrawn (injected/produced for prosumers)	1 s	30 s	X	-	-
	SC3	Peak shaving with appliances and storage systems	Instant active power withdrawn (injected/produced for prosumers)	1 s	2 min	X	X	-
	SC4	Load shifting with storage systems	Active power withdrawn (interval average)	1 min	1 min	X	X	-
	SC5	Load shifting with appliances	Active power withdrawn (interval average)	1 min	1 min	X	X	-
	SC6	Monitoring for elderly people	Instant active power withdrawn (injected for prosumers)	15 min	15 min	X	-	-
Network services	N1	Active demand for network issues	Active power set point (withdrawn/injected) active power (interval average)	1 min	10 s	X	X	-
	N2	tertiary reserves	Active power set point (withdrawn/injected) reactive set point, active power (interval average), reactive power (interval average)	3 min	1 min	X	X	-
	N3	secondary reserves	Active power set point (withdrawn/injected) reactive set point, active/reactive power	3 min	1 min	X	X	-
	N4	reactive power exchange	active/reactive power set points	-	1 min	X	X	X
	N5	Demand Response	Max active power withdrawn/injected set point	-	1 min	X	X	-
Diagnostics	D1	Supply service anomalies monitoring	rms voltage, outages registers	30 s	1 min	X	X	-

4.1. Awareness

This category includes all those services aiming at informing the final customers about contractual information, special events (e.g., network issues), and energy consumption/production, with the final goal of modifying their energy usage towards smarter and more environmentally friendly behavior.

Thanks to a simple display, all the details of the supply contract can be visualized directly at the customer's premises; DSOs can update this information in case of contractual changes. Moreover, the energy consumed or produced can be shown as a table or graph pairing the power (or energy) exchanged with the time of usage. The customer, made aware about costly peak-hours, can decide to shift deferrable loads such as a dishwasher cycle or an electric vehicle recharge. With more complex technology, the same display can show the corresponding daily or monthly total cost, even reporting an estimate for the remaining period. Increasing device features and data sampling time, the display could report appliance anomalies detected thanks to disaggregation algorithms. Information about blackout events or scheduled network maintenance can be displayed as close as possible to the event.

4.2. Market

All the services aimed at enabling the user to manage a contract and save money are grouped in the Market category. Thanks to real-time metering data, ToU or even RTP can be effective and prepaid contracts can be activated. Retailers could start to offer customized contracts based on the collected measurements and send hourly price signals for helping the customer to identify the cheaper moments. It is worth noting that price signals do not flow through the SM and must be received through a separate channel.

4.3. Scheduling & Control

In a more sophisticated environment (e.g., a smart home), some deferrable appliances or EMSs can schedule their activation, selecting the cheapest moment of the day. Customers could plug in their electric car and forget it there until the following day. With a ToU or RTP contract, the customer (or an EMS) can shift the load to select the best interval, thereby minimizing the recharging cost for the same final result (i.e., the vehicle is charged for the morning). Moreover, a smart home with a photovoltaic system coupled with a storage system can schedule a time that is more convenient to use local generation for storing energy (i.e., off-peak intervals) and when it is better to use stored energy to feed appliances, avoiding energy withdrawals during peak moments.

4.4. Network Services

Real-time services can help customers to be smarter about energy and, consequently, reduce their bills. One activator for such a savings is the electric network stability: in critical moments caused by unbalancing or faults, DSOs could ask for a reduction of electric power consumption or for an injection of locally produced energy in exchange for an adequate reward [34]. The customer (or an EMS on behalf of the customer) can receive Demand Response signals from the DSO or his/her retail supplier, directly through the SM or through a different channel, and make a decision about whether to contribute to solve the issue or not [35–38]. In the near future, small renewable energy sources owned by private customers could even be used for unbalancing problems and sold in ancillary services markets as secondary or tertiary reserves by means of an energy aggregator [2].

Table 2 summarizes the identified services based on [39] with a particular focus on the corresponding minimum sampling time and maximum latency required for their activation.

The last three columns show the stakeholders involved who can benefit from the activation of the corresponding real-time service.

As shown, latency can vary from one second to almost one hour down. It is worth noting that communications frames, sent to the IHDs, can contain one sample or aggregated data. The more data are available to IHDs, the smarter the services available. For instance, a reliable dashboard reporting the daily energy consumption and production curves for awareness requires at least one transaction per hour, containing the past energy measurements averaged every 15 min. Differently, home automation performed by IHDs requires fresh metering data every five to 15 seconds for a prompt response.

On the other hand, the smarter the service chosen, the higher the cost required for the total exploitation. An EMS can forecast and schedule appliances according to expected PV generation, storage systems, market price (ToU or RTP contract), and DR, hence ensuring the highest possible savings, but at the cost of high data transmission rates from SM. At the current energy prices, savings ensured by a similar system could not compensate for the initial purchasing cost of an EMS, which might discourage manufacturers and service providers from promoting similar products at the household level [40].

5. Architectures for Real-Time Home Services

Real-time services aim at sending metering data with the appropriate frequency and latency to customer devices or to authorized third parties. As discussed above, IHDs range from a simple external display to more sophisticated smart appliances or home automation and EMS. They can present information to the customer either locally (in the proximity of the SM) or remotely (e.g., through smartphone applications). Authorized third parties are entities providing value-added services to customers. Such services can be as simple as directly providing the measurements to the final user, or controlling the behavior of customers' appliances in order to better manage energy consumption. In general, the authorized third parties will communicate to customer devices through a public Wide Area Network (WAN). We identify four possible architectures for real-time services, with different complexity and degree of involvement of the consumer in the deployment of the services:

(1) The SM sends the data to the consumer IHDs, which locally uses the data without forwarding them to any other device or entity.
(2) The SM makes the data available to the devices connected to the consumer's Home Area Network (HAN).
(3) The SM sends the data to an authorized third party.
(4) The SM sends the data to an IHD acting as a gateway (IHD-GW), which then makes the data available for locally connected devices and any authorized third party.

These architectures are suitable for consumers with different constraints and needs. The SM should be flexible enough to support all of them even at the same time.

Figure 3 shows the first architecture, in which the SM directly sends the data to the consumer devices. In its simplest form, the IHD for this case could be, for instance, an external display showing real-time measurements to the customer or a device with limited home automation capabilities. The main characteristics of this architecture are:

- Data are sent only to the IHDs and no third party is involved.
- The customer does not provision any home communications infrastructure.
- The IHD must be able to talk to the SM by means of a shared communications medium and a common communications protocol.

Figure 3. Architecture 1: the SM directly sends the data to the In-Home Devices (IHDs).

This architecture is most likely to be deployed for households with limited technology needs and makes it possible to increase user awareness about electricity consumption with a limited cost.

Figure 4 shows the second architecture, in which the SM is connected to the consumer's HAN and makes metering data available for locally connected IHDs. Eventually, an authorized third party can withdraw these data from the HAN, moving them through a WAN. In turn, the third party will be able to communicate to consumer smart devices locally connected to the cellular network or to the Internet. The main characteristics of this architecture are:

(1) The SM must be able to connect to the HAN.
(2) The SM must be able to talk to the IHDs by means of a standard communications protocol.
(3) If a third party is involved, the customer must ensure a connection to the public data network.

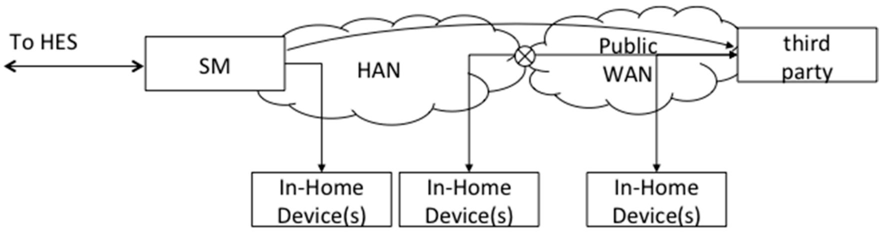

Figure 4. Architecture 2: the SM makes the data available to the consumer Home Area Network (HAN).

Architecture 2 is the most flexible solution, because it makes it possible to communicate with both locally connected devices and multiple authorized third parties, such as appliance control centers or energy management services. The main drawback is that it loads the end user with the burden of providing HAN and WAN access.

Figure 5 shows the third architecture, in which the SM sends the data to an authorized third party through a public WAN. In turn, the third party provides the data to the IHDs through the same network. The main characteristics of this architecture are:

(1) The SM is connected to a public WAN, which must be available in the area.
(2) The SM sends metering data only to a third party.
(3) The customer is not required to provision any home communications infrastructure.

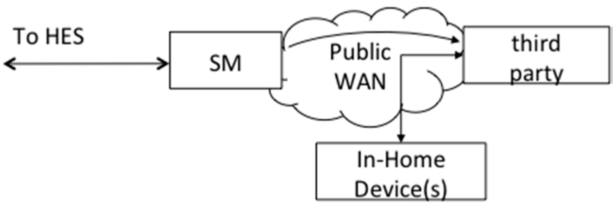

Figure 5. Architecture 3: The SM sends data only to an authorized third party.

The main advantage of this architecture is that it decouples the customer HAN from the network used for providing real-time services, thus making real-time services easier to provision and manage, especially remotely. The main disadvantage is that technology choices on the SM are made by the DSO (who is responsible for the deployment of the SM), while the consumer has a limited choice of WAN technology and, consequently, of the designated third party. As a consequence, the DSO is legally responsible for guaranteeing that the third party will make the data available to the end-user.

According to Directive 2012/27/EU [31], the SM must make the measurements available to the customer without any charge, implying that it should support at least one of the first two architectures, which do not require the involvement of a third party.

The SM is expected to stay in place several years. During this time the communications needs of the consumers, and the consumers themselves or even the DSO, could change. Therefore, it is important that the DSOs deploy SMs that support multiple architectures and are able to cope with evolving communications technologies, both in the home network domain and in the WAN domain. Additionally, many DSOs have concerns regarding the increase of the attack surface of the SM resulting from two-way communications, especially if connections to public networks are envisaged for cyber-security reasons.

A more flexible and secure solution can be achieved with a two-tier approach with Architecture 4, shown in Figure 6, in which the SM supports only Architecture 1 and only sends data over a one-way communications bus. Architectures 2 and 3 are achieved by means of gateway nodes (IHD-GW) deployed in the household premises and connected to the same one-way bus. This approach also has the advantage of enabling two-way communications from the IHDs to the IHD-GW, which can provide additional services such as past metering data, maintain the state of the system, carry measurements from multiple SMs (electric but also for gas or water), or even enable access to the services exposed by the DSO, which, in turn, can count on a two-way-like communications with the SM through the AMI infrastructure. Nevertheless, SM vulnerabilities would be minimized thanks to one-way communication along the branch from SM to IHD-GW.

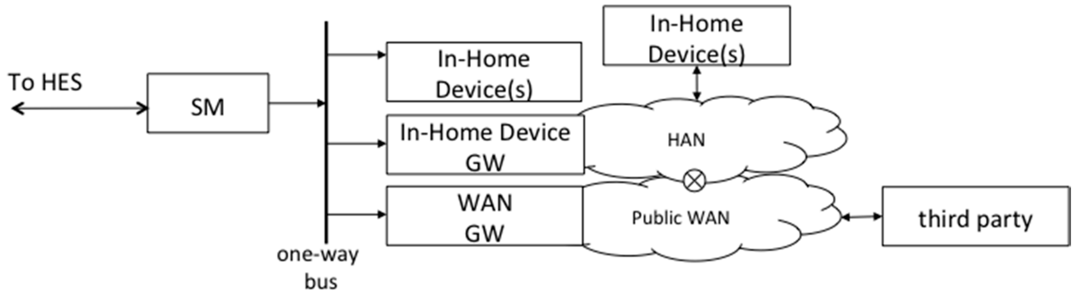

Figure 6. Architecture 4: two-tier model.

6. Communications Technologies for Real-Time Home Services

Depending on the specific application, different requirements in terms of data volume, data rate, transmission/propagation delay, and reliability of data transfer can be identified for the SM communications channel. In this section, we review the main existing wireline and wireless technologies for SM communications (see Table 3 for the taxonomy), with a particular emphasis on those that enable real-time metering services. A more detailed survey can be found, for example, in [41].

Table 3. Classification of enabling transmission technologies for smart metering.

Wired Technologies	Wireless Technologies		
	Cellular Mobile Networks	**IoT Dedicated Cellular Networks**	**Multi-Tier IoT Architectures**
PLC	EC-GSM	wM-Bus	Wi-Fi HaLow (802.11ah)
DSL	LTE-M	LoRa	Bluetooth Low Energy (BLE)
Fiber Optical	NB-IoT	SIGFOX	6loWPAN

6.1. Wireline Technologies

Wired communications for Smart Grids traditionally include three main technologies: Power Line Communications, Digital Subscriber Line, and Fiber Optical Communications.

Power Line Communications (PLC) technologies leverage the existing meter power supply cables as a transmission medium, thus avoiding the deployment costs of a new telecommunications infrastructure [42]. PLC can be categorized into narrow-band and broadband technologies: the former operate over transmission frequencies up to 500 kHz at a low data rate (up to 500 kb/s) and span distances of several kilometers, whereas the latter operate in the range 2–30 MHz and ensure a consistently higher capacity (up to 200 Mb/s) at the cost of a significantly reduced communications range, and are thus typically used only for domestic applications [43]. According to [26], four frequency allocation bands are identified for narrowband PLC:

- The A-band (3 kHz–95 kHz), reserved for DSOs;
- The B-band (95 kHz–125 kHz), which can be used by all applications without any access protocol;
- The C-band (125 kHz–140 kHz), reserved for IHDs, imposes CSMA;
- The D-band (140 kHz–148.5 kHz), which is specified for alarms and security systems without any access protocol.

For broadband PLC, the HomePlug standards defined by the HomePlug Powerline Alliance [44] represent the most widely adopted specifications.

The main issue with PLC is that aged electric wires, as well as the presence of devices that create EM interference, such as transformers, inverters, and LED lamps, significantly limit the communications performance, especially in the narrowband technologies. In addition, neighboring PLC networks can interfere if not properly insulated [45], causing severe performance reduction in terms of lower data rate, increased bit-error, and packet-loss rates, as shown in several studies [46,47].

Digital Subscriber Line (DSL) technologies enable digital data transmission over telephone lines, with variable rates depending on the line quality and length. Rates vary from a few hundred megabits per second up to 52 Mbit/s downstream and a few megabits per second upstream with latency in the order of milliseconds. DSL is a popular technology for providing Internet access to home users.

Fiber Optical Communications, traditionally used in backbone networks, nowadays represent a major technology for accessing networks, thanks to the success of Passive Optical Network (PON) technologies. PONs have therefore been proposed as an optical access architecture to support home multiservice, including smart grids [48]. The advantages of optical communications are the high bitrate on the order of gigabits per second and the long-distance reachability. Moreover, it is completely immune from electromagnetic interferences. On the other hand, the use of such a technology implies a costly installation of a new dedicated infrastructure, which might not compensate for the resulting benefits. It is worth noting that DSOs are increasingly deploying Fiber Optics networks for connecting Primary and Secondary Substations for implementing smart grid services such as anti-islanding techniques and fault detection [49].

6.2. Wireless Technologies

Several wireless solutions specifically tailored for Smart Cities and Smart Grid applications have recently been envisioned. Such solutions can be broadly categorized into three groups [50]: Cellular Mobile Networks, IoT Dedicated Networks, and Multi-Tier IoT Networks.

Cellular Mobile Networks are constituted by a front-end Radio Access Network (RAN) operating over a licensed spectrum and a backhand Core Network (CN) managing access and mobility. They are mainly designed to convey human-to-human or human-to-machine traffic and are especially suited for applications requiring high coverage and intensive data rates, with high mobility. Since cellular mobile networks operate on licensed frequencies, they provide high guarantees in terms of interference level and quality of service, even in case of massive numbers of transmitting devices. However, several legacy cellular technologies have recently evolved to support machine-to-machine (M2M) communications, such as smart metering, which is typically characterized by periodic and intermittent transmission of small amounts of data. Among those, we focus on *Extended Coverage GSM* (EC-GSM), *LTE Machine-to-machine* (LTE-M) and *Narrow Band IoT* (NB-IoT).

- *EC-GSM* [51] exploits the existing GSM/GPRS infrastructure and simply relies on a software update that strengthens the coverage by 20 dB w.r.t. the standard GPRS operating at 900 MHz and supporting communications for up to 50 thousand devices per cell. Power efficiency has also been improved, with the aim of increasing the battery lifetime up to 10 years.

- *LTE-M* [52,53], like EC-GSM, relies on the existing LTE infrastructure and only requires a software update of the base stations. After the standard Release 12 for M2M communications, which proposed Category 0 devices with reduced cost and complexity and increased battery duration w.r.t. the Category 1 devices discussed in Release 8, the latest Release 13 introduces further improvements such as the definition of narrowband channels with 1.4 MHz and 200 kHz bandwidth, thus allowing the use of less expensive and more energy-efficient hardware, which increases the link budget up to 100 dBm.
- *NB-IoT* [54] adopts a clean-slate approach aimed at re-farming the GSM spectrum to support a new narrowband air interface compatible with GSM 200 kHz-wide channels: every downlink channel is partitioned into 48 narrowband sub channels of 3.75 kHz width, whereas the uplink is divided into 36 sub-channels of 5 kHz width. The reference spectrum bands include the GSM licensed spectrum and the guard bands of the LTE in order to support three different deployment approaches: (i) standalone GSM carrier; (ii) carrier placed in the LTE guardband portion (normally not used for data transmission) adjacent to an LTE carrier; and (iii) inband LTE carrier. NB-IoT is specifically tailored for massive smart metering applications, since it supports transmission from deep indoor devices (located e.g., in the household basement) thanks to the achieved link budget target of 164 dB. It supports the usage of an embedded Subscriber Identity Module (e-SIM), which enables remote configuration of the user profile, supports interoperability, and allows the user to possibly change operator without the substitution of the physical device. Moreover, the authentication and encryption capabilities of the e-SIM guarantee secure data transmission over public networks.

The main characteristics of the three abovementioned technologies are reported in Table 4.

Table 4. Comparison of LTE-M, NB-IoT, and EC-GSM technologies.

Characteristics	NB-IoT	LTE-M	EC-GSM
Frequency (MHz)	700–800	LTE Band	800–900
Bandwidth (MHz)	0.005 (UL); 0.00375 (DL)	1.4	0.2
DataRate Upload	48 kbps	20 kbps	100 kbps
DataRate Download	200 kbps	<1 Mbps	100 kbps
Duplex	half	half	half
Interference tolerance	good, licensed spectrum	good, licensed spectrum	good, licensed spectrum
Coverage range	2–15 km	<11 km	<15 km
Specs/Standard	3 GPP R 13	3GPP R 12/13	3GPP R 13
Transmission power	23 dBm	-	23–33 dBm
Licensed/unlicensed band	Licensed	Licensed	Licensed
Standard & commercial products	Available	2016	2016

IoT Dedicated Networks such as wM-Bus, LoRa, and SIGFOX are dedicated point-to-multipoint architectures serving exclusively traffic originated from/destined to machine field devices. Their front-end operates over unlicensed spectrum and adopts a simplified backend infrastructure, thus ensuring lower deployment and operational costs w.r.t. traditional cellular mobile networks. This ensures high scalability even with a limited number of concentrator nodes (i.e., gateways that convey the machine field traffic to the core IP network). One additional benefit of IoT Dedicated Networks is the traffic offload from the legacy mobile cellular networks. However, they typically support low-rate streams (especially in the downlink channel) due to the need for reduced power consumption and to the narrow transmission bandwidths.

- *wM-Bus* [55] is the reference ETSI standard EN13757-4 for gas smart metering over the 169-MHz band, but can also be applied to water and electricity meters, possibly enabling multi-utility metering services. It supports only star-network topologies and requires the installation of dedicated concentrators.

- *LoRaWAN* [56] is a protocol stack defined by the LoRa Alliance for low-power, wide area IoT communications technologies supporting deep-indoor transmission. It can be operated over different spectrum portions according to local regulations and supports a two-tier star-like topology, with gateways collecting data from field devices and forwarding them to dedicated NetServers associated to a cloud platform. The medium access control layer specifies three different classes with different downlink capacities. Authentication and encryption capabilities are also supported.
- *SIGFOX* [57] exploits ultra-narrowband transmitters incorporated in the field devices. Like LoRaWAN, it supports a two-tier topology where SIGFOX gateways convey the traffic to cloud servers. The communications is mostly uplink, but it is possible to activate a tiny downlink control channel. Messages of at most 12 bytes are repeated multiple times over different frequency channels to increase the transmission robustness. A maximum of 140 messages per day is allowed for transmission.

A comparison of the three above presented technologies is reported in Table 5.

Table 5. Comparison of LoRa, SIGFOX, and wM-Bus technologies.

Characteristics	LoRa	SIGFOX	wM-Bus
Frequency (MHz)	433, 863–870	868, 902	169, 433, 868
Bandwidth (MHz)	0.125, 0.250	0.0001	0.01
DataRate Upload	250–50000 bps	<100 bps	2.4–4.8 kbps
DataRate Download	250 bps–50 kbps (adaptive)	256 b/day	2.4–4.8 kbps
Duplex	yes	no	yes
Interference tolerance	Good (spread spectrum)	Scarce (narrow band B-PSK)	Scarce
Coverage range	15–45 flat, 15–22 suburban, 3–8 urban	50 km rural; 10 km urban	<300 m
Specs/Standard	LoRaWAN	SIGFOX	ISO/IEC 14543
Transmission power	14 dBm	10 µW–100mW	1–100 mW
Licensed/unlicensed band	unlicensed	unlicensed	unlicensed
Standard & commercial products	Available	Proprietary	Available

Multi-Tier Networks leverage gateway nodes that concentrate the traffic generated by field devices through short-/medium-range wireless technologies and convey it to the backhand via a long-range backhaul infrastructure. They are specifically tailored for applications involving limited numbers of field devices and requiring low communications ranges. To compensate for such short ranges, the field devices may be organized in a mesh network topology supporting multi-hop transmission. Among the major solutions for low-power wireless personal area networks, we focus *on Bluetooth Low Energy (BLE)* and *Wi-Fi HaLow* (802.11 ah).

- *BLE* [58] aims at reducing the power consumption of the legacy Bluetooth for application to long-lasting battery-powered devices. Its protocol stack is designed for easy integration with IPv6, and supports packet segmentation and cryptographic capabilities. Presently, it supports only star topologies, though an extension to a mesh scenario is currently under study.
- *Wi-Fi HaLow* [59,60] extends the coverage range of previous Wireless Fidelity (Wi-Fi) solutions while maximizing the number of connected devices (up to 8000). It supports power-saving operating modes that deactivate the radio module during idle periods and includes optimization mechanisms to effectively alternate short data transmission periods and long sleeping periods.
- *6loWPAN* (6 Low-power Wireless Personal Area Network) was the first working group of the Internet Engineering Task Force (IETF) that investigated methods to allow the usage of IPv6 protocol over IEEE 802.15.4 (the same data link layer used by ZigBee), with the aim of supporting Internet connectivity among cheap and constrained WPAN devices (it requires only 30 kbytes of sensor memory). The 6loWPAN standard supports networks of arbitrary topologies and includes packet fragmentation methods and header compression techniques to fit IPv6 and UDP datagrams

in the (smaller) IEEE 802.15.4 frame size by means of cross-layer optimization approaches: for devices sharing the same network some portions of the IP header may be inferred from the Medium Access Control (MAC) header, thus reducing the IP/UDP headers by up to a few bytes.

7. Assessment of the Available Architectures

7.1. Methodology

In this section, we discuss the suitability of the architectures presented in Section 5 to support the use cases reported in Section 4. Since each architecture may be implemented using different combinations of communications technologies, for each architecture we also discuss the resulting implementation choices. The assessment considers the complexity of installation, the compliance to regulatory constraints, and the ability to meet the requirements of the use cases in terms of latency and sampling frequency. We will assume that the SM is able to achieve sampling periods on the order of seconds. Therefore, the limiting factors stem from the bandwidth and latency of the different communications architectures and technologies. Since most use cases in each of the categories identified in Table 2 share similar requirements, in the following we discuss each category independently. If necessary, we highlight those use cases that are an exception and require more in-depth analysis.

7.2. Awareness Category

This category comprises two use cases, namely A5 and A10, with strict latency requirements and sampling rates, both on the order of seconds, as well as several other use cases with loose latency requirements, ranging from 1 min to 1 h.

Architecture 1 is suitable for the use cases in this category in case of PLC-C or dedicated cabling, while 6loWPAN, BLE, or Wi-Fi HaLow can only be used if the SM is sufficiently close to the IHD (up to a few meters). With respect to use cases A5 and A10, which have stricter requirements, PLC-C can meet those requirements if the number of SMs communicating over the same power line is low enough. In fact, the limited available bandwidth, together with the usage of the CSMA protocol, may result in transmission delays or even lost messages.

Most of the use cases can be implemented by installing a stand-alone device at the user premises, except for A3, A7, and A8, which require information from external sources such as retailers, DSOs, and the electricity market, and therefore need a connection to an external communications network.

Architecture 2 leverages on the customer HAN, which generally has higher bandwidth, lower access delays, and also access to external sources of data through the public Internet, making this architecture suitable for all the services in the Awareness category. The main drawback of this architecture, which affects all the service categories, is that the SM may be out of reach of the customer HAN, or may not support its technology.

Architecture 3 is also a viable choice, making it possible to provision the use cases in this category without installing additional devices at the user premises, but only requiring the customer's authorization to deliver data from the SM to a third party service provider. Technologies suitable for this kind of architecture can be cellular technologies like LTE-M, EC-GSM, NB-IoT, or even dedicated LPWAN solutions such as LoRa, SIGFOX, and wM-Bus. The former generally provide higher service availability, stemming from the usage of licensed bandwidth, but require the involvement of a third party. It is worth noting that these technologies provide low bit-rate channels, making use cases A5 and A10 unfeasible if there are many subscribers. Latencies are generally low enough for any use case, but may vary according to the number of active nodes. In this case cellular-based technologies generally cope better with higher traffic conditions. It is also worth noting that some LPWAN solutions do not support downlink transmissions well, making these technologies less useful or not adequate for the use cases requiring access to external data, such as A3 (cost estimation).

The two-tier Architecture 4 uses the same technologies as Architecture 1, typically PLC-C, from the SM to an IHD-GW node and the same technologies as Architectures 2 and 3 from the IHD-GW to the end user. Architecture 4 makes it possible to receive data both from external sources and from SMs out of the HAN range, making it possible to satisfy the requirements of all the use cases in the Awareness category. With respect to the use cases with stricter latency requirements, the PLC-C segment or the LPWAN segment, if present, might become a bottleneck if there are many subscribers.

7.3. Market Category

This category of use cases requires signals from external sources such as the retailers' channels. Therefore, Architecture 1 is not suitable for such services. Using Architecture 2, market data can be obtained from the public network and, together with metering data coming from the HAN, used to feed services such Energy Management Systems (EMSs), dynamic pricing, or prepaid contracts.

Architecture 3 generally provides a downlink channel, which can be used to receive data from external sources; additionally, the service provider can notify customers of events or provide real-time data using the customers' own devices such as smartphones. Given the loose requirements of such category, technologies suitable for Architecture 3 include cellular-based technologies as well as LPWAN.

Architecture 4 also supports this category well, making it possible to provide the service to SMs that only support Architecture 1. Since the transmission frequency is low and the latency is not critical, it is unlikely that the SM to IHD-GW segment is congested even if shared medium technologies, such as PLC-C, are used.

7.4. Scheduling and Control Category

This category gathers all the use cases regarding the smart usage of customer's appliances and local distributed generation. These include scheduling, peak shaving, and load shifting through local energy balances for the purpose of limiting the consumption below the contractual threshold or for the purpose of reducing the total bill. In this scenario, the customer appliances and generators are the IHDs. Architecture 1 for these services requires point-to-point connections for each IHD. Short-range wireless technologies, such as BLE or Wi-Fi, are the most suited for this architecture, but a PLC solution can also be used, except for use case SC1, which has a strict latency requirement.

Smart appliances could also exploit information coming from the market, network requests, or other sources for increasing the accuracy of their scheduling algorithms. They could also need to communicate and share data among themselves for coordination purposes. In this case, Architecture 2 or 4 is required. It is worth noting that extra time is needed by smart appliances or EMSs to process data, calculate results, and, eventually, communicate with the surrounding smart appliances. If a third party is involved, metering data can be transferred through WAN, processed and returned with energy prices, environmental hints, and customized contractual changes. In this case, the increase in latency from SM to the customer has to be evaluated. A scheme for this configuration using Architecture 4 is reported in Figure 7.

Architecture 3 makes it possible for an authorized third party to withdraw metering data directly from the SM with the scope of controlling and scheduling his/her connected smart appliances. This architecture simplifies service provisioning by moving the algorithms needed for coordination and scheduling into the service-provider domain. It requires all the controlled appliances to be connected to the public network through Cellular or IoT-dedicated technologies. It is worth noting, though, that scheduling and control services require a fast and constant refresh of data exchanged, which typical WAN technologies might not be able to provide.

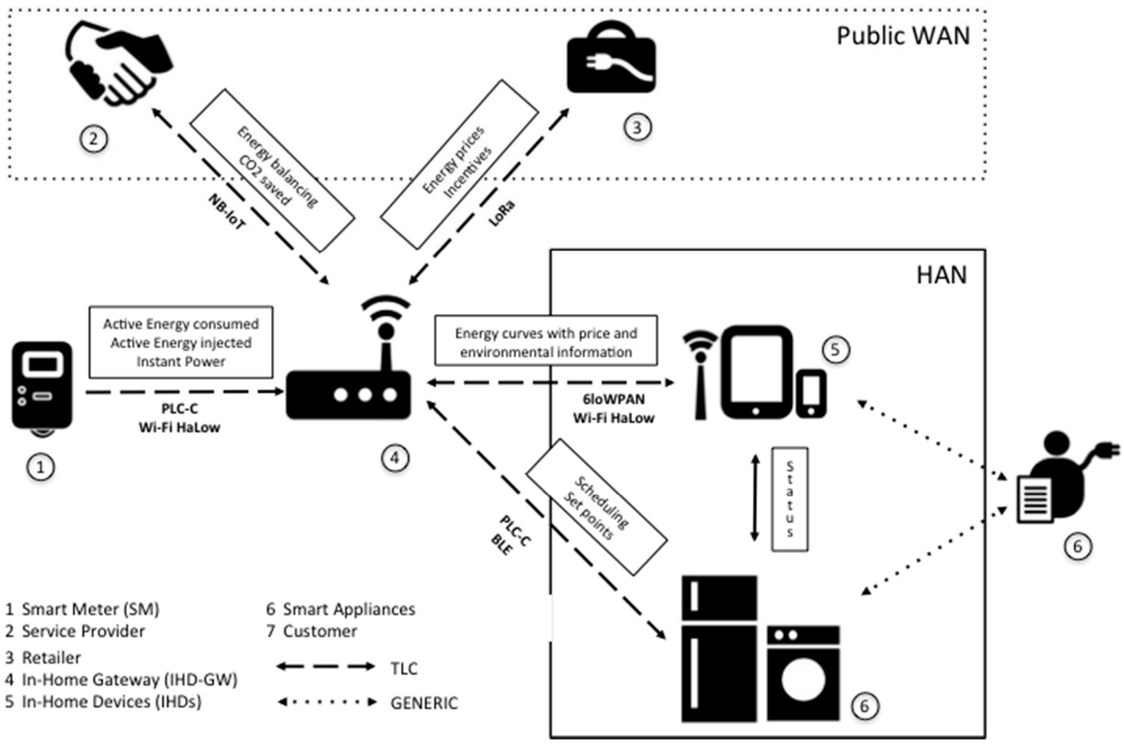

Figure 7. Example of Scheduling & Control services with Architecture 4: an IHD, acting as a gateway (IHD-GW), collects metering data from the SM using PLC-C and other information from a WAN with cellular or IoT-dedicated technologies. Finally, it calculates and/or forwards set points to the smart appliances and statistical data to the customer's devices.

7.5. Network Services Category

As for use cases regarding the support to the electric network stability, the customer could modify his/her scheduling according to signals coming from the grid. This implies the need for a different channel for forwarding information to the customer or to an. Requirements for these use cases are similar to the ones for market services, with more stringent requirements regarding latency. Hence, Architecture 1 is not suitable for this family of use cases, unless it is extended into Architecture 4.

Architecture 2 can let all the IHDs receive metering data, network signals, and, eventually, dedicated commands coming from an authorized third party, thanks to the WAN. As for the other scenarios, short-range wireless technologies such as BLE or Wi-Fi can be used for reaching the HAN with Architecture 2. For deep-indoor SM installations, PLC-C is a valid option, with some regards to use case N1, which requires higher speed, which might not be available over PLC.

Architecture 3 allows a service provider to supply the customer with customized requests based on the network status simply through a smartphone or a dedicated dashboard connected to the public network. This third party could also feed connected IHDs with scheduled activities. To achieve this, special agreements between DSOs and service providers are necessary to allow forwarding grid information. Technologies used with Architecture 3 can be wireless WANs over licensed spectrum, such as NB-IoT, or over unlicensed spectrum, such as LoRa or wM-Bus. Use case N1 could be challenging for all the solutions since the latency required for all the communications paths through the wireless network can be very long.

Finally, Architecture 4 can be adopted for extending a simple Architecture 1 thanks to the usage of an IHD-GW, able to collect metering data and network signals for making decisions.

It is worth noting that if network signals are sent simultaneously to different customers served by the same secondary substation, a shared communications medium (e.g., PLC-C) used by SMs and IHDs might not have enough capacity for fast notification.

7.6. Open Research Issues

Smart Meters are designed to stay in place several years with minimal maintenance. On the other hand, the growth of smart-grid services in the low-voltage part of the network and of smart-home services will reveal new needs. We identify the following research issues: scalability of the communications infrastructure, security, privacy, and interoperability.

Although PLC is a mature technology, its ability to support uncoordinated frequent transmission by several meters is yet to be proved. The interference pattern in CENELEC bands A and C is also evolving over time as newer devices are plugged into the home electrical system [61]. Similarly, both the LPWAN and the cellular-based IoT communications technologies are at their infancy and current studies have mostly focused on coverage issues. Frequent transmissions by hundreds of meters will likely push the capacity to the limit.

Cyber-physical security of SMs represents a growing concern of governments and operators, especially for their ability to cut the power supply from remote [62] or to take part in Automated Demand-Response. It is still an open issue how to deploy robust security controls capable of quickly detecting compromised devices and take countermeasures.

Frequent metering paved the way for high-accuracy Non-Intrusive Load Monitoring. Therefore, the privacy of metering data has become a concern for final customers. So far, the issue of privacy was dealt with at the regulatory level by obliging the DSOs and the retailers to comply with procedures ensuring that data are protected and not made available to third parties without consent. However, the expected growth of third-party services will make it more difficult to prevent data theft or misuse. Therefore, at the European level, there is thriving research on how to provide the customer with higher control of how his/her data are used.

Finally, if the SM is intended to be integrated into a network comprising a wide range of devices, it is necessary that they expose standard interfaces and data models [16,63]. At the moment, there are multiple possible choices including Device Language Message Specification/COmpanion Specification for Energy Metering (DLMS/COSEM) [64], Smart Metering Information and Telecommunication Protocol (SMITP) [27], or Zigbee's Smart Energy Profile [65]. In case the market fails in choosing a single interface, an IHD-GW could implement the functions of protocol translations in order to maximize interoperability.

8. Conclusions

In accordance with the European directives, new-generation SMs should be able to directly supply measurements to the final customer through the usage of different IHDs and smart devices, with the goal of enabling real-time services in the domains of energy awareness, home automation, load shifting, and demand response. In order to achieve and maintain customer engagement, metering data and other related information should be presented in a clear and intuitive way. Moreover, IHDs should be cheap and easy to install. Sampling time for metering data and latency for the communications between the SM and the final node are crucial parameters for the provisioning of these kinds of services: latency evaluation for each use case should consider the time required to pass through all the nodes of the communications path.

Due to the sensitive nature of the data exchanged, effort should be devoted to cyber security with the goal of ensuring authenticity, confidentiality, and integrity by exploiting cryptography techniques.

In this paper, we review different configurations in terms of architectures and telecommunications technologies. Generally, it is not possible to identify a common standard configuration since use cases and customers' availabilities vary on a case-by-case basis.

Architecture 1, along with communications over PLC-C, can satisfy most of the use cases regarding energy awareness with reduced costs and simple installation for the customer.

Architecture 2 is advised for the scheduling and control services involving deferrable loads such as washing machines, dishwashers, and electric vehicles. In a ToU or RTP regime, these devices can defer or interrupt their cycles according to the market or network, even without direct human interaction. This configuration implies the constant need for a HAN provided by the customer. Wired technologies like PLC-C or optical fibers are suited for connecting the SM to the HAN. For in-home SM installations, short-range wireless technologies like 6loWPAN, BLE, and Wi-Fi HaLow can also be used for this family of services.

With the presence of an authorized third party, Architecture 3 could be the best choice for cloud-based services, implying the need of metering data and additional information such as energy prices or DR requests. Cellular-based technologies as well as LPWAN match the majority of these kinds of use cases.

Finally, Architecture 4 provides the most flexibility. At the cost of an IHD-GW, it can provide simple and cheap services or advanced but costly solutions, with or without the presence of a service provider. The IHD-GW collects data coming from the SM and ancillary channels and forwards them to other IHDs such as smart appliances, smart devices, dedicated displays, or third-party services through the HAN. The presence of an authorized service provider always requires the availability of a public WAN supplied by the customer. Using Architecture 4, it is possible to start with a simple configuration and evolve it over time. Moreover, it simplifies the SM itself, eliminating the cybersecurity issues caused by bidirectional communications. The IHD-GW receives metering data from the SM, combines them with other information, and, possibly, forwards the enriched data to other IHDs or third parties.

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Abbreviations

The following abbreviations are used in this manuscript:

AEEGSI	Autorità per l'energia elettrica, il gas e il sistema idrico
AGCOM	Autorità per le garanzie nelle comunicazioni
AMI	Advanced Meter Infrastructure
AMM	Advance Metering Management
AMR	Automatic Meter Reading
BLE	Bluetooth Low Energy
CBA	Cost/Benefit Analysis
CEI	Comitato Elettrotecnico Italiano
CN	Core Network
COSEM	COmpanion Specification for Energy Metering
CSMA	Carrier Sense Multiple Access
DG	Distributed Generation
DLMS	Device Language Message Specification
DR	Demand-Response
DSO	Distribution System Operator
EMS	Energy Management System
EU	European Union
HAN	Home Area Network
HES	Head End System
IETF	Internet Engineering Task Force
IHD	In-home device
IHD-GW	In-home device acting as a gateway
IoT	Internet of Things
LPWA	Low-Power Wide-Area

LPWAN	Low-Power Wide-Area Network
LV	Low Voltage
M2M	Machine-to-machine
MID	Measuring Instruments Directive
MAC	Medium Access Control
MV	Medium Voltage
PLC	Power Line Carrier
PLC-C	Power Line Carrier in band CENELEC C
PON	Passive Optical Network
RAN	Radio Access Network
RTP	Real-Time Pricing
SM	Smart Meter
SM-1G	First-Generation Smart Meter
SM-2G	Second-Generation Smart Meter
ToU	Time-of-Use
WAN	Wide Area Network

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