Domestic Refrigerators in Smart Grids

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Domestic refrigeration and freezing appliances can be used for electrical load shifting from peak to off-peak demand periods, thus allowing greater penetration of renewable energy sources (RES) and significantly contributing to the reduction of CO_2 emissions. The full realization of this potential can be achieved with the synergistic combination of smart grid (SG) technologies and the application of phase-change materials (PCMs). Being permanently online, these ubiquitous appliances are available for the most advanced strategies of demand-side load management (DSLM), including real-time demand response (DR) and direct load control (DLC).

cold thermal energy storage (CTES) | phase-change materials (PCMs) | smart grids (SGs) | Demand-Side Load Management (DSLM) | Peak-Load Shifting (PLS) | Greenhouse Gases (GHG) emission mitigation | Latent Heat-Cold Storage (LHCS) | Internet-of-Things (IoT) | Smart Meters

1. Introduction

Domestic refrigerators have the potential to be used for demand-side load management (DSLM) and demand response (DR), due to their inherent capacity to store cold and, hence, postpone electric energy consumption to low energy demand periods [1]. Contrary to other household electrical appliances, they are permanently available for this purpose. This may not only result in immediate electricity bill savings, but also has the potential to contribute to decreasing the peak load on the grid [2]. This capability can be more effectively harnessed with: (a) connectivity to an SG framework and (b) the application of phase-change materials (PCMs) for enhanced latent cold storage (LCS) capacity [3][4][5].

Harmonization between energy production and demand is becoming increasingly difficult to achieve, as the contribution of renewable energy sources (RES) is becoming more important [6]. Unfortunately, the profile of renewable generation is rarely in phase with demand, giving rise to supply deficits and excesses (**Figure 1**). RES production fluctuations can be regularized with enough storage capacity. Unfortunately, viable solutions for the needed storage capacity are still lacking. Hence, the importance of augmenting the ability to control the grid from the demand side [6].

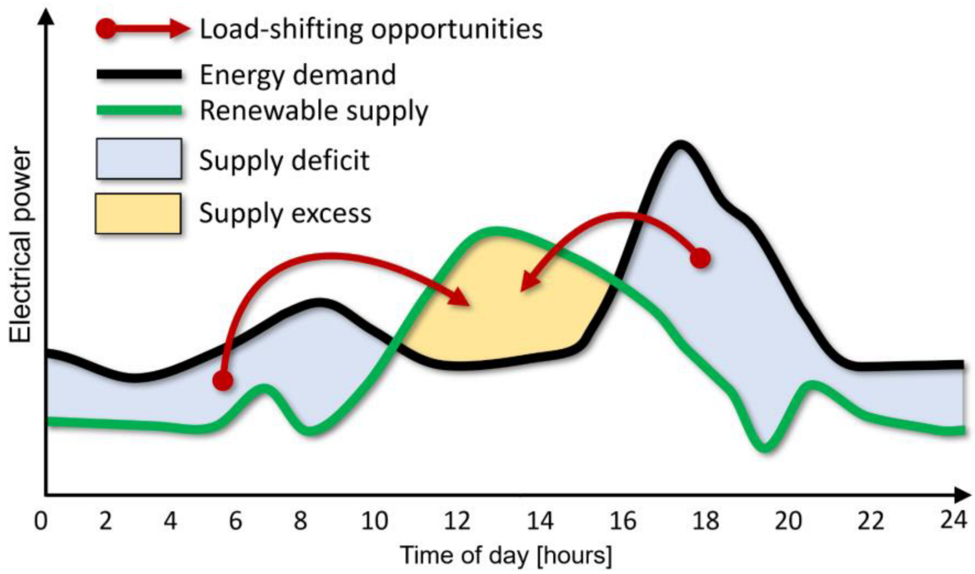

Figure 1. Typical daily renewable supply and demand profiles, and load-shifting opportunities.

Instead of relying solely on the supply side, SG approaches allow the active participation of the energy consumers in the task of grid regularization. Thanks to the advances in information and communication technologies (ICT) and their widespread availability, it is now feasible to respond to demand–supply imbalances—from the demand side—in real-time, without the need for human intervention [6].

The extensive adoption of SG technologies—particularly DSLM/DR and distributed small-scale storage—is virtually certain, mainly due to: (a) growing energy demand (especially in developing countries), (b) ageing infrastructures (especially in developed countries), and (c) increasing penetration of RES in the energy mix, stimulated by pressing greenhouse gases (GHG) emissions reduction objectives and the rising prices of fossil fuels [6][7]. If this was true some months ago, its relevance was strongly increased by the energy crisis associated with the military action of Russia on Ukraine.

PCMs can store a considerable amount of thermal energy and are very competitive when compared to electrochemical batteries: they are cheaper, long-lasting, and environmentally friendlier. This explains the large number of studies focusing on PCMs for thermal energy storage: a cursory search easily produces numerous results (on the order of hundreds of thousands). PCMs are particularly adequate for application in domestic refrigerators since they also help to (a) stabilize the cold box temperature (which is crucial for the preservation of goods) and (b) increase energy efficiency (as demonstrated by numerous studies). Furthermore, they increase the resilience to energy supply interruptions—which, unfortunately, are becoming more frequent, not only in countries with unreliable grids but, also, in developed regions (as demonstrated by recent events in the USA, specifically in California and Texas).

Vapor compression cycle refrigeration apparatuses with enhanced LCS capacity are particularly adequate for DSLM/DR as the idle time of the compressor can be considerably prolonged [8][9]. By harnessing the full potential of PCMs, it can be realistically speculated that close to 100% of the energy used for cooling, refrigeration, and freezing in a household, can be shifted to off-peak periods [1][10]. **Figure 2** illustrates the basic connective model of the reviewed technologies.

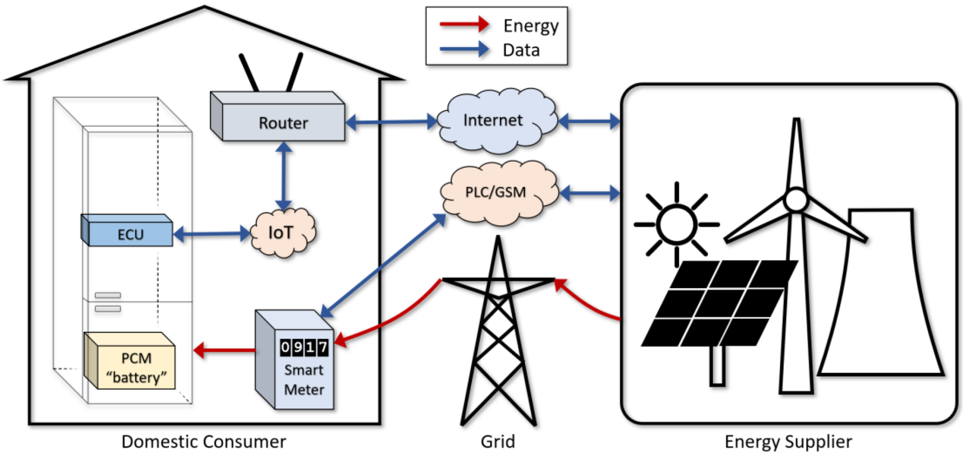

Figure 2. Topological overview of the reviewed technologies.

1.1. Global Context

1.1.1. Energy Demand Trends

Until 2019, energy demand had been steadily increasing, and this trend was consensually forecasted to continue (and even accelerate), mainly due to the emerging economies of developing countries. This demand increase stresses the existing infrastructures, incentivizing the investment in SG technologies [11][12].

The recent COVID-19 pandemic has momentarily broken this tendency. In 2012, the International Energy Agency (IEA) forecasted a 12% worldwide growth in energy demand for 2020 in comparison to 2010 [10][13]. In 2020, the IEA reassessed its forecasts and estimated a drop in global energy demand of about 5% (for the year). However, global electricity demand would only be down by a "relatively modest" 2% [14].

According to general expectations, the global electricity demand rebounded in 2021, growing by 6%, according to the IEA's Electricity Market Report. However, in its most recent July 2022 update, the IEA projects a growth of only 2.4% in 2022, a figure more in line with the five years preceding the COVID-19 pandemic [15]. This figure reflects the global slowdown in economic growth, mainly caused by the soar in energy prices following the invasion of Ukraine by Russia.

Despite the reported uncertainty of the most recent projections, the drop in energy demand triggered by the war in Ukraine is transient and unlikely to deter investment and research in renewables and energy utilization efficiency. Global energy demand is still projected to continue growing for the foreseeable future and the urgency of reducing GHG emissions has not diminished. Moreover, since the residential sector is one of the main drivers of this growth—greatly thanks to developing countries and increasing urbanization—achieving the global goal of reducing emissions will, necessarily, include the participation of the small residential consumers [5][16][17][18].

1.1.2. Potential for Thermal Energy Storage (TES) in The Residential Sector

Currently, the residential sector is responsible for about 30% to 40% of the total worldwide energy consumption [19]. Electrical loads with thermostatic control—e.g., refrigeration, freezing, cooking, water heating, washing machines, laundry drier, space heating and cooling—constitute the largest percentage of residential energy consumption, exceeding 50% [20][21]. If TES technologies (e.g., PCMs) are applied to these loads, 15% to 50% of the energy consumption—depending on the type of load—could be, realistically, shifted from peak to off-peak with potential systemic efficiency improvements [22][23].

1.1.3. Domestic Refrigeration: Global Impact on Energy Consumption and Emissions

Even though the impact of a refrigerator does not seem, a priori, particularly important in the total energy bill of a typical household, its cumulative weight at national, transnational, and continental levels, should not be underestimated. In particular, if its prevalence is accounted for (refrigerators are present in more than 89% of EU households [8][24][25][26]). On average, 13.4% of (all) residential energy consumption in member states of the OECD comes from the cooling and freezing of foodstuff [8]. In Germany, that percentage is about 20%, corresponding to about 7% of the national total energy budget [8].

The International Institute of Refrigeration (IIR) estimates that the refrigeration sector consumes about 17% of the electricity consumed worldwide, of which 45% comes from the residential sector, i.e., almost 8% of the total electricity produced [27][28]. In European countries, these percentages are slightly lower (presumably due to colder climates and more efficient appliances). For example, refrigeration (domestic, commercial, and industrial) accounted for 14% of the electric energy consumption in Germany in 2009. Of the total annual 71 TWh, 24 TWh were used by domestic refrigerators, which is about 5% of the total electric energy produced [13].

It is estimated that, in 2016, there were 1.4 billion domestic refrigerators and freezers worldwide, each with an average energy consumption of 450 kWh/year. These appliances are responsible for about 14% of the energy consumed by the residential sector, causing a yearly emission of about 450 million CO_2 tons [29][30].

The annual world production of domestic refrigerators was about 80 million units in 2009. This is about twice the numbers of the mid-1990s [31], corresponding to an average yearly growth of about 6.5%. Reliable production statistics for the last decade are difficult to gather, but it is reasonable to assume that these growth rates have been, at least, maintained. Barring the transient effects of the COVID-19 pandemic and the conflict in Ukraine, the global yearly GDP growth since 2010 has been reasonably stable at about 3%, and India's and China's at least double that, according to The World Bank [32]. This means that, for 2021, the yearly production of refrigerators should be, at least, about 160 million.

The global number of refrigerators in use was estimated to be, approximately, 1 billion in 2008 and 1.4 billion in 2016 [29][31], which corresponds to a yearly growth rate of, approximately, 4.5% (the 2% discrepancy can be explained by some inevitable obsolescence). Considering this growth rate, this number may be now between 1.7 billion and 2 billion (potentially closer to the latter). Assuming the most conservative figure of 1.7 billion (reflecting the recent drop in the world's GDP) and the improvement in the efficiency of more recent equipment, it is estimated that refrigerators and freezers should currently account for the annual emission of over 540 million CO_2 tons. According to the most recent numbers from the IEA, this represents about 1.7% of the world's total emissions in 2020 [33].

1.1.4. The Potential Impact of Domestic Refrigerators on Peak Load Shifting

In Germany, refrigerators and freezers account for a combined total power of 3.6 GW [10]. Using latent cold storage with PCMs and efficient control algorithms, all this power would be (theoretically) available for storage—allowing, for instance, the installation of an additional 3.6 GW solar wind farm, without any significant negative impact on grid stability [10]. Even without resourcing to cold storage with PCMs, it is estimated that the potential impact of all domestic refrigerators in Germany for load management can be up to 800 MW [21].

As mentioned before, Zehir and Bagriyanik (2012) calculated that, even without using latent cold storage, about 40% of electrical load can be postponed to off-peak hours [34]. If the refrigerator is equipped with LHCS, the peak load shifting (PLS) percentage should be higher. Nevertheless, keeping estimates conservative, 40% will be considered a reasonably attainable base percentage. In round figures, if 50% of worldwide refrigerators could shift 40% of their consumption to RES, annual emissions of more than 100 million CO_2 tons could be averted.

2. Smart Grids: Motivations, Goals and Paradigms

The essential aim of grid management is to match supply and demand. SG technologies help to achieve this goal by allowing control from the demand side (which is impossible to attain with conventional/classical control models, which rely exclusively on supply modulation). SGs incorporate the more recent advances in information and communication technologies (ICT) to gather and consolidate the relevant information from all the players in the energy chain—from producer to consumer—for accomplishing the following objectives [6][35][36]:

- Better integration and more economical, holistic, and rational management of distributed production (i.e., including distributed micro-generation resources);
- Curb GHG emissions by increasing the penetration of RES, improving their use, and minimizing production waste;
- Overall improvement of the quality of the energy supply (i.e., better voltage and frequency stability, better reliability, and consistency);
- Development and incorporation of demand response and demand-side resources, enhancing overall energy efficiency (essentially by reducing losses due to overloading of lines and transformers) and avoiding the need for fossil-fueled backup facilities;

- Enable the active participation of all consumers in the vital load balancing function (including small residential consumers);
- Implementation of real-time automated technologies that optimize the operation of appliances and consumer devices;
- Fully exploit the use of the latest information and control technologies to improve overall reliability, security, and efficiency of the energy infrastructure;
- Integration of advanced electricity storage and peak-shaving technologies, including plug-in and hybrid EVs, and residential thermal energy storage (e.g., HVAC and refrigerators/freezers);
- Better interoperability between transport and distribution networks (thanks to enhancements in communications and automation).

2.1. The Urgency for Smarter Grids

All the players in the energy sector—producers, transport and distribution owners, managers, governmental and non-governmental regulators, consumers, and their associations—consensually recognize the urgent need of acting on several challenging problems, affecting the present and future of the global electrical infrastructure [37]. Some of the main motivations leading toward the technological advancement of electrical grids are [6]:

- **Intermittency and fluctuations due to wind and solar generation:** Wind and solar production are characterized by large (often unpredictable) fluctuations [38]. This caps the share of these RES, since there is a need for extra controllable and rapid response generation capacity (i.e., thermal and hydro, usually), and/or energy storage facilities (e.g., pumped hydro, electrochemical batteries, thermal phase-change, flywheels, etc.), and/or DSM or peak load shifting [39][40], to assure the required stabilization [41][42][43].
- **Climate change:** The need to respect the agreed emission reductions (the Paris Agreement and global political pressures towards the reduction of CO_2 emissions) is pushing the investment in renewables, with their associated problems for the current infrastructures [44]. In this context, the implementation of SG paradigms becomes indispensable.
- **Rising energy prices:** The short, medium and long-term rising trend of oil and gas prices (due to diminishing reserves, conflicts, politics, instabilities, and market fluctuations) are among the strongest motivations supporting the increasing penetration of RES and efforts to enhance energy efficiency [45][46]. The recent invasion of Ukraine by Russia has caused an unprecedented spike in oil prices, which introduced additional instability and unpredictability in oil and gas prices.
- **Ageing, degradation, and obsolescence of infrastructures:** Capacity limitations, high losses, lack of reliability, and high maintenance costs are some of the problems associated with old infrastructures (some of

them date back to the 1950s and are still in full use); the adoption of SG paradigms will optimize the usage of the existing resources, thus curbing the upgrade costs and allowing more time for updating and/or replacing the degraded infrastructures [47].

- **Increase in global energy demand:** The existing infrastructure is being overloaded by the increase in energy demand, particularly in developing countries; this leads to a lack of reliability, quality, and consistency of the supply. Despite the significant drop in 2020, demand is still about 9% higher than in 2010 and is projected to continue rising [14][48][49]. Without the adoption of SG management models—actively involving the consumer—it will be very difficult (or even impossible) to respond adequately to this growth by investing solely in physical infrastructures.

- **Inefficiencies resulting from the need for backup generation capacity:** The large demand fluctuations, and the lack of synchronism between the demand and renewable production, lead to the underuse of the installed generation capacity, resulting in a considerable financial burden (i.e., the backup generators are inactive most of the time, being only used in very limited peak periods) [34].

- **Increasing distances between production, storage, and consumption sites:** RES production centers (i.e., hydro, wind, and solar) are often placed far away from the population and industries, requiring long transport infrastructures. This diverts financial resources that would be, otherwise, applied to the maintenance, renovation, and upgrade of current facilities. This also increases transport and distribution losses [50]. Distributed production and peer-to-peer (P2P) energy trading can attenuate these issues, but can also exacerbate the challenges for efficient grid control [50][51][52].

- **The growing profusion of small independent energy producers:** Small production installations (i.e., mini/micro-generation) of solar photovoltaic, wind, hydro, biomass, co-generation, etc., increase the difficulties in balancing the grid from the supply side, increasing the need for innovative communication and distributed control models and technologies [51][52].

- **New energy consumption patterns**: Energy consumption patterns have been changing considerably in the last decade, particularly in the residential sector [53]. The increasing profusion of electrical plug-in vehicles (EVs) [54], smart homes, and smart buildings offers new opportunities for control from the demand side, including load control and energy storage—e.g., charging EVs and home battery banks exclusively in off-peak hours, storing latent heat in HVAC systems, etc. [55][56][57].

- **Energy market liberalization:** The liberalization of the energy markets in developed countries increased the need for energy price transparency [58][59]. This has led to the adoption of technologies such as smart metering [60], which opens additional opportunities for implementing smarter models for DSLM by facilitating the collection of relevant consumption information and—in some more sophisticated implementations—allowing bidirectional communication.

- **Expanding transnational grid interconnections:** To best balance supply and demand—particularly with the increasing penetration of RES—transnational grid interconnections are becoming increasingly important [61][62][63][64], introducing additional control challenges and communication issues [65][66][67][68].

2.2. Increasing the Penetration of RES: Challenges to Grid Control

Matching production and demand is critical for the stable operation of electrical grids. Unfortunately, wind and solar generation are infamous for their lack of consistency: they cause significant fluctuations in production, which are frequently out of phase with the demand [6][69].

This could, theoretically, be solved by implementing enough storage capacity. Regrettably, large to medium-scale storage solutions (e.g., pumped hydro, thermal storage, and lithium battery banks) are very expensive and/or complex to implement [70][71]. Consequently, they currently still have a relative residual effect [72]. This results in the necessity of keeping fossil fuel-fed power plants, for the sole purpose of stabilizing and regularizing the grid voltage [73].

In the limit situation, the installed capacity of fossil fuel-fed generators needs to be matched to an equal capacity of wind and solar production, resulting in significant economic and environmental impacts. Moreover, during peak production and low demand, most of the energy produced by these RES is not even injected into the grid, leading to significant underuse of their capacities [69].

Balancing production with demand is most efficiently performed from the demand side since—among other advantages—this approach lessens the burden on the transport and distribution infrastructure. Thus, considering the inevitable increase of RES in the energy mix, the active participation of the smaller domestic consumers in the regularization of the grids is increasingly being seriously pondered [74][75].

2.3. Demand-Side Load Management Paradigms

The expression "Demand-Side Management" was coined, in the early 1980s, by the Electric Power Research Institute (EPRI), being defined as (paraphrasing): "planning, implementation, and monitoring of electrical networks with the objective of influencing the consumer to use electricity in a manner that produces desirable changes in the network load profile, i.e., reducing the magnitude of its fluctuations" [76][77][78].

This comprises all the strategies and models aiming at influencing the consumption profile in the direction of transferring load from peak to off-peak periods [39][78]. The greatest virtue of this approach resides in the fact that it is significantly less costly to manage the load profile from the consumer side than to build a new power plant and/or increase the carrying capacity of the transport and distribution infrastructure [77][78][79].

DSLM is especially decisive in the context of increasing energy production from RES since it can provide a means of mitigating the supply and demand imbalances caused by the inherent fluctuating and unpredictable character of some of these energy sources. Particularly, solar and wind intermittency constitutes the main obstacle to the growth of their share in the energy market [7][80].

Since the fundamental actors in DSLM are the consumers, these need sufficient motivation and incentive to incur the inevitable costs that the installation and operation of DSLM functionalities might imply, i.e., some financial advantage needs to be offered to the energy customers by the energy providers.

2.3.1. Price-Based Demand Response (PBDR)

One way of achieving a more rational load profile is by implementing price models that reflect the relation between demand and supply, thus incentivizing the implementation of load management (LM) methods and technologies by consumers [81][82]. This is the most common approach adopted by energy suppliers to motivate consumers to modify their consumption patterns, in a way that helps balance the grid, by attenuating demand peaks and, thus, minimizing costly interventions from the supply side [83][84][85].

- **Time-of-use pricing(ToU):** This is the currently most practiced variable price regime in the majority of countries since it is the most straightforward to implement: it defines differentiated rates for two or three daily periods, e.g., peak, mid-peak and off-peak. It is relatively trivial to implement a cooling equipment control firmware for managing the consumption in the context of this type of pricing schedule, minimizing the energy bill [86][87][88].

- **Critical peak pricing:** According to this pricing scheme, a normal rate (usually belonging to the previously described ToU family) is valid most of the time, during the year [83]. However, during known occasions with exceptionally high demand (or, conversely, low supply), a higher rate is applied. These periods happen only for a few days, or even a few hours, during the year [83]. For the consumer, the advantage of this scheme is that the regular rate can be kept lower than it would be possible otherwise. However, that is not, ultimately, the goal: the main objective is to curb the demand by motivating the client to consume less during the short critical high-demand/low-supply periods [88].

- **Real-time pricing:** In this pricing system, the energy supplier broadcasts to the consumers, continually, the constantly varying energy rate. This quotation indirectly represents the continually updated relation between supply and demand, as created by the market dynamics. Energy producers dynamically increase the energy price during high-demand/low-supply periods, discouraging consumption during these critical periods [88][89]. In an SG framework, an automatism can, conceivably, be implemented to react instantly to continuously updated price fluctuations, using all available controllable resources (i.e., manageable loads and energy storage devices) to reduce the consumer energy bill and, thus, indirectly help to balance supply and demand [74][83][88][89][90]. Despite their designation, current implemented plans are not truly/strictly “real-time”. There are, presently, two main modes of so-called “real-time” pricing being practiced: one broadcasts the quotations a day in advance (DA-RTP) and the other gives the hourly price within 60 min in advance (RT-RTP).

2.3.2. Incentive-Based Demand Response (IBDR)

This class of client-side energy demand modulation is based on incentives that are not directly connected to variable prices or quotations [91][92]. A contract is established between supplier and client, according to which the latter promises to respond to supplier demands for load restraints, depending on contingencies. In turn, the supplier awards the client with financial incentives (e.g., lower energy rates and/or one-off discounts) [91][92].

2.3.3. Direct Load Control (DLC)

In this system of demand control, the energy supplier directly controls the loads from the client side. The energy supplier benefits from an augmented ability to balance supply and demand, and the client receives financial rewards (e.g., lower rates and/or discounts) [83].

For larger clients, the supplier usually installs the necessary telemetry and telecontrol hardware at the client's site [88][93][94]. For domestic consumers, it is possible to implement direct control of appliances by factory-equipping them with electronic control units (ECUs) with appropriate firmware and Internet connectivity. Validation can be achieved with an Advanced Metering Infrastructure (AMI) (i.e., "smart meters"). Currently, programmable communicating thermostats (PCTs) have been successfully implemented in some regions.

2.3.4. Demand Bidding and Buyback

In these programs, a sophisticated automated negotiation protocol is established between energy suppliers and consumers. They both agree on the price—on a case-by-case basis and according to market fluctuations—for a predetermined quantity (or package) of voluntary cuts from peak-load demand made available by the consumer to the supplier [92][95][96].

These programs are currently being tried, with some success, with large consumers (e.g., industry, large commercial and office buildings). There is no fundamental obstacle to implementing these schemes for small residential consumers, although it is certainly more complicated and might prove to be, ultimately, impractical.

2.3.5. Emergency Demand Response (EDR)

In extraordinary cases of insufficient production and/or excess demand, energy producers set up a contingency program that includes communication with clients who can cut their load immediately, i.e., clients with energy storage facilities, backup generators, or the ability to postpone or throttle loads down—e.g., water heaters, HVAC, etc. [97].

The success of this approach depends on the ability of the supplier to predict such critical periods with enough antecedence, and on the existence of an open and effective communication channel between suppliers and consumers. This channel should be ideally telematic/digital, and the response from the demand side should be also automated, e.g., a group of electrical loads is deemed non-essential and is shut down during critical periods. Alternatively, variable power loads can be throttled down [98].

The fundamental difference between this modality and DLC is that the consumer is the one responsible for controlling the loads and not the supplier. Like with other programs, the client is rewarded with financial benefits [88].

2.3.6. Distributed Frequency Regulation Services

Consumers who adhere to this type of program help the suppliers maintain the stability of the AC frequency. Clients allow the supplier to directly modulate their loads, reacting quickly—in real-time—to frequency fluctuations [99]. This implies the implementation of DLC, i.e., by installing specialized equipment on the client's site, for frequency monitoring, telemetry, and load control. Again, the client receives incentives or financial compensation [83][91][92].

2.4. Practical Models of Load Management for the Household

In practice, the involvement of domestic consumers in DSLM can be classified in three levels, in increasing order of SG integration:

- **ToU**—Load shifting based on fixed time-of-use pricing differentiation: the consumer adheres to a pricing scheme where the supplier defines two or three fixed daily periods with differentiated tariffs—e.g., peak, mid-peak, and off-peak (these periods can change according to the season). Based on this, the consumer schedules the consumption to minimize the energy bill. "Smart" appliances (including refrigerator-freezers) can automatically (on a time-programmed basis) decide to postpone consumption to off-peak periods, whenever possible. In this "low-level" scheme, there is no need for continuous communication between consumers and suppliers. Thus, this scheme might not be considered entirely within the realm of an SG (it might be classified as "SG level zero"). However, it still implies the use of smart meters that can record the consumption that occurs within the two or three defined periods; this approach implies no costs from the energy provider side: the consumer can simply configure the time-programming control of the appliance with the ToU periods;

- **RTP**—Load shifting based on "real-time" forecasted pricing: instead of fixed daily periods, the supplier quotes the energy price to the consumer 24h to 1h in advance (usually an hourly price, but it can also be in fractions of an hour). The supplier can forecast future supply and demand based on various predictable factors (e.g., weather forecasts, which determine RES production). Since it is humanly impractical for the typical domestic consumer to manually manage the load optimally in this scheme (particularly for short in-advance periods), the process should be automated via "smart appliances" with IoT connectivity, allowing these to continually receive the real-time pricing from the energy supplier and algorithmically decide when to postpone consumption; costs from the provider side are relatively negligible: it only needs to broadcast the price information via the Internet and charge the client accordingly, based on the time-referenced consumption recorded by the smart meter (assuming one is already installed);

- **DLC**—Load management based on direct appliance control by the energy supplier: in this high-level SG scheme, the consumer grants the energy supplier direct control of some "smart appliances". The simplest implementation of DLC for the domestic consumer is the "remotely controllable HVAC thermostat" (PCT). The extension of DLC to other appliances (including refrigerator-freezers) implies the implementation of more sophisticated bidirectional IoT protocols (which implies an initial investment in information systems by the energy provider, although of relatively low financial impact). The energy supplier can use this facility to aid in load balancing, frequency regulation and emergency demand response (EDR). To make this economically advantageous for the consumer, the energy supplier can offer attractive discounts and pricing, allowing the consumer to reach a short break-even period on the required initial investment.

2.5. Smart Grid Enabling Technologies

A host of new technologies enables the participation of small residential consumers in SGs: Internet-of-things (IoT), smart meters (SMs) and advanced metering infrastructures (AMI) [60][100][101], home automation (HA), home area networks (HAN), neighborhood area networks (NAN), wide area networks (WAN) [102], meter data management systems (MDMS), home energy management systems (HEMS) [74][85], and building energy management systems (BEMS), just to mention the more relevant ones [83][103][104].

These technologies provide a workable environment for DSLM/DR programs, harmonizing supply and demand via the modulation of consumption. The participating consumers receive financial incentives from the energy suppliers, rewarding their participation in these programs [83][91][92].

In a Communication-Based Demand Response (CBDR) program, household appliances communicate with SMs, establishing an automated bidirectional communication between domestic consumers and energy suppliers. Consumer appliances receive updated information about energy prices—in real-time or not—and can, autonomously, make load management decisions, using their capacity to delay consumption and/or store energy (thus minimizing the electricity bill). Reciprocally, appliances can offer their available capacity for on-demand immediate consumption to the energy marketplace, where they can be commanded by suppliers [105].

2.5.1. Advanced Metering Infrastructures (AMI)

One of the assets that eases the evolution toward smarter electric grids, is the growing installed network of SMs in developed countries. These apparatuses contain a microcontroller, memory, updatable firmware, and means of remote communications with the energy suppliers (generally via PLC and/or GSM) [100][101][106].

The American Federal Energy Regulatory Commission (FERC) defines Advanced Metering Infrastructure as “meters that measure and record consumption data, hourly or with greater frequency, supplying this information to both users/clients and energy suppliers, at least daily, that information being used for billing and other purposes” [83].

SMs are essential for the implementation of SGs [60][107]. Their most basic function is to record daily consumption history, allowing ToU billing. Nevertheless, they can also offer several other functions in the context of DSLM/CBDR [75][108]. For example, these apparatuses can serve as a communications gateway with electrical loads that can be remotely controlled. They can also supply vital real-time information about where consumption is taking place. Importantly, they can also validate both energy saving and/or load shifting actions by the consumers [109].

2.5.2. Wide Area Network Infrastructures

A fundamental requirement for the implementation of SG functionalities is the availability of communication means between all the players (i.e., production, transport, control, distribution, and consumption). Fortunately, nowadays, wide-area wireless Internet access technologies are globally widespread. Güngör et al. (2011), Gao et al. (2012), Usman and Shami (2013), Supriya et al. (2015), Mahmood et al. (2015), and Emmanuel and Rayudu (2016), conducted very comprehensive reviews of available communication technologies and standards for SGs [103][104][110][111][112], which are still broadly applicable and up to date.

- **Mobile cellular infrastructure:** The widespread coverage of cellular infrastructure is a valuable resource for supplying the necessary means of communication for the implementation of SG paradigms. Given the relatively modest bandwidth needs of these applications, even the most basic GSM/2G coverage can be sufficient for this purpose [103][104][110]. Many SMs are equipped with GSM connectivity.

- **Power Line Communication (PLC):** Since all the constituent parts of the electrical grid are, inherently, physically interconnected by conductor wires, it is logical to use this pre-existing infrastructure as a communication medium. This would have the advantages of not depending on third-party infrastructures and allowing an economic means of communication between all grid constituents. Frequently, SMs are equipped with PLC transceivers. Plentiful technologies, protocols, and standards exist for this purpose—e.g., IEC 14908-3 (Lon Works), IEC 14543-3-5 (KNX, BUS), CEA-600.31 (CEBus), IEC 61334-3-1 (DLMS), IEC 61334-5-1, IEEE 1901.2, ITU-T G.henm, PRIME, G3-PLC, IEEE 1901, TIA-1113 (HomePlug 1.0), ITU-T G.hn (G.9960/G.9961), and HD-PLC [103][104]—but their implementation is still relatively limited and of local/regional scale.

2.5.3. Internet-of-Things

According to the Recommendation, ITU-T Y.2060 of the Telecommunication Standardization Sector of the International Telecommunications Union (ITU), the IoT "(…) can be viewed as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies (ICT)" [113].

It is unviable to list all the protocols encompassed under this concept: they are numerous and still growing (e.g., ZigBee [114]). The relevance of this definition in the current context is justified by the fact that the exchange of information between SG devices will adopt some of these protocols [24][80][115]. Furthermore, the application of IoT technologies for real-time demand response in the household, specifically narrowband-IoT (NB-IoT), is presently being investigated [116], particularly in the context of the newest SG paradigms [117][118].

References

1. Taneja, J.; Lutz, K.; Culler, D. The Impact of Flexible Loads in Increasingly Renewable Grids. In Proceedings of the 2013 IEEE International Conference on Smart Grid Communications (SmartGridComm), Vancouver, BC, Canada, 21–24 October 2013; pp. 265–270.
2. Torriti, J. Understanding the Timing of Energy Demand through Time Use Data: Time of the Day Dependence of Social Practices. Energy Res. Soc. Sci. 2017, 25, 37–47.
3. Mastani Joybari, M.; Haghighat, F.; Moffat, J.; Sra, P. Heat and Cold Storage Using Phase Change Materials in Domestic Refrigeration Systems: The State-of-the-Art Review. Energy Build. 2015, 106, 111–124.
4. Bista, S.; Hosseini, S.E.; Owens, E.; Phillips, G. Performance Improvement and Energy Consumption Reduction in Refrigeration Systems Using Phase Change Material (PCM). Appl. Therm. Eng. 2018, 142, 723–735.
5. Shakeri, M.; Shayestegan, M.; Abunima, H.; Reza, S.M.S.; Akhtaruzzaman, M.; Alamoud, A.R.M.; Sopian, K.; Amin, N. An Intelligent System Architecture in Home Energy Management Systems (HEMS) for Efficient Demand Response in Smart Grid. Energy Build. 2017, 138, 154–164.
6. Alotaibi, I.; Abido, M.A.; Khalid, M.; Savkin, A.V. A Comprehensive Review of Recent Advances in Smart Grids: A Sustainable Future with Renewable Energy Resources. Energies 2020, 13, 6269.
7. Ayalon, O.; Baum, Z.; Frant, S.; Elmakis, D.; Palatnik, R.R. Harnessing Households to Mitigate Renewables Intermittency in the Smart Grid. Renew. Energy 2018, 132, 1216–1229.
8. Sonnenrein, G.; Baumhögger, E.; Elsner, A.; Fieback, K.; Morbach, A.; Paul, A.; Vrabec, J. Copolymer-Bound Phase Change Materials for Household Refrigerating Appliances: Experimental Investigation of Power Consumption, Temperature Distribution and Demand Side Management Potential. Int. J. Refrig. 2015, 60, 166–173.
9. Barzin, R.; Chen, J.J.J.; Young, B.R.; Farid, M.M. Peak Load Shifting with Energy Storage and Price-Based Control System. Energy 2015, 92, 505–514.
10. Krauter, S.; Prior, D. Minimizing Storage Costs by Substituting Centralized Electrical Storage by Thermal Storage at the End User, Also Suppling Balancing Power for Grid Operation. Energy Procedia 2017, 135, 210–226.
11. Tuballa, M.L.; Abundo, M.L. A Review of the Development of Smart Grid Technologies. Renew. Sustain. Energy Rev. 2016, 59, 710–725.
12. OECD. Cool Appliances; Energy Efficiency Policy Profiles; OECD: Paris, France, 2003; ISBN 9789264196612.
13. Waschull, J.; Müller, R.; Hernschier, W.; Künanz, R. Cold Storage Devices for Smart Grid Integration. Energy Procedia 2014, 46, 48–57.

14. IEA. World Energy Outlook 2020; IEA: Paris, France, 2020.
15. International Energy Agency. IEA Electricity Market Report, July 2022 Update; International Energy Agency: Paris, France, 2022.
16. Ghasemian, S.; Faridzad, A.; Abbaszadeh, P.; Taklif, A.; Ghasemi, A.; Hafezi, R. An Overview of Global Energy Scenarios by 2040: Identifying the Driving Forces Using Cross-Impact Analysis Method. Int. J. Environ. Sci. Technol. 2020.
17. Iliopoulos, N.; Esteban, M.; Kudo, S. Assessing the Willingness of Residential Electricity Consumers to Adopt Demand Side Management and Distributed Energy Resources: A Case Study on the Japanese Market. Energy Policy 2020, 137, 111169.
18. Streimikiene, D.; Balezentis, T.; Alebaite, I. Climate Change Mitigation in Households between Market Failures and Psychological Barriers. Energies 2020, 13, 2797.
19. Tarish, H.; Hang, O.; Elmenreich, W. A Review of Residential Demand Response of Smart Grid. Renew. Sustain. Energy Rev. 2016, 59, 166–178.
20. Lizana, J.; Friedrich, D.; Renaldi, R.; Chacartegui, R. Energy Flexible Building through Smart Demand-Side Management and Latent Heat Storage. Appl. Energy 2018, 230, 471–485.
21. Zehir, M.A.; Batman, A.; Bagriyanik, M. Review and Comparison of Demand Response Options for More Effective Use of Renewable Energy at Consumer Level. Renew. Sustain. Energy Rev. 2016, 56, 631–642.
22. Prüggler, N. Economic Potential of Demand Response at Household Level—Are Central-European Market Conditions Sufficient? Energy Policy 2013, 60, 487–498.
23. Fotouhi Ghazvini, M.A.; Soares, J.; Abrishambaf, O.; Castro, R.; Vale, Z. Demand Response Implementation in Smart Households. Energy Build. 2017, 143, 129–148.
24. CECED. European Committee of Domestic Equipment Manufacturers. Available online: https://www.eceee.org/members/MembersForum/ceced/ (accessed on 30 August 2022).
25. Sonnenrein, G.; Elsner, A.; Baumhögger, E.; Morbach, A.; Fieback, K.; Vrabec, J. Reducing the Power Consumption of Household Refrigerators through the Integration of Latent Heat Storage Elements in Wire-and-Tube Condensers. Int. J. Refrig. 2015, 51, 154–160.
26. Stadler, M.; Krause, W.; Sonnenschein, M.; Vogel, U. Modelling and Evaluation of Control Schemes for Enhancing Load Shift of Electricity Demand for Cooling Devices. Environ. Model. Softw. 2009, 24, 285–295.
27. Arteconi, A.; Polonra, F. Demand Side Management in Refrigeration Applications. Int. J. Heat Technol. 2017, 35, S58–S63.

28. Coulomb, D.; Dupont, J.-L.; Pichard, A. The Role of Refrigeration in the Global Economy. 29th Informatory Note on Refrigeration Technologies/November 2015; International Institute of Refrigeration/Institut International du Froid: Paris, France, 2015; Available online: https://sainttrofee.nl/wp-content/uploads/2019/01/NoteTech_29-World-Statistics.pdf (accessed on 30 August 2022).
29. Ouali, M.; Djebiret, M.A.; Ouali, R.; Mokrane, M.; Merzouk, N.K.; Bouabdallah, A. Thermal Control Influence on Energy Efficiency in Domestic Refrigerator Powered by Photovoltaic. Int. J. Hydrog. Energy 2017, 42, 8955–8961.
30. Barthel, C.; Götz, T. The Overall Worldwide Saving Potential from Domestic Refrigerators and Freezers; Wuppertal Institute for Climate, Environment and Energy: Wuppertal, Germany, 2012.
31. James, C.; Onarinde, B.A.; James, S.J. The Use and Performance of Household Refrigerators: A Review. Compr. Rev. Food Sci. Food Saf. 2017, 16, 160–179.
32. Bank, T.W. GDP Growth (Annual %). Available online: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG (accessed on 30 August 2022).
33. IEA. Global Energy Review: CO2 Emissions in 2020; IEA: Paris, France, 2021.
34. Zehir, M.A.; Bagriyanik, M. Demand Side Management by Controlling Refrigerators and Its Effects on Consumers. Energy Convers. Manag. 2012, 64, 238–244.
35. Marah, R.; El Hibaoui, A. Algorithms for Smart Grid Management. Sustain. Cities Soc. 2018, 38, 627–635.
36. USC. Energy and Independence and Security Act of 2007; United States Congress: Washington, DC, USA, 2007.
37. Lu, X.; Zhou, K.; Zhang, X.; Yang, S. A Systematic Review of Supply and Demand Side Optimal Load Scheduling in a Smart Grid Environment. J. Clean. Prod. 2018, 203, 757–768.
38. Liebensteiner, M.; Wrienz, M. Do Intermittent Renewables Threaten the Electricity Supply Security? Energy Econ. 2020, 87, 104499.
39. Bigler, T.; Gaderer, G.; Loschmidt, P.; Sauter, T. SmartFridge: Demand Side Management for the Device Level. In Proceedings of the International Conference on Emerging Technologies and Factory Automation (ETFA), Toulouse, France, 5–9 September 2011.
40. Wang, H.; Jin, T. Prevention and Survivability for Power Distribution Resilience: A Multi-Criteria Renewables Expansion Model. IEEE Access 2020, 8, 88422–88433.
41. De Jonghe, C.; Hobbs, B.F.; Belmans, R. Optimal Generation Mix With Short-Term Demand Response and Wind Penetration. IEEE Trans. Power Syst. 2012, 27, 830–839.

42. Behboodi, S.; Chassin, D.P.; Crawford, C.; Djilali, N. Renewable Resources Portfolio Optimization in the Presence of Demand Response. Appl. Energy 2016, 162, 139–148.
43. Evans, A.; Strezov, V.; Evans, T.J. Assessment of Utility Energy Storage Options for Increased Renewable Energy Penetration. Renew. Sustain. Energy Rev. 2012, 16, 4141–4147.
44. Organizations, E.S. Recommendations for Smart Grid Standardization in Europe—Standards for Smart Grids (Extracted from the Final report of the CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids); European Standards Organization. 2011. Available online: ftp://ftp.cen.eu/PUB/Publications/Brochures/SmartGrids.pdf (accessed on 25 February 2019).
45. EIA (U.S.). Short-Term Energy Outlook; U.S. Energy Information Administration: Washington, DC, USA, 2022. Available online: https://www.eia.gov/outlooks/steo/pdf/steo_text.pdf (accessed on 30 August 2022).
46. EIA (U.S.). Annual Energy Outlook 2022; U.S. Energy Information Administration: Washington, DC, USA, 2022. Available online: https://www.eia.gov/outlooks/aeo/consumption/sub-topic-01.php (accessed on 30 August 2022).
47. Tweneboah-Koduah, S.; Prasad, R. The Threats of Infrastructure Obsolescence to Smart Grid: A Case Study. Wirel. Pers. Commun. 2020, 114, 1025–1043.
48. Enerdata. Global Energy Trends 2021; Enerdata: Grenoble, France, 2021.
49. Enerdata. World Energy & Climate Statistics—Yearbook 2022; Enerdata: Grenoble, France, 2022. Available online: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html (accessed on 30 August 2022).
50. Paudel, A.; Sampath, L.P.M.I.; Yang, J.; Gooi, H.B. Peer-to-Peer Energy Trading in Smart Grid Considering Power Losses and Network Fees. IEEE Trans. Smart Grid 2020, 11, 4727–4737.
51. Demirhan, C.D.; Tso, W.W.; Powell, J.B.; Heuberger, C.F.; Pistikopoulos, E.N. A Multiscale Energy Systems Engineering Approach for Renewable Power Generation and Storage Optimization. Ind. Eng. Chem. Res. 2020, 59, 7706–7721.
52. Grubic, T.; Varga, L.; Hu, Y.; Tewari, A. Micro-Generation Technologies and Consumption of Resources: A Complex Systems' Exploration. J. Clean. Prod. 2020, 247, 119091.
53. Heinonen, J.; Junnila, S. Residential Energy Consumption Patterns and the Overall Housing Energy Requirements of Urban and Rural Households in Finland. Energy Build. 2014, 76, 295–303.
54. Umoren, I.A.; Shakir, M.Z.; Tabassum, H. Resource Efficient Vehicle-to-Grid (V2G) Communication Systems for Electric Vehicle Enabled Microgrids. IEEE Trans. Intell. Transp. Syst. 2020, 22, 4171–4180.

55. Zhu, J.; Lauri, F.; Koukam, A.; Hilaire, V. Scheduling Optimization of Smart Homes Based on Demand Response; Springer: Berlin/Heidelberg, Germany, 2015; pp. 223–236.

56. Jindal, A.; Kumar, N.; Singh, M. Internet of Energy-Based Demand Response Management Scheme for Smart Homes and PHEVs Using SVM. Futur. Gener. Comput. Syst. 2020, 108, 1058–1068.

57. Kamilaris, A.; Pitsillides, A. Exploiting Demand Response in Web-Based Energy-Aware Smart Homes. In Proceedings of the ENERGY 2011: The First International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies, Venice, Italy, 22–27 May 2011; IARIA: Venice/Mestre, Italy, 2011; pp. 27–32.

58. Nicolli, F.; Vona, F. Energy Market Liberalization and Renewable Energy Policies in OECD Countries. Energy Policy 2019, 128, 853–867.

59. Pepermans, G. European Energy Market Liberalization: Experiences and Challenges. Int. J. Econ. Policy Stud. 2019, 13, 3–26.

60. Barai, G.R.; Krishnan, S.; Venkatesh, B. Smart Metering and Functionalities of Smart Meters in Smart Grid—A Review. In Proceedings of the 2015 IEEE Electrical Power and Energy Conference (EPEC), London, ON, Canada, 26–28 October 2015; pp. 138–145.

61. Aghahosseini, A.; Bogdanov, D.; Barbosa, L.S.N.S.; Breyer, C. Analysing the Feasibility of Powering the Americas with Renewable Energy and Inter-Regional Grid Interconnections by 2030. Renew. Sustain. Energy Rev. 2019, 105, 187–205.

62. Mac Domhnaill, C.; Ryan, L. Towards Renewable Electricity in Europe: Revisiting the Determinants of Renewable Electricity in the European Union. Renew. Energy 2020, 154, 955–965.

63. Child, M.; Kemfert, C.; Bogdanov, D.; Breyer, C. Flexible Electricity Generation, Grid Exchange and Storage for the Transition to a 100% Renewable Energy System in Europe. Renew. Energy 2019, 139, 80–101.

64. Taggart, S.; James, G.; Dong, Z.; Russell, C. The Future of Renewables Linked by a Transnational Asian Grid. Proc. IEEE 2012, 100, 348–359.

65. Parvez, M.; Elias, M.F.M.; Rahim, N.A.; Osman, N. Current Control Techniques for Three-Phase Grid Interconnection of Renewable Power Generation Systems: A Review. Sol. Energy 2016, 135, 29–42.

66. Hammons, T.J. Integrating Renewable Energy Sources into European Grids. Int. J. Electr. Power Energy Syst. 2008, 30, 462–475.

67. Lynch, M.Á.; Tol, R.S.J.; O’Malley, M.J. Optimal Interconnection and Renewable Targets for North-West Europe. Energy Policy 2012, 51, 605–617.

68. Van den Bergh, K.; Couckuyt, D.; Delarue, E.; D'haeseleer, W. Redispatching in an Interconnected Electricity System with High Renewables Penetration. Electr. Power Syst. Res. 2015, 127, 64–72.
69. Boyle, G. Renewable Electricity and the Grid—The Challenge of Variability; Boyle, G., Ed.; Earthscan: London, UK; Sterling, VA, USA, 2007; ISBN 978-1-84407-418-1.
70. Battke, B.; Schmidt, T.S.; Grosspietsch, D.; Hoffmann, V.H. A Review and Probabilistic Model of Lifecycle Costs of Stationary Batteries in Multiple Applications. Renew. Sustain. Energy Rev. 2013, 25, 240–250.
71. Gür, T.M. Review of Electrical Energy Storage Technologies, Materials and Systems: Challenges and Prospects for Large-Scale Grid Storage. Energy Environ. Sci. 2018, 11, 2696–2767.
72. Yao, L.; Yang, B.; Cui, H.; Zhuang, J.; Ye, J.; Xue, J. Challenges and Progresses of Energy Storage Technology and Its Application in Power Systems. J. Mod. Power Syst. Clean Energy 2016, 4, 519–528.
73. Schlachtberger, D.P.; Becker, S.; Schramm, S.; Greiner, M. Backup Flexibility Classes in Emerging Large-Scale Renewable Electricity Systems. Energy Convers. Manag. 2016, 125, 336–346.
74. Qu, X.; Hui, H.; Ding, Y.; Luan, K. Optimal Control of Intelligent Electricity Consumption for Residential Customers Considering Demand Response. Energy Procedia 2018, 145, 510–515.
75. Tchawou Tchuisseu, E.B.; Gomila, D.; Colet, P. Reduction of Power Grid Fluctuations by Communication between Smart Devices. Int. J. Electr. Power Energy Syst. 2019, 108, 145–152.
76. Arteconi, A.; Hewitt, N.J.; Polonara, F. State of the Art of Thermal Storage for Demand-Side Management. Appl. Energy 2012, 93, 371–389.
77. Rabl, V.A.; Gellings, C.W. The Concept of Demand-Side Management. In Demand-Side Management and Electricity End-Use Efficiency; Springer: Dordrecht, The Netherlands, 1988; pp. 99–112.
78. Gellings, C.W. Evolving Practice of Demand-Side Management. J. Mod. Power Syst. Clean Energy 2017, 5, 1–9.
79. Palensky, P.; Dietrich, D. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. IEEE Trans. Ind. Inform. 2011, 7, 381–388.
80. Callaway, D.S. Tapping the Energy Storage Potential in Electric Loads to Deliver Load Following and Regulation, with Application to Wind Energy. Energy Convers. Manag. 2009, 50, 1389–1400.
81. Khan, R.; Khan, S.U. Design and Implementation of UPnP-Based Energy Gateway for Demand Side Management in Smart Grid. J. Ind. Inf. Integr. 2017, 8, 8–21.

82. Tang, Q.; Yang, K.; Zhou, D.; Luo, Y.; Yu, F. A Real-Time Dynamic Pricing Algorithm for Smart Grid With Unstable Energy Providers and Malicious Users. IEEE Internet Things J. 2016, 3, 554–562.

83. Hussain, M.; Gao, Y. A Review of Demand Response in an Efficient Smart Grid Environment. Electr. J. 2018, 31, 55–63.

84. Wang, Y.; Lin, H.; Liu, Y.; Sun, Q.; Wennersten, R. Management of Household Electricity Consumption under Price-Based Demand Response Scheme. J. Clean. Prod. 2018, 204, 926–938.

85. Vale, Z.; Pau, M.; Soares, J.; Ponci, F.; Lipari, G.; Castro, R.; Monti, A.; Fotouhi Ghazvini, M.A. Congestion Management in Active Distribution Networks through Demand Response Implementation. Sustain. Energy Grids Netw. 2019, 17, 100185.

86. Celebi, E.; Fuller, J.D. Time-of-Use Pricing in Electricity Markets Under Different Market Structures. IEEE Trans. Power Syst. 2012, 27, 1170–1181.

87. Datchanamoorthy, S.; Kumar, S.; Ozturk, Y.; Lee, G. Optimal Time-of-Use Pricing for Residential Load Control. In Proceedings of the 2011 IEEE International Conference on Smart Grid Communications (SmartGridComm), Brussels, Belgium, 17–20 October 2011; pp. 375–380.

88. Shariatzadeh, F.; Mandal, P.; Srivastava, A.K. Demand Response for Sustainable Energy Systems: A Review, Application and Implementation Strategy. Renew. Sustain. Energy Rev. 2015, 45, 343–350.

89. Lujano-Rojas, J.M.; Monteiro, C.; Dufo-López, R.; Bernal-Agustín, J.L. Optimum Residential Load Management Strategy for Real Time Pricing (RTP) Demand Response Programs. Energy Policy 2012, 45, 671–679.

90. Allcott, H. Rethinking Real-Time Electricity Pricing. Resour. Energy Econ. 2011, 33, 820–842.

91. Yu, M.; Hong, S.H.; Ding, Y.; Ye, X. An Incentive-Based Demand Response (DR) Model Considering Composited DR Resources. IEEE Trans. Ind. Electron. 2019, 66, 1488–1498.

92. Khajavi, P.; Abniki, H.; Arani, A.B. The Role of Incentive Based Demand Response Programs in Smart Grid. In Proceedings of the 2011 10th International Conference on Environment and Electrical Engineering, Rome, Italy, 8–11 May 2011; pp. 1–4.

93. Mortaji, H.; Ow, S.H.; Moghavvemi, M.; Almurib, H.A.F. Load Shedding and Smart-Direct Load Control Using Internet of Things in Smart Grid Demand Response Management. IEEE Trans. Ind. Appl. 2017, 53, 5155–5163.

94. Chen, C.; Wang, J.; Kishore, S. A Distributed Direct Load Control Approach for Large-Scale Residential Demand Response. IEEE Trans. Power Syst. 2014, 29, 2219–2228.

95. Sharifi, R.; Fathi, S.H.; Vahidinasab, V. A Review on Demand-Side Tools in Electricity Market. Renew. Sustain. Energy Rev. 2017, 72, 565–572.

96. Saebi, J.; Taheri, H.; Mohammadi, J.; Nayer, S.S. Demand Bidding/Buyback Modeling and Its Impact on Market Clearing Price. In Proceedings of the 2010 IEEE International Energy Conference, Manama, Bahrain, 18–22 December 2010; pp. 791–796.
97. Tyagi, R.; Black, J.W. Emergency Demand Response for Distribution System Contingencies. In Proceedings of the IEEE PES T&D 2010, New Orleans, LA, USA, 19–22 April 2010; pp. 1–4.
98. Rahmani-Andebili, M.; Abdollahi, A.; Moghaddam, M.P. An Investigation of Implementing Emergency Demand Response Program (EDRP) in Unit Commitment Problem. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–7.
99. Zhang, S.; Mishra, Y.; Shahidehpour, M. Utilizing Distributed Energy Resources to Support Frequency Regulation Services. Appl. Energy 2017, 206, 1484–1494.
100. Kabalci, Y. A Survey on Smart Metering and Smart Grid Communication. Renew. Sustain. Energy Rev. 2016, 57, 302–318.
101. Depuru, S.S.S.R.; Wang, L.; Devabhaktuni, V. Smart Meters for Power Grid: Challenges, Issues, Advantages and Status. Renew. Sustain. Energy Rev. 2011, 15, 2736–2742.
102. Kuzlu, M.; Pipattanasomporn, M.; Rahman, S. Communication Network Requirements for Major Smart Grid Applications in HAN, NAN and WAN. Comput. Netw. 2014, 67, 74–88.
103. Usman, A.; Shami, S.H. Evolution of Communication Technologies for Smart Grid Applications. Renew. Sustain. Energy Rev. 2013, 19, 191–199.
104. Emmanuel, M.; Rayudu, R. Communication Technologies for Smart Grid Applications: A Survey. J. Netw. Comput. Appl. 2016, 74, 133–148.
105. LeMay, M.; Nelli, R.; Gross, G.; Gunter, C.A. An Integrated Architecture for Demand Response Communications and Control. In Proceedings of the 41st Annual Hawaii International Conference on System Sciences (HICSS 2008), Waikoloa, HI, USA, 7–10 January 2008; p. 174.
106. Finn, P.; Fitzpatrick, C.; Connolly, D.; Leahy, M.; Relihan, L. Facilitation of Renewable Electricity Using Price Based Appliance Control in Ireland’s Electricity Market. Energy 2011, 36, 2952–2960.
107. Paterakis, N.G.; Erdinç, O.; Catalão, J.P.S. An Overview of Demand Response: Key-Elements and International Experience. Renew. Sustain. Energy Rev. 2017, 69, 871–891.
108. Ali, S.; Khan, I.; Jan, S.; Hafeez, G. An Optimization Based Power Usage Scheduling Strategy Using Photovoltaic-Battery System for Demand-Side Management in Smart Grid. Energies 2021, 14, 2201.
109. AEIC Demand Response Measurement and Verification; Association of Edison Illuminating Companies: Birmingham, AL, USA, 2009.

110. Mahmood, A.; Javaid, N.; Razzaq, S. A Review of Wireless Communications for Smart Grid. Renew. Sustain. Energy Rev. 2015, 41, 248–260.

111. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. Smart Grid Technologies: Communication Technologies and Standards. IEEE Trans. Ind. Inform. 2011, 7, 529–539.

112. Gao, J.; Xiao, Y.; Liu, J.; Liang, W.; Chen, C.L.P. A Survey of Communication/Networking in Smart Grids. Futur. Gener. Comput. Syst. 2012, 28, 391–404.

113. ITU. Overview of the Internet of Things (Recommendation ITU-T Y.2060); International Telecommunication Union—Telecommunication Standardization Sector (ITU-T): 2012. Available online: https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=y.2060 (accessed on 30 August 2022).

114. Alliance, Z. ZigBee Specification. Zigbee Alliance: 2015. Available online: https://zigbeealliance.org/wp-content/uploads/2019/11/docs-05-3474-21-0csg-zigbee-specification.pdf (accessed on 30 August 2022).

115. Luo, T.; Ault, G.; Galloway, S. Demand Side Management in a Highly Decentralized Energy Future. Available online: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5649164 (accessed on 26 July 2022).

116. Sultania, A.K.; Mahfoudhi, F.; Famaey, J. Real-Time Demand Response Using NB-IoT. IEEE Internet Things J. 2020, 7, 11863–11872.

117. Shahinzadeh, H.; Moradi, J.; Gharehpetian, G.B.; Nafisi, H.; Abedi, M. IoT Architecture for Smart Grids. In Proceedings of the 2019 International Conference on Protection and Automation of Power System (IPAPS), Tehran, Iran, 8–9 January 2019; pp. 22–30.

118. Bello, O.; Zeadally, S. Toward Efficient Smartification of the Internet of Things (IoT) Services. Futur. Gener. Comput. Syst. 2019, 92, 663–673.