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Review

Demand-Side Flexibility in Power Systems: A Survey of Residential, Industrial, Commercial, and Agricultural Sectors

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Abstract: In recent years, environmental concerns about climate change and global warming have encouraged countries to increase investment in renewable energies. As the penetration of renewable power goes up, the intermittency of the power system increases. To counterbalance the power fluctuations, demand-side flexibility is a workable solution. This paper reviews the flexibility potentials of demand sectors, including residential, industrial, commercial, and agricultural, to facilitate the integration of renewables into power systems. In the residential sector, home energy management systems and heat pumps exhibit great flexibility potential. The former can unlock the flexibility of household devices, e.g., wet appliances and lighting systems. The latter integrates the joint heat–power flexibility of heating systems into power grids. In the industrial sector, heavy industries, e.g., cement manufacturing plants, metal smelting, and oil refinery plants, are surveyed. It is discussed how energy-intensive plants can provide flexibility for energy systems. In the commercial sector, supermarket refrigerators, hotels/restaurants, and commercial parking lots of electric vehicles are pointed out. Large-scale parking lots of electric vehicles can be considered as great electrical storage not only to provide flexibility for the upstream network but also to supply the local commercial sector, e.g., shopping stores. In the agricultural sector, irrigation pumps, on-farm solar sites, and variable-frequency-drive water pumps are shown as flexible demands. The flexibility potentials of livestock farms are also surveyed.

Keywords: flexibility potential; demand-side flexibility; demand response; renewable energy

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1. Introduction

Recently, the environmental concerns about climate change have increased noticeably [1]. To overcome global warming, the EU Commission committed to emit at least 55% less greenhouse gas emissions by 2030 and become climate-neutral by 2050. To decarbonize the energy systems, one solution is to increase renewable power penetration, e.g., solar and wind, in energy systems [2]. By increasing the penetration of renewable energies, the intermittency of power systems increases considerably. To counterbalance the renewable power intermittency, demand-side flexibility is a practical solution. Flexibility potentials of electrical consumers can be unlocked in response to power system requirements when a power shortage occurs on the supply side [3] or system reliability is jeopardized due to unforeseen failure. Demand-side flexibility is discussed in different sectors, including residential [4], industrial [5], commercial [6], and agricultural sectors [7]. Therefore, it needs expert knowledge to unlock, aggregate, and finally integrate flexibility potentials into power systems. It is evident that the knowledge of demand flexibility for heavy industry, e.g., an oil refinery plant, is quite different from Home Energy Management Systems (HEMSs). As a result, the flexibility potentials should be discussed in each sector individually.

In the residential sector, the HEMS is a smart control panel to manage the energy consumption of household appliances [8]. The flexibility of household appliances is discussed for wet appliances [9], electric water heaters [10], refrigerators [11], and ovens [12]. Heat pumps are flexible demands not only to decarbonize the residential heating systems but also to increase energy efficiency [13]. The private parking of Electric Vehicles (EVs) with charging stations is addressed to increase the flexibility potential of households [14].

In the industrial sector, heavy and light industries can provide demand flexibility for power systems. Industries, especially heavy industries, are energy-intensive plants that integrate demand flexibility of the industrial processes as well as the self-generation facilities, e.g., gas turbines and diesel engines, into energy systems. In cement manufacturing plants, some processes, e.g., crushers, can be exploited during off-peak hours [15]. Therefore, they can provide peak shaving and/or valley filling for the power system. Moreover, the raw and cement mills can provide power flexibility at short advance notice without causing an interruption to the production line. In the steel, metal, and aluminum industries, the operation of smelting pots can be scheduled during off-peak hours [16]. Generally, the smelting pots are operated in discrete processes; therefore, the next round of pots' operation can be shifted or delayed in response to power system requirements. In oil refinery industries, the energy demand mainly includes electricity, heat, and steam [17]. Therefore, self-generation facilities, e.g., gas turbines and heat boilers, provide flexibility for the gas and power networks.

In the commercial sector, supermarket refrigerators [18] and ice bank storage are practical solutions. The flexibility potentials of retail and strip malls, restaurants, and hotels are discussed in the research study [19]. Recently, by increasing the penetration of EVs, public parking lots with smart charging stations are considered a great electrical storage plant to charge/discharge electrical energy from/to power grids when the upstream network encounters excess/deficit of electrical power [20].

In the agricultural sector, the water irrigation pump is the dominant electrical demand [21]. In the open-air farms, the solar-based irrigation system can be operated to meet the crops' needs when the peak demand of the power system coincides with the peak crop evapotranspiration [22]. In the greenhouse farms, the operation of the cooling and heating system exhibits great flexibility potential [23]. In livestock farms, the application of heat pumps can provide power flexibility [24].

The abovementioned survey shows that there are many flexibility opportunities in different demand sectors. This paper aims to elaborate on the flexibility potentials of the demand sectors, including residential, industrial, commercial, and agricultural. Figure 1 describes a schematic diagram of flexibility potentials for demand sectors. As the figure reveals, the four major demand sectors are classified into subsectors. The subsectors are explained in separate sections in the paper. Despite the demand sector classification, the applications of demand flexibility in power systems can be stated as follows:

(1) Frequency control [25,26];
(2) Up-/down-power regulation [27];
(3) Voltage support [28];
(4) Reserve market support (spinning, non-spinning) [29];
(5) Power congestion mitigation [30];
(6) Peak shaving and/or valley filling [31];
(7) Energy system decarbonization [32];
(8) Renewable power integration [33].

The rest of the paper is organized as follows. In Section 2, the general insight of power flexibility is described for demand sectors. Section 3 explains the flexibility potential of the residential sector. The Demand Response (DR) opportunities of industrial processes are surveyed in Section 4. In Section 5, the commercial sector is discussed. The agricultural sector and possible flexible demands are stated in Section 6. Section 7 explains the necessity of intermediary demand response aggregators, challenges, and future insights. Finally, Section 8 concludes the study.

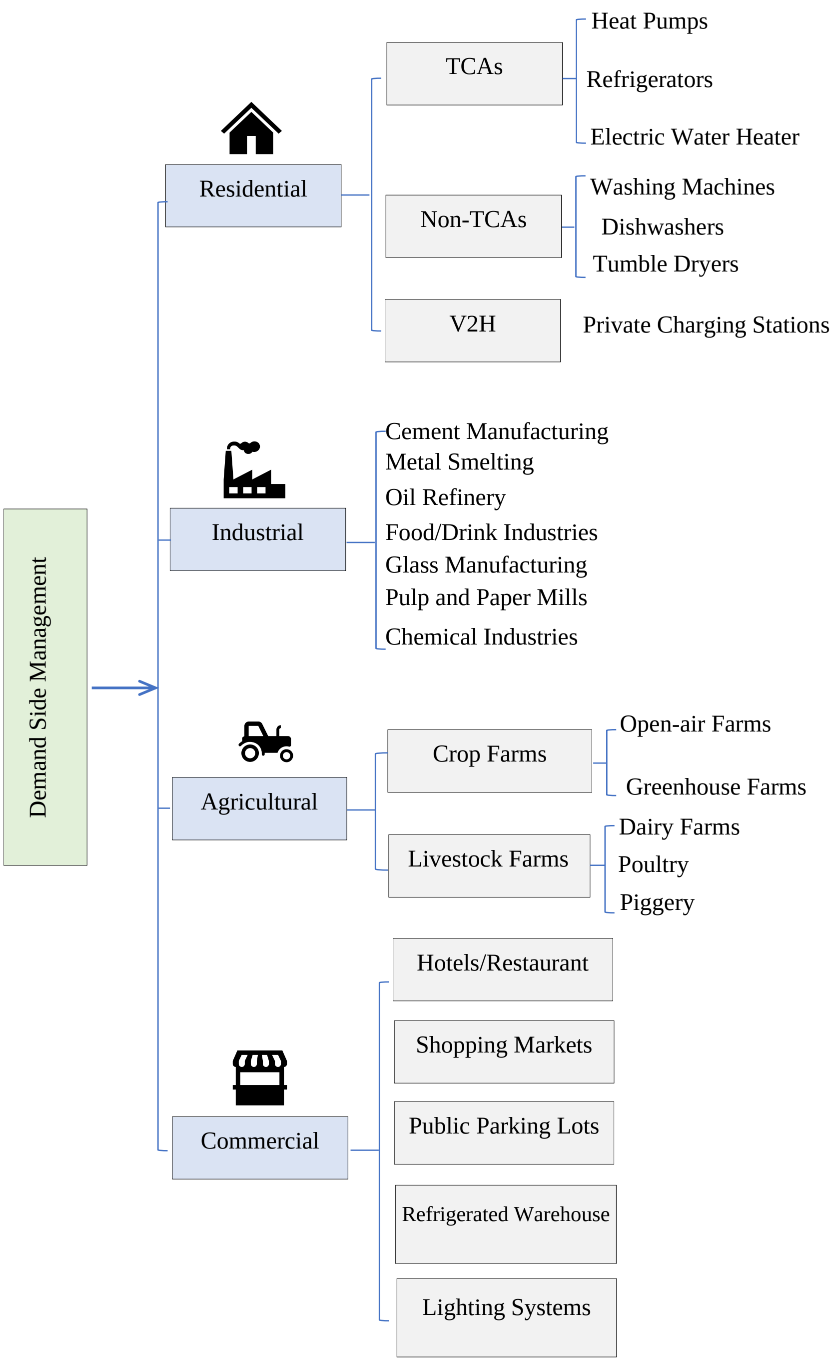

Figure 1. Classification of demand flexibility for four different sectors: residential [34], industrial [35], agricultural [36], and commercial [37].

2. Demand Flexibility

Demand flexibility refers to the ability of electrical consumption to change/shift/adjust/curtail the electricity consumption in response to an external request, e.g., electricity price, financial incentives, and technical requirements [38]. Therefore, the flexible demands respond to Demand Response Programs (DRPs) to provide benefits for the demand side and/or the supply side [39]. Demand response studies encounter great sources of uncertainties about renewable power generation, electricity price, demand participation, and load level. To hedge against the uncertainties, stochastic programming and robust optimization are addressed widely. In stochastic programming, uncertain variables can be modeled as different scenarios with special probability distribution functions [40]. In robust optimization, demand flexibility is evaluated over the most important uncertain variable. In this approach, the uncertain variable is defined by upper and lower thresholds, while no probability function is stated [41].

From the benefits point of view, the DRPs can be observed from the demand- and supply-side separately. Regarding the demand side, the consumers can take advantage of reduced electricity bills and financial incentives in the form of bill deduction, financial rewards, and low electricity prices directly [42]. Moreover, as the penetration of DRPs increases on the demand side, the reliability of power systems and distribution grids increases [43]. As a result, the consumers take advantage of more stable power grids with lower outage probability, as an indirect advantage [44]. To implement DRPs, the consumers respond to two types of programs: (i) price-based programs [45] and (ii) incentive-based programs [46]. In the former, the demand flexibility is unlocked in response to the electricity price. Different energy pricing schemes are used in power systems to encourage consumers to actively respond to energy price variations. Among them, Time-of-Use (TOU) [47], Critical Peak Pricing (CPP) [48], and dynamic pricing [49] are widely used. In the latter, some financial incentives are offered to consumers to persuade them to contribute to DRPs.

On the supply side, DRPs and flexible demands provide two types of power system support, including global and local support [50]. In the former, the whole power system benefits from the demand flexibility. In the literature, many global benefits are addressed in power systems worldwide. Frequency control [51], power regulation [52], flexibility reserve [53], peak shaving/valley filling [54], decarbonizing the power systems [55], optimization of power system operation cost [56], facilitation of renewable power integration [57], enhancement of power system reliability [58], and reduction of investment cost in power systems are the most important global support. In the local support, the local distribution network takes the advantage of the flexible demands. Mitigation of power congestion [59,60], voltage support [61], power loss minimization [62], and power quality improvement [63] are the key local support. Volt–Var energy management approach is addressed in distribution systems to improve voltage profile and Var injection in demand sectors [34]. It is worth mentioning that although most electrical consumers are supplied by low- and medium-voltage distribution grids, some large power consumers, e.g., heavy industries, are connected to transmission networks directly. Therefore, the local power system support conveys local benefits for both the distribution and transmission networks.

Renewable energy can be integrated as large-scale generation units into the supply side or small-scale Distributed Generation (DG) into the demand side. On the supply side, large-scale wind farms [64], solar farms [65], geothermal [66], hydropower [67], run-of-river [68], and biomass [68] are addressed. On the demand side, Roof-top Photovoltaic (RPV) [69] and micro-wind turbines are used. Despite the type of renewable energy, demand-side flexibility is a necessity to counterbalance the renewable energy intermittency. It is worth mentioning that the Renewable DGs (RDGs) may be integrated into stand-alone (off-grid) or grid-connected demands. In the former, the off-grid RDGs are used for sustainable rural electrification [70]. In the latter, the RDGs supply the demand sectors to provide global and local support, e.g., cost reduction, voltage improvement, and power loss reduction [71].

3. Residential Demand Flexibility

Demand flexibility in residential buildings is normally managed by the HEMS [72]. The HEMS can control the energy consumption of household appliances, e.g., washing machines [73], tumble dryers [74], dishwashers [75], lighting systems [76], and Heat Ventilation and Air conditioning (HVAC) [77]. In the literature, the household appliances are classified into uncontrollable, Thermostatically Controlled Appliances (TCAs) [78], and Non-Thermostatically Controlled Appliances (NTCAs). The uncontrollable appliances include audio/video devices, elevators, and emergency lighting systems. No flexibility is expected from this class of appliances. The TCAs are the key flexibility resource of residential dwellings. These appliances follow thermal dynamic models to unlock joint heat-to-power flexibility. They include water heaters [79], refrigerators [80], HVAC, and heat pumps. The NTCAs provide lower flexibility in comparison to the TCAs. Non-emergency lighting systems and wet appliances are the most flexible NTCAs. Some studies have been conducted to show how the HEMS can optimize the energy consumption of household appliances in response to electricity price variations [81].

Recently, the penetration of heat pumps has increased in residential dwellings, and it is expected to replace the traditional heating systems in many regions. In some case studies, it was proposed that the HEMS controls the operation of HVAC and heat pumps. However, due to the complexity of heat controllers, the operation of heat pumps is delegated to sophisticated controllers [82]. The heat controllers unlock the heat flexibility of the building while meeting the residents' comfort [83]. The resident comfort bound is normally defined as a setpoint with lower and upper thresholds. Therefore, the heat controller aims to maintain the indoor temperature within the comfort bound. The flexibility of heat pumps stems from the existing gap between the upper and lower thresholds of indoor temperature. When a power shortage/excess occurs in the electricity market, the heat controller optimizes the operation of the heat pump and maintains the indoor temperature close to the lower/upper threshold of the bound [84]. In some studies, the heat controller is integrated with thermal storage devices [85]. In many studies, water tanks are suggested as economic thermal storage for residential buildings [86]. Therefore, the heat controllers integrated with thermal storage can provide much more flexibility potential for upstream networks. The water tank stores the heat energy when the energy price is low or when the power system encounters renewable power excess. Consequently, it supplies the demand, including space heating and Domestic Hot Water (DHW) consumption, when the power system faces a renewable power shortage and/or the electricity price is high [87].

The energy consumption of the heating system depends on the physical characteristics of the buildings and weather conditions. For buildings with high-quality materials and good insulation, the energy efficiency of the building is relatively high [88]. Therefore, the energy consumption of the building is more robust to weather conditions. Adversely, in buildings with poor thermal insulation, the energy consumption of the heat pumps is more sensitive to ambient conditions. As a result, the flexibility potentials of the former are more than the latter. The heat controllers optimize the energy consumption by solving the thermal dynamics of the buildings. The thermal dynamics are normally described by Ordinary Differential Equations (ODEs) [89]. The ODEs of thermal dynamics include thermal coefficients which are specific to target buildings. Therefore, in order to design a heat controller, the thermal coefficients should be estimated.

In the literature, three general approaches are addressed to estimate the thermal dynamics, including white-box [90], gray-box [91], and black-box algorithms [92]. The white-box approach addresses the physical models of buildings and requires a lot of input data. The input data may include indoor air temperature, inflow/outflow water temperature, mass flow, and heat pump power consumption. In some cases, such data are not available due to the residents' privacy. In contrast to white-box models, the black-box approaches are model-free methods that are easy to implement. Artificial neural networks [93], genetic algorithm [94], and support vector machine [95] have been addressed recently. Still, they need a large amount of input data to train the machine learning algorithms. As a result, they are not applicable in case studies with building data scarcity. The gray-box models address both the physical model of the white-box and statistical methods of the black-box approaches simultaneously. Therefore, it is the most robust approach to estimate the thermal dynamic of buildings. This model is compatible with Model Predictive Control (MPC) theory. MPC has been widely used in recent studies to unlock the flexibility potential of heat pumps [96]. In [97], Economic MPC (EMPC) was suggested to optimize the operation of heat pumps in response to electricity market prices. To provide a general insight, Table 1 explains some key residential flexibility potentials and applications.

Table 1. Classification of flexibility application in household electricity consumption.

Household Appliances		Flexibility Targets	Ref.
Thermostatically Controlled Appliances TCAs	Heat Pump	(1) Reduction of energy costs for heating of household buildings (2) Reduction of annual emission (CO_2) (3) Reduction of energy consumption for heating system during peak hours	[98]
		Maximizing profit of buildings through trading flexibility in intraday markets	[99]
		(1) Minimization of life cycle cost (2) Reduction of environmental impacts of heat pumps and district heating	[100]
		Improving power system frequency control	[101]
	Refrigerator	(1) Minimization of household electricity bill (2) Reduction of peak load	[102]
		Load shifting of electrical demand using cooling devices	[103]
		(1) Minimize electricity consumption cost of households (2) Regulation of peak demand in power systems	[104]
		(1) Cost saving of smart household appliances (2) Providing residential load for shifting to help balance demand and supply	[105]
	Electric Water Heater	(1) Minimization of electricity cost under TOU (2) Satisfying the comfort water temperature within the predefined bound	[106]
		Minimization of cost function under Spanish electricity price tariff	[107]
		(1) Minimization of energy cost under day-ahead and real-time pricing (2) Maximization of residents' comfort	[108]
		Cost saving for household to remote control electric water heater	[109]
Non-Thermostatically Controlled Appliances Non-TCAs	Wet Appliances	(1) Minimization of energy cost (2) Maximization of renewable energy demand (3) Minimization of carbon emission	[110]
		Proposing compensation contract to increase flexibility of wet appliances	[111]
		Harness energy flexibility of buildings to flatten demand consumption	[112]
		Providing load balancing for power system and minimizing the energy cost	[113]
		(1) Minimizing energy consumption (2) Reduction of emission and environmental impacts (3) Reduction of peak demand	[114]
		(1) Flattening of peak demand (2) Meeting residents' convenience	[115]
Private Parking	Vehicle-to-Home (V2H)	(1) Increase energy efficiency of homes (2) Improvement of energy consumption pattern (3) Shift of peak demand	[116]
		(1) Increase electrification of off-grid smart homes (2) Reduction of investment cost on the electronification	[117]
		(1) Reduction of building peak demand (2) Increase profit of household (3) Reduction of emission production	[118]

4. Industrial Demand Flexibility

Industries are energy-intensive consumers; therefore, the nominal energy consumption of industrial processes is high in comparison to other demand sectors. If the flexibility potentials of industrial processes are unlocked, a great value of power flexibility is provided for the upstream networks. Industrial processes are divided into interruptible and uninterruptible processes. The interruptible processes are those which can be turned off/on without causing damage to the equipment and products. In contrast, the uninterruptible processes are not allowed to be turned off/on regularly or it results in severe damage to the installations or feedstocks. In many studies, the uninterruptible processes are capable of turning up/down the energy consumption on short advance notice without causing any damage to the production line and product.

In modern cement manufacturing plants, crushers are considered interruptible processes. Therefore, they can be switched off on short advance notice. Moreover, the operation of crushers can be scheduled on long advance notice, e.g., 24 h, in the day-ahead markets [119]. The mills, including raw and cement mills, are critical to keep the production line in service. Therefore, the flexibility potentials of the mills are lower than crushers [35]. In some studies, it is suggested that the rotational speed of mills can be adjusted within a very limited bound without causing any interruption. Therefore, the energy consumption of the mills can be turned up/down to provide power flexibility. In [119], material storage was suggested to increase the flexibility of cement and raw mills. It proposed constructing storage for the output of raw and cement mills to supply the feedstock for the next processes uninterruptedly. In this way, the mills can be switched off/on in response to the flexibility requirements of the power system. Financial incentives are suggested in some studies to encourage heavy industries to participate in DRPs when the power system encounters a severe power shortage [120].

Metal smelting plants comprise different smelting pots. Generally, the smelting process is uninterruptible. Therefore, it is not allowed to switch off the melting furnaces once it is started or severe damage and financial costs are incurred. Although it is impossible to turn off the running furnaces, it is still possible to turn down/up the power consumption [121]. As a result, the running furnace can provide limited power flexibility. A research study suggested adjusting the transformers' tab to unlock the flexibility of the electric arc furnace [122]. Once the duty of the furnace is completed, the next working round can be delayed in response to the flexibility requirements of the power system. To meet the production value constraint of the factory, the energy engineers rotate the operation of the smelting furnace between different lines.

The oil refinery industries are consumers of power, heat, and steam. The key point is that most of these industries are supplied partially by self-generation facilities. Therefore, some part of the required heat and steam is produced by local gas turbines, Combined Heat and Power (CHP), and boilers. While there is a strong correlation between the generation of power, heat, and steam, the oil refinery plants are capable of providing energy flexibility for gas and power networks. In [123], cogeneration facilities and on-site solar generation units were suggested to increase the flexibility of the industrial plant. A robust optimization model is proposed to unlock the flexibility of the refinery processes in response to energy prices [124].

Although some key industries are stated, there are many flexibility potentials in other industries which need further investigations. Table 2 classifies some flexible industrial processes with their applications in power systems.

Table 2. Flexibility potentials in some heavy industries.

Industry	Key Objective(s)	Ref.
Cement Manufacturing	(1) Cost reduction (2) Emission reduction (3) Reduction of electricity cost	[125]
Metal Smelting Industry	(1) Providing reserve for electricity market (2) Minimization of operation cost (3) Integration of flexibility into capacity market	[126]
Pulp and Paper	Providing up-regulation for power markets	[127]

Table 2. *Cont.*

Industry	Key Objective(s)	Ref.
Textile Industry	Energy- and cost-saving measures in industrial processes	[128]
Food/Drink Industry	(1) Reduction of energy consumption (2) Reduction of emission production (3) Facilitate use of heat pumps in the industry	[129]
Ceramics Industry	(1) Optimize energy cost (2) Increase energy efficiency (3) The industrial DRPs benefit the environment, economy, society	[130]
Chemical Industry	(1) Improving grid operation, e.g., reliability, resilience (2) Making profit in the industry	[131]
Oil Refinery Industries	Providing industrial load control in smart-grid operation	[132]
Glass Manufacturing	(1) Making balance for power and gas (2) Reduction of energy consumption cost (3) Reduction of strain on power grids	[133]
Data Centers	(1) Facilitate the integration of renewable energies to power grids (2) Providing peak-load shaving	[134]
Industrial Parks and Zones	(1) Optimization of investment cost on industrial parks (2) Prevent imbalance of energy shifting	[135]

5. Commercial Demand Flexibility

The commercial demand sector is normally defined as electricity consumption in non-manufacturing business establishments, e.g., restaurants, hotels, shopping stores, and warehouses. Recently, by increasing the penetration of EVs, commercial parking lots with smart charging stations emerged to provide flexibility for the power grid and offer a benefit for vehicle owners. In contrast to the residential and industrial sectors, the commercial DRPs are not well defined. Therefore, more studies are needed to investigate the flexibility opportunities.

Supermarket refrigerators are flexible demands in the commercial sector. The flexibility potential of supermarket refrigerators stems from the stored energy in the thermal mass of refrigerated foodstuff [136]. To unlock the flexibility of refrigerators, the study proposed a novel approach to estimating the food temperature. Based on results, the approach can increase demand flexibility between 60% and 100% during the first 70 to 150 min. A comprehensive evaluation was conducted in Germany to investigate the flexibility potentials of hotels, restaurants, and offices called the service sector [137]. The results conclude that the flexible appliances of the service sector can provide 22 TWh of theoretical potential, i.e., approximately equivalent to 35% of the total power consumption of the service sector. In [138], the demand response potentials of hotels and tourist accommodation facilities were stated using joint heat-to-power energy flexibility. The study emphasized that the potentials are independent of tourists' behaviors and aim to increase the share of renewables in the sector. The demand response opportunities of refrigerated warehouses were surveyed [139]. As the study revealed, the duration, the percentage of warehouse load, and the season are the key factors affecting the flexibility potential of a refrigerated warehouse. A methodology was proposed in a research study [140] to quantify the demand flexibility of lighting systems in commercial buildings. The approach uses dynamic daylight simulation considering stochastic occupancy. Based on the simulation, the average capacity of lighting curtailment is around 32% of the peak lighting demand.

Recently, the penetration of EVs has been increasing noticeably worldwide. Therefore, many commercial parking lots are retrofitted with smart charging stations. The parking lots supply parking space for commercial complexes. The parked EVs function as electrical storage with a dwell time. Therefore, a significant amount of power storage is available for the parking operator to integrate into the power system. In this way, the parking operator acts as a Demand Response Aggregator (DRA) to optimize the charging/discharging strategies of the parked EVs. The parking lots can use the storage capacity to supply the local electrical demand of the commercial complexes, e.g., food court, cinema, and shopping stores [141]. The parked EVs can discharge to the commercial microgrid when the electricity price is high and charge from the main grid when the electricity price is low [142]. Length of dwelling time, number of parked EVs, and consent of EV owners to participate in DRPs are key factors that impact the flexibility potential of the commercial parking lots. If the charging/discharging schedule of EVs is coordinated properly, the EV owners and parking lot operator can make a profit, and the power system operator takes the advantage of power flexibility.

6. Agricultural Demand Flexibility

Agricultural or farming refers to activities to cultivate plants and breed livestock. The plant farms are split into open-air farms and greenhouse farms. In the open-air farms, the water irrigation systems are the most energy-intensive consumption. The water pumps draw water from underground wells and/or surface water resources. In [143], the water pool was suggested to increase the flexibility of water irrigation pumps. The study proposed stochastic energy management to unlock the flexibility potentials of water irrigation pumps in response to uncertain electricity prices in power systems with high renewable power penetration. Therefore, the water pumps can store water in the storage pools when an excess of renewable power occurs (low-price hours). Afterward, the farm can be irrigated by the stored water during the shortage of renewable power (high-price hours). Moreover, it was suggested to store water in water tank towers during high renewable power availability. Consequently, the farms' sprinklers will be supplied by the stored water via gravity during low-renewable-power hours. In some studies, photovoltaic irrigation pumps are addressed as practical solutions to provide flexibility for both the power grid and farms [144].

In countries with tropical or hot weather conditions, the peak demand of the power grid perfectly coincides with the peak demand of the water irrigation system. The reason is that the hot weather normally occurs at midday hours when the peak demand of cooling systems and peak crop evapotranspiration occur concurrently. To overcome the problem, a research study suggested a robust optimization to draw water from underground reservoirs to water tank towers in off-peak hours and supply the crops at midday hours without needing to run energy-intensive pumps [145]. In [146], agricultural DRPs were introduced to decarbonize power systems. It was suggested to restructure the agricultural sector to utilize renewable power, including wind and solar, in farms. A review study was conducted to survey the main challenges and opportunities of DRPs in the agricultural sector [36]. Based on the scoping study, water irrigation capacity, time of water delivery, on-farm crew availability, and financial incentives are the main barriers to implement DRPs on farms.

In greenhouse farms, the operation of cooling and heating systems can provide power flexibility [147]. The heat pumps are addressed not only to increase the energy efficiency of greenhouse farming but also to decrease CO_2 emissions. The study concluded that the heat pump system can provide energy efficiency of 25% to 65% more than traditional combustion-based systems [148]. Technical assessment is provided to harness geothermal energy for heating/cooling systems of greenhouse farming in Ecuador [149].

In livestock farms, some flexibility potentials were discussed in recent studies. Poultry, piggery, and dairy farms are the most important studies in this field. In the research study, a new term "poultry demand-side management" was suggested to increase the penetration of solar energies in poultry electricity consumption and decrease dependency on the main grid [150]. In New Zealand, dairy farms were studied to shift the main electricity consumption out of peak hours and to provide balance for the power systems [151]. Based on the results, the power consumption of the irrigation and milking-related processes contribute to the peak demand of the farm. In [152], it was discussed that piggery waste can be used to generate electricity. The study reviewed current potentials in Cyprus. The on-farm electricity generation can provide flexibility for the farm and upstream grid. Air-source heat pumps are addressed in pig farms to increase the use of renewable energy, reduce greenhouse gas emissions, and provide economic benefits for the farm [153].

7. Challenges and Future Insights

In the previous sections, different flexibility potentials of demand sectors were surveyed. It was shown how the industrial processes, commercial sectors, agricultural farms, and household appliances can provide flexibility for the power systems. Although the flexibility potential is known in some sectors, more studies are required to investigate new potentials. Moreover, the flexibility potentials of different sectors should be aggregated and integrated into power systems. In other words, segregated and unintegrated potentials may not meet power system requirements. To achieve the aim, intermediary entities emerged in recent years to play a pivotal role between the supply and demand sides. The entities are called Demand Response Aggregators (DRAs), Demand Response Providers (DRPs), and Flexibility Management Systems (FMSs). Although the applications of the mentioned entities are different in detail, they aim to facilitate the integration of demand flexibilities into energy systems. Demand response management needs expert knowledge in different sectors. Therefore, the coordination mechanism of DRPs between demand sectors is quite complex. As a result, sophisticated control schemes are required to coordinate DRPs between demand sectors with different response times and flexibility. Despite the coordination issues, there are still some barriers to unlocking demand flexibility or motivating consumers to participate in DRPs. Among them, the most important challenges can be stated as follows (but not limited to):

(1) Regulatory barriers, e.g., lack of regulation or tax issues for flexible industries;
(2) Financial incentives for flexible consumers;
(3) Lack of motivation and widespread adoption of DRPs;
(4) Technological challenges, e.g., lack of IoT and data storage/processing facilities.

Currently, many research studies and projects are being conducted to increase the share of Power-to-X (P2X) in energy systems. To provide sustainable energy in the P2X, more flexibility opportunities are expected for multi-carrier and energy hubs. By increasing the penetration of renewable hydrogen in future energy systems, the flexibility potentials of the power network, heat network, mobility sector, and gas network should be unlocked to counterbalance the renewable energy fluctuations. Therefore, future studies will focus more on the flexible operation of electrolyzer facilities and demand sectors.

8. Conclusions

In this paper, the flexibility potentials of demand sectors were surveyed. The sectors included residential, industrial, commercial, and agricultural demands. In the residential sector, HEMSs can unlock the flexibility potential of household appliances. The TCAs, e.g., heat pumps, HVAC, and electric water heaters, exhibit great potentials. The non-TCAs, including wet appliances, are practical solutions to shift power consumption out of peak hours. In the industrial sector, many interruptible processes can provide great values of flexibility for power systems. Among them, cement crushes and mills can be curtailed with prior notification. The power consumption of smelting furnaces can be adjusted on short advance notice through transformers' tabs. In the commercial sector, the flexibility opportunities of commercial buildings and tourist accommodation facilities, e.g., hotels and restaurants, were addressed. The refrigerated supermarkets and refrigerated warehouses are workable solutions to integrate flexibility into power systems. Moreover, by increasing the penetration of EVs, public parking lots are turning into great electrical storage facilities to provide power regulation for power systems. In the agricultural sector, open-air farms take the advantage of flexible water irrigation pumps. Water tank towers are great sources of energy flexibility not only to provide peak shaving for the power grid but also to decrease the farms' operation costs. In greenhouse farming, heat pumps can provide flexibility for cooling and heating purposes. The livestock farms, dairy farms, poultry, and piggery farms are capable of shifting power consumption out of peak hours.

Although the flexibility potentials of demand sectors were described, more studies should be conducted to coordinate the flexibility potentials of demand sectors in response to power system requirements. The penetration of power-to-x facilities is increasing in energy systems worldwide. Therefore, future studies should focus on the flexible interoperation of hydrogen energy, electrolyzers, and demand sectors.

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