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Review

A Survey of Commercial and Industrial Demand Response Flexibility with Energy Storage Systems and Renewable Energy

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Abstract: The transition from traditional fuel-dependent energy systems to renewable energy-based systems has been extensively embraced worldwide. Demand-side flexibility is essential to support the power grid with carbon-free generation (e.g., solar, wind.) in an intermittent nature. As extensive energy consumers, commercial and industrial (C&I) consumers can play a key role by extending their flexibility and participating in demand response. Onsite renewable generation by consumers can reduce the consumption from the grid, while energy storage systems (ESSs) can support variable generation and shift demand by storing energy for later use. Both technologies can increase the flexibility and benefit by integrating with the demand response. However, a lack of knowledge about the applicability of increasing flexibility hinders the active participation of C&I consumers in demand response programs. This survey paper provides an overview of demand response and energy storage systems in this context following a methodology of a step-by-step literature review covering the period from 2013 to 2023. The literature review focuses on the application of energy storage systems and onsite renewable generation integrated with demand response for C&I consumers and is presented with an extensive analysis. This survey also examines the demand response participation and potential of wastewater treatment plants. The extended research on the wastewater treatment plant identifies the potential opportunities of coupling biogas with PV, extracting the thermal energy and onsite hydrogen production. Finally, the survey analysis is summarised, followed by critical recommendations for future research.

Keywords: commercial and industrial consumers; demand response; distributed energy resources; energy consumption; energy storage systems; onsite renewable energy generation

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1. Introduction

The worldwide increases in energy demand, global emissions and energy costs have driven the necessity of the shift in generation from traditional fuel to distributed generation [1]. Distributed generation (DG), or onsite generation or distributed energy refers to decentralised energy generation at or near the location of use, which is accomplished through distributed energy resources (DERs) [1]. DERs can be operated using conventional fuel technology or renewable energy sources (RESs). Conventional fuel technology includes gas turbines, microturbines, diesel engines or combustion turbines, whereas solar, wind, biomass, geothermal, hydropower, wave, and tidal energy are the most common RESs [1,2], representing the abundant availability in nature. Due to the advantage of carbon-free, low price, and low operational and maintenance cost, RES-based DERs are deemed to be a promising technology to combat climate change compared to their counterparts bearing high production costs and contributing to the greenhouse effect [2]. The energy transition from the fossil carbon-based energy system to zero-carbon-based energy system using RESs has been extensively embraced worldwide [3]. In Australia, the share of electricity

generation from renewables was 27% in 2021, referring to a 4% increase from 2020 [4]. Renewable electricity generation in the USA doubled from 2008 to 2018 and is continually rising to meet their renewable energy (RE) target [5]. However, renewable generation, such as solar or wind, is uncertain and has a sporadic nature [6]. Moreover, bi-directional power flow caused by the increasing distributed generation can affect the power grid stability with voltage fluctuations and require more flexibility to the system [7].

Demand response (DR) is one of the demand-side management (DSM) techniques which can provide demand flexibility with existing capable resources and play a significant role in reducing peak demand, balancing the grid, and avoiding electrical network installation or upgradation [8]. Also, an energy storage system (ESS) is one of the DERs that can shift demand by storing energy for later use and supporting the variable generation of renewables [9]. ESSs can support the grid flexibility through the front of the meter application (FTM), and the consumer's demand-side flexibility or demand shifting and reduction is through the behind-the-meter (BTM) application (the focus of this study) [10], as shown in Figure 1. Meanwhile, to reduce energy costs sustainably, the use of onsite renewable generation (ORG) by consumers is considered a promising approach, where an ESS can be coupled to mitigate the variable generation [11]. Consumers can meet their energy consumption without purchasing electricity from the grid and sell it back to the grid if there is a generation surplus [12]. DR and ESSs can smooth variable renewable generation with the electricity demand patterns [13,14], enabling them to complement each other by reducing complete dependency on a single technology in a system [15]. Integration of DR with ORG can reduce energy costs and help better utilise renewable generation [16].

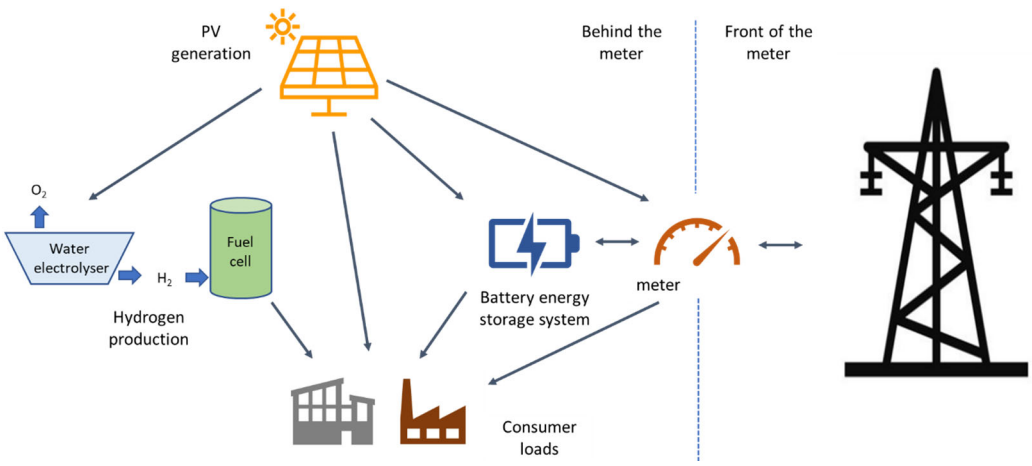

Figure 1. Schematic of behind-the-meter application.

Commercial and industrial (C&I) consumers are more extensive energy users. About 42% of the world's electricity is consumed by the industrial sector alone [17], so the carbon emission from these consumers is significant. Wastewater treatment plants (WWTPs) in the water industry consume about 2–3% of the electrical energy in the world [18,19]. About 25% to 50% of these plants operational costs are accounted for in electricity costs, so WWTPs represent a significant carbon emitter [20] and also a potential DR candidate. Through DR participation, WWTPs can gain energy cost savings, assist in grid pressure reduction, and decarbonization. However, due to business regulations, restricted interconnected industrial processes, or quality requirements, frequent load or process interruption is difficult for C&I consumers like WWTPs, which is an obstacle to the efficient implementation of DR [21]. An integrated system with DR-ESS-ORG can enable DR participation with restricted loads and increase demand flexibility for C&I consumers, which requires research attention.

Different DR approaches with programs in industries' manufacturing and production processes are reviewed by the authors of [17], who developed a taxonomy characterising the industrial DR application. In [22], the authors analysed the characteristics of industries to identify DR potential. DR progress in industries is studied in [23], which emphasised a

systematic evaluation of industrial flexibility by analysing data and information. Progress in DR for industries, including commercial consumers, is also reviewed in [24], where heat pumps and EVs are considered the main loads for commercial DR. DR-based research for C&I consumers mainly focuses on management and control, modelling and optimisation techniques, programs and services, or barriers, for example [17,23,25–27]. However, an integrated energy system framework including DR-, ESS-, and ORG-focused review for C&I consumers is needed to the best of the authors' knowledge. Insufficient knowledge about the available flexibility is one of the main barriers for C&I consumers [21,23,28] which requires a knowledge transfer through further research. So, an exclusive survey is crucial for the C&I consumers which can assist the energy stakeholders to obtain knowledge about the means of available flexibility in a single study and further analysis for making decisions.

In this context, this study is interested in surveying the application of ESS and ORG integrated with DR to increase demand flexibility for C&I consumers. Herein, this survey can contribute to the existing research as below:

1. An assessment of potential DR flexibility exclusively for C&I consumers;
2. A survey analysis incorporating ESS, ORG, and DR—three promising systems in one study;
3. An analysis of wastewater treatment plants as an example within the water industry, which has not yet been extensively covered in previous DR survey studies.

The rest of the paper is organised as follows: Section 2 discusses the methodology of the survey, Section 3 provides an overview of DR and ESS techniques, and Section 4 includes the analysis of how an integrated framework including ESS, ORG, and DR applies to C&I consumers. Section 5 investigates the application of such a framework in the wastewater treatment plant (WWTP) industry, Section 6 summarises the survey with a brief analysis and recommendations, and Section 7 concludes the study.

2. Methodology

This survey is formulated on two steps in review of the literature. Considering the significance of DR participation by C&I consumers with increased flexibility, relevant review papers were searched using the databases Scopus, IEEE Explorer, and Web of Science (WoS). The keywords used are "demand response", "demand flexibility", "demand side management", "distributed energy resources", "energy storage system", "onsite renewable generation", "commercial consumer", and "industrial consumer". The inclusion criterion is time range (2013 to 2023), language (English), paper types (journals and scientific conference papers), and the exclusion criteria is "residential demand response". Furthermore, the search was limited to "review" to select the review papers. There was a lack of related review papers; hence, the search was expanded using different combinations of the above-mentioned keywords and the 30 most relevant review papers were selected. These papers were analysed, and a database was prepared using a research matrix planning tool. A lack of reviews focusing on DR, ESS, and ORG for C&I consumers was identified as a gap in the existing literature which provided this research direction. At this stage, scientific research articles were sourced from the same databases—Scopus, IEEE Explorer, and WoS—while using the keywords and the inclusion and exclusion criteria mentioned above. This search provided 247 papers which were scanned considering the titles, abstract, and focus of the papers and in this way, 38 papers were extracted. Further, the literature mapping tool ResearchRabbit was used to expand the search for relevant papers. This tool uses a machine learning approach in identifying the pertinent research based on the paper initially added and provides a map of the literature with the interconnected papers [29]. The most suitable papers were selected as seed papers and a forward and backward search was performed using the ResearchRabbit tool. It allowed the analysis of similar works, later works, and earlier works of the selected papers' widening search area. Through this process, another seven articles were added and finally 45 papers were selected for extensive study. These papers were accumulated in another database and analysed using the research matrix planning tool which are discussed in Section 4. A schematic of the methodology process is

included in Figure 2. Figure 3 presents the DR-based research studies completed in the last 10 years, which shows the year-wise growing interest in the DR field for industries.

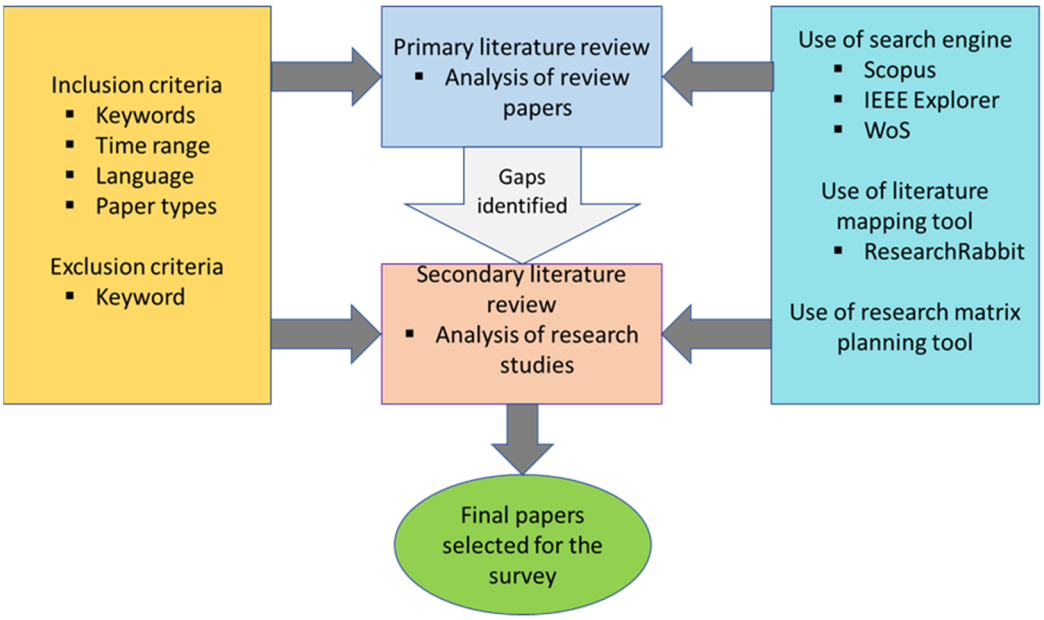

Figure 2. Methodology process of the study.

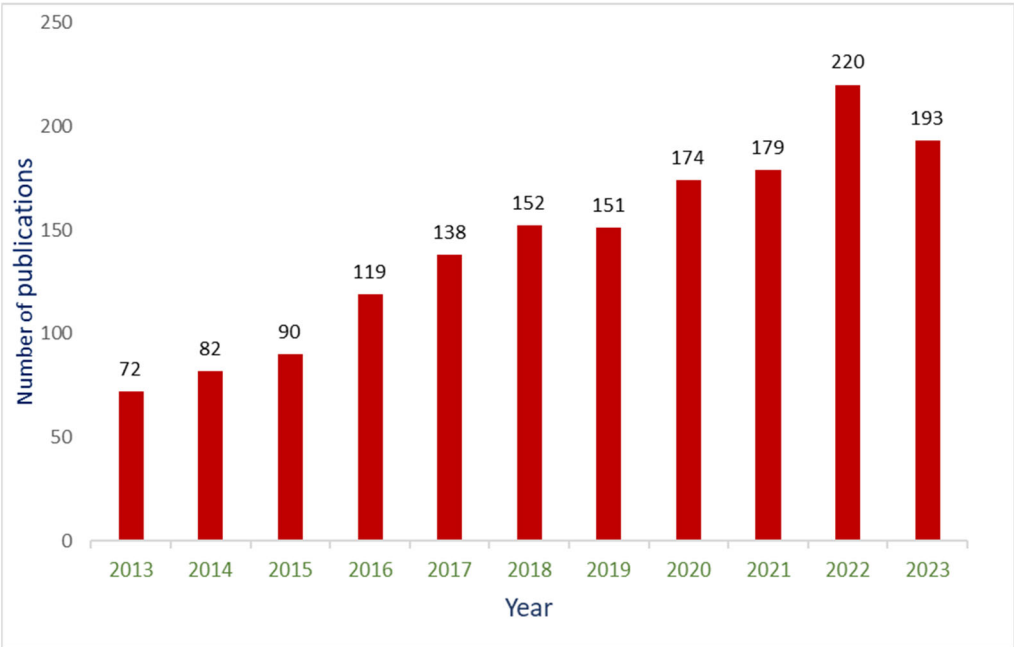

Figure 3. Demand response research trend of industrial consumers.

3. Demand Response and ESS Technology

By providing temporal flexibility through shifting energy demand from one period to another and spatial flexibility extracted from spatially distributed capable energy consumers [30], DR is considered an economic DER option [8]. Effective use of ESSs can reduce peak demand while evading the expensive capacity addition by the peaking plants [31]. The limitations of DR in terms of temporal availability can also be minimised by charging or discharging the ESS. A brief overview of DR and ESS is included in the following sub-sections.

3.1. Overview of Demand Response

Flexibility indicates a system's response capacity to mitigate energy demand and generation gap in need [32]. Flexibility should be harnessed from every possible means [30] for the sustainable transition from fossil fuel- to RESs-based systems. Supply-side flexibility by employing peaking plants is cost-intensive, and reviving traditional fossil fuel generation is undesired [33]. The addition of demand-side flexibility in the system is a promising solution, considering the benefits of adding RESs and their challenges to the power system [34]. Demand-side flexibility enables consumers to reshape their load profile [21], and when this flexibility is effected to respond to a high electricity price signal or any hazardous condition of power system issue in exchange for incentives, this action is known as demand response (DR) [35].

3.1.1. Demand Response Operation

DR through load reduction is common. However, to facilitate over-generation, load increasing also applies [34]. Consumers can participate in DR events with existing flexible loads. However, smart meters and advanced metering infrastructure (AMI) are vital in providing energy usage records and communication facilities [36,37]. Based on the pre-set strategies, a consumer's load can be controlled automatically while using control equipment and energy management system located at the consumer's premises [34,38]. Unlike expensive peaking plants, DR requires no fuel cost to support the power grid, including valuable ancillary services such as frequency regulation and voltage control, leading to an increased benefit to the power system [33]. The DR program is generally performed through four key players, including consumers, the demand response service provider (DRSP), the distribution system operator (DSO), and the independent system operator (ISO) [39]. Consumers are the DR program participants who provide the DR resources where a DRSP or an aggregator is responsible for aggregating these DR resources for program execution. The main responsibility of the DSO is to manage the distribution system, and the ISO regulates the demand size and time for any DR event [39]. Based on the DR signals (e.g., incentive-based, precontracts, load profile instructions, direct load control) sent by the DR provider, consumers shape their load profiles for DR actions [34]. Figure 4 summarises the steps of an automated DR participation.

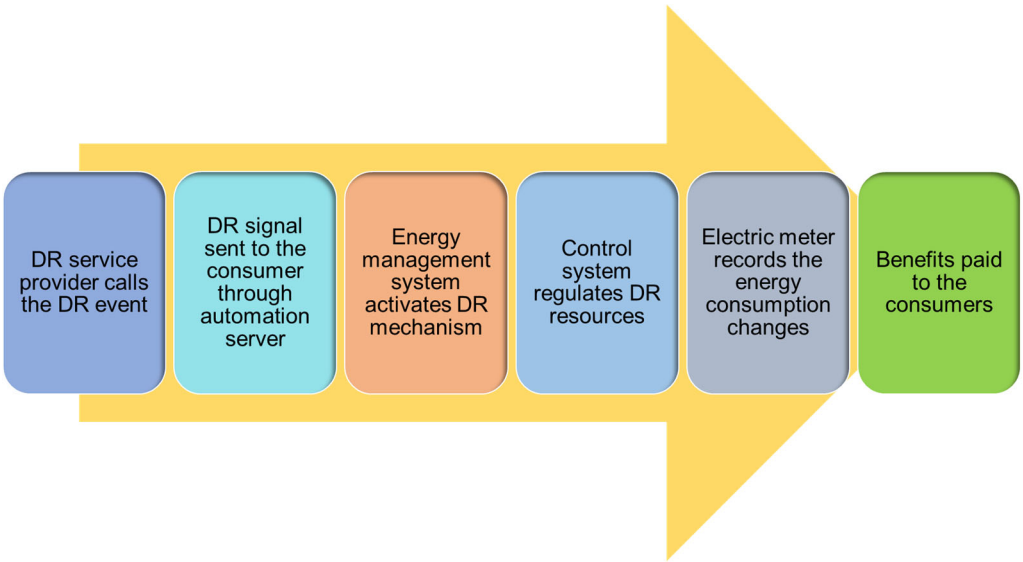

Figure 4. Steps of an automated demand response system.

3.1.2. Demand Response Programs

Broadly, classification of DR programs involves two groups: price-based or implicit DR and incentive-based or explicit DR [2,40]. Price-based DR is followed by different tariff

structures based on the electricity use at different times and seasons. Some of the common types are time of use (ToU) tariff, real-time pricing (RTP), and critical peak pricing (CPP) [2]. In the ToU program, consumers are charged for energy use at distinct time intervals [41]. Usually, there are three-time blocks: peak, off-peak, and mid-day or shoulder [41]. The higher rate at peak periods encourages consumers to shift their electricity use to other times of the day to gain benefits through lower electricity prices, resulting in the reduction in peak demand. As frequently responding to the varying time blocks is not convenient for the consumers, this type of program is usually used for medium- and long-term load regulation [42]. RTP or dynamic pricing varies according to the wholesale electricity price, which can change at each market interval with a price signal sent to the consumers ahead on an hourly or intra-hourly basis [43]. Reflecting the real price, however, with higher price volatility, RTP suits C&I consumers better than residential customer [44]. The CPP pricing is used to curb seasonal peak energy consumption, usually during some prespecified event days in a year. Consumers are given advance notice to lower their consumption against substantially higher prices with the benefit of discounted prices during the other days of the year. Research shows that by participating in the CPP program, industrial consumers can save on electricity bills and contribute to notable carbon emission reductions [45].

Incentive-based programs offer consumers fixed or time-varying benefits rather than saving on electricity bills [46]. Consumers are contracted or committed to the provider to dispatch their flexible resources according to the system demand and participate in the spot market [40]. A range of incentive programs can be offered by the service provider. In the direct load control (DLC) program, the provider has access to remotely control the registered load at the consumer's premises in need of any economic or reliability event. DLC is usually suitable for aggregated residential consumers having non-critical appliances [37,39]. In the load curtailment program, consumers are required to reduce their demand as per the contract and will be penalised for failure to meet the condition [36,47]. Joining in the wholesale market provides consumers with a contracting to demand bidding program, which accepts a bid with a lower price than the spot price. The consumer is obliged to meet the bid-for demand to avoid any penalties [39]. Large consumers can directly bid against particular demand reductions, whilst small consumers need to bid through third-party aggregators [37]. Recently, Australia offered a DR scheme to motivate capable consumers to directly participate in the wholesale market as a DRSP in a group or alone [48]. Emergency, capacity, and ancillary services are the other event-driven programs that can aid in grid-balancing activities, voltage and frequency regulation, or grid congestion [49]. Considering the capacity of larger demand reductions, incentive-based programs are mainly suitable for large C&I consumers [40]. An illustration of price-based DR and incentive-based DR is included in Figures 5 and 6, respectively.

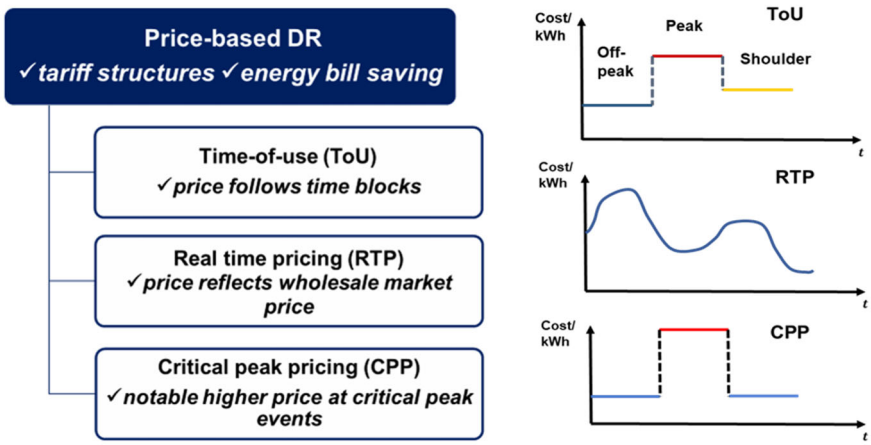

Figure 5. Price-based DR program.

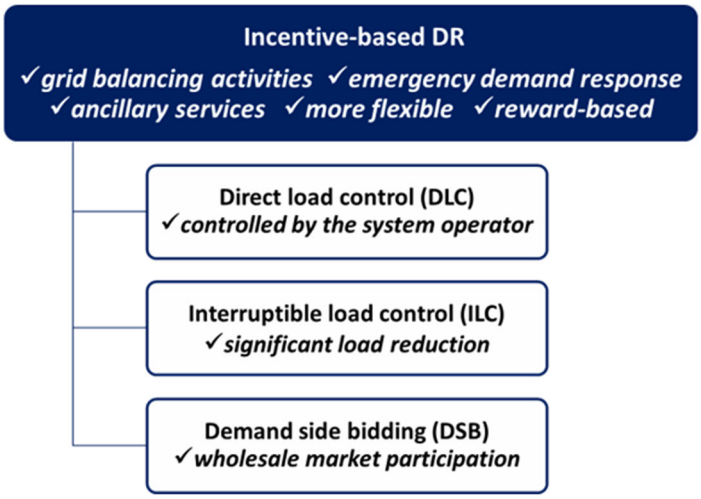

Figure 6. Incentive-based DR program.

3.1.3. Demand Response Strategies

Consumers can follow different DR strategies to participate in the DR programs. Peak clipping, also known as peak shaving or load shaving, is one of the strategies in which loads can be curtailed or interrupted to respond to peak demand. This technique supports the power system through increased power supply adequacy, reducing the chance of blackouts, and avoiding the use of expensive fast-ramping generators [15].Load shaving can also reduce consumers' electricity bills by reducing their demand charges [50], (which is a per kW fee calculated based on the maximum energy consumption by a consumer in a specific period) [51]. Demand increasing or valley filling and demand shifting are the two other strategies. The former supports the overgeneration by the RES through consuming more, and the latter reduces peak demand and supports grid stability by shifting demand to off-peak periods [38]. This enables a change in energy consumption patterns by the consumers without affecting the load application preferences mentioned to the demand flexibility. However, it is constrained by consumers' flexible loads. Depending on the application/process, the load can be interrupted, making it flexible. Otherwise, it is considered as non-flexible. Identification of the flexible loads of the system provides knowledge about the consumption pattern and control over the loads' energy use, which is essential to assess the available flexibility to support DR events [52].

The demand shifting potential of a load can be derived by using the reference profile method, where the flexibility magnitude in kW (P_{flex}) can be expressed by Equation (1) [53,54]:

$$P_{flex} = P_{ref} - P_{DR} \tag{1}$$

In Equation (1), P_{ref} is the load profile of the load during normal operations and can be considered as the reference or baseline for energy consumption and P_{DR} is the power consumed during a DR event. If P_{ref} is greater than P_{DR}, it refers to a decrease in energy consumption by the load or an increase in generation in the system, providing positive flexibility to the system. On the other hand, the system provides negative flexibility. This scenario can be expressed by Equations (2) and (3) [53]:

$$P_{flex} = P_{flex,\ positive}\ ,\ \text{if}\ P_{flex} > 0 \tag{2}$$

$$P_{flex} = P_{flex,\ negative}\ ,\ if\ \ P_{flex} < 0 \tag{3}$$

A system with higher flexibility has higher DR potential and provides more profit for DR services [54].

3.2. Overview of ESSs

ESSs are smart devices that have the twin quality of acting as a source by supplying stored energy and as a load by consuming the energy for charging [55]. ESSs can charge energy from an external source [51] and store the energy in different forms [56]. The traditional use of ESSs is limited with backup generation during any grid supply outage or unavailability of electricity. With the fast charging and discharging capabilities [9], the ESS has emerged as a potential solution to mitigate the stability issues of power system due to the variable RES generation [57]. Using the inherent technology of discharging and charging, ESS supports peak shaving and valley filling, respectively [58]. With the advancements in ESS technology, dynamic pricing programs, government subsidies and incentives, the application of ESS on the consumer side (BTM application) is rapidly increasing worldwide including in Germany, Australia, and the United States [59]. Based on the type of energy stored, ESS can be classified as electrochemical, electrical, thermal, mechanical, chemical, or magnetic energy, which are briefly discussed below.

3.2.1. Electrochemical ESS

Electrochemical ESS stores chemical energy and generate electricity through chemical reactions. The process involves the ionisation of molecules, transfer of charged ions, and then a recombination of the charges [60]. Batteries belong to this category with high energy density. Batteries are commonly used for both FTM and BTM systems [51]. Lithium-ion (Li-ion), lead acid (Pb-acid), nickel-based, sodium-based, and flow are the common types of batteries. Further details on the battery energy storage system (BESS) are included in Section 3.3.

3.2.2. Electrical ESS

Electrical ESS refers to capacitors and supercapacitors (SC), which can store energy in the form of electric current. Supercapacitor is a high power and low energy density storage with higher efficiency and life-time than the batteries [51,61]. The fast discharge properties of SC enables them to smooth the ramping effect due to the intermittent operation of solar or wind [62]. However, due to the shorter discharge time (approx. few seconds), they are not suitable for continuous operation. Very high charge/discharge capability makes SCs suitable to use in conjunction with batteries to minimise the low power density issues of batteries and improve response time and storage operation [51,63]. Superconducting magnetic energy storage (SMES) also provides high power output [64] with a fast response. It is applicable for short-period use to improve power quality [51]. However, it suffers from complexity and high cost due to the necessity of superconductivity maintenance of the coil with cryogenic cooling [64]. Due to the lower capacity to discharge energy, SC and SMES are not suitable for BTM applications with DR scheme except for auxiliary applications [51].

3.2.3. Mechanical ESS

Mechanical ESS (MESS) stores energy in the form of kinetic or potential energy [56]. Pumped hydro energy storage (PHES), compressed air energy storage (CAES), and flywheel energy storage (FES) are the most common mechanical ESS. PHES is a widely accepted technology as a grid-scale application with load-balancing activities [65]. It pumps water from a lower elevated reservoir to an upper elevated reservoir during favourable conditions such as sunny or windy days [65], or off-peak hours [57]. Then, it stores the gravitational potential energy and releases water back to the lower reservoir using a hydroelectric turbine, allowing it to generate electricity and meet peak demand [65]. It offers high efficiency and a long operational life with less operational and maintenance costs [57]. However, its use is limited due to the larger geographical demand and slow response properties [66]; therefore, it is not suitable for wider application in C&I consumers.

3.2.4. Compressed Air ESS

Compressed air energy is stored in a CAES where the storage can be an underground reservoir or aboveground container [51,66] and provides a potent energy reserve [56]. It releases energy through a combustion process using a gas turbine and generates electricity [66]. It has the advantage of storing energy for a long period, more than a year, with a long asset life [57]. However, the larger geographical demand and release of harmful pollutants from combustion limits its wider application [66]. FES uses an electric motor to extract the energy to rotate [66]. As it rotates, it produces kinetic energy and stores it as rotational energy [67]. To discharge the energy, the flywheel slows down, and the motor acts as a generator to produce electricity from the kinetic energy [67]. Although MESS is generally used for FTM application, the flywheel can be used in the BTM setting to provide the service of UPS [51].

3.2.5. Thermal ESS

Thermal energy storage (TES) provides heating or cooling energy to be stored in a medium, which can be extracted for later use [56]. TES is widely used in the residential and commercial sectors for space heating and cooling and industrial processes in industries. It can store energy in the latent heat form or by using sensible heat techniques. Implicit heat storage is also possible based on thermochemical process [56]. The latent heat form uses the characteristics of phase change materials (PCMs) to produce or store thermal energy during the phase change process [57]. The storage of sensible heat is accomplished by directly heating a medium [57] as molten salt in liquid form; sand, stone, and others as a solid form; and molten salt/stone as a liquid with a solid filter form [56]. The thermochemical type stores heat indirectly based on the absorption and adsorption principle [56]. Combined with some generating technologies such as solar power plants, TES can be used in the FTM setting [51]. The thermal properties of large residential or commercial buildings can additionally provide virtual energy storage (VES) in terms of thermal energy [68]. Using the building's envelope structure, building materials, and the building's thermal inertia, thermal energy can be stored from an overproduction of PV generation, providing demand flexibility, reducing grid energy consumption, and minimising the reverse power flow effect [68].

3.2.6. Chemical ESS

In chemical energy storage (CES), energy is stored in chemical bonds, which are released during a chemical reaction. Coal, gasoline, diesel fuel, natural gas, liquefied petroleum gas (LPG), propane, butane, ethanol, biodiesel, and hydrogen are widely used chemical fuels that can be transformed into thermal and mechanical energy to produce electricity [56]. Hydrogen, synthetic natural gas (SNG), solar fuel [60], and biofuels [56] are some of the common CES systems. Hydrogen is one of the most focused forms of energy used by industry and governments. Hydrogen is an energy carrier rather than a primary source of energy [56,69]. Hydrogen production using renewables generates carbon-free electricity in which water is broken down through an electrolysis process to produce oxygen and hydrogen [59]. The produced hydrogen is known as green or renewable hydrogen [59]. This hydrogen can be stored in a vessel providing electricity production using a fuel cell [60]. Hydrogen ESS (HESS) has recently been deemed as having potential for BTM application due to its uninterrupted power supply capability [59]. Moreover, the sustainability analysis performance of various ESS using a multi-criteria decision model reveals that the hydrogen fuel cell (HFC) is the most suitable technology with high commercialisation adaptability [70]. The integration of hydrogen storage with batteries has been investigated in prior studies [71–73] and is considered a cost-effective option, particularly for seasonal energy storage [74]. A comparison of the technical characteristics of different types of ESSs is included in Table 1.

Table 1. Technical characteristics of energy storage systems.

ESS Type	Power Capacity (MW)	Power Density (W/L)	Energy Density (Wh/L)	Response Time	Discharge Time	Efficiency (%)	* Cycle	* Year
Li-ion	0–100 [58] 0–0.1 [59] 0.1–100 [57] 0.1 [75]	1500–1 × 10^4 [57,58]	250–750 [58] 200–500 [57]	ms [58] ms [75] <5 ms [57]	min-h [58] s-h [57]	90–95 [58] 85–90 [59,75] 90–97 [57]	2 × 10^3–1 × 10^4 [58] 4.5 × 10^3 [75] 1 × 10^3–1 × 10^4 [59]	5–15 [57,59,75]
Pb-acid	0–40 [57,58,75] 0–20 [59]	10–100 [58] 10–400 [57]	50–80 [58] 50–90 [57]	ms [58] <5 ms [57]	s-h [57,58]	70–90 [58,59,76] 75 [75] 75–85 [57]	500–2000 [58] 5 × 10^2–1 × 10^3 [59] 2 × 10^3 [75]	5–15 [57,59,75]
Na-S	0–100 [58] 0.15–10 [57]	120–180 [58] 140–180 [57]	150–250 [58] 150–300 [57]	<10 s [58] <5 ms [57]	s-h [57,58]	75–85 [58] 75–90 [57] 89 [75]	2500–4500 [58]	15–20 [57]
Ni-cd	0–40 [57,75]	80–600 [57]	15–150 [57]	ms [75] <5 ms [57]	s-h [57]	60–65 [75] 60–80 [57] 80 [76]	3 × 10^3 [75]	10–20 [57,75]
PSB Flow	0.1–15 [57]	<2 [57,58]	20–30 [57,58]	<100 ms [58] 20 ms [57]	s-10 h [57,58]	65–85 [58] 60–75 [57]	2000–2500 [58]	10–15 [57]
VRB Flow	0.03–3 [58,75] 0.3–15 [57]	0.5–2 [58] 0.03–3 [59] <2 [57]	20–70 [58] 25–35 [57]	<100 ms [58] ms [75] <5 ms [57]	s-10 h [57,58]	65-85 [58] 75-85 [57,59,75]	1 × 10^4–1.3 × 10^4 [58] >1 × 10^4 [75] >1.2 × 10^4 [59]	15–20 [75] 5–10 [59] 5–20 [57]
ZnBr Flow	0.05–2 [58] 0.05–10 [57]	<25 [57,58]	30–60 [58] 30–65 [57]	<100 ms [58] <5 ms [57]	s-10 h [57,58]	70–80 [58] 65–80 [57]	2 × 10^3–1 × 10^4 [58]	5–20 [57]
SC	0–0.3 [58] 0.2 [75] 0.01–1 [57]	4 × 10^4–1.2 × 10^5 [58] >1 × 10^5 [57]	10–30 [57,58]	ms [58] <4 ms [75] <5 ms [57]	ms-1 h [58] s-min [57]	90–95 [58,75] 90–98 [57]	1 × 10^5–1 × 10^6 [58] >1 × 10^5 [75]	10–20 [57] 20^+ [75]
SMES	0.1–10 [57,58,75]	1000–4000 [57,58]	0.2–2.5 [58] 0.2–6 [57]	ms [58] 5 ms [57]	ms-8 s [58] s-30 min [57]	93–98 [58,75] 95–97 [57]	>1 × 10^5 [58,75]	20–30 [57] 20^+ [75]
FES	0–1.5 [58] 0.25 [75] 0–2 [59] 0.01–20 [57]	1000–5000 [58] 1000–2000 [57]	20–80 [57,58]	s [57,58]	ms-15 min [58] s-min [57]	93–95 [58,75] 85–90 [59] 90–98 [57]	2 × 10^4–1 × 10^5 [58] >1 × 10^5 [75]	~15 [75] >20 [59] 15–20 [57]
PHS	100–5000 [57,58,75]	0.5–1.5 [58] 1–1.5 [57]	0.5–1.5 [58] 1–2 [57]	s [58] s [57]	1–24 h+ [58] hour-day [57]	75–85 [58] 75–85 [75] 70–85 [57]	2 × 10^4–5 × 10^4 [58] >1.3 × 10^4 [75]	40–60 [75] 30–60 [57]
CAES	5–400 [58] 3–400 [75] 5–300 [57]	0.2–0.6 [58] 1–2 [57]	2–6 [58] 3–6 [57]	9–12 min [58] s-min [57]	1–24 h+ [58] hour-day [57]	40-70 [58] 70 [57] 50–88 [75]	8 × 10^3–1.2 × 10^4 [58] >1.3 × 10^4 [75]	20–40 [75] 30–40 [57]
TES	0.1–300 [57]	-	80–500 [57]	Not for rapid [57]	hour [57]	30–60 [57]	-	5–20 [57]
HFC	0–50 [59,75] 0.001–50 [57]	>500 [57]	500–3000 [57]	<5 ms [57]	min-hour [57]	20–50 [75] 30–45 [59] 30–50 [57] 20–66 [76]	>1 × 10^3 [59,75]	5–15 [75] 5–20 [57] 3–10 [59]

* Lifetime.

Furthermore, based on the power rating, ESSs can be classified as a large-scale, medium-scale, and small-scale ESS. The power rating of large-scale ESSs is usually more than 100 MW, whereas the medium-scale rating can vary from 5 MW to 100 MW. The power rating of the small-scale ESSs is usually less than 5 MW. This type of classification helps in ESS sizing [59]. The classifications of ESSs are given in Figure 7.

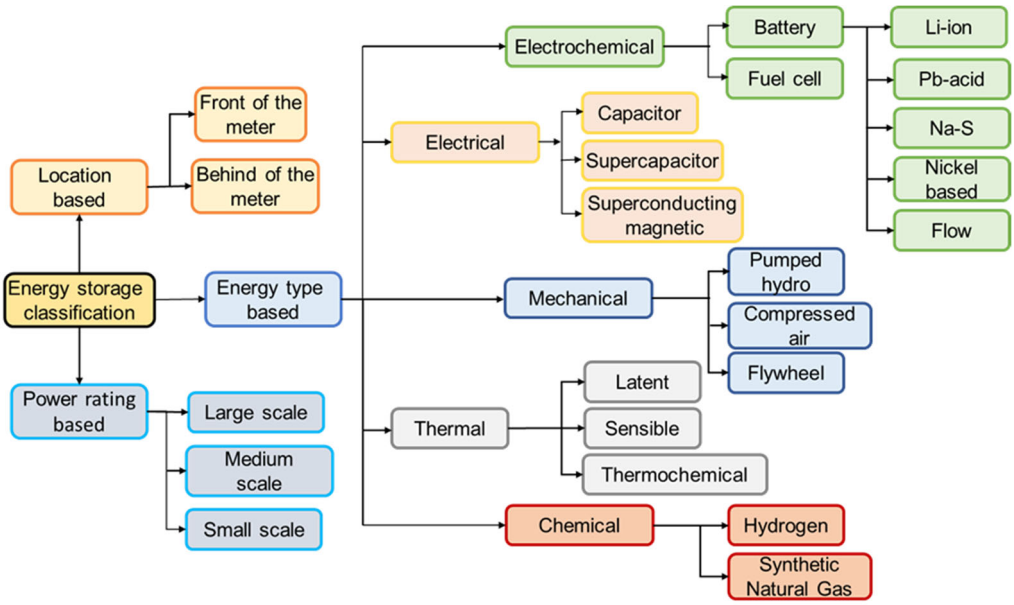

Figure 7. ESS classification.

3.3. Battery Energy Storage System (BESS)

BESS has significant potential as ESS technology to support intermittent RES generation [76]. Broadly speaking, batteries can be classified as primary and rechargeable. Primary or disposable batteries cannot be recharged, and rechargeable batteries, as the name implies, can be charged for repeated use, and are usually used in BESSs. Battery energy storages with their fast response, easy application, and high flexibility [77] apply to BTM applications [59]. The basic structure involves a positive electrode, a separator, an electrolyte, and a negative electrode. Due to the electrochemical reaction occurring at the electrode, the battery chemistry usually varies according to the electrode materials [66]. Types of BESS can vary based on different chemical reactions with several advantages and disadvantages and need to be selected based on the applicability for better performance [51]. For instance, lead acid batteries perform best under a temperature of 40 °C; therefore, they are not suitable for peak load reduction with high temperature operation. However, sodium-sulphur batteries are different, with a low recharge time and high operating temperature and so are ideal for a consumer's daily load-shifting application [62]. Some of the common battery types are briefly included below.

3.3.1. Lead-Acid Battery

This is the oldest type in battery groups [59], and the lead-acid battery is commonly used in various power sector applications including off-grid, emergency, and backup power [51]; thereby, these are suitable for the DR application. The capability of providing pulsed power also makes them suitable for BTM applications [59]. They have the advantages of very high-power density, low cost and maintenance requirements, and moderate round-trip efficiencies compared to the other batteries. However, they suffer from a poor life cycle and low energy density [51]. Lead emissions also pose environmental and health concerns [77], which can be minimised with sealed, maintenance-free design and mature recycling technologies [78]. According to the CSIRO report published in 2015 [62], the advanced lead-acid battery is highly applicable for C&I energy management in Australia.

3.3.2. Li-Ion Battery

Among the battery chemistries, Li-ion is widely used as a BTM application [51,59] and uses a lithium compound injected as an electrode material [69]. These batteries can supply a charge for longer periods compared to the other battery types [59] and are well-adapted to power applications and EVs [60]. Moderate power density and life cycle, high round-trip

efficiency, low maintenance requirements, and moderate cost are the other features of these batteries. However, they are prone to high temperatures leading to fires or explosions and require overcurrent, overvoltage, and overheating protection [59]; therefore, this limits their use in the regional, harsh environments in Australia. Surpassing the safety concerns, the application of the Li-ion battery is growing rapidly due to the rapid price drop and technological advances with safer operation in power systems [51].

3.3.3. Nickel-Based Battery

Nickel-based batteries use nickel hydroxide as a cathode and alkaline aqueous as an electrolyte with a range of anode materials, including zinc, cadmium, and iron [57]. The use of these batteries with low power, low energy density, and the memory effect is usually limited to power tool applications rather than large-scale power system applications [51].

3.3.4. Sodium-Based Batteries

With the advantage of its easy availability in nature and low price, sodium-based batteries show price competitiveness with Li-ion batteries and can be a promising option for future low-cost batteries [51,69]. In the sodium-sulphide (Na-S) type, molten sodium and sulphur are used as the anode and cathode, respectively. It uses beta alumina, a solid electrolyte, which makes the battery chemistry distinct from the others [57]. Due to the rigid housing requirements born of the material properties and high operating temperature, sodium-based batteries are usually unsuitable for BTM application; hence, these batteries can be used for DR schemes in C&I consumers [51].

3.3.5. Flow Batteries

Unlike conventional batteries, the electrodes of flow batteries are kept in two separate tanks immersed with distinct electrolytes. Energy is stored in the electrolytes instead of the electrode material [59,69]. Such a configuration provides stability in electrodes and life cycles [57]. Although these batteries possess high efficiency, large depth of discharge, long lifetime (up to 20 years) [57], and much safer operation, due to the bigger size, low energy and power density, and high cost, their BTM application is still limited [51]. Vanadium redox, zinc-bromine, polysulfide bromide, and hybrid are the commonly used flow batteries [57,59]. For more detail on each type of battery, interested readers are referred to [56,59].

BESS can greatly support in DR events by providing flexibility through fast response in load increasing or reduction [79] and enabling avoidance of interruption of critical loads, where battery sizing is crucial to gain the maximum benefits. BESS for BTM application usually possesses a small energy capacity requiring frequent deep cycles [80]. For the optimal battery sizing, the technical constraints of the whole system and uncertainties in input parameters including renewable generation, load, energy price, weather conditions, and discount rate need to be considered [81]. Nevertheless, an accurate model is required for optimised battery performance [82].

Additionally, BESS modelling is crucial in BESS management and control while ensuring cost efficiency and technological advantage. Generic models based on the tracking of changes in the state of the charge (SOC) parameter are widely used for BESS modelling for DR schemes. SOC is one of the most important parameters which indicates the level of charge corresponding to the battery capacity with relation to the charging and discharging process; hence, SOC is generally used to determine the energy status of the battery [83]. The relation of the charging and discharging process with SoC can be expressed by Equations (4) and (5):

$$SOC(t+\Delta t) = SOC(t) + \frac{P_B(t)\eta_c \Delta t}{EC_B}, \text{when charging} \tag{4}$$

$$SOC(t+\Delta t) = SOC(t) + \frac{P_B(t)\Delta t}{\eta_d EC_B}, \text{when discharging} \tag{5}$$

In Equations (4) and (5), P_B refers to the power required to charge and discharge the battery. A positive and negative P_B value shows the charging state and the discharging state of the BESS, respectively, where the efficiency of battery charging is η_c, the efficiency provided with battery discharging is η_d, and the battery capacity is EC_B [83].

Further, the cell structure [76], temperature, SOC, and charge/discharge rate accompanying day-by-day operation can affect battery life with degradation [50]. The maximum cycle number for the battery needs to be considered in the DR scheme modelling. Battery degradation is mainly caused by the chemical reaction involving the electrolyte, the cathode, and the anode performed over time and is indicated by calendar ageing and cycle ageing. The battery's intrinsic degradation due to the storage (with or without charging/discharging) refers to the calendar cycling, whereas the charging and discharging process over time results in cyclic ageing [83,84]. It is widely accepted that a battery with a working capacity lower than 80% comes to its end in life requiring a replacement [83]. Besides SOC, state of the health (SOH) is another crucial parameter for BESS modelling [82] and an effective indicator to evaluate battery degradation. SOH refers to the loss of rated capacity and can be expressed by Equation (6) [83]:

$$SOH = \frac{C_{actual} - C_{EOL}}{C_{nominal} - C_{EOL}} \cdot 100\%, \;\; C_{actual} \geq C_{EOL} \tag{6}$$

In Equation (6), C_{actual} is the capacity of the brand-new battery. At this point, nominal capacity, $C_{nominal} = C_{actual}$, and $SOH = 100\%$. If C_{EOL} is the end of the useful life capacity, then at the end of the battery life, $C_{actual} = C_{EOL}$ and $SOH = 0\%$. Considering battery life ends at 80% of its useful capacity, the end of the useful life capacity can be represented by Equation (7) [83].

$$C_{EOL} = 0.8 \cdot C_{nominal} \tag{7}$$

Minimising battery degradation cost through efficient charge/discharge cycles is crucial for optimised battery management [83]. A brief conceptualisation of some of the common battery parameters required to be considered in DR scheme design is included in Table 2.

Table 2. Battery parameters [51,62,64,85,86].

Parameters	Description
Capacity	The amount of energy possessed by a battery at its highest level.
State of Charge	The energy level referring the charging condition during a certain period which is required to maintain to prevent any damage.
Depth of discharge	The amount of charge has been used. A battery with 100% charge has a DoD of 0%.
Power density	The amount of power per unit volume in a system is usually measured in W/L.
Energy density	Measurement of energy stored in a system's per unit volume which is usually measured in Wh/L.
Efficiency	The ratio of the energy charged to and discharged from the battery.
Cycle	Charging action of a battery and discharging it throughout a certain time with specific energy limits. It can be used to represent the battery lifetime.

3.4. Technology Readiness Level

The technical maturity of the ESS can be trialled using technological readiness level (TRL) metrics [87]. TRL provides a range of scales representing the different stages of the technology starting from the basic level to full-scale operations which is useful in taking investment decisions [88]. According to ARENA [89], the TRL scales can be defined as included in Table 3. Figure 8 shows the TRL levels of different ESS. Among the batteries, Li-ion and flow batteries are found to be more matured techniques compared to the Na-ion battery.

Table 3. Technology readiness level chart.

Levels	Description
1	Observation of fundamental principles and reporting completed.
2	Concept of the technology and/or application established.
3	Analysis with experiments of critical function and/or validation of proof of concept.
4	Laboratory scale validation of component/subsystem.
5	Validation of system/subsystem/component application in respective environment.
6	Demonstration of system/subsystem model or prototype with respective end-to-end testing.
7	Demonstration of system prototype in operational environment.
8	System development completed; qualification of operation achieved through practical demonstration and testing.
9	Successful operation observed confirming the system application.

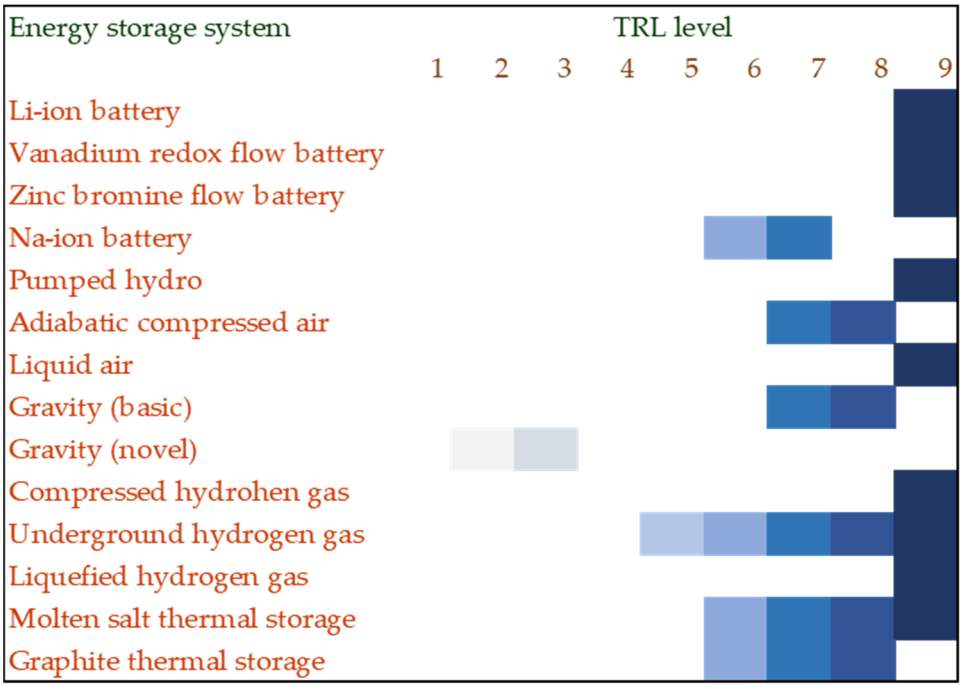

Figure 8. Technology readiness level of ESS. The information is sourced from CSIRO [87].

4. Application of ESS and ORG with DR

4.1. Background

Traditionally, DR-based research is focused on residential, commercial, and industrial consumers. Residential electricity consumption is primarily driven by human desires, such as thermal comfort or entertainment [21]. Hence, DR flexibility is mainly extracted from thermostatically controlled loads, including heat pumps, refrigerators, air conditioners, water heaters, and others [90,91]. Appliances such as washing machines, dishwashers, and dryers [91] are the main DR resources in the residential settings. With the rapid growth in carbon-neutral electric vehicles (EVs), peak demand is increasing [92] which makes EVs a leading upcoming DR resource [93]. Smart EV charging benefits the EV owner with cost savings and the system with demand–supply balancing [94], and has been used for residential energy management in many studies [70,92,94,95]. Pool pumps [96] or lighting systems [97] are the other options for residential DR. However, the energy consumption by residential consumers is lower than that of C&I consumers.

Research shows that C&I consumers, as large energy users, are the main sources of DR [98,99]. The review study [21] analysed DR participation as a part of DSM for industrial,

commercial, and residential consumers. The use of thermal storage from the electric furnace and cold storage, wind, and solar generation was reviewed to analyse demand flexibility for the industrial consumer. For commercial consumers, the use of inherent energy storage such as thermal storage from refrigerators and the batteries of EVs was reviewed. All these DR activities are reviewed, focusing on economic, technical, and behavioural constraints. In [90], the authors analysed the flexibility potentials of industrial processes including the challenges and opportunities and pointed out the capability of flexibility provision by interruptible industrial processes with a short notice in advance [90]. Focusing on industrial microgrids, difficulties in consumer demand prediction, including renewable DG, were highlighted in [24]. Research shows that DR modelling with efficient load scheduling is imperative for successful DR execution for industries realising decreased energy use and cost saving [100]. However, the standardisation of communication interfaces for energy management, the uncertain generation of renewables such as wind or PV, and maintaining the balance between accuracy and efficiency in optimisation problem-solving remains challenging [100]. The impacts of combining supply-side ESS with DR and other smart grid technologies including dynamic thermal rating (DTR) and optimal transmission switching (OTS), to improve the grid reliability, focusing on supply-side flexibility, are reviewed in [66]. Further, the applications of DR for industrial consumers to assist in ancillary services are surveyed, and the importance of improved knowledge of DR programs is highlighted for consumer awareness and increased participation [26]. In [101], the authors reviewed how to improve the energy flexibility of commercial and residential buildings for DR. It highlighted the use of RES combined with ESS for DR events to increase flexibility. Due to the recent surge in EVs, the impacts of DR application using non-residential EV fleets with battery degradation are reviewed in [28]. Enabling smooth DR participation for C&I consumers with the integration of ESS and/or ORG in the DR framework has been studied in several studies [102–105], which can contribute to a survey of the literature. Usually, industries can accommodate onsite renewable generation for energy efficiency and employ ESS to store the energy for later use [11]. Further, installation of a PV module is sensible for those industries where the peak demand matches the peak generation of PVs, and also the high energy demand of thermal units can be met with the low generation cost [24]. The significance of integration of onsite renewable energy and ESS with DR is addressed in several review studies [23,24]. Here, we surveyed how such an integration has applied in past research for the C&I consumers and this is presented in the sub-sections below.

4.2. Analysis with Commercial Consumers

4.2.1. Demand Flexibility with HVAC

In the commercial sector, most of the energy consumption is encompassed by heating and cooling systems, space lighting, the hot water system, and various electronic devices [21], where the heating, ventilation, and cooling (HVAC) system accounts for the major loads [106,107]. These energy-consuming loads can respond to electricity demand by managing building energy and consumption behaviour [39], for instance, by turning off partial lighting facilities, reducing HVAC use or lowering the temperature setpoint, limiting energy-consuming office equipment [108], and so on. Commercial buildings with large thermal capacitance are often considered as thermal storage providing inherent demand flexibility [109]. With the interaction of the thermal dynamics of the building and control of the supply fans of the HVAC system, ancillary services such as frequency regulation can be delivered [109]. Different control methods, including balancing of fan speed, supply pressure or mass flow, and thermostat setpoint, can provide varied response rates [110]. Software-based control of HVAC systems can also be applied in appraising the reaction of commercial intelligent buildings where the control of the temperature threshold can be a flexible strategy [102]. However, irrespective of any method, there should be a balance between energy saving and the comfort of the occupants [111]. Additionally, commercial consumers are restricted by business regulations and operations such as sufficient lighting in office spaces or on-demand operation of critical restaurant appliances for customer

services. Failure to meet these requirements might adversely affect productivity and revenue [21]. These economic and technical constraints added with behavioural constraints provide obstacles to commercial DR [21]. DR participation with ESS and ORG can be a potential means for those commercial consumers restricted by business operations or regulations, which is analysed in the sub-subsection below.

4.2.2. Demand Flexibility with ESS and ORG

Demand flexibility availability from energy-consuming commercial buildings using building thermodynamics and power to heat conversion technology has attracted wide research attention. Space heating and cooling provide greater potential for commercial DR. Therefore, heat pumps, electric heaters, and others are considered as potential flexible loads that can operate through power-to-heat (P2H) technology. An addition of thermal energy storage to the system can fully exploit the flexibility potential of P2H technology and increase the system's flexibility [40]. Thermal energy stored during low grid-price periods (off-peak hours) can be used during peak times to meet the heating and cooling demand, resulting in a flattened demand profile [112]. An underground insulated concrete water tank has been used in [112] as a TES enabling maximum heat preservation. Charging the TES with PV generation during weekdays or when it is in surplus could help the consumers to reduce energy costs and the grid by avoiding the electricity feeding from non-deterministic behaviour generation. The water tank has been charged during weekends or before and after working hours using the heat pump with PV generation or off-peak electricity rate. The stored heat has been used to meet the thermal needs of the industrial building during working hours instead of running the heat pump, thereby saving peak-time electricity consumption and cost. However, the TES with thermal insulation presents a high cost and longer payback period. Alternatively, existing storage tanks, such as for fire protection, might be used to reduce the initial investment [112].

TES added with combined heat and power (CHP) units also gained research attention. Onsite generation through CHP units can reduce energy costs when added to the heating–cooling systems of commercial buildings through simultaneous heat and electricity production [113]. Adding TES and ESS allows thermal and electrical energy to be stored and used during peak periods for demand shifting, resulting in further energy savings. The addition of ESS can help keep up with real-time price fluctuations and is more beneficial than a flat tariff. However, the high investment cost of the ESS can increase the payback period and decrease the benefits. The experiment in [113] showed that a CHP unit operation with the DR strategy can reduce energy costs by 1% to 14% rather than the thermal load follow strategy. Nevertheless, for real-time optimisation with DR, monitoring and control equipment are crucial, as reported in [113]. Furthermore, it is required to evaluate the flexibility of the loads, including TES, for optimal control. Finck et al., 2018 [35], utilised three dimensions of flexibility, i.e., size, time, and cost, to measure energy flexibility provided by a TES added to the loads. The demand flexibility of an office building's heating system consisting of a heat pump, electric heater, heat exchanger, and thermal energy storage tank is evaluated to participate in a dynamic program. Responding to hourly day-ahead electricity prices, the system could provide flexibility for a short period (up to 24 h) [35]. Commercial consumers can also utilise a flexible load optimal regulation strategy to participate in ancillary services [108]. Based on the flexible load characteristics, the loads can be controlled following the real-time pricing signal. Charging the ESS by low-price grid powers and energy use through discharging it when the price goes high can maximise the benefit of saving on electricity bills and providing grid support [108].

4.3. Analysis with Industrial Consumers

Industries are the major consumers of electricity [103], and are anticipated to have more DR potential for their high energy use compared to the residential and commercial customers. Scheduled operations and already installed smart technologies (sensors, smart meters, advanced communication infrastructure, etc.) [23] are making DR participation

easy [114]. The thermal mass of industrial loads is notable, providing instantaneous power change and enabling ancillary services provision [115]. However, industrial processes are usually highly complex, have safety concerns [116], and demand precision and fine accuracy in the load control [39]. Some processes require continuous operation with a lack of flexibility [117]. In addition, the interconnected processes pose constraints with production scheduling, inventory management, maintenance scheduling, personnel scheduling [118], and workstation interdependencies [12] and cannot be interrupted frequently, hindering the flexibility potential of industrial DR [90]. In particular, the risk of failure to conform to quality requirements due to any interrupted operation prevents these large consumers from accepting the DR technology [117]. One of the major barriers is that these consumers are not well informed about the flexibility potential in their processes or how they can increase flexibility for DR participation [117] which needs to explore.

4.3.1. DR with ESS

Industrial consumers usually employ their aggregated flexible loads to support operational reserves through load curtailment/shedding programs [40]. Having complicated and restricted processes, they consider implementing DR with the loads that are interruptible at short notice [119]. By including ESS technology, they can overcome the limitations of load complexities, leading to increased system flexibility and cost reduction [114]. The energy costs of large industry can be reduced by charging the ESS at off-peak hours and discharging it during peak hours along with shifting demand [120]. It is reported that the energy cost was 11% lower than the base case. Besides load shifting, DR provision through ancillary services can be implemented efficiently using ESS. Participation in ancillary services as regulation and load following requires a continuous change in power, which cannot be achieved effectively with some of the industrial loads posing coarse granularity. To overcome this barrier, a model predictive control (MPC) method was proposed for cement industries [121]. A coordination framework including onsite energy storage providing continuous power change could follow the desired power signal, based on hourly operation [121] and day-ahead scheduling [114].

Participation in incentive-based DR programs through a third party or system operator (SO) requires providing access to SO to control the industrial loads for DR, which is a concern regarding privacy and internal business operation. Information access regarding load profiles is highly confidential and competition-sensitive, posing the barrier for many consumers [24,39]. For instance, under an automated curtailment DR program in Australia, the customer's load is controlled remotely by DR operators using a load control device (LCD) located at the customer's premises, which is not well tolerated by many consumers [48]. To alleviate such barriers, the facility operator can generate a load reduction curve (LRC) internally and communicate with the SO, informing them of the available flexibility potential without sharing any internal information [118]. By using a battery, a continuous load reduction can be achieved by covering the DR event. Following the proposed LRC, the SO can request the facility to reduce loads during the DR event without directly controlling the consumer's load [118].

4.3.2. DR with ESS and ORG

To participate in a day-ahead market, an optimal bidding strategy can be formulated for the benefit of both the aggregator and the large load (data centre) by the coordinated deployment of the working loads, generator, and BESS [86]. The use of ORG can also provide power purchase decision options. Scheduling flexible workloads, data centres can purchase low-price power following price-varying rates and use ORG during high-price periods, which can also provide a better utilisation of ORG [11,122]. However, to respond to peak reduction, frequent charge/discharge is required, which can cause UPS battery degradation, and this can be minimised through a hybrid energy storage system, including a supercapacitor [63]. A supercapacitor has a greater charge/discharge capability than a battery, provides less energy waste, and is suitable for power shaving. A hybrid energy

system integrating a supercapacitor with a battery required less capacity to shave power with energy saving by 34% than a battery-only system [63].

The application of a commercial energy management system (CEMS) for incentive-based DR program participation is studied in [47]. CEMS involves both the utility and the consumer through a communication protocol and bidirectional smart meters. Instead of the utility doing so, consumers can control their load and generation by themselves. Based on the DR signal, the CEMS inspects the availability of the resources to meet the demand, then curtails the interruptible loads or opts for the onsite generation coupled with ESS to meet the demand. Thus, peak shaving could benefit both the consumer and the utility [47]. Nevertheless, the ESS configuration with benefit evaluation is crucial for energy management. The ESS configuration for ancillary services by industrial users, comparing different strategies, is examined in [123]. The benefit of using ESS for peak shaving and demand management outperforms when added to demand response and emergency services [123].

4.3.3. Role of Load Scheduling

Load scheduling is an important part of industrial DR modelling. Using the technique of state task network (STN), the study in [103] controlled the energy consumption by dividing the operational tasks into schedulable tasks (ST) and non-schedulable tasks (NST). Operating low energy-consuming STs at high prices and high energy-consuming STs at low price periods could shift the demand and reduce energy costs efficiently. It was applied to a DR model on oxygen generation facilities where hourly electricity pricing was reduced by shifting the STs, storing energy in an ESS at low prices for the use in high price periods, as well as generating additional electricity with solar systems at lower cost. It further showed that the hourly electricity price is reduced to 5% with only ESS and 17.9% with both ESS and onsite generation [103]. Modelling with the uncertainty of RES generation is challenging. Herein, load scheduling can be optimised considering the worst-case renewable generation [85]. However, further study is required for uncertainty modelling associated with the DR mechanism in industrial consumers.

4.3.4. DR with VPP

DR participation by means of an industrial park used as a virtual power plant (VPP) has recently been considered as an interesting research area. Aggregated industrial loads in an industrial park combined with RE generation and ESS can operate as an industrial virtual power plant (IVPP) and participate in load regulation ancillary services through a DR model [124]. In [125], a DR with load shedding mechanisms was studied on an industrial VPP combining solar and wind generation systems, ESS, and industrial loads. The optimisation model, constructed by supply side and demand side sources, represented that DR and ESS's capacity can positively influence renewables' integration with lower electricity purchasing [125]. Moreover, the study [126] also focused on the importance of DR and ESS in forecasting the RES availability and integration. Considering the importance of the energy storage configuration, including PVs and adjustable loads, a general electrical energy storage despatching model was developed in [127], which can be expressed as in Equations (8)–(14):

$$P_c = \left(p_c(t)\right)_{T\times 1} \tag{8}$$

$$P_d = \left(p_d(t)\right)_{T\times 1} \tag{9}$$

$$P_c^{min} \leq p_c(t) \leq P_c^{max} \tag{10}$$

$$P_d^{min} \leq p_d(t) \leq P_d^{max} \tag{11}$$

$$S(t) - S(t-1) = (\eta_c p_c - \frac{p_d}{\eta_d})\Delta t \tag{12}$$

$$S^{min} \leq S(t) \leq S^{max} \tag{13}$$

$$\sum_{t=1}^{T}(p_c(t) - (p_d(t))\Delta t = 0 \tag{14}$$

Here, the ESS is charged by the power $p_c(t)$ and discharged through the power $p_d(t)$ with a dispatching period T. The charging power is bounded by two limits, where P_c^{max} refers to the higher level and P_c^{min} indicates the lower one. Similarly, the power of discharge is constrained by the higher level, P_d^{max} and the lower level, P_d^{min}. $S(t)$ is the ESS capacity covering the time t where S^{max} refers to the highest charging capacity and S^{min} denotes the lowest amount; η_c indicates the charging efficiency, and η_d accounts for the discharging efficiency;

A VPP can also include commercial and residential consumers, which requires considering consumer-wise attitudes and responses towards the program and setting incentives in VPP modelling [125]. Furthermore, using CHP generation to meet peak demand and storing the waste heat from the CHP in thermal storage for later use can provide flexibility to an industrial park. Industrial parks' peak load can be reduced through integrated DR, including the CHP units and thermal storage, and electricity bill savings can be gained [128].

4.3.5. DR with EV

The recent surge in EVs have made them an attractive DR resource for C&I consumers in parallel with residential consumers. Several studies have considered this low-carbon technology energy storage [57,129]. With the capability of providing demand flexibility [21], EVs can take energy from the grid directly as a plug-in method and discharge as necessary through vehicle-to-grid (V2G) mode [57]. The parked EVs in commercial buildings can be charged during off-peak hours and discharged during peak periods, aiding in grid power supply and demand balancing [130]. Integrating industrial EV fleets, thermal storage, and PV generation with DR can maximise the benefits, as reported in [131]. However, optimal scheduling is essential [132], where employee numbers owning EVs can be an influential factor [131].

4.4. Outlook

For successful DR operation, well-informed knowledge about the loads or processes is paramount. Industrial processes may involve highly correlated critical loads requiring following strict operational constraints. For efficient participation, it is required to identify the correlation of available processes/loads for flexible operation or any viable means to make the system flexible or increase flexibility [30]. Efficient DR and ESS modelling with load/process scheduling is crucial to ensure the benefits. Commercial consumers usually have constant daily demands, which might be less beneficial for ToU program participation [133]. To gain the benefits from ToU pricing, consumers need to change their consumption patterns following the ToU periods and shift their energy demand, which might hinder business operations. In this respect, storing energy can assist in enjoying ToU pricing without interrupting daily operations [133]. It is evaluated that although ESS degradation costs affect the payback period of the ESS investment, after the payback recovery, the benefits could be maximised by increasing the energy consumption during peak periods through the ESS [133]. Interestingly, a DR strategy appraising the non-linear relationship between the discharging rate and the unused charge can extend the battery life [105]. Energy losses during discharge can increase gradually with the discharging rate. Hence, considering the objectives to minimize this energy loss with continuous optimisation time approach could increase DR savings [105].

A summary of the technologies used in the studies is included in Table 4 which shows that batteries and PV are the frequently used ESS and ORG technologies, respectively. A

tabular analysis of the application of ESS and ORG with DR is included in Appendix A which represents the salient features of the research studies including the highlighted aspects. The tabular analysis reflects that onsite renewable generation coupled with energy storage technology is mostly used which indicates the applicability and benefits of this dual technology providing energy saving with carbon emission reduction compared to the energy storage only technology.

Table 4. Application of the technologies with DR in surveyed research studies.

Technologies		References
ESS	Battery	[11,12,79,85,86,105,107,113,118,125,127,133–145]
	Thermal storage	[102,113,131,146]
	Compressed air energy storage	[147]
	Fuel cell	[148]
	Pumped hydro storage	[53]
Onsite renewable generation	PV	[11,12,53,79,85,105,118,125,127,131,134,138,143,144,148,149]
	Wind	[53,125,141,144,148]
Onsite non-renewable generation	CHP	[113,135,149]
	Generator	[86]
Low-carbon technology	EV	[131]

4.5. Case Studies

4.5.1. Australian Case Study

The case study [150] performed included the C&I consumers of regional Australia and examined the DR effect on the distribution network. All the consumers have onsite PV generation and BESS system. A ToU-based DR strategy was followed, where PV and BESS were used to increase the generation during DR event. Benefits of DR was evaluated considering maximum and minimum load on the distribution network. Initially, a steady state analysis was performed which allowed the network stability to be assumed, in order to facilitate DR participation with feasible loads. In the ToU-based DR participation, battery SoC was tracked to formulate charge and discharge strategy. The battery was charged during overgeneration by PV and was discharged during the deficit of generation to support the demand maintaining the allowable SoC level. The results show a 25% reduction in load could improve the network voltage profile from (0.945–0.97) pu to (0.975 0.995) pu [150], which demonstrates the applicability of DR-integrated PV and ESS energy system.

4.5.2. Mexican Metal Structure Manufacturer

Integration of DR and onsite renewable generation and efficient production scheduling in an industry was observed developing a real-world scenario [85]. The Mexican manufacturer discussed in this case study involves production processes of plasma cutting, press brake bending, metal inert gas welding, spray painting, and assembling. The system was modelled to consume grid energy following the efficient coordination of PV, ESS charge–discharge, and the production process scheduling. The case study considered participating in the time and level of use (TLoU) program and also responding to the reduction in power consumption request. Green energy coefficient (GEC) is used to track energy efficiency and carbon footprint. The experiment, with and without PV generation and ESS, shows that a PV- and ESS-integrated system provides optimal cost savings which are 28.38% lower than the highest cost system. The PV- and ESS-integrated system also permits highest renewable integration and gives maximum GEC [85].

5. DR in Wastewater Treatment Plant (WWTP)

Industry-wise load and operational characteristics can differ from each other and require distinctly different analyses to identify individual DR potential. Many of the past studies reviewed the application of DR in cement [17,23,24,90], steel [17,23,24], alu-

minium [23,24,90], or the food industry [17,23]. The water industry is one of the extensive energy users; however, it lacks DR-based research attention. Australia's water industry accounts for about 19% of its energy consumption [4], whereas treating wastewater requires significant energy use [38]. The potential of DR integrated with ESS and ORG in wastewater treatment plants (WWTPs) is analysed in this section.

WWTPs consume about 1% of the total energy use of a country. They are also a significant greenhouse gas emitters [20]. The stringent quality requirements for treating wastewater need intensive energy, where electricity costs can vary from 25% to 50% of the total cost depending on the treatment type or plant size [151]. However, some energy-consuming processes, such as pumping or aeration, offer flexible operation, enabling the plants to provide DR services [152]. Additionally, usually the peak load operation of these plants coincides with the peak period of grid demand, which makes WWTPs a potential DR participant [19]. A WWTP can also be considered a chemical and thermal energy source, due to its energy generation capacity [153]. Energy management of such plants is pragmatic and beneficial for the plant in terms of cost reduction. The WWTP operation is typically executed by pumps, air compressors, dewatering machines, surface aerators, analysis equipment, mixers, and other machinery and equipment. There are four major steps in the treatment process named as the preliminary, primary, secondary, and tertiary (advanced) process. In the preliminary process, wastewater is pumped into the system through screening to remove large particles such as paper and rocks, before going on to primary treatment [154]. Primary treatment involves the removal of suspended particles and organic matter by sedimentation, which produces sludge [154]. Aeration and secondary clarification, typically involving biological treatment such as the activated sludge process, are the main parts of the secondary treatment [135,154]. The sludge produced from the primary and secondary treatments goes for anaerobic digestion and produces biosolids after dewatering for agricultural/commercial use. Biogas can also be captured and used to generate electricity using CHP units [135,154]. The effluent from the secondary treatment stage finally goes for tertiary treatment. Using chemical disinfection or UV filtration, the water is made ready for reuse or discharge to the surface water [135,154]. Figure 9 presents the process diagram of a typical WWTP and Figure 10 shows the typical energy consumption by the main processes in a WWTP.

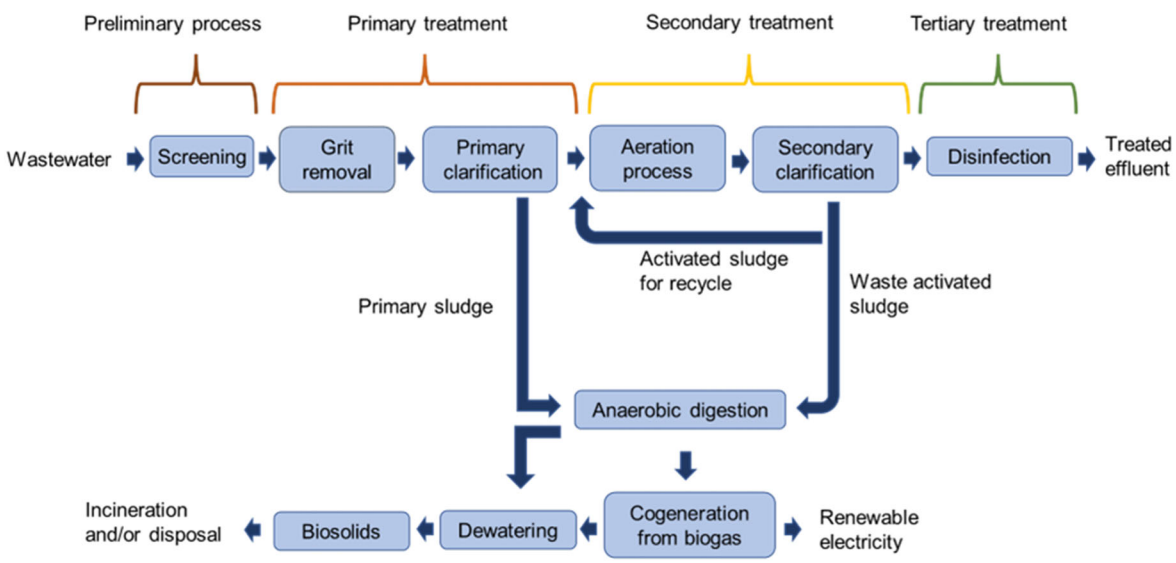

Figure 9. Typical WWTP process diagram.

Although the WWTP operational steps require substantial energy use, some of the processes provide flexible operation and DR potential to WWTP through load-shifting strategies [155]. The flexible resources and DR potential within a WWTP are reviewed and included in the sub-sections next.

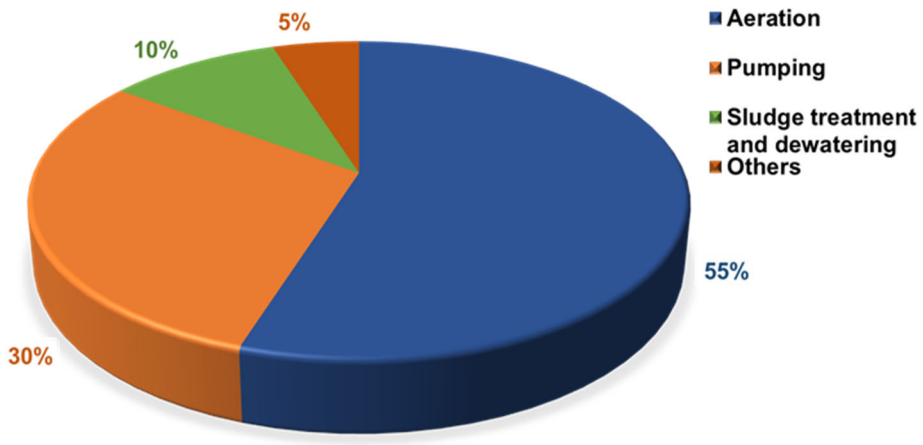

Figure 10. General energy consumption breakdown of a WWTP. Data are sourced from [151,156].

5.1. Flexible Resources

5.1.1. Aeration Process

The aeration process promotes biochemical reactions [156], where the air is introduced into the bioreactors at the secondary treatment [155]. This continuous process facilities the decomposition of organic matter to an acceptable level through biological degradation, accounting for about 45–60% of the total energy used for treatment [155]. To meet the wastewater quality requirements with energy saving, an analysis of aeration control is critical [156]. Among the three components of the aeration system, including airflow generation by blowers, airflow distribution, and aeration tanks, aerator blowers consume most of the energy [151,154]. Switching off the aeration process for justified time limits can provide DR potential while considering appropriate control parameters [157,158]. Regulating the dissolved oxygen (DO) concentration is a common process for aeration control [159]. Over-oxygenating stored wastewater during off-peak time can provide load-shifting opportunities by delaying the aeration process to avoid energy consumption during peak periods [155]. Nevertheless, the DO concentration can vary according to diurnal and seasonal variations. Hence, to avoid the risk of degraded effluent quality, maintenance of strict control parameters with monitoring of oxygenation levels should be highly considered [155]. However, further research is required to investigate DR potential using over-oxygenation modelling [155].

5.1.2. Pumping

Pumping is an essential process in WWTP encompassing raw water pumping, in-plant, and finished water pumping [160]. The use of pumping throughout the treatment process makes it the second highest energy-consuming process, taking up about 15–70% of total energy use [155]. Subject to sufficient storage, pumping can be used in load shedding and shifting strategies. The use of lift pumps with low ramp rates in intermittent operation or turning off the return pump for a period in an activated sludge application, was found to have the potential for load shifting. However, further research is required regarding intermittent operations, and interconnected and interdependent system effects [155].

5.1.3. Built-in Redundancy

Total WWTP design capacity is usually notably greater than the used operational capacity, which can offer excess storage capacity. As discussed in [155], this additional capacity can be used to store wastewater at different stages of treatment—in untreated form or partly/fully treated form to avoid high-price periods. At off-peak time, further processing or final discharge of this stored water can save energy costs. Further, the peaks of wastewater's daily inflow patterns match the peak electricity demand, offering huge potential for energy savings through load shifting while providing pumping flexibility [155].

However, these redundancies aim to counteract the risk of heavy rainfall events. Hence, utilising the opportunity for DR requires a prudent appraisal of high-quality weather forecasts to avoid any risk of over-stressed systems and discharging untreated wastewater including operational contingencies [155].

5.1.4. Onsite Generation

The anaerobic digestion during sludge processing results in biogas production which is a valuable source of energy for the flexibility. This biogas, including natural gas (methane), can generate electricity using CHP units, and shifting CHP operations to generate energy at different periods allows for curtailing grid energy usage [135,157]. Australia is effectively using this technology to produce energy by biogas, where Sydney Water WWTP meets about 21% of the operational energy requirements by using this technology [151]. Furthermore, WWTPs usually have large areas that can allow them to install PV panels and batteries. These DERs can assist in using electricity at a low price and support DR events [38]. Besides biogas, energy recovery through hydrogen production is another potential technology [161]. Hydrogen can be produced from biogas through the thermochemical method, usually by steam reforming or the partial oxidation process in the presence of a suitable catalyst. A membrane reactor is another technology that uses a membrane to separate the hydrogen from the non-hydrogen particles of the biogas feed [162]. Further detail on each method can be found in [162]. Green hydrogen (solar to hydrogen) production using proton exchange membrane (PEM) technology was also studied in [163]. The use of treated effluent water for the electrolysis process provided an efficient water reclamation strategy with increased revenue. In [163], the authors showed that applying PEM electrolysis technology provided oxygen as the only by-product without any carbon emissions. PEM technology can effectively produce pure hydrogen using renewables [164]. Highly purified input water is essential for efficient hydrogen production, so the reverse osmosis (RO) process is used for improved effluent quality [163]. Although the system requires high capital investment, the revenue earned by hydrogen selling could cover the investment cost shortly. Microbial fuel cells (MFC) are emerging technologies that can simultaneously treat wastewater and produce bioelectricity to harvest more renewable generation in a sustainable way. In this way, hydrogen can be obtained as a by-product [165,166]. MFC uses the inherent chemical energy of organic or inorganic matter to produce electricity through electrochemical reactions [165]. Although it shows potential advantages such as reduction in waste aeration and solid sludge production and odour control; however, the technology is yet to be matured for the commercial use [167]. Rescheduling the processes, including backwash pumps, biosolids thickening, and dewatering operation to off-peak periods [154] or diverting flow equalization basin [135] are the other measures to reduce peak demand in WWTPs. A brief analysis of the demand response flexibility in WWTP examined in past studies is included in Table 5.

Table 5. Research studies on wastewater treatment process demand flexibility.

Loads/Processes	References	Strategies	Remarks
Aeration control	[20,154,157,158]	Load shed and shift	Effluent quality concern: strict maintenance of control parameter needed
CHP unit	[153,154,157]	Load shed and shift	Use of waste heat for process and space heating
Equalisation basin	[135,154,168]	Load shift	Can be used for water storage
Excess storage capacity	[135,154]	Load shift	Oversize facility required
Return sludge pump	[157]	Load shift	Strict maintenance of control parameter needed
Inlet pump	[154,157]	Load shed and shift	Strict maintenance of control parameter needed
Battery	[135]	Load shift	No interruption of load
Compressed oxygenenergy storage	[169]	Load shift	Integration of water electrolysis in the activated sludge process

5.2. DR Potential in WWTP with Increased Flexibility

DR potential of WWTP through load shifting or ancillary services has been discussed in past studies [159,169]. However, the strict quality restrictions pose some concerns to implement the flexibility in the WWTP. As discussed in Section 6.1, aeration control is a flexible resource where biological nitrogen removal can provide flexible up–down regulation in the electricity market. However, the permissible limit of ammonium and total nitrogen (TN) should be considered [20]. Intermittent operation of aeration by switching off the blower can affect the DO concentration and result in effluent turbidity. It might lead to a stronger aeration activity requiring increased energy use and might offset DR benefits [19], and hence requires well-justified means to ensure flexibility.

In [170], the authors analysed the capability of different residential and industrial loads to provide frequency regulation services. The experiment showed that the control of the non-critical loads in WWTP, such as induction motors (used for pumping water and moving cleaning brushes), enables provision of ancillary services as frequency regulation. Based on the signal sent by the frequency controller, the plant control system was reprogrammed to interrupt the processes prioritising the system constraints [170].

The application of CAES technology in aeration system was examined for demand shifting [171]. Using an air compressor, air can be stored in the tank during off-peak periods and used for aeration during high-price periods. In addition, various factors are required to be considered, including wastewater characteristics and biological energy demand. Also, the operation of the activated sludge process needs to be accounted for [171]. However, CAES poses particular geographical demand and is not a well-accepted technology in Australia [62].

The VPP-based ancillary services can be obtained by aggregating the WWTPs. However, to provide a positive control reserve, flexible plant components should be examined to identify the maximum downtime, ensuring the smooth operation of WWTP processes [172].

Having substantial DR potential for WWTP, the concern of quality degradation is a significant barrier to DR implementation and obtaining the benefits of cost saving. Focusing on this concern, the study in [135] investigated the load-shifting effects on a full-scale WWTP in California. The three load-shifting strategies reported in [149] are—CHP generation time shifting, diverting flow-equalisation basin, and discharging an onsite battery. It reported that the assets which do not affect wastewater quality treatment as the CHP unit can be used for load shifting. However, the additional infrastructure capable of load stabilising like batteries, is crucial in meeting the energy reduction commitment. Coupling biogas with solar energy can also reduce energy demand and increase flexibility in plants' energy management strategies [173]. In California, a 7 MW/34 MWh network of battery arrays is installed at six water treatment, recycling, and pumping facilities. The stored energy is purchased during cheap price periods allowed to support DR events [38].

A more sustainable approach to shifting the energy demand of WWTP is studied by integrating an electrolysis process with an activated sludge process in [169]. It also considered the shifting energy demand during the aeration process using a compressed oxygen energy storage (COES) unit. Stored oxygen, the by-product of the electrolysis process, provided longer durations in load shifting than intermittent aeration without interrupting the process and affecting wastewater treatment quality. Eliminating the use of the aeration blower during peak periods could reduce energy bills. The hydrogen produced can be stored to produce electricity using a fuel cell or sold to the market to add revenues. Moreover, WWTP is also a source of thermal energy; hence, potential research should be performed focusing on extracting thermal energy from the WWTP system to meet thermal demand. Heat generated by a CHP unit using the biogas produced from the digester and the heat reclaimed from the wastewater effluent using a heat pump met internal heating demand. Further, the excess thermal energy was supplied to a residential site resulting in revenue earning [174].

Dynamic load shifting in a hybrid WWTP comprised of centralised and satellite water resource recovery facilities (WRRF) was studied to curb energy cost, power demand, and

greenhouse gas emissions (GHG) [168]. The study [168] performed three scenarios. In the first scenario, the ToU DR program was used for load shifting by diverting the influent to the main plant, while regulating the pre-set influent control parameter. In the second scenario, equalisation of the flow of the centralized plant performed, which improved the process stability and the variance in operation. The indirect GHG emissions from the use of energy for treating wastewater was reduced in the third scenario by shifting the load to the periods of lower emission intensity. The interconnection between the facilities provided the benefits of load diversion without shutting down any process. The result gives a decrease in power demand up to 25%, use of energy 4%, operating cost 8.5%, and indirect GHG emission 4.5% [168].

5.3. Outlook

The energy demand of a WWTP is influenced by the size, location, treatment process, age, wastewater quality requirements, and others [175]. Understanding tariff structure is crucial to assume a plant's energy cost. Energy consumption can also vary based on aeration control strategies using different control parameters (TN, DO, etc.) [176]. So, a cost analysis considering the tariff structure and different charges in conjunction with an efficient control strategy can reduce energy costs. Capacity charges of such plants are usually estimated against the peak demand over 12 months. A notable reduction in peak demand can result in reduced capacity charges [151]. However, reluctance and concern in participating in DR by the operators due to the absence of informed education about the program and energy data relevancy show the importance of educating the concerned operators and relevant staff, which can increase WWTP DR participation [135]. WWTP is a source of valuable energy, where renewable energy can be extracted from the biogas generated from the process, or the effluent, even the influent through advanced technology, which requires more research attention and support to utilise these opportunities in a sustainable way.

6. Summary

Energy consumption by C&I consumers is extensive, which also puts them as substantial carbon emitters. However, by exploiting the flexible loads and processes, the C&I consumers can provide substantial demand-side flexibility and participate in DR programs. Utilisation of potential technologies as energy storage and onsite renewable generation can increase their flexibility which can be briefly assessed in following sub-sections including several recommendations.

6.1. Flexibility Assessment

6.1.1. Role of ESS and ORG

Participating in DR simply with flexible loads can limit the benefits or obstacles to successful implementation. Integrating onsite renewable generation can aid consumers in reducing their grid demand and energy costs, which can be integrated with DR for operational flexibility [148,177]. PV and wind energies are the most accepted RES generation for industrial consumers [24], where PV + ESS modules are common and widely used as BTM applications [59]. In addition, installing PV modules is sensible, as the peak demand of industries usually matches the peak generation of PVs. Moreover, PV can meet the high energy demand of thermal units used in industries, providing reduced operational costs [24]. Consumers can integrate ESS or PV + ESS with DR for efficient DR participation and to enhance their demand flexibility. By using ORG, they not only can offset their energy bill and reduce dependency on grid power, but also efficiently use system flexibility [117]. Moreover, the granular restrictions of some industrial processes can be minimised with the help of onsite ESS to participate in ancillary services [114,121]. For industrial DR, utilisation of the full flexibility potential requires optimal load scheduling and a highly developed DR model considering the impact on complex processes [118]. Using ESS can allow DR participation without affecting the critical loads and processes. Further, participating in DR

with energy storage can reduce the peak demand, yielding a demand charge reduction and an increase in revenue from DR compensation [142]. The justification of the investment cost of a dedicated battery compared to the DR reward can also be improved by using a PV-coupled battery system [79]. PV generation can supply power to the loads during a DR event, decreasing the battery charging and discharging cycle and, hence, the battery degradation effects. Conversely, controlling the DR framework integrated with volatile-natured RES is challenging [24], which ESS can support.

HVAC control, as the main source of commercial DR, requires careful control and monitoring, considering the thermal comfort of the users and avoiding any negative impact [111]. An adaptive approach can enable DR implementation in commercial buildings; however, the heating and cooling of the temperature should be set considering the impact of the increase in humidity level to avoid any moisture ingress and degradation of air quality. Thermal comfort depends on the building structure, application and services, local climate and culture, and user's perception and acceptance, where a careful field analysis with a proper balance between energy consumption and thermal comfort can aid in successful DR implementation [111]. While adding thermal storage, careful consideration should be taken to avoid any surplus of energy saving strategy over the occupant's thermal comfort. Utilisation of a PV-coupled battery can be another option to enable DR events without any adverse effects. Furthermore, passive thermal storage of large commercial buildings borne by thermal inertia can reduce a building's thermal demand cost. With the benefits of small inside temperature fluctuations, shifting of the heating and cooling demand to off-peak hours is possible, and energy bill saving can be earned through the ToU scheme while considering thermal comfort [178].

6.1.2. Techno–Economic Benefits

The benefits of the ESS-ORG-DR framework can be influenced by the DR program and strategies. Tariff structures such as ToU rate encourage consumers to use ESS and PV to gain reduced energy costs [51,59]. An efficient use of electricity tariff structure demand flexibility can be achieved with reduced cost [179]. Herein, an adequate understanding of the electricity charges and tariff structure is necessary to appraise the right DR program. Consumers can reduce their electricity bills by reducing peak demand, resulting in demand charge reduction using an ESS. In addition, they can save on the electricity bill through the DR program.

Furthermore, C&I consumers can participate in the CPP rate program for energy cost savings. The rate at critical periods might be six times higher than the normal price, which restricts energy consumption during those critical periods. To avoid the high price and the risk of unavailability of variable PV generation, consumers can employ ESS to store energy and use it during those critical periods. In the case of RTP, the consumers might experience price shock due to the greatly volatile market price, which makes ESS a dependable technology to store energy and avoid the uncertain high price [59].

The variation in cost saving for DR programs was studied in [143]. It is found that the day-ahead program provided more profit than ToU and peak pricing program, and the profit was further increased by adding PV and ESS into the system. However, optimal scheduling of loads is crucial to secure the benefits [143]. The cost savings can also vary based on seasonal variations and RES size. In a PV-wind-battery energy system, the authors of [144] observed a 6.9% higher energy cost in winter than summer using the PV alone integrated with DR. Use of a 50 kW PV provided a cost saving of 8.1%, which was increased to more than 48% with a 300 kW PV capacity. When the wind generation capacity was increased from 50 kW to 300 kw, it resulted in a cost saving from 11.6% to 67%, which demonstrated better results than PV [144]. However, the variation in battery size from 50 kWh to 200 kwh provided an increased cost saving of 2.9% only. The analysis shows that increasing the size of RESs is more beneficial than increasing the battery size. A viable design should be developed considering optimal component size, operational condition, and the cost benefit analysis of a PV and battery hybrid system [180]. The cost benefit

analysis identifying the net present value, net present cost, and payback period of the hybrid system can assist in efficient investment decision [180].

To maximise the benefits, capable C&I consumers can increase onsite generation using more than one technology. Increased onsite generation can provide self-sufficiency, increase flexibility for DR participation, and provide benefits with cost savings and system peak reduction. Combining more than one ESS such as TES and battery can increase flexibility further. WWTP, with potential energy recovery sources, can extend onsite generation through hydrogen production added to PV energy. Hydrogen production using effluent water through electrolysis or using wastewater through microbial fuel cells can double the benefits—one by producing clean energy and the other by providing an economical approach for hydrogen production without using scarce drinking water. However, further research is required for techno–economic viability.

Apart from cost savings, onsite generation can avoid the rebound effect of DR due to load shifting. As consumers shift their loads to off-peak hours after the DR event due to their increased energy consumption, the benefits of valley filling can be surpassed by regenerating another peak. Thus, load shifting for valley filing can regenerate another peak at off-peak time, which might require activating peaking power plants [181]. Participation with the aid of ORG consumers can simply use onsite energy rather than load shifting. They can continue their operation, avoiding high-priced grid power while obtaining DR benefits. So, it can help the system to balance demand and supply and avoid reviving expensive peaking plants. However, more motivating DR incentives and subsidies for DER investment can encourage consumers to accept this technology and should be considered for greater benefits.

6.1.3. Environmental Benefits

Integrating renewables, such as PV or wind in an energy system, can promote RES integration, reduce conventional energy use; hence, an improved environmental impact is expected. A hybrid system including PV and battery can provide huge environmental benefits with reduced CO2 and other pollutants compared to a non-renewable enriched system [182]. DR participation reduces grid consumption, facilitate renewable penetration, and consequently assists in carbonisation reduction. Hence, integrating DR and a hybrid energy system as PV + ESS can double the benefits which is compelling to combat decarbonisation and gain economic benefits. However, a life cycle analysis (LCA) might provide more concrete measure of the environmental impact of a PV, battery hybrid system, as manufacturing of these products have environmental impacts [183]. In [183], the authors performed a LCA using a multi-crystalline PV and a Li-ion battery. It considered the production process of raw materials, fabrication of the components, their use, and end of life waste management in the analysis. The experiment was performed on the hybrid system consisting of 1 kWp PV, a 1kWh converter, and a 2.1 kwh battery. It was found that the emission contributions by PV, battery, and converter were 50%, 35%, and 15%, respectively, during their manufacturing [183]. However, compared to the grid electricity emission the benefit of hybrid system outperformed presenting a 1.6–82.6 times lower impact than the grid emission, which could save 558000t CO2-eq/year [183] referring to the environmental benefits of a PV and battery hybrid system.

6.1.4. Challenges and Limitations

Although DR provides energy cost saving, a careful consideration is crucial focusing on the demand charge (DC) of the electricity bill. Getting benefits from DR differs from DC reduction, which might defer the realisation of both benefits simultaneously; instead, consumers can lose DR incentives. In [138], different types of DR programs were analysed with DC reduction using a BTM ESS and show that using an optimum battery control strategy integrated with DR can secure both benefits while avoiding any penalties from DR events. By setting a demand charge threshold, the peak demand has been lowered to reduce DC. The battery enables the use of maximum PV generation where the use of

the stored energy at high price periods during DR events led to a DC reduction at the same time. Hence, a careful design of the DR framework to obtain maximum benefits and avoid any penalties is crucial. Employing ESS for load reduction is one of the demand-side management strategies. However, integrating ESS with DR implementation can increase the benefits, including demand charge reduction [142].

ESS sizing can also greatly influence the investment cost and savings. For instance, the optimal sizing of a Li-ion battery considering the maximum monthly cost-saving found to be larger than the optimally sized one based on maximum ROI [184], clearly showing a higher investment cost. Further, this can vary based on the ESS types. It was inferred that the use of ESS (Li-ion battery and CAES) for peak reduction demand was more profitable for users with intermittent operation than continuous operation. Furthermore, an experiment on Li-ion battery showed that an optimally sized battery was more beneficial with a shorter payback period when participated in incentive-based DR rather than merely used for peak clipping and load shifting [136].

With renewable generation, DR management requires shaping the load profile, considering the demand and the stochastic energy generation; hence, ESS is crucial for efficient coordinated control [24]. PV generation is highly variable due to the weather conditions where ESS can supply power during the absence of PV generation [85]. For efficient use in load management, the ESS characteristics must match the application's purpose and technology. Different conditions and parameters, including time horizon, PV uncertainty, process scheduling, tariff rates, buffer capacity of processes, production and inventory quantity, should also be considered for optimal load scheduling [85]. Further, the size of the BESS should be selected considering PV generation capacity, load demand, and user consumption pattern (to track charge/discharge cycles) [50]. A study in [184] found that a facility with continuous operation has a flatter demand profile than WWTP, which has less potential for peak demand reduction, requiring a smaller sizing than an intermittent operational manufacturing facility with a striking load profile [184].

Furthermore, battery parameters can be impacted by DR price signals. As the battery charge–discharge behaviour for ToU tariff varies from RTP to support the DR operation, the degree of SoC fluctuation is influenced by the DR prices [134]. The battery capacity can be reduced due to aging born out of external factors such as temperature and time, and internal factors such as SoC, DoD, and current [84]. Hence, battery degradation due to the charging and discharging can impact the battery life [59], which decreases exponentially as the depth of discharge (DoD) increases [185]. Accordingly, the flexibility provision provided by the battery comes with a significant cost of battery aging [118]. However, using onsite PV generation to support DR events can reduce dependency on batteries. Careful analysis with PV uncertainty and ESS degradation needs to be considered in integrated model optimization. Consumers can extend the use of their ESS to provide useful services to utilities, where utility providers can aggregate ESS assets to pursue reserve capacity and ancillary services as required [59]. However, this value increase might come with a cost of degraded battery life and added operational costs, which need to be considered [51]. Installation of ORG as PV also requires substantial space which might limit the access to this technology for many consumers. A hybrid system including ESS and ORG is promising; however, this requires substantial investment which necessitates cost–benefit evaluation before making an investment decision.

6.2. Further Work and Recommendations

Although the use of ESS can ease the DR program participation, the investment cost is always a factor due to the longer payback period. The use of onsite diesel generators to support any DR event should also be limited to reduce the carbon emission [119]. Nonetheless, more awareness programs and research studies can assist in behavioural and social acceptance. It should be ensured that the DR reward should be considerable compared to the reduced energy cost. Therefore, it is necessary to set incentives to attract the greater interest of consumers [59]. More initiatives with government subsidies are required to pro-

mote this technology with affordability [59]. Nevertheless, focusing on distributed energy technologies requires more work on regulation, policymaking considering energy market reformation, and a more favourable tariff structure to motivate business participation with real benefits [186]. Based on the survey conducted, several recommendations can be made as below:

- C&I consumers with inflexible loads and processes can increase their flexibility by implementing a DR-ESS-ORG framework. They can maximise benefits by using a hybrid energy system, including more than one energy storage and/or renewable generation technology, through optimal DR modelling and extensive cost–benefit analysis.
- With the aid of ESS, C&I consumers can pre-plan their load reduction/shifting strategy, generate their load reduction curve (LRC), protect their privacy, and communicate this LRC with the system operator facilitating direct load control program participation.
- Considering thermal storage as an inexpensive technology, the C&I facility can include thermal storage in the DR framework while prioritising thermal comfort for the users. Thermal comfort can be evaluated through practical field surveys involving the users.
- Considering the effect of the DR program on battery life, a good appraisal of demand profile, electricity charges, tariff structures, and/or DR incentives should be inspected for suitable battery sizing and cost-effective investment.
- WWTPs as a source of valuable energy from waste should be supported with necessary research, education, and technical know-how to cultivate their opportunity of producing green energy for their own and wider interest.

7. Conclusions

As energy costs are a significant part of operational costs, this will motivate C&I consumers to consider many strategies for reductions, including onsite generation for cost reduction, storing energy by ESS during cheap price periods, or avoiding high prices through deferring loads by DR. However, an integrated approach encompassing these sound technologies can be a potential, more sustainable, and reliable energy management platform. An integrated energy system with ORG, ESS, and DR can provide self-sufficiency in energy use. In this context, this paper surveyed the application of ESS and onsite generation to the C&I consumers integrated with DR. An overview of DR and ESS technology was presented with their classification. A detailed analysis was performed and presented to identify how ESS and ORG apply with DR implementation focusing on C&I consumers. To provide more insight into the applicability, DR in the WWTP industry was analysed and the potential of ORG integrated with DR framework was identified. Future work can be carried out to evaluate the viability of such a DR-ORG-ESS framework accompanied by a cost–benefit analysis.

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Abbreviations

DG	Distributed generation
DER	Distributed energy resources
RES	Renewable energy sources
RE	Renewable energy
DR	Demand response

DSM	Demand side management
C&I	Commercial and industrial
ESS	Energy storage system
FTM	Front of the meter
BTM	Behind-the-meter
ORG	Onsite renewable generation
EV	Electric vehicle
WWTP	Wastewater treatment plant
HVAC	Heating, ventilation and cooling
PV	Photovoltaic
DTR	Dynamic thermal rating
OTS	Optimal transmission switching
EGS	Energy generation system
AMI	Advanced metering infrastructure
DRSP	Demand response service provider
DSO	Distribution system operator
ISO	Independent system operator
ToU	Time of use
RTP	Real time pricing
CPP	Critical peak pricing
DLC	Direct load control
SC	Supercapacitor
SMES	Superconducting magnetic energy storage
MESS	Mechanical energy storage system
PHES	Pumped hydro energy storage
CAES	Compressed air energy storage
FES	Flywheel energy storage
TES	Thermal energy storage
BESS	Battery energy storage system
PCM	Phase change material
VES	Virtual energy storage
CES	Chemical energy storage
LPG	Liquified petroleum gas
SNG	Synthetic natural gas
HESS	Hydrogen energy storage system
HFC	Hydrogen fuel cell
SOC	State of the charge
SOH	State of the health
DOD	Depth of discharge
P2H	Power-to-heat
CHP	Combined heat and power
MPC	Model predictive control
STN	State task network
ST	Schedulable task
NST	Non schedulable task
CEMS	Commercial energy management system
VPP	Virtual power plant
IVPP	Industrial virtual power plant
V2G	Vehicle-to-grid
DO	Dissolved oxygen
PEM	Proton exchange membrane
RO	Reverse osmosis
MFC	Microbial fuel cell
TN	Total nitrogen
COES	Compressed oxygen energy storage
DC	Demand charge
SO	System operator

LCD	Load control device
LRC	Load reduction curve
ROI	Return of investment

Appendix A

Table A1. A summarized analysis of the research studies used in the survey.

Consumer	References	Year	DR Program/Market	ESS	ORG	Process/Loads/Main Strategy	Facilities	Highlighted Aspects
C *	[105]	2017	x	√	√	Use of optimum RE harvesting and ESS capacity	Non-deferable load facility	The nonlinear relationship between the discharging rate and the remaining charge of ESS was highlighted.
C	[136]	2023	Incentive-based	√	x	The battery itself	Large commercial building	Participation in event-based DR provided a shorter discounted payback period for the Li-ion battery.
C	[102]	2023	x	√	x	HVAC with chilled water storage	Commercial building	Flexibility potential provided through the control of temperature threshold and energy use reduced.
C	[187]	2014	Price-based: ToU	√	x	Chiller system	Commercial building	Energy management algorithms, including chiller and ESS could reduce operational cost
C	[134]	2021	Price-based: flat rate, ToU, RTP	√	√	x	Office building	Battery behaviour can vary according to different DR price signals
C&I **	[53]	2019	x	√	√	Water system including wells, pumps, seawater reverse osmosis system	Seawater desalination plant	Demand shifting of loads to utilise onsite RES generation using probabilistic weather data.
C	[79]	2021	Peak shaving and intra-day request	√	√	AHU fan, heat pump	Commercial building	Quality of flexibility introduced to address the variability of flexibility of resources
C	[108]	2023	Price-based: RTP	√	x	Refrigerators, freezers, AC, water heater, washing machine, disinfection cabinet	Commercial building	Flexible loads, optimal regulation strategy could reduce power consumption costs and peak demand
C	[133]	2019	Price-based: ToU	√	x	ESS control strategy following price signal	x	Users can maximise benefits by increasing energy consumption from ESS during peak periods.
C	[113]	2018	Price-based: RTP	√	x	Gas turbine CHP unit	Office building	Use of TES with CHP provided more economic benefits than EES
C	[107]	2017	Price-based: ToU	√	x	Flexible building loads	Commercial building	Coordination of real and virtual storages to save energy cost and demand charge
C	[139]	2015	Price-based: ToU	√	x	HVAC control	Commercial building	Load was reduced by the cooperation of pre-cooling the chiller and discharging of ESS
C	[141]	2021	Price-based: RTP	√	√	Controlling AC and non-AC loads	Food court and commercial kitchen	Increase in non-AC appliances can provide better cost saving than AC loads
C	[146]	2022	Price-based: ToU	√	x	Ice storage air conditioning system operation	Shopping mall	With the collaborative optimization of the operation and planning of ice storage and cooling air conditioning systems electricity cost was reduced

Table A1. *Cont.*

Consumer	References	Year	DR Program/Market	ESS	ORG	Process/Loads/Main Strategy	Facilities	Highlighted Aspects
C	[188]	2015	Incentive-based	√	x	chiller	Office building	Model predictive control of TES considering multi-tiered demand charge
C	[138]	2018	Ancillary services	√	√	Battery control with DC threshold	C&I site	DR with demand charge reduction using an ESS
C	[145]	2019		√	x	HVAC scheduling	Office building	MPC optimisation results reduced demand charge with improved battery life
C&I	[137]	2019	Price-based	√	x	Transferrable, deferrable, power adjustable loads	Industrial enterprise	By rationally regulating demand side resources could save electricity bill notably while satisfying user's energy consumption
C, I & R ***	[47]	2019	Incentive-based	√	√	Next-generation industrial and household level system	C&I site, residences	Provided grid support with accumulated loads and renewable generation in real time
C&I	[147]	2016	x	√	x	Compressed air energy system with air storage	Car repair shop	Load management potential notably increases with the CAES storage size
I	[127]	2021	Price-based: ToU	√	√	Transferable and reducible loads	Industrial Park	Optimal configuration of energy storage capacity was established considering ESS despatching strategy and DR
I	[86]	2021	Incentive-based	√	x	Shifting of workloads	Data centre	Simultaneous schedule of workloads, generator and battery could maximise benefit
I	[131]	2018	Price-based: ToU	√	√	HVAC with chilled water storage, EV	Tire manufacturing facility	Using the flexibility available at all parts of the facility electricity cost was reduced
I	[12]	2015	Price-based: CPP	√	√	Luxury vehicle cockpit assembly	Automobile industry	Taking advantage of onsite generation, demand scheduling and DR profit was maximised
I	[104]	2017	Ancillary services	√	√	Raw mills	Cement industry	Integration of solar energy with ESS provided cost-efficient plant scheduling and promising load following capability
I	[11]	2018	Real time and day-ahead and	√	√	server operations with delay-tolerant workload	Data centre	Co-optimization of server provisioning and power procurement fitted with DR reduced energy cost and increased RE use
I	[189]	2017	Day-ahead market	√	√	Flexible and inflexible loads	Large industrial manufacturer	Using ORG and ESS enabled DR operation for both flexible and inflexible loads
I	[122]	2016	Real time and day-ahead and	√	√	x	Data centre and manufacturing	Provided a decision-making methodology to procure energy with cut generation and aggregation strategy
I	[112]	2017	Price-based	√	√	Temperature control of HVAC system	Factory building	TES charged by PV energy is beneficial, however consideration need on the installation cost
I	[85]	2020	Price based (TimeLevel-of-Use); load reduction	√	√	Optimal production scheduling and EMS decisions	Metal structure manufacturing industry	Optimised production schedule coordinated with RES, ESS, and grid power back up could reduce energy cost

Table A1. *Cont.*

Consumer	References	Year	DR Program/Market	ESS	ORG	Process/Loads/Main Strategy	Facilities	Highlighted Aspects
I	[103]	2014	Day-ahead market	√	√	STN based production scheduling integrated with DERs	Oxygen generation facilities	DER integration with DR reduced energy cost
I	[121]	2016	Ancillary services	√	x	Cement crushing process	Cement industry	Granularity restrictions of industrial loads was reduced with ESS considering hourly operation
I	[114]	2018	Ancillary services	√	x	Cement crushing process	Cement industry	Granularity restrictions of industrial loads was reduced with ESS considering day ahead optimal scheduling
I	[149]	2018	Incentive-based	x	√	Refinery process	Oil refinery industry	An EMS framework including cogeneration facility, PV and DR could reduce electricity cost
I	[143]	2015	Price and incentive-based	√	√	Various industrial units including interdependent loads	Steel mill industry	Optimal load control scheduling through optimal energy and material usage
I	[190]	2017	Price-based: RTP	√	x	Optimal scheduling of still powder manufacturing process	Steel industry	Hourly ahead DR with ESS provided better cost reduction than day ahead DR
I	[118]	2019	Incentive-based	√	√	Discrete manufacturing process	Metal processing industry	load reduction curves generated to infer potential load reduction
I	[144]	2018	Day ahead pricing and RTP	√	√	Industrial machine, lighting, HVAC loads	Manufacturing facility	A varied cast saving was observed according to seasonal changes having RESs in the system
I	[120]	2016	Day ahead hourly pricing	√	x	Stamping process	Automobile manufacturing industry	DR energy management scheme with ESS reduced energy cost without degrading production processes
I	[125]	2020	Day ahead market	√	x	Reducible industrial loads	Eco-industrial park	Increased capacity of DR and ESS gives better RES integration and reduced grid power purchase
I	[135]	2021	Incentive-based	√	√	flow equalization basin; CHP unit	Wastewater treatment plant	Adding energy stabilising load as battery can secure DR participation
I	[142]	2020	Price-based	√	x	x	Large industries	By integrating DR commercial benefit of energy storage was increased
I	[148]	2017	Contract and incentive-based scheme	√	√	Chlor-alkali process	Chlor-alkali plant	By onsite generation using wind, solar and hydrogen integrated with DR increased revenue
I	[140]	2018	Price-based: RTP	√	x	Plastic packaging process	Food industry	Shifting of industrial load utilising battery was proposed through particular modelling
I	[191]	2023	Price-based; Incentive-based	√	x	x	Industry	Application of Reinforcement Learning algorithm focusing on economic assessment of DR

* Commercial; ** Industrial; *** Residential.

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